MSP430x2xx Family

User's Guide

Literature Number: SLAU144J
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About This Manual

This manual discusses modules and peripherals of the MSP430x2xx family of devices. Each discussion presents the module or peripheral in a general sense. Not all features and functions of all modules or peripherals are present on all devices. In addition, modules or peripherals may differ in their exact implementation between device families, or may not be fully implemented on an individual device or device family.

Pin functions, internal signal connections, and operational paramenters differ from device to device. The user should consult the device-specific datasheet for these details.

Related Documentation From Texas Instruments

For related documentation see the web site http://www.ti.com/msp430.

FCC Warning

This equipment is intended for use in a laboratory test environment only. It generates, uses, and can radiate radio frequency energy and has not been tested for compliance with the limits of computing devices pursuant to subpart J of part 15 of FCC rules, which are designed to provide reasonable protection against radio frequency interference. Operation of this equipment in other environments may cause interference with radio communications, in which case the user at his own expense will be required to take whatever measures may be required to correct this interference.

Notational Conventions

Program examples, are shown in a special typeface.

Glossary

ACLK	Auxiliary Clock	See *Basic Clock Module*
ADC	Analog-to-Digital Converter	
BOR	Brown-Out Reset	See *System Resets, Interrupts, and Operating Modes*
BSL	Bootstrap Loader	See *www.ti.com/msp430*for application reports
CPU	Central Processing Unit	See *RISC 16-Bit CPU*
DAC	Digital-to-Analog Converter	
DCO	Digitally Controlled Oscillator	See *Basic Clock Module*
dst	Destination	See *RISC 16-Bit CPU*
FLL	Frequency Locked Loop	See *FLL*+in MSP430x4xx Family User's Guide
GIE	General Interrupt Enable	See *System Resets, Interrupts, and Operating Modes*
INT(N/2)	Integer portion of N/2	
I/O	Input/Output	See *Digital I/O*
ISR	Interrupt Service Routine	
LSB	Least-Significant Bit	
LSD	Least-Significant Digit	
LPM	Low-Power Mode	See *System Resets, Interrupts, and Operating Modes*
MAB	Memory Address Bus	
MCLK	Master Clock	See *Basic Clock Module*

MDB	Memory Data Bus	
MSB	Most-Significant Bit	
MSD	Most-Significant Digit	
NMI	(Non)-Maskable Interrupt	See *System Resets, Interrupts, and Operating Modes*
PC	Program Counter	See *RISC 16-Bit CPU*
POR	Power-On Reset	See *System Resets, Interrupts, and Operating Modes*
PUC	Power-Up Clear	See *System Resets, Interrupts, and Operating Modes*
RAM	Random Access Memory	
SCG	System Clock Generator	See *System Resets, Interrupts, and Operating Modes*
SFR	Special Function Register	
SMCLK	Sub-System Master Clock	See *Basic Clock Module*
SP	Stack Pointer	See *RISC 16-Bit CPU*
SR	Status Register	See *RISC 16-Bit CPU*
src	Source	See *RISC 16-Bit CPU*
TOS	Top-of-Stack	See *RISC 16-Bit CPU*
WDT	Watchdog Timer	See *Watchdog Timer*

Register Bit Conventions

Each register is shown with a key indicating the accessibility of the each individual bit, and the initial condition:

Register Bit Accessibility and Initial Condition

Key	Bit Accessibility
rw	Read/write
r	Read only
r0	Read as 0
r1	Read as 1
w	Write only
w0	Write as 0
w1	Write as 1
(w)	No register bit implemented; writing a 1 results in a pulse. The register bit is always read as 0.
h0	Cleared by hardware
h1	Set by hardware
-0,-1	Condition after PUC
-(0),-(1)	Condition after POR

Introduction

This chapter describes the architecture of the MSP430.

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1.1 Architecture

The MSP430 incorporates a 16-bit RISC CPU, peripherals, and a flexible clock system that interconnect using a von-Neumann common memory address bus (MAB) and memory data bus (MDB) (see Figure 1-1). Partnering a modern CPU with modular memory-mapped analog and digital peripherals, the MSP430 offers solutions for demanding mixed-signal applications.

Key features of the MSP430x2xx family include:

- Ultralow-power architecture extends battery life
  - 0.1 µA RAM retention
  - 0.8 µA real-time clock mode
  - 250 µA/MIPS active
- High-performance analog ideal for precision measurement
  - Comparator-gated timers for measuring resistive elements
- 16-bit RISC CPU enables new applications at a fraction of the code size.
  - Large register file eliminates working file bottleneck
  - Compact core design reduces power consumption and cost
  - Optimized for modern high-level programming
  - Only 27 core instructions and seven addressing modes
  - Extensive vectored-interrupt capability
- In-system programmable Flash permits flexible code changes, field upgrades and data logging

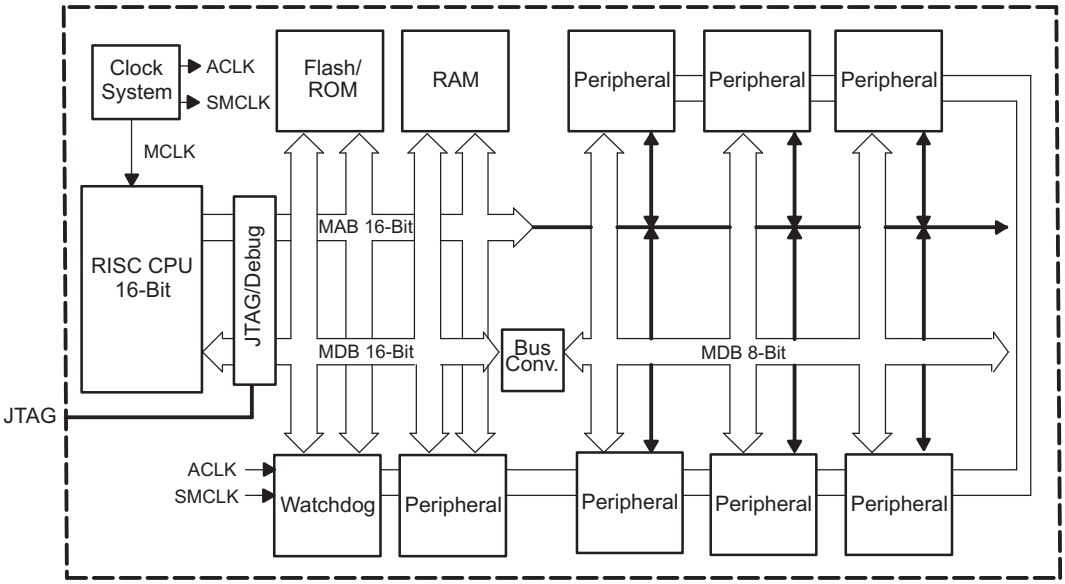

Figure 1-1. MSP430 Architecture

1.2 Flexible Clock System

The clock system is designed specifically for battery-powered applications. A low-frequency auxiliary clock (ACLK) is driven directly from a common 32-kHz watch crystal. The ACLK can be used for a background real-time clock self wake-up function. An integrated high-speed digitally controlled oscillator (DCO) can source the master clock (MCLK) used by the CPU and high-speed peripherals. By design, the DCO is active and stable in less than 2 µs at 1 MHz. MSP430-based solutions effectively use the high-performance 16-bit RISC CPU in very short bursts.

- Low-frequency auxiliary clock = Ultralow-power stand-by mode
- High-speed master clock = High performance signal processing

1.3 Embedded Emulation

Dedicated embedded emulation logic resides on the device itself and is accessed via JTAG using no additional system resources.

The benefits of embedded emulation include:

- Unobtrusive development and debug with full-speed execution, breakpoints, and single-steps in an application are supported.
- Development is in-system subject to the same characteristics as the final application.
- Mixed-signal integrity is preserved and not subject to cabling interference.

1.4 Address Space

The MSP430 von-Neumann architecture has one address space shared with special function registers (SFRs), peripherals, RAM, and Flash/ROM memory as shown in Figure 1-2. See the device-specific data sheets for specific memory maps. Code access are always performed on even addresses. Data can be accessed as bytes or words.

The addressable memory space is currently 128 KB.

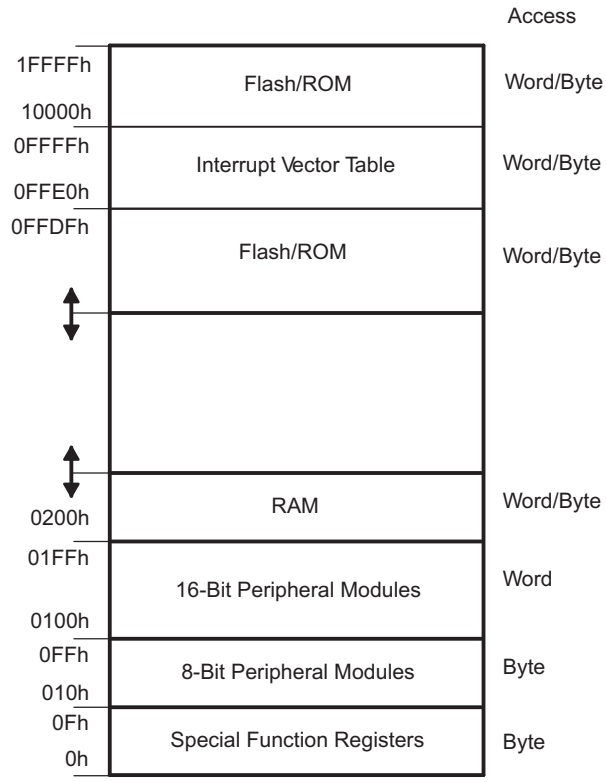

Figure 1-2. Memory Map

1.4.1 Flash/ROM

The start address of Flash/ROM depends on the amount of Flash/ROM present and varies by device. The end address for Flash/ROM is 0x0FFFF for devices with less that 60KB of Flash/ROM. Flash can be used for both code and data. Word or byte tables can be stored and used in Flash/ROM without the need to copy the tables to RAM before using them.

The interrupt vector table is mapped into the upper 16 words of Flash/ROM address space, with the highest priority interrupt vector at the highest Flash/ROM word address (0x0FFFE).

1.4.2 RAM

RAM starts at 0200h. The end address of RAM depends on the amount of RAM present and varies by device. RAM can be used for both code and data.

1.4.3 Peripheral Modules

Peripheral modules are mapped into the address space. The address space from 0100 to 01FFh is reserved for 16-bit peripheral modules. These modules should be accessed with word instructions. If byte instructions are used, only even addresses are permissible, and the high byte of the result is always 0.

The address space from 010h to 0FFh is reserved for 8-bit peripheral modules. These modules should be accessed with byte instructions. Read access of byte modules using word instructions results in unpredictable data in the high byte. If word data is written to a byte module only the low byte is written into the peripheral register, ignoring the high byte.

1.4.4 Special Function Registers (SFRs)

Some peripheral functions are configured in the SFRs. The SFRs are located in the lower 16 bytes of the address space, and are organized by byte. SFRs must be accessed using byte instructions only. See the device-specific data sheets for applicable SFR bits.

1.4.5 Memory Organization

Bytes are located at even or odd addresses. Words are only located at even addresses as shown in Figure 1-3. When using word instructions, only even addresses may be used. The low byte of a word is always an even address. The high byte is at the next odd address. For example, if a data word is located at address xxx4h, then the low byte of that data word is located at address xxx4h, and the high byte of that word is located at address xxx5h.

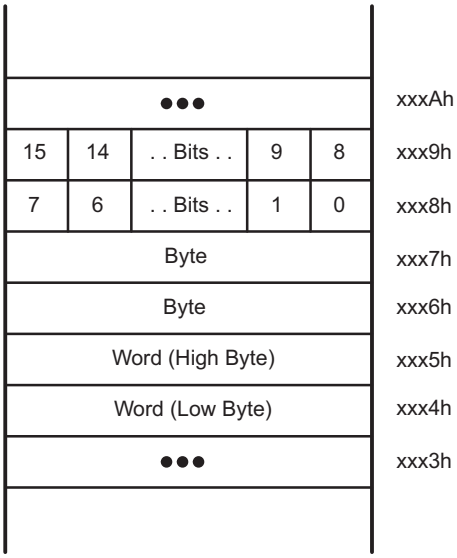

Figure 1-3. Bits, Bytes, and Words in a Byte-Organized Memory

1.5 MSP430x2xx Family Enhancements

Table 1-1 highlights enhancements made to the MSP430x2xx family. The enhancements are discussed fully in the following chapters, or in the case of improved device parameters, shown in the device-specific data sheet.

Table 1-1. MSP430x2xx Family Enhancements

Subject	Enhancement
Reset	• Brownout reset is included on all MSP430x2xx devices. • PORIFG and RSTIFG flags have been added to IFG1 to indicate the cause of a reset. • An instruction fetch from the address range 0x0000 - 0x01FF will reset the device.
Watchdog Timer	• All MSP430x2xx devices integrate the Watchdog Timer+ module (WDT+). The WDT+ ensures the clock source for the timer is never disabled.
Basic Clock System	• The LFXT1 oscillator has selectable load capacitors in LF mode. • The LFXT1 supports up to 16-MHz crystals in HF mode. • The LFXT1 includes oscillator fault detection in LF mode. • The XIN and XOUT pins are shared function pins on 20- and 28-pin devices. • The external R_{OSC} feature of the DCO not supported on some devices. Software should not set the LSB of the BCSCTL2 register in this case. See the device-specific data sheet for details. • The DCO operating frequency has been significantly increased. • The DCO temperature stability has been significantly improved.
Flash Memory	• The information memory has 4 segments of 64 bytes each. • SegmentA is individually locked with the LOCKA bit. • All information if protected from mass erase with the LOCKA bit. • Segment erases can be interrupted by an interrupt. • Flash updates can be aborted by an interrupt. • Flash programming voltage has been lowered to 2.2 V • Program/erase time has been reduced. • Clock failure aborts a flash update.
Digital I/O	• All ports have integrated pullup/pulldown resistors. • P2.6 and P2.7 functions have been added to 20- and 28- pin devices. These are shared functions with XIN and XOUT. Software must not clear the P2SELx bits for these pins if crystal operation is required.
Comparator_A	• Comparator_A has expanded input capability with a new input multiplexer.
Low Power	• Typical LPM3 current consumption has been reduced almost 50% at 3 V. DCO startup time has been significantly reduced.
Operating frequency	• The maximum operating frequency is 16 MHz at 3.3 V.
BSL	• An incorrect password causes a mass erase. • BSL entry sequence is more robust to prevent accidental entry and erasure.

System Resets, Interrupts, and Operating Modes

This chapter describes the MSP430x2xx system resets, interrupts, and operating modes.

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2.1 System Reset and Initialization

The system reset circuitry shown in Figure 2-1 sources both a power-on reset (POR) and a power-up clear (PUC) signal. Different events trigger these reset signals and different initial conditions exist depending on which signal was generated.

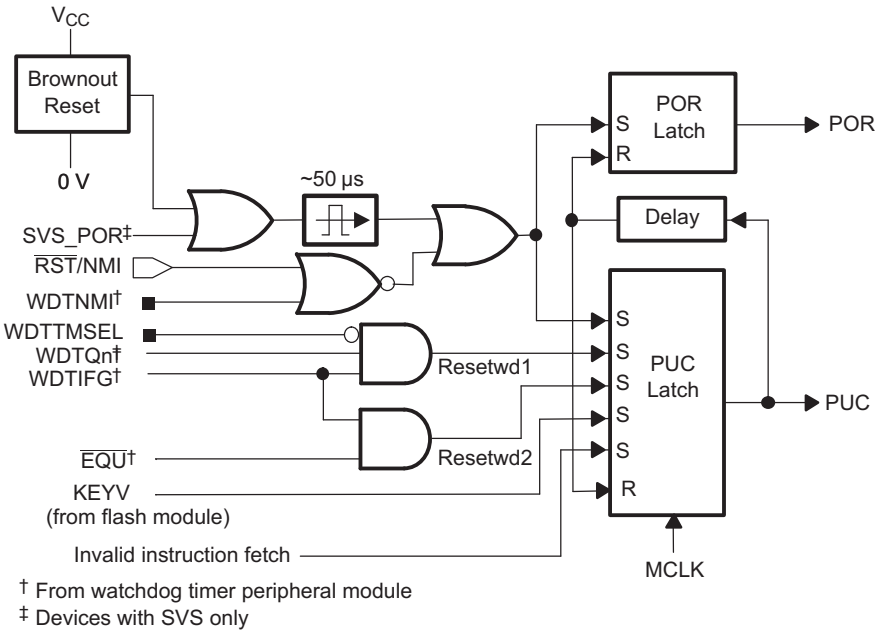


Figure 2-1. Power-On Reset and Power-Up Clear Schematic

A POR is a device reset. A POR is only generated by the following three events:

- Powering up the device
- A low signal on the $\overline{\text{RST}}$/NMI pin when configured in the reset mode
- An SVS low condition when PORON = 1.

A PUC is always generated when a POR is generated, but a POR is not generated by a PUC. The following events trigger a PUC:

- A POR signal
- Watchdog timer expiration when in watchdog mode only
- Watchdog timer security key violation
- A Flash memory security key violation
- A CPU instruction fetch from the peripheral address range 0h to 01FFh

2.1.1 Brownout Reset (BOR)

The brownout reset circuit detects low supply voltages such as when a supply voltage is applied to or removed from the V_{CC} terminal. The brownout reset circuit resets the device by triggering a POR signal when power is applied or removed. The operating levels are shown in Figure 2-2.

The POR signal becomes active when V_{CC} crosses the $V_{CC(start)}$ level. It remains active until V_{CC} crosses the $V_{(B\_IT+)}$ threshold and the delay $t_{(BOR)}$ elapses. The delay $t_{(BOR)}$ is adaptive being longer for a slow ramping V_{CC}. The hysteresis $V_{hys(B\_IT-)}$ ensures that the supply voltage must drop below $V_{(B\_IT-)}$ to generate another POR signal from the brownout reset circuitry.

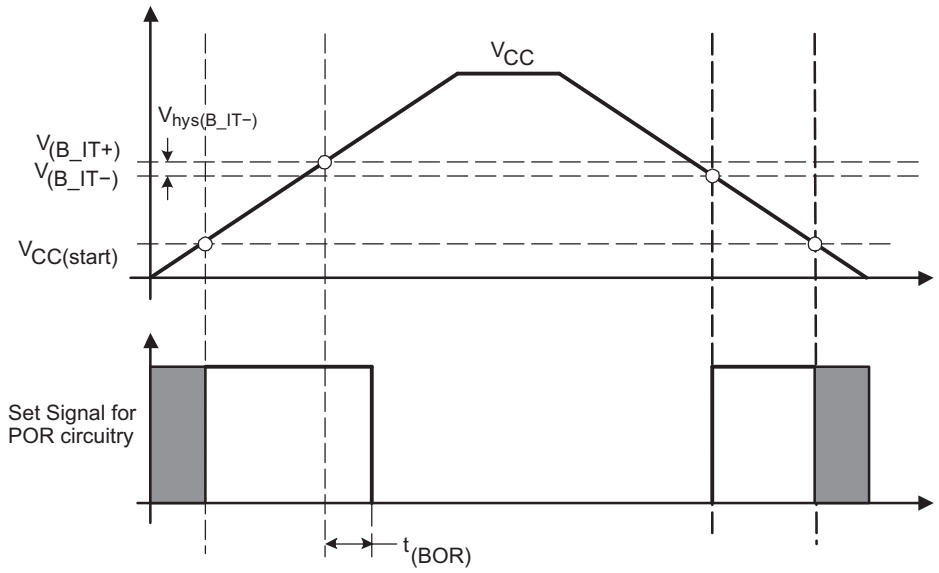


Figure 2-2. Brownout Timing

As the $V_{(B\_IT-)}$ level is significantly above the V_{min} level of the POR circuit, the BOR provides a reset for power failures where V_{CC} does not fall below V_{min}. See device-specific data sheet for parameters.

2.1.2 Device Initial Conditions After System Reset

After a POR, the initial MSP430 conditions are:

- The $\overline{RST}$/NMI pin is configured in the reset mode.
- I/O pins are switched to input mode as described in the *Digital I/O* chapter.
- Other peripheral modules and registers are initialized as described in their respective chapters in this manual.
- Status register (SR) is reset.
- The watchdog timer powers up active in watchdog mode.
- Program counter (PC) is loaded with address contained at reset vector location (0FFFEh). If the reset vectors content is 0FFFFh the device will be disabled for minimum power consumption.

2.1.2.1 Software Initialization

After a system reset, user software must initialize the MSP430 for the application requirements. The following must occur:

- Initialize the SP, typically to the top of RAM.
- Initialize the watchdog to the requirements of the application.
- Configure peripheral modules to the requirements of the application.

Additionally, the watchdog timer, oscillator fault, and flash memory flags can be evaluated to determine the source of the reset.

2.2 Interrupts

The interrupt priorities are fixed and defined by the arrangement of the modules in the connection chain as shown in Figure 2-3. The nearer a module is to the CPU/NMIRS, the higher the priority. Interrupt priorities determine what interrupt is taken when more than one interrupt is pending simultaneously.

There are three types of interrupts:

- System reset
- (Non)-maskable NMI
- Maskable

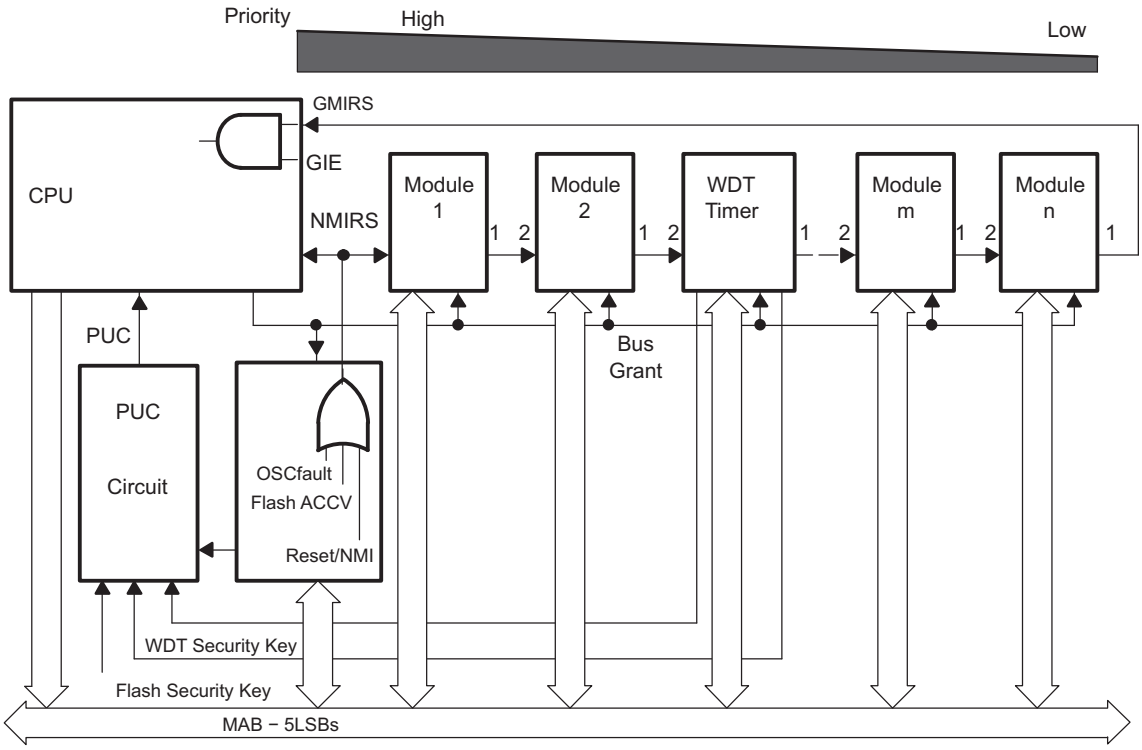


Figure 2-3. Interrupt Priority

2.2.1 (Non)-Maskable Interrupts (NMI)

(Non)-maskable NMI interrupts are not masked by the general interrupt enable bit (GIE), but are enabled by individual interrupt enable bits (NMIIE, ACCVIE, OFIE). When a NMI interrupt is accepted, all NMI interrupt enable bits are automatically reset. Program execution begins at the address stored in the (non)-maskable interrupt vector, 0FFFCh. User software must set the required NMI interrupt enable bits for the interrupt to be re-enabled. The block diagram for NMI sources is shown in Figure 2-4.

A (non)-maskable NMI interrupt can be generated by three sources:

- An edge on the $\overline{\text{RST}}$/NMI pin when configured in NMI mode
- An oscillator fault occurs
- An access violation to the flash memory

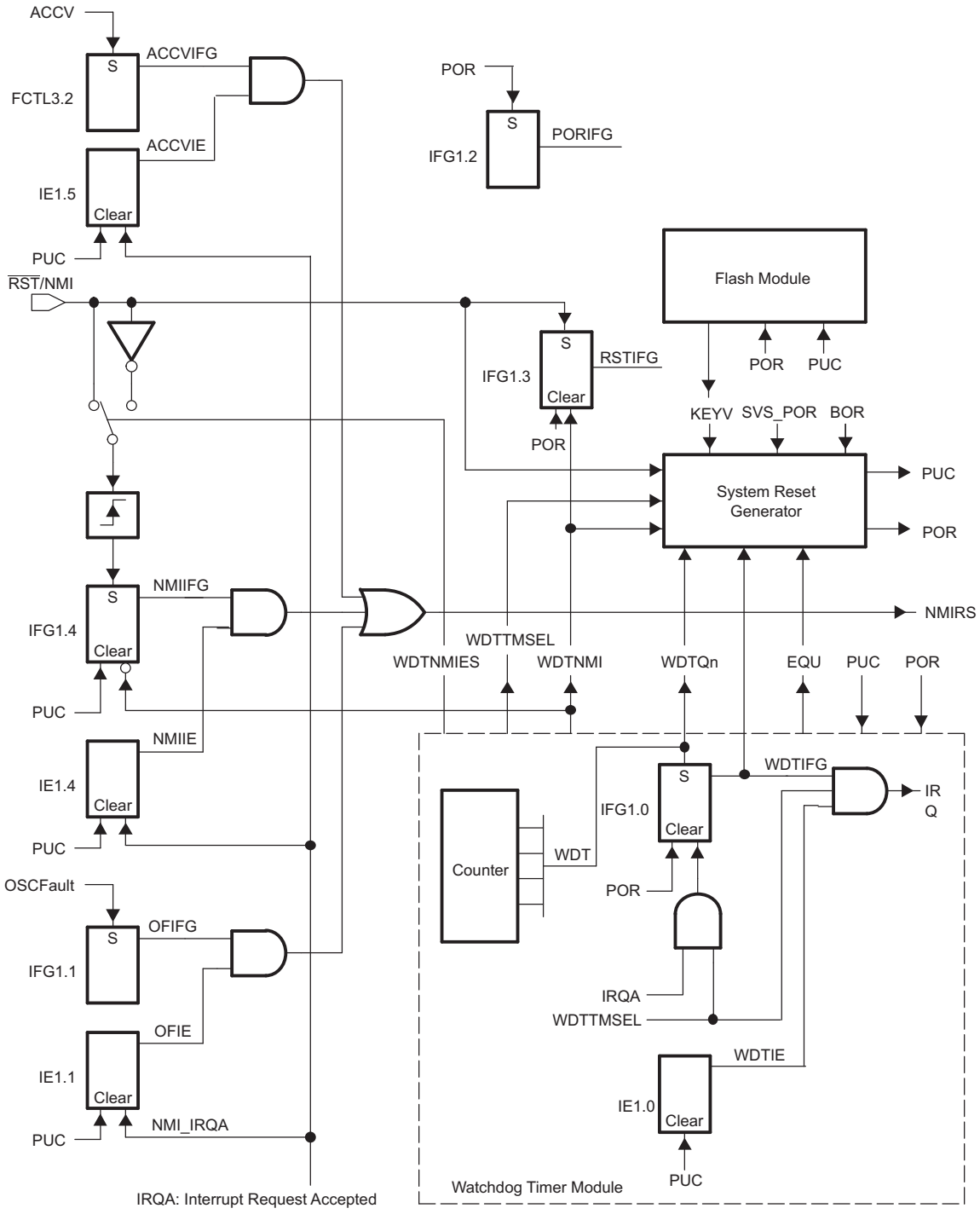


Figure 2-4. Block Diagram of (Non)-Maskable Interrupt Sources

2.2.1.1 Reset/NMI Pin

At power-up, the $\overline{\text{RST}}$/NMI pin is configured in the reset mode. The function of the $\overline{\text{RST}}$/NMI pins is selected in the watchdog control register WDTCTL. If the $\overline{\text{RST}}$/NMI pin is set to the reset function, the CPU is held in the reset state as long as the $\overline{\text{RST}}$/NMI pin is held low. After the input changes to a high state, the CPU starts program execution at the word address stored in the reset vector, 0FFFEh, and the RSTIFG flag is set.

If the $\overline{\text{RST}}$/NMI pin is configured by user software to the NMI function, a signal edge selected by the WDTNMIES bit generates an NMI interrupt if the NMIIE bit is set. The $\overline{\text{RST}}$/NMI flag NMIIFG is also set.

NOTE: Holding $\overline{\text{RST}}$/NMI Low

When configured in the NMI mode, a signal generating an NMI event should not hold the $\overline{\text{RST}}$/NMI pin low. If a PUC occurs from a different source while the NMI signal is low, the device will be held in the reset state because a PUC changes the $\overline{\text{RST}}$/NMI pin to the reset function.

NOTE: Modifying WDTNMIES

When NMI mode is selected and the WDTNMIES bit is changed, an NMI can be generated, depending on the actual level at the $\overline{\text{RST}}$/NMI pin. When the NMI edge select bit is changed before selecting the NMI mode, no NMI is generated.

2.2.1.2 Flash Access Violation

The flash ACCVIFG flag is set when a flash access violation occurs. The flash access violation can be enabled to generate an NMI interrupt by setting the ACCVIE bit. The ACCVIFG flag can then be tested by the NMI interrupt service routine to determine if the NMI was caused by a flash access violation.

2.2.1.3 Oscillator Fault

The oscillator fault signal warns of a possible error condition with the crystal oscillator. The oscillator fault can be enabled to generate an NMI interrupt by setting the OFIE bit. The OFIFG flag can then be tested by NMI the interrupt service routine to determine if the NMI was caused by an oscillator fault.

A PUC signal can trigger an oscillator fault, because the PUC switches the LFXT1 to LF mode, therefore switching off the HF mode. The PUC signal also switches off the XT2 oscillator.

2.2.1.4 Example of an NMI Interrupt Handler

The NMI interrupt is a multiple-source interrupt. An NMI interrupt automatically resets the NMIIE, OFIE and ACCVIE interrupt-enable bits. The user NMI service routine resets the interrupt flags and re-enables the interrupt-enable bits according to the application needs as shown in Figure 2-5.

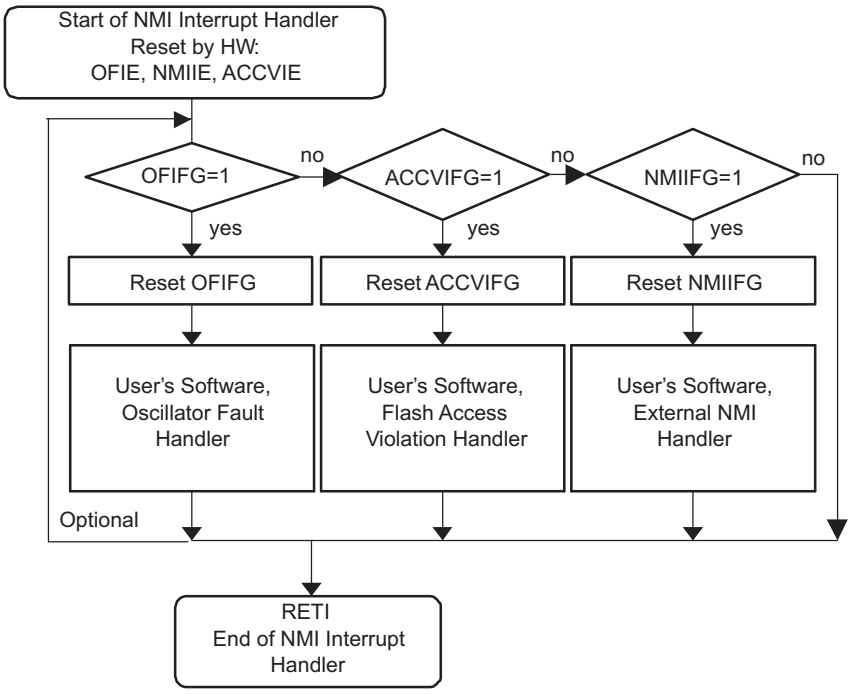


Figure 2-5. NMI Interrupt Handler

NOTE: Enabling NMI Interrupts with ACCVIE, NMIIE, and OFIE

To prevent nested NMI interrupts, the ACCVIE, NMIIE, and OFIE enable bits should not be set inside of an NMI interrupt service routine.

2.2.2 Maskable Interrupts

Maskable interrupts are caused by peripherals with interrupt capability including the watchdog timer overflow in interval-timer mode. Each maskable interrupt source can be disabled individually by an interrupt enable bit, or all maskable interrupts can be disabled by the general interrupt enable (GIE) bit in the status register (SR).

Each individual peripheral interrupt is discussed in the associated peripheral module chapter in this manual.

2.2.3 Interrupt Processing

When an interrupt is requested from a peripheral and the peripheral interrupt enable bit and GIE bit are set, the interrupt service routine is requested. Only the individual enable bit must be set for (non)-maskable interrupts to be requested.

2.2.3.1 Interrupt Acceptance

The interrupt latency is 5 cycles (CPUx) or 6 cycles (CPU), starting with the acceptance of an interrupt request and lasting until the start of execution of the first instruction of the interrupt-service routine, as shown in Figure 2-6. The interrupt logic executes the following:

1. Any currently executing instruction is completed.
2. The PC, which points to the next instruction, is pushed onto the stack.
3. The SR is pushed onto the stack.
4. The interrupt with the highest priority is selected if multiple interrupts occurred during the last instruction and are pending for service.
5. The interrupt request flag resets automatically on single-source flags. Multiple source flags remain set for servicing by software.
6. The SR is cleared. This terminates any low-power mode. Because the GIE bit is cleared, further interrupts are disabled.
7. The content of the interrupt vector is loaded into the PC: the program continues with the interrupt service routine at that address.

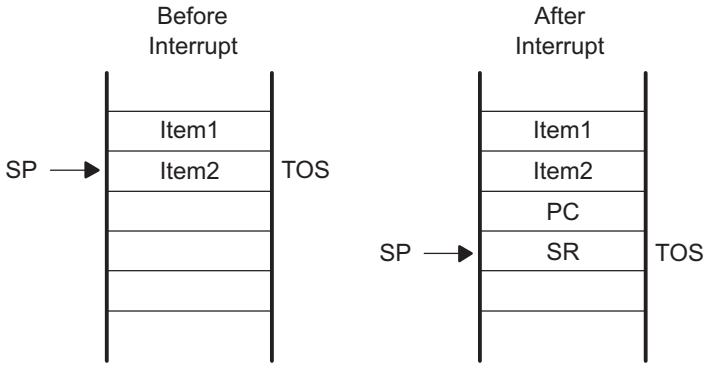


Figure 2-6. Interrupt Processing

2.2.3.2 Return From Interrupt

The interrupt handling routine terminates with the instruction:

RETI (return from an interrupt service routine)

The return from the interrupt takes 5 cycles (CPU) or 3 cycles (CPUx) to execute the following actions and is illustrated in Figure 2-7.

1. The SR with all previous settings pops from the stack. All previous settings of GIE, CPUOFF, etc. are now in effect, regardless of the settings used during the interrupt service routine.
2. The PC pops from the stack and begins execution at the point where it was interrupted.

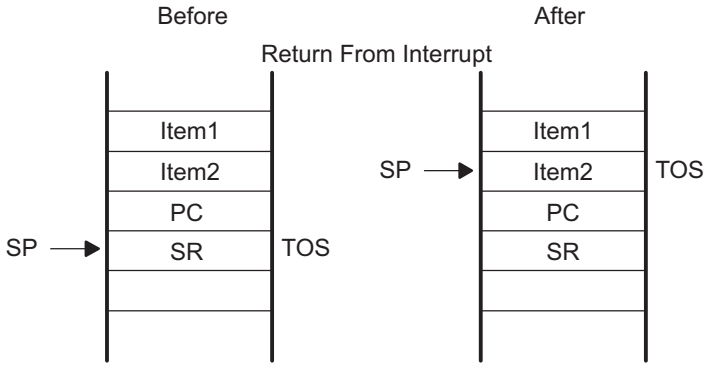


Figure 2-7. Return From Interrupt

2.2.3.3 Interrupt Nesting

Interrupt nesting is enabled if the GIE bit is set inside an interrupt service routine. When interrupt nesting is enabled, any interrupt occurring during an interrupt service routine will interrupt the routine, regardless of the interrupt priorities.

2.2.4 Interrupt Vectors

The interrupt vectors and the power-up starting address are located in the address range 0FFFFh to 0FFC0h, as described in Table 2-1. A vector is programmed by the user with the 16-bit address of the corresponding interrupt service routine. See the device-specific data sheet for the complete interrupt vector list.

It is recommended to provide an interrupt service routine for each interrupt vector that is assigned to a module. A dummy interrupt service routine can consist of just the RETI instruction and several interrupt vectors can point to it.

Unassigned interrupt vectors can be used for regular program code if necessary.

Some module enable bits, interrupt enable bits, and interrupt flags are located in the SFRs. The SFRs are located in the lower address range and are implemented in byte format. SFRs must be accessed using byte instructions. See the device-specific data sheet for the SFR configuration.

Table 2-1. Interrupt Sources, Flags, and Vectors

Interrupt Source	Interrupt Flag	System Interrupt	Word Address	Priority
Power-up, external reset, watchdog, flash password, illegal instruction fetch	PORIFG RSTIFG WDTIFG KEYV	Reset	0FFFEh	31, highest
NMI, oscillator fault, flash memory access violation	NMIIFG OFIFG ACCVIFG	(non)-maskable (non)-maskable (non)-maskable	0FFFCh	30
device-specific			0FFFAh	29
device-specific			0FFF8h	28
device-specific			0FFF6h	27
Watchdog timer	WDTIFG	maskable	0FFF4h	26
device-specific			0FFF2h	25
device-specific			0FFF0h	24
device-specific			0FFEEh	23
device-specific			0FFECh	22
device-specific			0FFEAh	21
device-specific			0FFE8h	20
device-specific			0FFE6h	19
device-specific			0FFE4h	18
device-specific			0FFE2h	17
device-specific			0FFE0h	16
device-specific			0FFDEh	15
device-specific			0FFDCh	14
device-specific			0FFDAh	13
device-specific			0FFD8h	12
device-specific			0FFD6h	11
device-specific			0FFD4h	10
device-specific			0FFD2h	9
device-specific			0FFD0h	8
device-specific			0FFCEh	7
device-specific			0FFCCh	6
device-specific			0FFCAh	5
device-specific			0FFC8h	4
device-specific			0FFC6h	3
device-specific			0FFC4h	2
device-specific			0FFC2h	1
device-specific			0FFC0h	0, lowest

2.3 Operating Modes

The MSP430 family is designed for ultralow-power applications and uses different operating modes shown in Figure 2-9.

The operating modes take into account three different needs:

- Ultralow-power
- Speed and data throughput
- Minimization of individual peripheral current consumption

The MSP430 typical current consumption is shown in Figure 2-8.

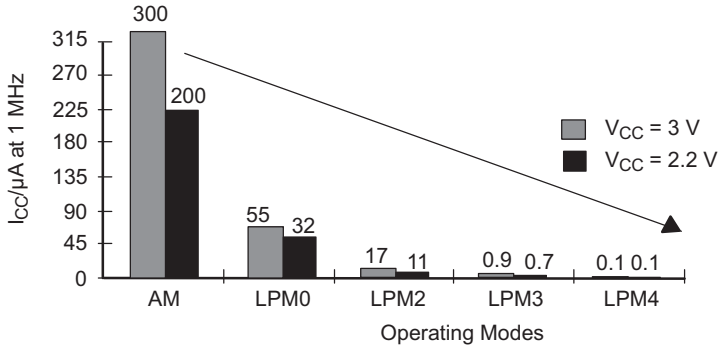


Figure 2-8. Typical Current Consumption of 'F21x1 Devices vs Operating Modes

The low-power modes 0 to 4 are configured with the CPUOFF, OSCOFF, SCG0, and SCG1 bits in the status register The advantage of including the CPUOFF, OSCOFF, SCG0, and SCG1 mode-control bits in the status register is that the present operating mode is saved onto the stack during an interrupt service routine. Program flow returns to the previous operating mode if the saved SR value is not altered during the interrupt service routine. Program flow can be returned to a different operating mode by manipulating the saved SR value on the stack inside of the interrupt service routine. The mode-control bits and the stack can be accessed with any instruction.

When setting any of the mode-control bits, the selected operating mode takes effect immediately (see Figure 2-9). Peripherals operating with any disabled clock are disabled until the clock becomes active. The peripherals may also be disabled with their individual control register settings. All I/O port pins and RAM/registers are unchanged. Wake up is possible through all enabled interrupts.

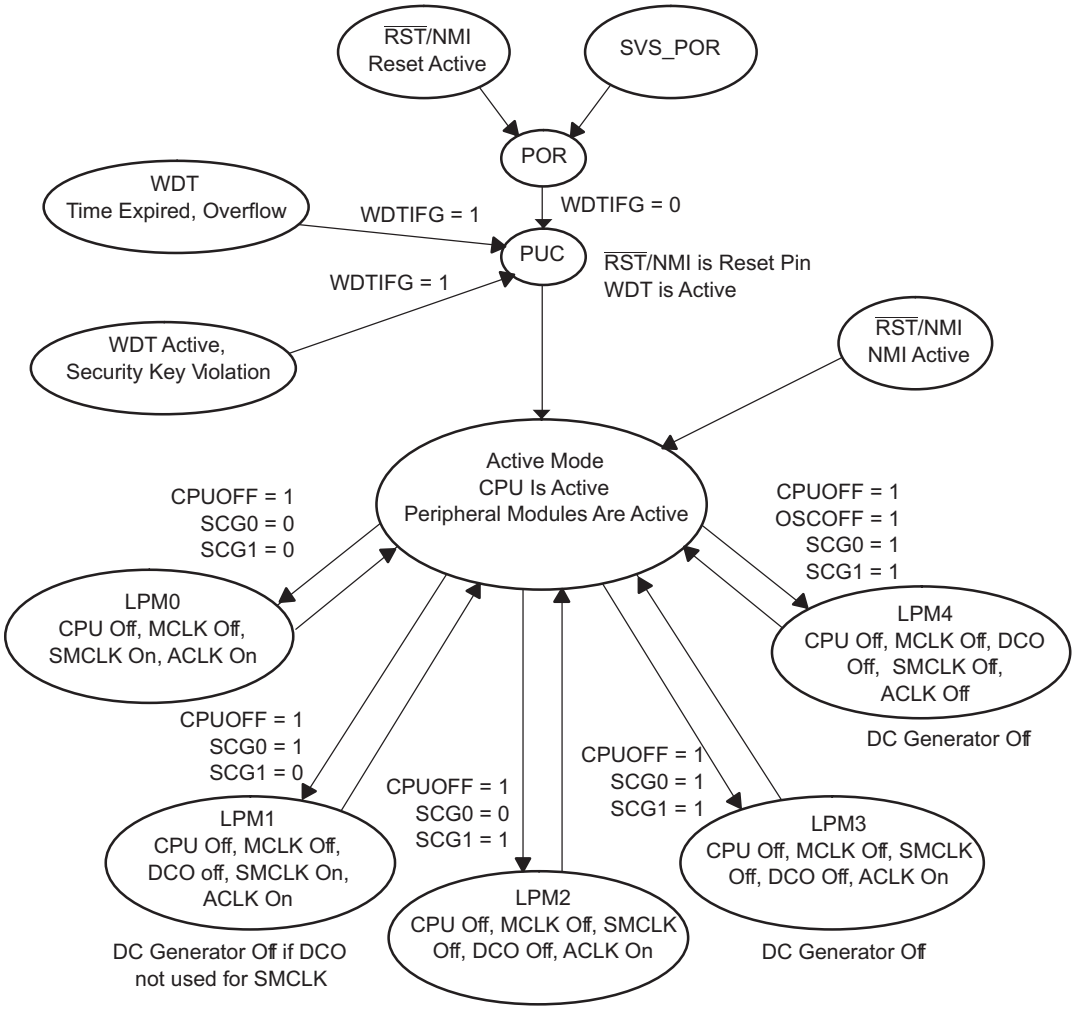


Figure 2-9. Operating Modes For Basic Clock System

Table 2-2. Operating Modes For Basic Clock System

SCG1	SCG0	OSCOFF	CPUOFF	Mode	CPU and Clocks Status
0	0	0	0	Active	CPU is active, all enabled clocks are active
0	0	0	1	LPM0	CPU, MCLK are disabled, SMCLK, ACLK are active
0	1	0	1	LPM1	CPU, MCLK are disabled. DCO and DC generator are disabled if the DCO is not used for SMCLK. ACLK is active.
1	0	0	1	LPM2	CPU, MCLK, SMCLK, DCO are disabled. DC generator remains enabled. ACLK is active.
1	1	0	1	LPM3	CPU, MCLK, SMCLK, DCO are disabled. DC generator disabled. ACLK is active.
1	1	1	1	LPM4	CPU and all clocks disabled

2.3.1 Entering and Exiting Low-Power Modes

An enabled interrupt event wakes the MSP430 from any of the low-power operating modes. The program flow is:

- Enter interrupt service routine:
  - The PC and SR are stored on the stack
  - The CPUOFF, SCG1, and OSCOFF bits are automatically reset
- Options for returning from the interrupt service routine:
  - The original SR is popped from the stack, restoring the previous operating mode.
  - The SR bits stored on the stack can be modified within the interrupt service routine returning to a different operating mode when the RETI instruction is executed.

```
; Enter LPM0 Example
  BIS    #GIE+CPUOFF,SR            ; Enter LPM0
;  ...                             ; Program stops here
;
; Exit LPM0 Interrupt Service Routine
  BIC    #CPUOFF,0(SP)             ; Exit LPM0 on RETI
  RETI

; Enter LPM3 Example
  BIS    #GIE+CPUOFF+SCG1+SCG0,SR  ; Enter LPM3
;  ...                             ; Program stops here
;
; Exit LPM3 Interrupt Service Routine
  BIC    #CPUOFF+SCG1+SCG0,0(SP)   ; Exit LPM3 on RETI
  RETI
```

2.4 Principles for Low-Power Applications

Often, the most important factor for reducing power consumption is using the MSP430 clock system to maximize the time in LPM3. LPM3 power consumption is less than 2 µA typical with both a real-time clock function and all interrupts active. A 32-kHz watch crystal is used for the ACLK and the CPU is clocked from the DCO (normally off) which has a 1-µs wake-up.

- Use interrupts to wake the processor and control program flow.
- Peripherals should be switched on only when needed.
- Use low-power integrated peripheral modules in place of software driven functions. For example Timer_A and Timer_B can automatically generate PWM and capture external timing, with no CPU resources.
- Calculated branching and fast table look-ups should be used in place of flag polling and long software calculations.
- Avoid frequent subroutine and function calls due to overhead.
- For longer software routines, single-cycle CPU registers should be used.

2.5 Connection of Unused Pins

The correct termination of all unused pins is listed in Table 2-3.

Table 2-3. Connection of Unused Pins

Pin	Potential	Comment
AV_{CC}	DVCC	
AV_{SS}	DVSS	
V_{REF+}	Open	
V_{eREF+}	DVSS	
V_{REF-}/V_{eREF-}	DVSS	
XIN	DVCC	For dedicated XIN pins only. XIN pins with shared GPIO functions should be programmed to GPIO and follow Px.0 to Px.7 recomendations.
XOUT	Open	For dedicated XOUT pins only. XOUT pins with shared GPIO functions should be programmed to GPIO and follow Px.0 to Px.7 recomendations.
XT2IN	DVSS	For dedicated X2IN pins only. X2IN pins with shared GPIO functions should be programmed to GPIO and follow Px.0 to Px.7 recomendations.
XT2OUT	Open	For dedicated X2OUT pins only. X2OUT pins with shared GPIO functions should be programmed to GPIO and follow Px.0 to Px.7 recomendations.
Px.0 to Px.7	Open	Switched to port function, output direction or input with pullup/pulldown enabled
$\overline{RST}$/NMI	DVCC or VCC	47 kΩ pullup with 10 nF (2.2 nF[(1)]) pulldown
Test	Open	20xx, 21xx, 22xx devices
TDO	Open	
TDI	Open	
TMS	Open	
TCK	Open	

(1) The pulldown capacitor should not exceed 2.2 nF when using devices with Spy-Bi-Wire interface in Spy-Bi-Wire mode or in 4-wire JTAG mode with TI tools like FET interfaces or GANG programmers.

CPU

This chapter describes the MSP430 CPU, addressing modes, and instruction set.

Topic **Page**

3.1 CPU Introduction

The CPU incorporates features specifically designed for modern programming techniques such as calculated branching, table processing, and the use of high-level languages such as C. The CPU can address the complete address range without paging.

The CPU features include:

- RISC architecture with 27 instructions and 7 addressing modes.
- Orthogonal architecture with every instruction usable with every addressing mode.
- Full register access including program counter, status registers, and stack pointer.
- Single-cycle register operations.
- Large 16-bit register file reduces fetches to memory.
- 16-bit address bus allows direct access and branching throughout entire memory range.
- 16-bit data bus allows direct manipulation of word-wide arguments.
- Constant generator provides six most used immediate values and reduces code size.
- Direct memory-to-memory transfers without intermediate register holding.
- Word and byte addressing and instruction formats.

The block diagram of the CPU is shown in Figure 3-1.

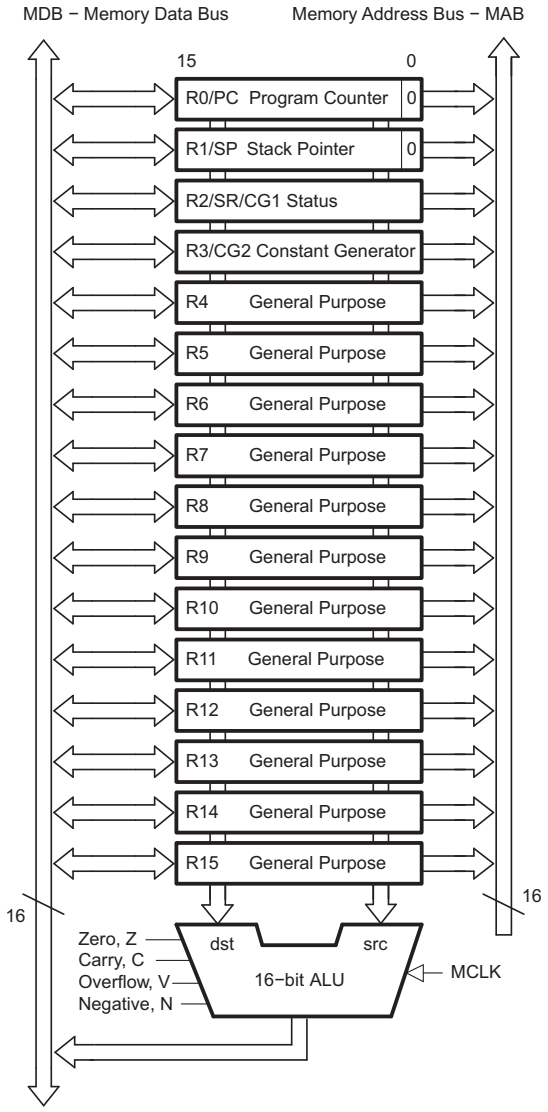


Figure 3-1. CPU Block Diagram

3.2 CPU Registers

The CPU incorporates sixteen 16-bit registers. R0, R1, R2, and R3 have dedicated functions. R4 to R15 are working registers for general use.

3.2.1 Program Counter (PC)

The 16-bit program counter (PC/R0) points to the next instruction to be executed. Each instruction uses an even number of bytes (two, four, or six), and the PC is incremented accordingly. Instruction accesses in the 64-KB address space are performed on word boundaries, and the PC is aligned to even addresses. Figure 3-2 shows the program counter.

Figure 3-2. Program Counter

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Program Counter Bits 15 to 1															0

The PC can be addressed with all instructions and addressing modes. A few examples:

```
MOV  #LABEL,PC    ; Branch to address LABEL
MOV  LABEL,PC     ; Branch to address contained in LABEL
MOV  @R14,PC      ; Branch indirect to address in R14
```

3.2.2 Stack Pointer (SP)

The stack pointer (SP/R1) is used by the CPU to store the return addresses of subroutine calls and interrupts. It uses a predecrement, postincrement scheme. In addition, the SP can be used by software with all instructions and addressing modes. Figure 3-3 shows the SP. The SP is initialized into RAM by the user, and is aligned to even addresses.

Figure 3-4 shows stack usage.

Figure 3-3. Stack Counter

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Stack Pointer Bits 15 to 1															0

```
MOV   2(SP),R6    ; Item I2 -> R6
MOV   R7,0(SP)    ; Overwrite TOS with R7
PUSH  #0123h      ; Put 0123h onto TOS
POP   R8          ; R8 = 0123h
```

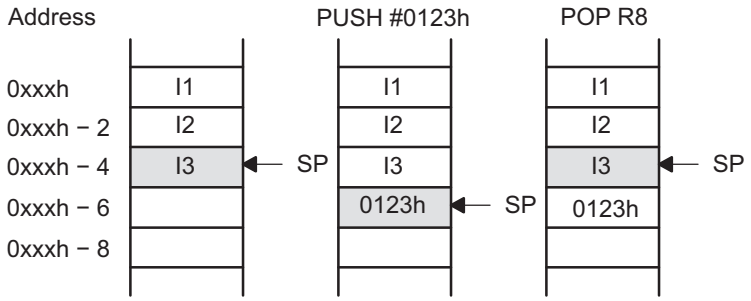
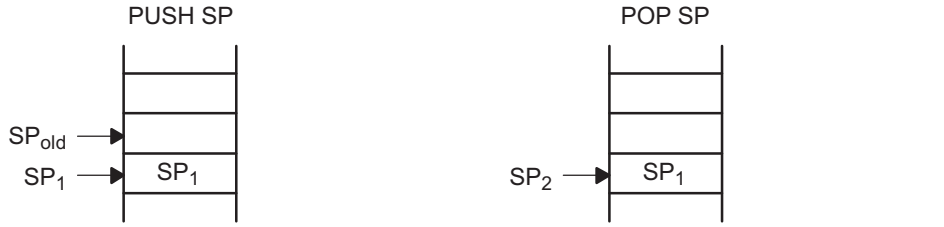


Figure 3-4. Stack Usage

The special cases of using the SP as an argument to the PUSH and POP instructions are described and shown in Figure 3-5.



The stack pointer is changed after a PUSH SP instruction.

The stack pointer is not changed after a POP SP instruction. The POP SP instruction places SP1 into the stack pointer SP (SP2=SP1)

Figure 3-5. PUSH SP - POP SP Sequence

3.2.3 Status Register (SR)

The status register (SR/R2), used as a source or destination register, can be used in the register mode only addressed with word instructions. The remaining combinations of addressing modes are used to support the constant generator. Figure 3-6 shows the SR bits.

Figure 3-6. Status Register Bits

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Reserved							V	SCG1	SCG0	OSC OFF	CPU OFF	GIE	N	Z	C
rw-0							rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

Table 3-1 describes the status register bits.

Table 3-1. Description of Status Register Bits

Bit	Description	
V	Overflow bit. This bit is set when the result of an arithmetic operation overflows the signed-variable range.	
	ADD(.B),ADDC(.B)	Set when: Positive + Positive = Negative Negative + Negative = Positive Otherwise reset
	SUB(.B),SUBC(.B),CMP(.B)	Set when: Positive – Negative = Negative Negative – Positive = Positive Otherwise reset
SCG1	System clock generator 1. When set, turns off the SMCLK.	
SCG0	System clock generator 0. When set, turns off the DCO dc generator, if DCOCLK is not used for MCLK or SMCLK.	
OSCOFF	Oscillator Off. When set, turns off the LFXT1 crystal oscillator, when LFXT1CLK is not use for MCLK or SMCLK.	
CPUOFF	CPU off. When set, turns off the CPU.	
GIE	General interrupt enable. When set, enables maskable interrupts. When reset, all maskable interrupts are disabled.	
N	Negative bit. Set when the result of a byte or word operation is negative and cleared when the result is not negative. Word operation: N is set to the value of bit 15 of the result. Byte operation: N is set to the value of bit 7 of the result.	
Z	Zero bit. Set when the result of a byte or word operation is 0 and cleared when the result is not 0.	
C	Carry bit. Set when the result of a byte or word operation produced a carry and cleared when no carry occurred.	

3.2.4 Constant Generator Registers CG1 and CG2

Six commonly-used constants are generated with the constant generator registers R2 and R3, without requiring an additional 16-bit word of program code. The constants are selected with the source-register addressing modes (As), as described in Table 3-2.

Table 3-2. Values of Constant Generators CG1, CG2

Register	As	Constant	Remarks
R2	00	– – – – –	Register mode
R2	01	(0)	Absolute address mode
R2	10	00004h	+4, bit processing
R2	11	00008h	+8, bit processing
R3	00	00000h	0, word processing
R3	01	00001h	+1
R3	10	00002h	+2, bit processing
R3	11	0FFFFh	-1, word processing

The constant generator advantages are:

- No special instructions required
- No additional code word for the six constants
- No code memory access required to retrieve the constant

The assembler uses the constant generator automatically if one of the six constants is used as an immediate source operand. Registers R2 and R3, used in the constant mode, cannot be addressed explicitly; they act as source-only registers.

3.2.4.1 Constant Generator - Expanded Instruction Set

The RISC instruction set of the MSP430 has only 27 instructions. However, the constant generator allows the MSP430 assembler to support 24 additional, emulated instructions. For example, the single-operand instruction

```
CLR   dst
```

is emulated by the double-operand instruction with the same length:

```
MOV   R3,dst
```

where the #0 is replaced by the assembler, and R3 is used with As=00.

```
INC   dst
```

is replaced by:

```
ADD   0(R3),dst
```

3.2.5 General-Purpose Registers R4 to R15

The twelve registers, R4-R15, are general-purpose registers. All of these registers can be used as data registers, address pointers, or index values and can be accessed with byte or word instructions as shown in Figure 3-7.

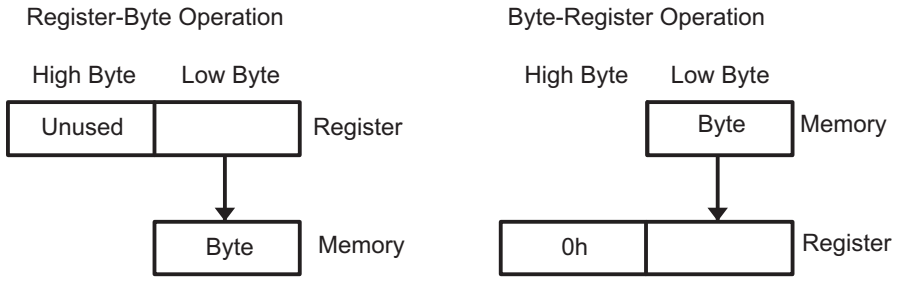


Figure 3-7. Register-Byte/Byte-Register Operations

Example Register-Byte Operation

R5 = 0A28Fh
R6 = 0203h
Mem(0203h) = 012h

```
ADD.B     R5,0(R6)
```

```
  08Fh
+ 012h
-------
  0A1h
```

Mem (0203h) = 0A1h
C = 0, Z = 0, N = 1

(Low byte of register)
+ (Addressed byte)
->(Addressed byte)

Example Byte-Register Operation

R5 = 01202h
R6 = 0223h
Mem(0223h) = 05Fh

```
ADD.B     @R6,R5
```

```
  05Fh
+ 002h
-------
 00061h
```

R5 = 00061h
C = 0, Z = 0, N = 0

(Addressed byte)
+ (Low byte of register)
->(Low byte of register, zero to High byte)

3.3 Addressing Modes

Seven addressing modes for the source operand and four addressing modes for the destination operand can address the complete address space with no exceptions. The bit numbers in Table 3-3 describe the contents of the As (source) and Ad (destination) mode bits.

Table 3-3. Source/Destination Operand Addressing Modes

As/Ad	Addressing Mode	Syntax	Description
00/0	Register mode	Rn	Register contents are operand
01/1	Indexed mode	X(Rn)	(Rn + X) points to the operand. X is stored in the next word.
01/1	Symbolic mode	ADDR	(PC + X) points to the operand. X is stored in the next word. Indexed mode X(PC) is used.
01/1	Absolute mode	&ADDR	The word following the instruction contains the absolute address. X is stored in the next word. Indexed mode X(SR) is used.
10/-	Indirect register mode	@Rn	Rn is used as a pointer to the operand.
11/-	Indirect autoincrement	@Rn+	Rn is used as a pointer to the operand. Rn is incremented afterwards by 1 for .B instructions and by 2 for .W instructions.
11/-	Immediate mode	#N	The word following the instruction contains the immediate constant N. Indirect autoincrement mode @PC+ is used.

The seven addressing modes are explained in detail in the following sections. Most of the examples show the same addressing mode for the source and destination, but any valid combination of source and destination addressing modes is possible in an instruction.

NOTE: Use of Labels *EDE, TONI, TOM, and LEO*

Throughout MSP430 documentation EDE, TONI, TOM, and LEO are used as generic labels. They are only labels. They have no special meaning.

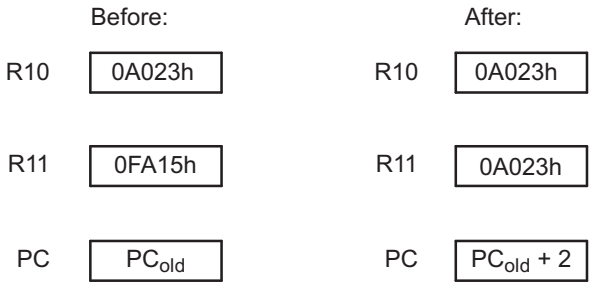
3.3.1 Register Mode

The register mode is described in Table 3-4.

Table 3-4. Register Mode Description

Assembler Code	Content of ROM
`MOV R10,R11`	`MOV R10,R11`

Length: One or two words
Operation: Move the content of R10 to R11. R10 is not affected.
Comment: Valid for source and destination
Example: `MOV R10,R11`



NOTE: Data in Registers

The data in the register can be accessed using word or byte instructions. If byte instructions are used, the high byte is always 0 in the result. The status bits are handled according to the result of the byte instructions.

3.3.2 Indexed Mode

The indexed mode is described in Table 3-5.

Table 3-5. Indexed Mode Description

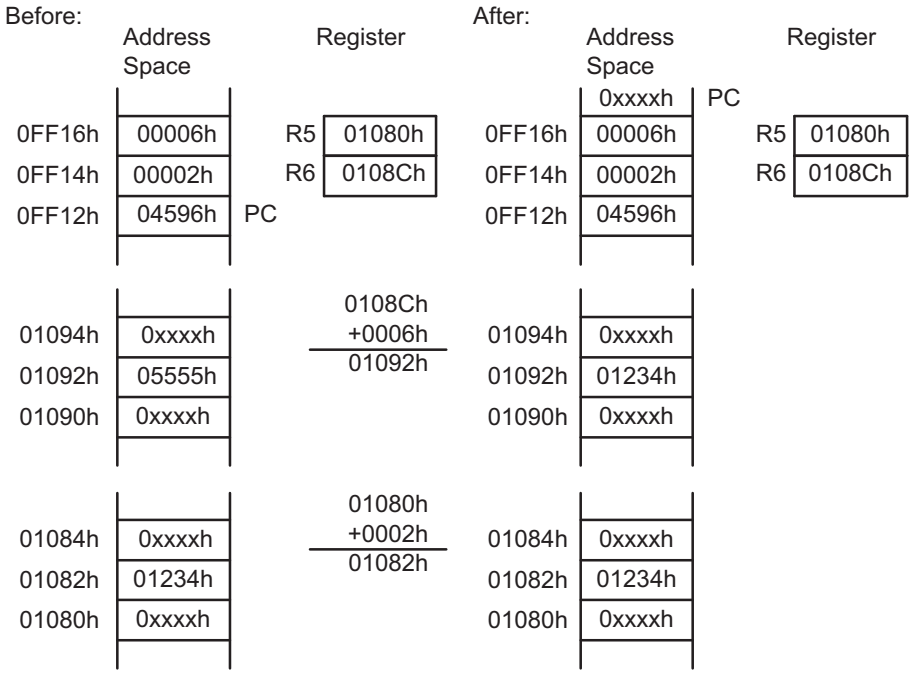
Assembler Code	Content of ROM
MOV 2(R5),6(R6)	MOV X(R5),Y(R6) X = 2 Y = 6

Length: Two or three words

Operation: Move the contents of the source address (contents of R5 + 2) to the destination address (contents of R6 + 6). The source and destination registers (R5 and R6) are not affected. In indexed mode, the program counter is incremented automatically so that program execution continues with the next instruction.

Comment: Valid for source and destination

Example:
```
MOV 2(R5),6(R6);
```



3.3.3 Symbolic Mode

The symbolic mode is described in Table 3-6.

Table 3-6. Symbolic Mode Description

Assembler Code	Content of ROM
MOV EDE,TONI	MOV X(PC),Y(PC) X = EDE – PC Y = TONI – PC

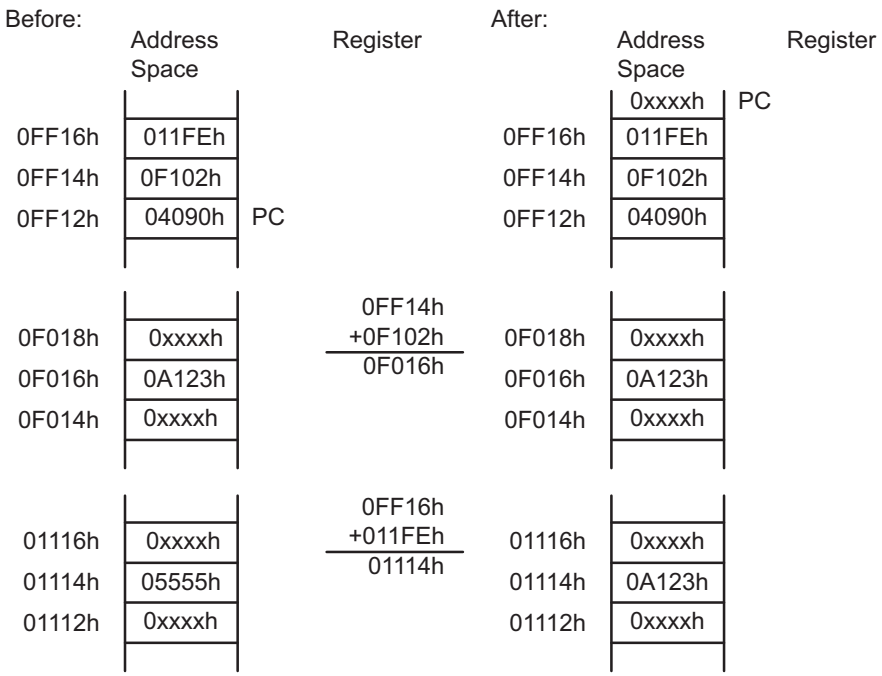
Length: Two or three words

Operation: Move the contents of the source address EDE (contents of PC + X) to the destination address TONI (contents of PC + Y). The words after the instruction contain the differences between the PC and the source or destination addresses. The assembler computes and inserts offsets X and Y automatically. With symbolic mode, the program counter (PC) is incremented automatically so that program execution continues with the next instruction.

Comment: Valid for source and destination

Example:

```
MOV  EDE,TONI  ;Source address EDE = 0F016h
               ;Dest. address TONI = 01114h
```



3.3.4 Absolute Mode

The absolute mode is described in Table 3-7.

Table 3-7. Absolute Mode Description

Assembler Code	Content of ROM
MOV &EDE,&TONI	MOV X(0),Y(0) X = EDE Y = TONI

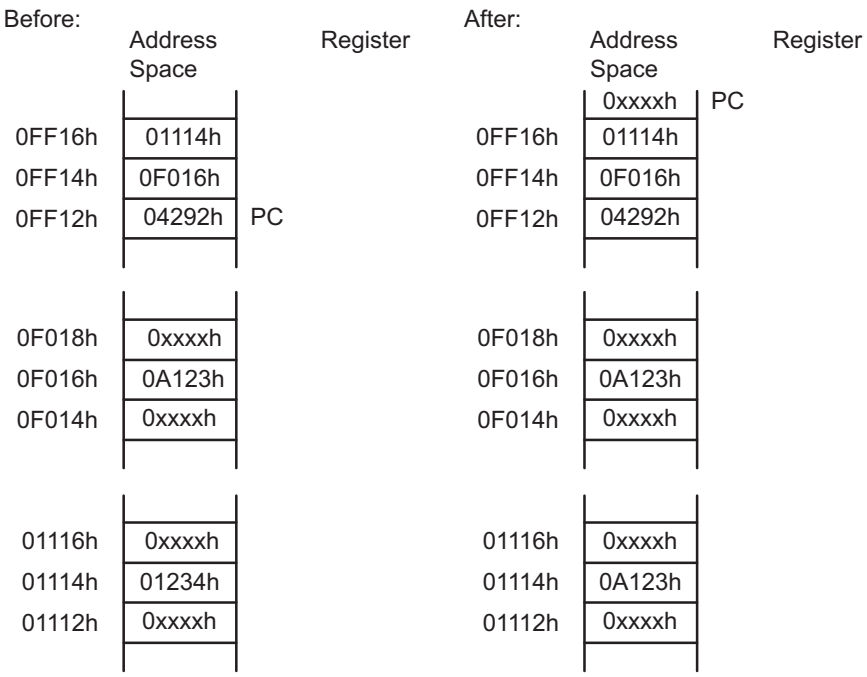
Length: Two or three words

Operation: Move the contents of the source address EDE to the destination address TONI. The words after the instruction contain the absolute address of the source and destination addresses. With absolute mode, the PC is incremented automatically so that program execution continues with the next instruction.

Comment: Valid for source and destination

Example:

```
MOV  &EDE,&TONI  ;Source address EDE = 0F016h
                 ;Dest. address TONI = 01114h
```



This address mode is mainly for hardware peripheral modules that are located at an absolute, fixed address. These are addressed with absolute mode to ensure software transportability (for example, position-independent code).

3.3.5 Indirect Register Mode

The indirect register mode is described in Table 3-8.

Table 3-8. Indirect Mode Description

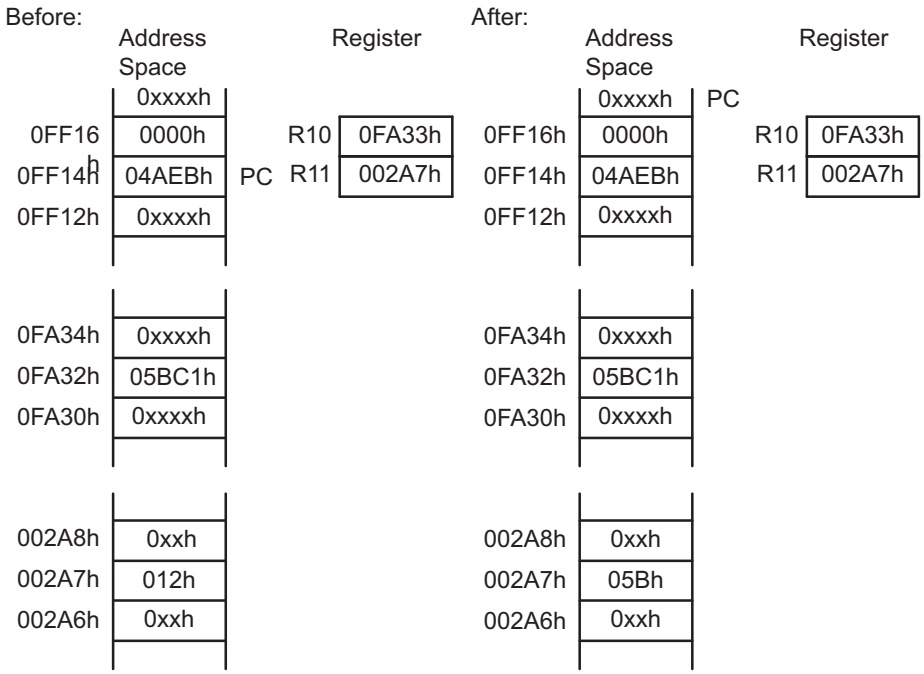
Assembler Code	Content of ROM
`MOV @R10,0(R11)`	`MOV @R10,0(R11)`

Length: One or two words

Operation: Move the contents of the source address (contents of R10) to the destination address (contents of R11). The registers are not modified.

Comment: Valid only for source operand. The substitute for destination operand is 0(Rd).

Example: `MOV.B @R10,0(R11)`



3.3.6 Indirect Autoincrement Mode

The indirect autoincrement mode is described in Table 3-9.

Table 3-9. Indirect Autoincrement Mode Description

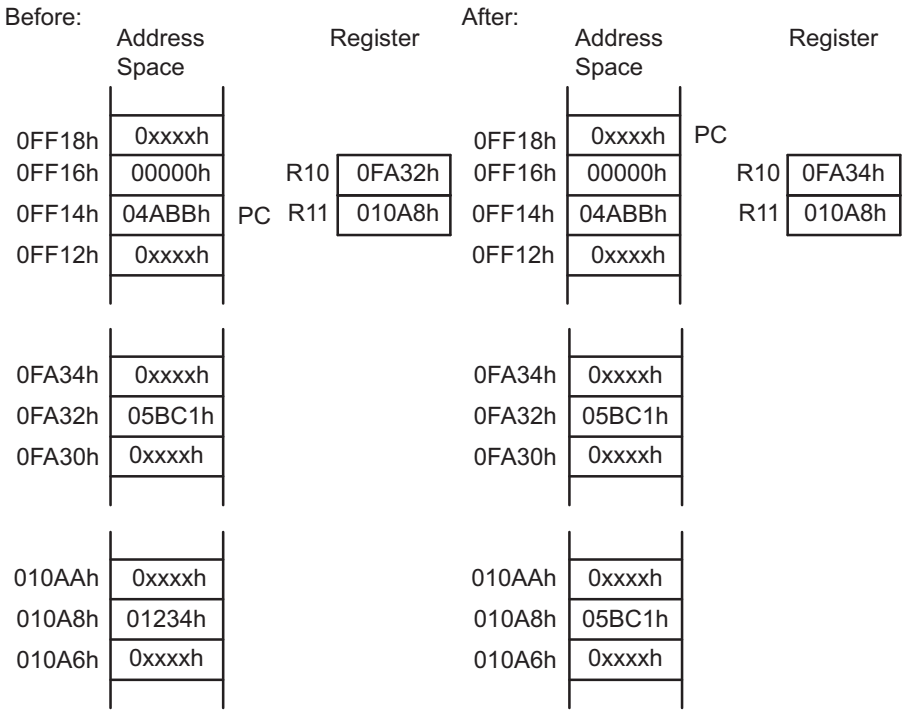
Assembler Code	Content of ROM
`MOV @R10+,0(R11)`	`MOV @R10+,0(R11)`

Length: One or two words

Operation: Move the contents of the source address (contents of R10) to the destination address (contents of R11). Register R10 is incremented by 1 for a byte operation, or 2 for a word operation after the fetch; it points to the next address without any overhead. This is useful for table processing.

Comment: Valid only for source operand. The substitute for destination operand is 0(Rd) plus second instruction INCD Rd.

Example: `MOV @R10+,0(R11)`



The auto-incrementing of the register contents occurs after the operand is fetched. This is shown in Figure 3-8.

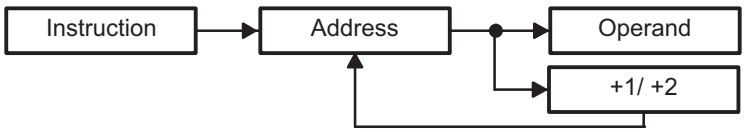


Figure 3-8. Operand Fetch Operation

3.3.7 Immediate Mode

The immediate mode is described in Table 3-10.

Table 3-10. Immediate Mode Description

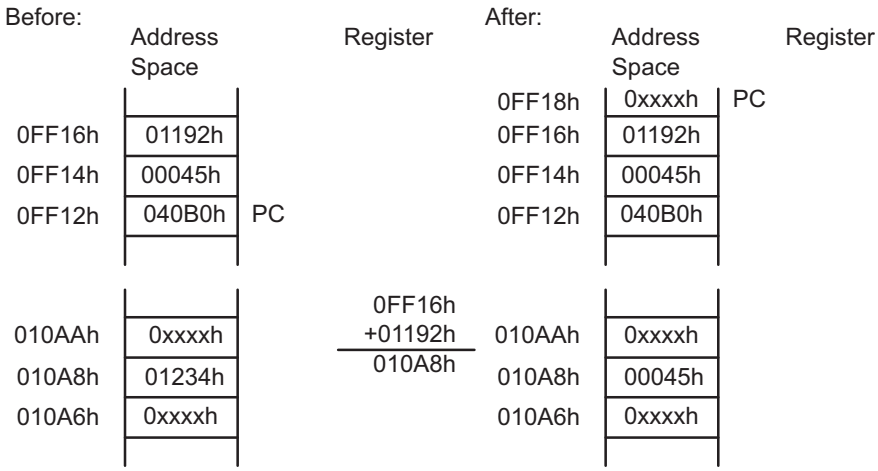
Assembler Code	Content of ROM
MOV #45h,TONI	MOV @PC+,X(PC) 45 X = TONI – PC

Length: Two or three words
It is one word less if a constant of CG1 or CG2 can be used.

Operation: Move the immediate constant 45h, which is contained in the word following the instruction, to destination address TONI. When fetching the source, the program counter points to the word following the instruction and moves the contents to the destination.

Comment: Valid only for a source operand.

Example:
```
MOV #45h,TONI
```



3.4 Instruction Set

The complete MSP430 instruction set consists of 27 core instructions and 24 emulated instructions. The core instructions are instructions that have unique op-codes decoded by the CPU. The emulated instructions are instructions that make code easier to write and read, but do not have op-codes themselves, instead they are replaced automatically by the assembler with an equivalent core instruction. There is no code or performance penalty for using emulated instruction.

There are three core-instruction formats:

- Dual-operand
- Single-operand
- Jump

All single-operand and dual-operand instructions can be byte or word instructions by using .B or .W extensions. Byte instructions are used to access byte data or byte peripherals. Word instructions are used to access word data or word peripherals. If no extension is used, the instruction is a word instruction.

The source and destination of an instruction are defined by the following fields:

src	The source operand defined by As and S-reg
dst	The destination operand defined by Ad and D-reg
As	The addressing bits responsible for the addressing mode used for the source (src)
S-reg	The working register used for the source (src)
Ad	The addressing bits responsible for the addressing mode used for the destination (dst)
D-reg	The working register used for the destination (dst)
B/W	Byte or word operation: 0: word operation 1: byte operation

NOTE: Destination Address

Destination addresses are valid anywhere in the memory map. However, when using an instruction that modifies the contents of the destination, the user must ensure the destination address is writable. For example, a masked-ROM location would be a valid destination address, but the contents are not modifiable, so the results of the instruction would be lost.

3.4.1 Double-Operand (Format I) Instructions

Figure 3-9 illustrates the double-operand instruction format.

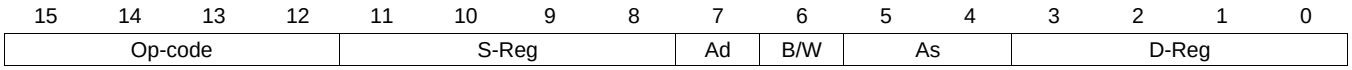


Figure 3-9. Double Operand Instruction Format

Table 3-11 lists and describes the double operand instructions.

Table 3-11. Double Operand Instructions

Mnemonic	S-Reg, D-Reg	Operation	Status Bits			
			V	N	Z	C
MOV(.B)	src,dst	src → dst	-	-	-	-
ADD(.B)	src,dst	src + dst → dst	*	*	*	*
ADDC(.B)	src,dst	src + dst + C → dst	*	*	*	*
SUB(.B)	src,dst	dst + .not.src + 1 → dst	*	*	*	*
SUBC(.B)	src,dst	dst + .not.src + C → dst	*	*	*	*
CMP(.B)	src,dst	dst - src	*	*	*	*
DADD(.B)	src,dst	src + dst + C → dst (decimally)	*	*	*	*
BIT(.B)	src,dst	src .and. dst	0	*	*	*
BIC(.B)	src,dst	not.src .and. dst → dst	-	-	-	-
BIS(.B)	src,dst	src .or. dst → dst	-	-	-	-
XOR(.B)	src,dst	src .xor. dst → dst	*	*	*	*
AND(.B)	src,dst	src .and. dst → dst	0	*	*	*

* The status bit is affected
– The status bit is not affected
0 The status bit is cleared
1 The status bit is set

NOTE: Instructions CMP and SUB

The instructions CMP and SUB are identical except for the storage of the result. The same is true for the BIT and AND instructions.

3.4.2 Single-Operand (Format II) Instructions

Figure 3-10 illustrates the single-operand instruction format.

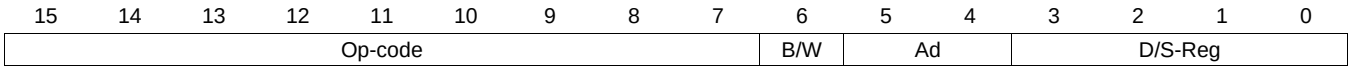


Figure 3-10. Single Operand Instruction Format

Table 3-12 lists and describes the single operand instructions.

Table 3-12. Single Operand Instructions

Mnemonic	S-Reg, D-Reg	Operation	Status Bits			
			V	N	Z	C
RRC(.B)	dst	C → MSB →.....LSB → C	*	*	*	*
RRA(.B)	dst	MSB → MSB →....LSB → C	0	*	*	*
PUSH(.B)	src	SP – 2 → SP, src → @SP	-	-	-	-
SWPB	dst	Swap bytes	-	-	-	-
CALL	dst	SP – 2 → SP, PC+2 → @SP dst → PC	-	-	-	-
RETI		TOS → SR, SP + 2 → SP TOS → PC,SP + 2 → SP	*	*	*	*
SXT	dst	Bit 7 → Bit 8.....Bit 15	0	*	*	*

* The status bit is affected
– The status bit is not affected
0 The status bit is cleared
1 The status bit is set

All addressing modes are possible for the CALL instruction. If the symbolic mode (ADDRESS), the immediate mode (#N), the absolute mode (&EDE) or the indexed mode x(RN) is used, the word that follows contains the address information.

3.4.3 Jumps

Figure 3-11 shows the conditional-jump instruction format.

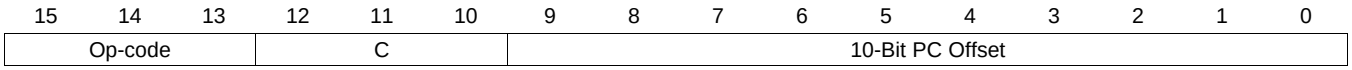


Figure 3-11. Jump Instruction Format

Table 3-13 lists and describes the jump instructions

Table 3-13. Jump Instructions

Mnemonic	S-Reg, D-Reg	Operation
JEQ/JZ	Label	Jump to label if zero bit is set
JNE/JNZ	Label	Jump to label if zero bit is reset
JC	Label	Jump to label if carry bit is set
JNC	Label	Jump to label if carry bit is reset
JN	Label	Jump to label if negative bit is set
JGE	Label	Jump to label if (N .XOR. V) = 0
JL	Label	Jump to label if (N .XOR. V) = 1
JMP	Label	Jump to label unconditionally

Conditional jumps support program branching relative to the PC and do not affect the status bits. The possible jump range is from –511 to +512 words relative to the PC value at the jump instruction. The 10-bit program-counter offset is treated as a signed 10-bit value that is doubled and added to the program counter:

$PC_{new} = PC_{old} + 2 + PC_{offset} \times 2$

3.4.4 Instruction Cycles and Lengths

The number of CPU clock cycles required for an instruction depends on the instruction format and the addressing modes used - not the instruction itself. The number of clock cycles refers to the MCLK.

3.4.4.1 Interrupt and Reset Cycles

Table 3-14 lists the CPU cycles for interrupt overhead and reset.

Table 3-14. Interrupt and Reset Cycles

Action	No. of Cycles	Length of Instruction
Return from interrupt (RETI)	5	1
Interrupt accepted	6	-
WDT reset	4	-
Reset ($\overline{\text{RST}}$/NMI)	4	-

3.4.4.2 Format-II (Single Operand) Instruction Cycles and Lengths

Table 3-15 lists the length and CPU cycles for all addressing modes of format-II instructions.

Table 3-15. Format-II Instruction Cycles and Lengths

	No. of Cycles				
Addressing Mode	RRA, RRC SWPB, SXT	PUSH	CALL	Length of Instruction	Example
Rn	1	3	4	1	`SWPB R5`
@Rn	3	4	4	1	`RRC @R9`
@Rn+	3	5	5	1	`SWPB @R10+`
#N	(See note)	4	5	2	`CALL #0F000h`
X(Rn)	4	5	5	2	`CALL 2(R7)`
EDE	4	5	5	2	`PUSH EDE`
&EDE	4	5	5	2	`SXT &EDE`

NOTE: Instruction Format II Immediate Mode

Do not use instruction RRA, RRC, SWPB, and SXT with the immediate mode in the destination field. Use of these in the immediate mode results in an unpredictable program operation.

3.4.4.3 Format-III (Jump) Instruction Cycles and Lengths

All jump instructions require one code word, and take two CPU cycles to execute, regardless of whether the jump is taken or not.

3.4.4.4 Format-I (Double Operand) Instruction Cycles and Lengths

Table 3-16 lists the length and CPU cycles for all addressing modes of format-I instructions.

Table 3-16. Format 1 Instruction Cycles and Lengths

Addressing Mode					
Src	Dst	No. of Cycles	Length of Instruction		Example
Rn	Rm	1	1	MOV	R5,R8
	PC	2	1	BR	R9
	x(Rm)	4	2	ADD	R5,4(R6)
	EDE	4	2	XOR	R8,EDE
	&EDE	4	2	MOV	R5,&EDE
@Rn	Rm	2	1	AND	@R4,R5
	PC	2	1	BR	@R8
	x(Rm)	5	2	XOR	@R5,8(R6)
	EDE	5	2	MOV	@R5,EDE
	&EDE	5	2	XOR	@R5,&EDE
@Rn+	Rm	2	1	ADD	@R5+,R6
	PC	3	1	BR	@R9+
	x(Rm)	5	2	XOR	@R5,8(R6)
	EDE	5	2	MOV	@R9+,EDE
	&EDE	5	2	MOV	@R9+,&EDE
#N	Rm	2	2	MOV	#20,R9
	PC	3	2	BR	#2AEh
	x(Rm)	5	3	MOV	#0300h,0(SP)
	EDE	5	3	ADD	#33,EDE
	&EDE	5	3	ADD	#33,&EDE
x(Rn)	Rm	3	2	MOV	2(R5),R7
	PC	3	2	BR	2(R6)
	TONI	6	3	MOV	4(R7),TONI
	x(Rm)	6	3	ADD	4(R4),6(R9)
	&TONI	6	3	MOV	2(R4),&TONI
EDE	Rm	3	2	AND	EDE,R6
	PC	3	2	BR	EDE
	TONI	6	3	CMP	EDE,TONI
	x(Rm)	6	3	MOV	EDE,0(SP)
	&TONI	6	3	MOV	EDE,&TONI
&EDE	Rm	3	2	MOV	&EDE,R8
	PC	3	2	BRA	&EDE
	TONI	6	3	MOV	&EDE,TONI
	x(Rm)	6	3	MOV	&EDE,0(SP)
	&TONI	6	3	MOV	&EDE,&TONI

3.4.5 Instruction Set Description

The instruction map is shown in Figure 3-12 and the complete instruction set is summarized in Table 3-17.

	000	040	080	0C0	100	140	180	1C0	200	240	280	2C0	300	340	380	3C0
0xxx																
4xxx																
8xxx																
Cxxx																
1xxx	RRC	RRC.B	SWPB		RRA	RRA.B	SXT		PUSH	PUSH.B	CALL		RETI			
14xx																
18xx																
1Cxx																
20xx	JNE/JNZ															
24xx	JEQ/JZ															
28xx	JNC															
2Cxx	JC															
30xx	JN															
34xx	JGE															
38xx	JL															
3Cxx	JMP															
4xxx	MOV, MOV.B															
5xxx	ADD, ADD.B															
6xxx	ADDC, ADDC.B															
7xxx	SUBC, SUBC.B															
8xxx	SUB, SUB.B															
9xxx	CMP, CMP.B															
Axxx	DADD, DADD.B															
Bxxx	BIT, BIT.B															
Cxxx	BIC, BIC.B															
Dxxx	BIS, BIS.B															
Exxx	XOR, XOR.B															
Fxxx	AND, AND.B															

Figure 3-12. Core Instruction Map

Table 3-17. MSP430 Instruction Set

Mnemonic		Description		V	N	Z	C
ADC(.B) (1)	dst	Add C to destination	dst + C → dst	*	*	*	*
ADD(.B)	src,dst	Add source to destination	src + dst → dst	*	*	*	*
ADDC(.B)	src,dst	Add source and C to destination	src + dst + C → dst	*	*	*	*
AND(.B)	src,dst	AND source and destination	src .and. dst → dst	0	*	*	*
BIC(.B)	src,dst	Clear bits in destination	not.src .and. dst → dst	-	-	-	-
BIS(.B)	src,dst	Set bits in destination	src .or. dst → dst	-	-	-	-
BIT(.B)	src,dst	Test bits in destination	src .and. dst	0	*	*	*
BR (1)	dst	Branch to destination	dst → PC	-	-	-	-
CALL	dst	Call destination	PC+2 → stack, dst → PC	-	-	-	-
CLR(.B) (1)	dst	Clear destination	0 → dst	-	-	-	-
CLRC (1)		Clear C	0 → C	-	-	-	0
CLRN (1)		Clear N	0 → N	-	0	-	-
CLRZ (1)		Clear Z	0 → Z	-	-	0	-
CMP(.B)	src,dst	Compare source and destination	dst - src	*	*	*	*
DADC(.B) (1)	dst	Add C decimally to destination	dst + C → dst (decimally)	*	*	*	*
DADD(.B)	src,dst	Add source and C decimally to dst	src + dst + C → dst (decimally)	*	*	*	*
DEC(.B) (1)	dst	Decrement destination	dst - 1 → dst	*	*	*	*

(1) Emulated Instruction

Table 3-17. MSP430 Instruction Set (continued)

Mnemonic		Description		V	N	Z	C
DECD(.B) [1]	dst	Double-decrement destination	dst - 2 → dst	*	*	*	*
DINT [1]		Disable interrupts	0 → GIE	-	-	-	-
EINT [1]		Enable interrupts	1 → GIE	-	-	-	-
INC(.B) [1]	dst	Increment destination	dst +1 → dst	*	*	*	*
INCD(.B) [1]	dst	Double-increment destination	dst+2 → dst	*	*	*	*
INV(.B) [1]	dst	Invert destination	.not.dst → dst	*	*	*	*
JC/JHS	label	Jump if C set/Jump if higher or same		-	-	-	-
JEQ/JZ	label	Jump if equal/Jump if Z set		-	-	-	-
JGE	label	Jump if greater or equal		-	-	-	-
JL	label	Jump if less		-	-	-	-
JMP	label	Jump	PC + 2 × offset → PC	-	-	-	-
JN	label	Jump if N set		-	-	-	-
JNC/JLO	label	Jump if C not set/Jump if lower		-	-	-	-
JNE/JNZ	label	Jump if not equal/Jump if Z not set		-	-	-	-
MOV(.B)	src,dst	Move source to destination	src → dst	-	-	-	-
NOP [2]		No operation		-	-	-	-
POP(.B) [2]	dst	Pop item from stack to destination	@SP → dst, SP+2 → SP	-	-	-	-
PUSH(.B)	src	Push source onto stack	SP - 2 → SP, src → @SP	-	-	-	-
RET [2]		Return from subroutine	@SP → PC, SP + 2 → SP	-	-	-	-
RETI		Return from interrupt		*	*	*	*
RLA(.B) [2]	dst	Rotate left arithmetically		*	*	*	*
RLC(.B) [2]	dst	Rotate left through C		*	*	*	*
RRA(.B)	dst	Rotate right arithmetically		0	*	*	*
RRC(.B)	dst	Rotate right through C		*	*	*	*
SBC(.B) [2]	dst	Subtract not(C) from destination	dst + 0FFFFh + C → dst	*	*	*	*
SETC [2]		Set C	1 → C	-	-	-	1
SETN [2]		Set N	1 → N	-	1	-	-
SETZ [2]		Set Z	1 → Z	-	-	1	-
SUB(.B)	src,dst	Subtract source from destination	dst + .not.src + 1 → dst	*	*	*	*
SUBC(.B)	src,dst	Subtract source and not(C) from dst	dst + .not.src + C → dst	*	*	*	*
SWPB	dst	Swap bytes		-	-	-	-
SXT	dst	Extend sign		0	*	*	*
TST(.B) [2]	dst	Test destination	dst + 0FFFFh + 1	0	*	*	1
XOR(.B)	src,dst	Exclusive OR source and destination	src .xor. dst → dst	*	*	*	*

[2] Emulated Instruction

3.4.6 Instruction Set Details

3.4.6.1 ADC

***ADC[.W]**	Add carry to destination
***ADC.B**	Add carry to destination
Syntax	`ADC dst or ADC.W dst` `ADC.B dst`
Operation	dst + C → dst
Emulation	`ADDC #0,dst` `ADDC.B #0,dst`
Description	The carry bit (C) is added to the destination operand. The previous contents of the destination are lost.
Status Bit	N: Set if result is negative, reset if positive Z: Set if result is zero, reset otherwise C: Set if dst was incremented from 0FFFFh to 0000, reset otherwise Set if dst was incremented from 0FFh to 00, reset otherwise V: Set if an arithmetic overflow occurs, otherwise reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The 16-bit counter pointed to by R13 is added to a 32-bit counter pointed to by R12.

```
ADD   @R13,0(R12)   ; Add LSDs
ADC   2(R12)        ; Add carry to MSD
```

Example The 8-bit counter pointed to by R13 is added to a 16-bit counter pointed to by R12.

```
ADD.B   @R13,0(R12)   ; Add LSDs
ADC.B   1(R12)        ; Add carry to MSD
```

3.4.6.2 ADD

ADD[.W]	Add source to destination
ADD.B	Add source to destination
Syntax	`ADD src,dst or ADD.W src,dst` `ADD.B src,dst`
Operation	src + dst → dst
Description	The source operand is added to the destination operand. The source operand is not affected. The previous contents of the destination are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if result is zero, reset otherwise C: Set if there is a carry from the result, cleared if not V:Set if an arithmetic overflow occurs, otherwise reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	R5 is increased by 10. The jump to TONI is performed on a carry.

```
ADD     #10,R5
JC      TONI     ; Carry occurred
......           ; No carry
```

Example R5 is increased by 10. The jump to TONI is performed on a carry.

```
ADD.B   #10,R5   ; Add 10 to Lowbyte of R5
JC      TONI     ; Carry occurred, if (R5) ≥ 246 [0Ah+0F6h]
......           ; No carry
```

3.4.6.3 ADDC

ADDC[.W]	Add source and carry to destination
ADDC.B	Add source and carry to destination
Syntax	`ADDC src,dst  or  ADDC.W src,dst` `ADDC.B src,dst`
Operation	src + dst + C → dst
Description	The source operand and the carry bit (C) are added to the destination operand. The source operand is not affected. The previous contents of the destination are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if result is zero, reset otherwise C: Set if there is a carry from the MSB of the result, reset otherwise V: Set if an arithmetic overflow occurs, otherwise reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The 32-bit counter pointed to by R13 is added to a 32-bit counter, eleven words (20/2 + 2/2) above the pointer in R13.

```
ADD      @R13+,20(R13)   ; ADD LSDs with no carry in
ADDC     @R13+,20(R13)   ; ADD MSDs with carry
...                      ; resulting from the LSDs
```

Example The 24-bit counter pointed to by R13 is added to a 24-bit counter, eleven words above the pointer in R13.

```
ADD.B    @R13+,10(R13)   ; ADD LSDs with no carry in
ADDC.B   @R13+,10(R13)   ; ADD medium Bits with carry
ADDC.B   @R13+,10(R13)   ; ADD MSDs with carry
...                      ; resulting from the LSDs
```

3.4.6.4 AND

AND[.W] Source AND destination

AND.B Source AND destination

Syntax

```
AND src,dst  or  AND.W src,dst
AND.B src,dst
```

Operation

src .AND. dst → dst

Description The source operand and the destination operand are logically ANDed. The result is placed into the destination.

Status Bits

N: Set if result MSB is set, reset if not set

Z: Set if result is zero, reset otherwise

C: Set if result is not zero, reset otherwise (= .NOT. Zero)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The bits set in R5 are used as a mask (#0AA55h) for the word addressed by TOM. If the result is zero, a branch is taken to label TONI.

```
MOV     #0AA55h,R5   ; Load mask into register R5
AND     R5,TOM       ; mask word addressed by TOM with R5
JZ      TONI         ;
......               ; Result is not zero
;
;
;   or
;
;
AND     #0AA55h,TOM
JZ      TONI
```

Example The bits of mask #0A5h are logically ANDed with the low byte TOM. If the result is zero, a branch is taken to label TONI.

```
AND.B   #0A5h,TOM     ; mask Lowbyte TOM with 0A5h
JZ      TONI          ;
......                ; Result is not zero
```

3.4.6.5 BIC

BIC[.W]	Clear bits in destination
BIC.B	Clear bits in destination
Syntax	`BIC src,dst  or  BIC.W src,dst` `BIC.B src,dst`
Operation	.NOT.src .AND. dst → dst
Description	The inverted source operand and the destination operand are logically ANDed. The result is placed into the destination. The source operand is not affected.
Status Bits	Status bits are not affected.
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The six MSBs of the RAM word LEO are cleared. `BIC    #0FC00h,LEO  ; Clear 6 MSBs in MEM(LEO)`
Example	The five MSBs of the RAM byte LEO are cleared. `BIC.B  #0F8h,LEO    ; Clear 5 MSBs in Ram location LEO`

3.4.6.6 BIS

BIS[.W]	Set bits in destination
BIS.B	Set bits in destination
Syntax	`BIS src,dst  or  BIS.W src,dst` `BIS.B src,dst`
Operation	src .OR. dst → dst
Description	The source operand and the destination operand are logically ORed. The result is placed into the destination. The source operand is not affected.
Status Bits	Status bits are not affected.
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The six LSBs of the RAM word TOM are set. `BIS    #003Fh,TOM   ; set the six LSBs in RAM location TOM`
Example	The three MSBs of RAM byte TOM are set. `BIS.B  #0E0h,TOM    ; set the 3 MSBs in RAM location TOM`

3.4.6.7 BIT

BIT[.W] Test bits in destination

BIT.B Test bits in destination

Syntax

```
BIT src,dst  or  BIT.W src,dst
```

Operation src .AND. dst

Description The source and destination operands are logically ANDed. The result affects only the status bits. The source and destination operands are not affected.

Status Bits

N: Set if MSB of result is set, reset otherwise

Z: Set if result is zero, reset otherwise

C: Set if result is not zero, reset otherwise (.NOT. Zero)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example If bit 9 of R8 is set, a branch is taken to label TOM.

```
BIT   #0200h,R8   ; bit 9 of R8 set?
JNZ   TOM         ; Yes, branch to TOM
...               ; No, proceed
```

Example If bit 3 of R8 is set, a branch is taken to label TOM.

```
BIT.B   #8,R8
JC      TOM
```

Example A serial communication receive bit (RCV) is tested. Because the carry bit is equal to the state of the tested bit while using the BIT instruction to test a single bit, the carry bit is used by the subsequent instruction; the read information is shifted into register RECBUF.

```
;
; Serial communication with LSB is shifted first:
                      ; xxxx   xxxx   xxxx   xxxx
BIT.B   #RCV,RCCTL    ; Bit info into carry
RRC     RECBUF        ; Carry -> MSB of RECBUF
                      ; cxxx    xxxx
......                ; repeat previous two instructions
......                ; 8 times
                      ; cccc   cccc
                      ; ^         ^
                      ; MSB       LSB
; Serial communication with MSB shifted first:
BIT.B   #RCV,RCCTL    ; Bit info into carry
RLC.B   RECBUF        ; Carry -> LSB of RECBUF
                      ; xxxx   xxxc
......                ; repeat previous two instructions
......                ; 8 times
                      ; cccc   cccc
                      ; |
                      ; MSB       LSB
```

3.4.6.8 BR, BRANCH

***BR, BRANCH** Branch to ..... destination

Syntax `BR dst`

Operation dst → PC

Emulation `MOV dst,PC`

Description An unconditional branch is taken to an address anywhere in the 64K address space. All source addressing modes can be used. The branch instruction is a word instruction.

Status Bits Status bits are not affected.

Example Examples for all addressing modes are given.

```
BR  #EXEC  ; Branch to label EXEC or direct branch (e.g. #0A4h)
           ; Core instruction MOV @PC+,PC
BR  EXEC   ; Branch to the address contained in EXEC
           ; Core instruction MOV X(PC),PC
           ; Indirect address
BR  &EXEC  ; Branch to the address contained in absolute
           ; address EXEC
           ; Core instruction MOV X(0),PC
           ; Indirect address
BR  R5     ; Branch to the address contained in R5
           ; Core instruction MOV R5,PC
           ; Indirect R5
BR  @R5    ; Branch to the address contained in the word
           ; pointed to by R5.
           ; Core instruction MOV @R5+,PC
           ; Indirect, indirect R5
BR  @R5+   ; Branch to the address contained in the word pointed
           ; to by R5 and increment pointer in R5 afterwards.
           ; The next time--S/W flow uses R5 pointer--it can
           ; alter program execution due to access to
           ; next address in a table pointed to by R5
           ; Core instruction MOV @R5,PC
           ; Indirect, indirect R5 with autoincrement
BR  X(R5)  ; Branch to the address contained in the address
           ; pointed to by R5 + X (e.g. table with address
           ; starting at X). X can be an address or a label
           ; Core instruction MOV X(R5),PC
           ; Indirect, indirect R5 + X
```

3.4.6.9 CALL

CALL	Subroutine
Syntax	`CALL dst`
Operation	dst → tmp dst is evaluated and stored SP - 2 → SP PC → @SP PC updated to TOS tmp → PC dst saved to PC
Description	A subroutine call is made to an address anywhere in the 64K address space. All addressing modes can be used. The return address (the address of the following instruction) is stored on the stack. The call instruction is a word instruction.
Status Bits	Status bits are not affected.
Example	Examples for all addressing modes are given.

```
CALL  #EXEC  ; Call on label EXEC or immediate address (e.g. #0A4h)
             ; SP-2 -> SP, PC+2 -> @SP, @PC+ -> PC
CALL  EXEC   ; Call on the address contained in EXEC
             ; SP-2 -> SP, PC+2 ->SP, X(PC) -> PC
             ; Indirect address
CALL  &EXEC  ; Call on the address contained in absolute address
             ; EXEC
             ; SP-2 -> SP, PC+2 -> @SP, X(0) -> PC
             ; Indirect address
CALL  R5     ; Call on the address contained in R5
             ; SP-2 -> SP, PC+2 -> @SP, R5 -> PC
             ; Indirect R5
CALL  @R5    ; Call on the address contained in the word
             ; pointed to by R5
             ; SP-2 -> SP, PC+2 -> @SP, @R5 -> PC
             ; Indirect, indirect R5
CALL  @R5+   ; Call on the address contained in the word
             ; pointed to by R5 and increment pointer in R5.
             ; The next time S/W flow uses R5 pointer
             ; it can alter the program execution due to
             ; access to next address in a table pointed to by R5
             ; SP-2 -> SP, PC+2 -> @SP, @R5 -> PC
             ; Indirect, indirect R5 with autoincrement
CALL  X(R5)  ; Call on the address contained in the address pointed
             ; to by R5 + X (e.g. table with address starting at X)
             ; X can be an address or a label
             ; SP-2 -> SP, PC+2 -> @SP, X(R5) -> PC
             ; Indirect, indirect R5 + X
```

3.4.6.10 CLR

***CLR[.W]**	Clear destination
***CLR.B**	Clear destination
Syntax	`CLR dst  or  CLR.W dst` `CLR.B dst`
Operation	0 → dst
Emulation	`MOV #0,dst` `MOV.B #0,dst`
Description	The destination operand is cleared.
Status Bits	Status bits are not affected.
Example	RAM word TONI is cleared. `CLR    TONI   ; 0 -> TONI`
Example	Register R5 is cleared. `CLR    R5`
Example	RAM byte TONI is cleared. `CLR.B  TONI   ; 0 -> TONI`

3.4.6.11 CLRC

***CLRC**	Clear carry bit
Syntax	`CLRC`
Operation	0 → C
Emulation	`BIC #1,SR`
Description	The carry bit (C) is cleared. The clear carry instruction is a word instruction.
Status Bits	N: Not affected Z: Not affected C: Cleared V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The 16-bit decimal counter pointed to by R13 is added to a 32-bit counter pointed to by R12.

```
CLRC                ; C=0: defines start
DADD   @R13,0(R12)  ; add 16=bit counter to low word of 32=bit counter
DADC   2(R12)       ; add carry to high word of 32=bit counter
```

3.4.6.12 CLRN

***CLRN**	Clear negative bit
Syntax	`CLRN`
Operation	0 → N or (.NOT.src .AND. dst → dst)
Emulation	`BIC #4,SR`
Description	The constant 04h is inverted (0FFFBh) and is logically ANDed with the destination operand. The result is placed into the destination. The clear negative bit instruction is a word instruction.
Status Bits	N: Reset to 0 Z: Not affected C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The Negative bit in the status register is cleared. This avoids special treatment with negative numbers of the subroutine called.

```
        CLRN
        CALL   SUBR
        ......
        ......
SUBR    JN     SUBRET   ; If input is negative: do nothing and return
        ......
        ......
        ......
SUBRET  RET
```

3.4.6.13 CLRZ

***CLRZ**	Clear zero bit
Syntax	`CLRZ`
Operation	0 → Z or (.NOT.src .AND. dst → dst)
Emulation	`BIC #2,SR`
Description	The constant 02h is inverted (0FFFDh) and logically ANDed with the destination operand. The result is placed into the destination. The clear zero bit instruction is a word instruction.
Status Bits	N: Not affected Z: Reset to 0 C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The zero bit in the status register is cleared. `CLRZ`

3.4.6.14 CMP

CMP[.W] Compare source and destination

CMP.B Compare source and destination

Syntax

```
CMP src,dst  or  CMP.W src,dst
CMP.B src,dst
```

Operation

dst + .NOT.src + 1

or

(dst - src)

Description The source operand is subtracted from the destination operand. This is accomplished by adding the 1s complement of the source operand plus 1. The two operands are not affected and the result is not stored; only the status bits are affected.

Status Bits

N: Set if result is negative, reset if positive (src ≥ dst)

Z: Set if result is zero, reset otherwise (src = dst)

C: Set if there is a carry from the MSB of the result, reset otherwise

V: Set if an arithmetic overflow occurs, otherwise reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R5 and R6 are compared. If they are equal, the program continues at the label EQUAL.

```
CMP   R5,R6   ; R5 = R6?
JEQ   EQUAL   ; YES, JUMP
```

Example Two RAM blocks are compared. If they are not equal, the program branches to the label ERROR.

```
     MOV   #NUM,R5      ; number of words to be compared
     MOV   #BLOCK1,R6   ; BLOCK1 start address in R6
     MOV   #BLOCK2,R7   ; BLOCK2 start address in R7
L$1  CMP   @R6+,0(R7)   ; Are Words equal? R6 increments
     JNZ   ERROR        ; No, branch to ERROR
     INCD  R7           ; Increment R7 pointer
     DEC   R5           ; Are all words compared?
     JNZ   L$1          ; No, another compare
```

Example The RAM bytes addressed by EDE and TONI are compared. If they are equal, the program continues at the label EQUAL.

```
CMP.B   EDE,TONI   ; MEM(EDE) = MEM(TONI)?
JEQ     EQUAL      ; YES, JUMP
```

3.4.6.15 DADC

***DADC[.W]** Add carry decimally to destination

***DADC.B** Add carry decimally to destination

Syntax

```
DADC dst  or  DADC.W src,dst
DADC.B dst
```

Operation dst + C → dst (decimally)

Emulation

```
DADD #0,dst
DADD.B #0,dst
```

Description The carry bit (C) is added decimally to the destination.

Status Bits

N: Set if MSB is 1

Z: Set if dst is 0, reset otherwise

C: Set if destination increments from 9999 to 0000, reset otherwise

Set if destination increments from 99 to 00, reset otherwise

V: Undefined

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The four-digit decimal number contained in R5 is added to an eight-digit decimal number pointed to by R8.

```
CLRC                ; Reset carry
                    ; next instruction's start condition is defined
DADD     R5,0(R8)   ; Add LSDs + C
DADC     2(R8)      ; Add carry to MSD
```

Example The two-digit decimal number contained in R5 is added to a four-digit decimal number pointed to by R8.

```
CLRC                ; Reset carry
                    ; next instruction's start condition is defined
DADD.B   R5,0(R8)   ; Add LSDs + C
DADC.B   1(R8)      ; Add carry to MSDs
```

3.4.6.16 DADD

DADD[.W] Source and carry added decimally to destination

DADD.B Source and carry added decimally to destination

Syntax

```
DADD src,dst  or  DADD.W src,dst
DADD.B src,dst
```

Operation src + dst + C → dst (decimally)

Description The source operand and the destination operand are treated as four binary coded decimals (BCD) with positive signs. The source operand and the carry bit (C)are added decimally to the destination operand. The source operand is not affected. The previous contents of the destination are lost. The result is not defined for non-BCD numbers.

Status Bits

N: Set if the MSB is 1, reset otherwise

Z: Set if result is zero, reset otherwise

C: Set if the result is greater than 9999

Set if the result is greater than 99

V: Undefined

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The eight-digit BCD number contained in R5 and R6 is added decimally to an eight-digit BCD number contained in R3 and R4 (R6 and R4 contain the MSDs).

```
CLRC                ; clear carry
DADD    R5,R3       ; add LSDs
DADD    R6,R4       ; add MSDs with carry
JC      OVERFLOW    ; If carry occurs go to error handling routine
```

Example The two-digit decimal counter in the RAM byte CNT is incremented by one.

```
CLRC              ; clear carry
DADD.B  #1,CNT
```

or

```
SETC
DADD.B  #0,CNT    ; equivalent to DADC.B CNT
```

3.4.6.17 DEC

***DEC[.W]** Decrement destination

***DEC.B** Decrement destination

Syntax

```
DEC dst  or  DEC.W dst
DEC.B dst
```

Operation dst - 1 → dst

Emulation

```
SUB #1,dst
SUB.B #1,dst
```

Description The destination operand is decremented by one. The original contents are lost.

Status Bits

N: Set if result is negative, reset if positive

Z: Set if dst contained 1, reset otherwise

C: Reset if dst contained 0, set otherwise

V: Set if an arithmetic overflow occurs, otherwise reset.

Set if initial value of destination was 08000h, otherwise reset.

Set if initial value of destination was 080h, otherwise reset.

Mode Bits OSCOFF, CPUOFF,and GIE are not affected.

Example R10 is decremented by 1.

```
     DEC     R10    ; Decrement R10

; Move a block of 255 bytes from memory location starting with EDE to
memory location starting with
; TONI. Tables should not overlap: start of destination address TONI
must not be within the range EDE
; to EDE+0FEh

     MOV     #EDE,R6
     MOV     #255,R10
L$1  MOV.B   @R6+,TONI-EDE-1(R6)
     DEC     R10
     JNZ     L$1
```

Do not transfer tables using the routine above with the overlap shown in Figure 3-13.

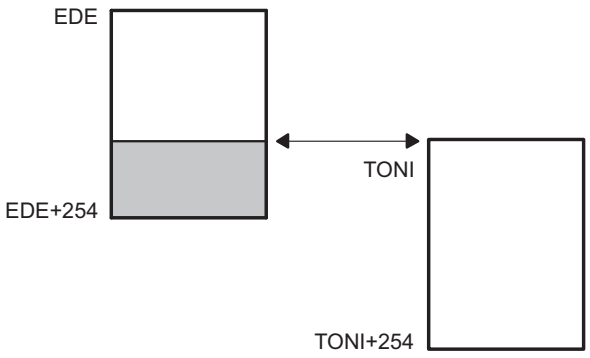


Figure 3-13. Decrement Overlap

3.4.6.18 DECD

***DECD[.W]**	Double-decrement destination
***DECD.B**	Double-decrement destination
Syntax	`DECD dst or DECD.W dst` `DECD.B dst`
Operation	dst - 2 → dst
Emulation	`SUB #2,dst`
Emulation	`SUB.B #2,dst`
Description	The destination operand is decremented by two. The original contents are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if dst contained 2, reset otherwise C: Reset if dst contained 0 or 1, set otherwise V: Set if an arithmetic overflow occurs, otherwise reset. Set if initial value of destination was 08001 or 08000h, otherwise reset. Set if initial value of destination was 081 or 080h, otherwise reset.
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	R10 is decremented by 2.

```
      DECD   R10      ; Decrement R10 by two
; Move a block of 255 words from memory location starting with EDE to
; memory location starting with TONI
; Tables should not overlap: start of destination address TONI must not be
; within the range EDE to EDE+0FEh

      MOV    #EDE,R6
      MOV    #510,R10
L$1   MOV    @R6+,TONI-EDE-2(R6)
      DECD   R10
      JNZ    L$1
```

Example Memory at location LEO is decremented by two.

```
DECD.B   LEO   ; Decrement MEM(LEO)
```

Decrement status byte STATUS by two.

```
DECD.B   STATUS
```

3.4.6.19 DINT

***DINT**	Disable (general) interrupts
Syntax	`DINT`
Operation	0 → GIE or (0FFF7h .AND. SR → SR / .NOT.src .AND. dst → dst)
Emulation	`BIC #8,SR`
Description	All interrupts are disabled. The constant 08h is inverted and logically ANDed with the status register (SR). The result is placed into the SR.
Status Bits	Status bits are not affected.
Mode Bits	GIE is reset. OSCOFF and CPUOFF are not affected.
Example	The general interrupt enable (GIE) bit in the status register is cleared to allow a nondisrupted move of a 32-bit counter. This ensures that the counter is not modified during the move by any interrupt.

```
DINT               ; All interrupt events using the GIE bit are disabled
NOP
MOV   COUNTHI,R5   ; Copy counter
MOV   COUNTLO,R6
EINT               ; All interrupt events using the GIE bit are enabled
```

NOTE: Disable Interrupt

If any code sequence needs to be protected from interruption, the DINT should be executed at least one instruction before the beginning of the uninterruptible sequence, or should be followed by a NOP instruction.

3.4.6.20 EINT

***EINT** Enable (general) interrupts

Syntax `EINT`

Operation 1 → GIE

or

(0008h .OR. SR → SR / .src .OR. dst → dst)

Emulation `BIS #8,SR`

Description All interrupts are enabled.

The constant #08h and the status register SR are logically ORed. The result is placed into the SR.

Status Bits Status bits are not affected.

Mode Bits GIE is set. OSCOFF and CPUOFF are not affected.

Example The general interrupt enable (GIE) bit in the status register is set.

```
; Interrupt routine of ports P1.2 to P1.7
; P1IN is the address of the register where all port bits are read. P1IFG is
; the address of the register where all interrupt events are latched.

        PUSH.B   &P1IN
        BIC.B    @SP,&P1IFG   ; Reset only accepted flags
        EINT                  ; Preset port 1 interrupt flags stored on stack
                              ; other interrupts are allowed
        BIT      #Mask,@SP
        JEQ      MaskOK       ; Flags are present identically to mask: jump
        ......
MaskOK  BIC      #Mask,@SP
        ......
        INCD     SP           ; Housekeeping: inverse to PUSH instruction
                              ; at the start of interrupt subroutine. Corrects
                              ; the stack pointer.
        RETI
```

NOTE: Enable Interrupt

The instruction following the enable interrupt instruction (EINT) is always executed, even if an interrupt service request is pending when the interrupts are enable.

3.4.6.21 INC

***INC[.W]**	Increment destination
***INC.B**	Increment destination
Syntax	`INC dst  or  INC.W dst` `INC.B dst`
Operation	dst + 1 → dst
Emulation	`ADD #1,dst`
Description	The destination operand is incremented by one. The original contents are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if dst contained 0FFFFh, reset otherwise Set if dst contained 0FFh, reset otherwise C: Set if dst contained 0FFFFh, reset otherwise Set if dst contained 0FFh, reset otherwise V: Set if dst contained 07FFFh, reset otherwise Set if dst contained 07Fh, reset otherwise
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.

Example	The status byte, STATUS, of a process is incremented. When it is equal to 11, a branch to OVFL is taken.
	`INC.B  STATUS`
	`CMP.B  #11,STATUS`
	`JEQ  OVFL`

3.4.6.22 INCD

***INCD[.W]**	Double-increment destination
***INCD.B**	Double-increment destination
Syntax	`INCD dst  or  INCD.W dst` `INCD.B dst`
Operation	dst + 2 → dst
Emulation	`ADD #2,dst` `ADD.B #2,dst`
Example	The destination operand is incremented by two. The original contents are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if dst contained 0FFFEh, reset otherwise Set if dst contained 0FEh, reset otherwise C: Set if dst contained 0FFFEh or 0FFFFh, reset otherwise Set if dst contained 0FEh or 0FFh, reset otherwise V: Set if dst contained 07FFEh or 07FFFh, reset otherwise Set if dst contained 07Eh or 07Fh, reset otherwise
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.

Example The item on the top of the stack (TOS) is removed without using a register.

```
PUSH     R5     ; R5 is the result of a calculation, which is stored
                ; in the system stack
INCD     SP     ; Remove TOS by double-increment from stack
                ; Do not use INCD.B, SP is a word-aligned register
RET
```

Example The byte on the top of the stack is incremented by two.

```
INCD.B   0(SP)  ; Byte on TOS is increment by two
```

3.4.6.23 INV

***INV[.W]**	Invert destination
***INV.B**	Invert destination
Syntax	`INV dst` `INV.B dst`
Operation	.NOT.dst → dst
Emulation	`XOR #0FFFFh,dst` `XOR.B #0FFh,dst`
Description	The destination operand is inverted. The original contents are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if dst contained 0FFFFh, reset otherwise Set if dst contained 0FFh, reset otherwise C: Set if result is not zero, reset otherwise (= .NOT. Zero) Set if result is not zero, reset otherwise (= .NOT. Zero) V: Set if initial destination operand was negative, otherwise reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.

Example Content of R5 is negated (twos complement).

```
MOV    #00AEh,R5  ;                      R5 = 000AEh
INV    R5         ; Invert R5,           R5 = 0FF51h
INC    R5         ; R5 is now negated,   R5 = 0FF52h
```

Example Content of memory byte LEO is negated.

```
MOV.B  #0AEh,LEO  ;                      MEM(LEO) = 0AEh
INV.B  LEO        ; Invert LEO,          MEM(LEO) = 051h
INC.B  LEO        ; MEM(LEO) is negated, MEM(LEO) = 052h
```

3.4.6.24 JC, JHS

JC Jump if carry set

JHS Jump if higher or same

Syntax

```
JC label
JHS label
```

Operation

If C = 1: PC + 2 offset → PC

If C = 0: execute following instruction

Description The status register carry bit (C) is tested. If it is set, the 10-bit signed offset contained in the instruction LSBs is added to the program counter. If C is reset, the next instruction following the jump is executed. JC (jump if carry/higher or same) is used for the comparison of unsigned numbers (0 to 65536).

Status Bits Status bits are not affected.

Example The P1IN.1 signal is used to define or control the program flow.

```
BIT.B   #02h,&P1IN   ; State of signal -> Carry
JC      PROGA        ; If carry=1 then execute program routine A
......               ; Carry=0, execute program here
```

Example R5 is compared to 15. If the content is higher or the same, branch to LABEL.

```
CMP     #15,R5
JHS     LABEL        ; Jump is taken if R5 >= 15
......               ; Continue here if R5 < 15
```

3.4.6.25 JEQ, JZ

JEQ, JZ	Jump if equal, jump if zero
Syntax	`JEQ label` `JZ label`
Operation	If Z = 1: PC + 2 offset → PC If Z = 0: execute following instruction
Description	The status register zero bit (Z) is tested. If it is set, the 10-bit signed offset contained in the instruction LSBs is added to the program counter. If Z is not set, the instruction following the jump is executed.
Status Bits	Status bits are not affected.

Example	Jump to address TONI if R7 contains zero.
	`TST R7 ; Test R7`
	`JZ TONI ; if zero: JUMP`

Example	Jump to address LEO if R6 is equal to the table contents.
	`CMP R6,Table(R5) ; Compare content of R6 with content of`
	`; MEM (table address + content of R5)`
	`JEQ LEO ; Jump if both data are equal`
	`..... ; No, data are not equal, continue here`

Example	Branch to LABEL if R5 is 0.
	`TST R5`
	`JZ LABEL`
	`.....`

3.4.6.26 JGE

JGE	Jump if greater or equal
Syntax	`JGE label`
Operation	If (N .XOR. V) = 0 then jump to label: PC + 2 P offset → PC If (N .XOR. V) = 1 then execute the following instruction
Description	The status register negative bit (N) and overflow bit (V) are tested. If both N and V are set or reset, the 10-bit signed offset contained in the instruction LSBs is added to the program counter. If only one is set, the instruction following the jump is executed. This allows comparison of signed integers.
Status Bits	Status bits are not affected.
Example	When the content of R6 is greater or equal to the memory pointed to by R7, the program continues at label EDE.

```
CMP   @R7,R6   ; R6 >= (R7)?, compare on signed numbers
JGE   EDE      ; Yes, R6 >= (R7)
......         ; No, proceed
......
......
```

3.4.6.27 JL

JL	Jump if less
Syntax	`JL label`
Operation	If (N .XOR. V) = 1 then jump to label: PC + 2 offset → PC If (N .XOR. V) = 0 then execute following instruction
Description	The status register negative bit (N) and overflow bit (V) are tested. If only one is set, the 10-bit signed offset contained in the instruction LSBs is added to the program counter. If both N and V are set or reset, the instruction following the jump is executed. This allows comparison of signed integers.
Status Bits	Status bits are not affected.
Example	When the content of R6 is less than the memory pointed to by R7, the program continues at label EDE.

```
CMP   @R7,R6   ; R6 < (R7)?,  compare on signed numbers
JL    EDE      ; Yes, R6 < (R7)
......         ; No, proceed
......
......
```

3.4.6.28 JMP

JMP	Jump unconditionally
Syntax	`JMP label`
Operation	PC + 2 × offset → PC
Description	The 10-bit signed offset contained in the instruction LSBs is added to the program counter.
Status Bits	Status bits are not affected.
Hint	This one-word instruction replaces the BRANCH instruction in the range of –511 to +512 words relative to the current program counter.

3.4.6.29 JN

JN Jump if negative

Syntax `JN label`

Operation if N = 1: PC + 2 ×offset → PC

if N = 0: execute following instruction

Description The negative bit (N) of the status register is tested. If it is set, the 10-bit signed offset contained in the instruction LSBs is added to the program counter. If N is reset, the next instruction following the jump is executed.

Status Bits Status bits are not affected.

Example The result of a computation in R5 is to be subtracted from COUNT. If the result is negative, COUNT is to be cleared and the program continues execution in another path.

```
      SUB   R5,COUNT   ; COUNT - R5 -> COUNT
      JN    L$1        ; If negative continue with COUNT=0 at PC=L$1
      ......           ; Continue with COUNT>=0
      ......
      ......
      ......
L$1   CLR   COUNT
      ......
      ......
      ......
```

3.4.6.30 JNC, JLO

JNC Jump if carry not set

JLO Jump if lower

Syntax

```
JNC label
JLO label
```

Operation

if C = 0: PC + 2 offset → PC

if C = 1: execute following instruction

Description The status register carry bit (C) is tested. If it is reset, the 10-bit signed offset contained in the instruction LSBs is added to the program counter. If C is set, the next instruction following the jump is executed. JNC (jump if no carry/lower) is used for the comparison of unsigned numbers (0 to 65536).

Status Bits Status bits are not affected.

Example The result in R6 is added in BUFFER. If an overflow occurs, an error handling routine at address ERROR is used.

```
        ADD     R6,BUFFER   ; BUFFER + R6 -> BUFFER
        JNC     CONT        ; No carry, jump to CONT
ERROR   ......              ; Error handler start
        ......
        ......
        ......
CONT    ......              ; Continue with normal program flow
        ......
        ......
```

Example Branch to STL2 if byte STATUS contains 1 or 0.

```
        CMP.B   #2,STATUS
        JLO     STL 2       ; STATUS < 2
        ......              ; STATUS >= 2, continue here
```

3.4.6.31 JNE, JNZ

JNE	Jump if not equal
JNZ	Jump if not zero
Syntax	`JNE label` `JNZ label`
Operation	If Z = 0: PC + 2 a offset → PC If Z = 1: execute following instruction
Description	The status register zero bit (Z) is tested. If it is reset, the 10-bit signed offset contained in the instruction LSBs is added to the program counter. If Z is set, the next instruction following the jump is executed.
Status Bits	Status bits are not affected.
Example	Jump to address TONI if R7 and R8 have different contents.

```
CMP   R7,R8   ; COMPARE R7 WITH R8
JNE   TONI    ; if different: jump
......        ; if equal, continue
```

3.4.6.32 MOV

MOV[.W] Move source to destination

MOV.B Move source to destination

Syntax

```
MOV src,dst  or  MOV.W src,dst
MOV.B src,dst
```

Operation src → dst

Description The source operand is moved to the destination.

The source operand is not affected. The previous contents of the destination are lost.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF,and GIE are not affected.

Example The contents of table EDE (word data) are copied to table TOM. The length of the tables must be 020h locations.

```
       MOV   #EDE,R10               ; Prepare pointer
       MOV   #020h,R9               ; Prepare counter
Loop   MOV   @R10+,TOM-EDE-2(R10)   ; Use pointer in R10 for both tables
       DEC   R9                     ; Decrement counter
       JNZ   Loop                   ; Counter not 0, continue copying
       ......                       ; Copying completed
       ......
       ......
```

Example The contents of table EDE (byte data) are copied to table TOM. The length of the tables should be 020h locations

```
       MOV     #EDE,R10             ; Prepare pointer
       MOV     #020h,R9             ; Prepare counter
Loop   MOV.B   @R10+,TOM-EDE-1(R10) ; Use pointer in R10 for
                                    ; both tables
       DEC   R9                     ; Decrement counter
       JNZ   Loop                   ; Counter not 0, continue
                                    ; copying
       ......                       ; Copying completed
       ......
       ......
```

3.4.6.33 NOP

***NOP**	No operation
Syntax	`NOP`
Operation	None
Emulation	`MOV #0, R3`
Description	No operation is performed. The instruction may be used for the elimination of instructions during the software check or for defined waiting times.
Status Bits	Status bits are not affected.

The NOP instruction is mainly used for two purposes:

- To fill one, two, or three memory words
- To adjust software timing

NOTE: Emulating No-Operation Instruction

Other instructions can emulate the NOP function while providing different numbers of instruction cycles and code words. Some examples are:

```
MOV  #0,R3         ; 1 cycle, 1 word
MOV  0(R4),0(R4)   ; 6 cycles, 3 words
MOV  @R4,0(R4)     ; 5 cycles, 2 words
BIC  #0,EDE(R4)    ; 4 cycles, 2 words
JMP  $+2           ; 2 cycles, 1 word
BIC  #0,R5         ; 1 cycle, 1 word
```

However, care should be taken when using these examples to prevent unintended results. For example, if `MOV 0(R4), 0(R4)` is used and the value in R4 is 120h, then a security violation occurs with the watchdog timer (address 120h), because the security key was not used.

3.4.6.34 POP

***POP[.W]** Pop word from stack to destination

***POP.B** Pop byte from stack to destination

Syntax

```
POP dst
POP.B dst
```

Operation

@SP → temp

SP + 2 → SP

temp → dst

Emulation

```
MOV @SP+,dst or MOV.W @SP+,dst
MOV.B @SP+,dst
```

Description The stack location pointed to by the stack pointer (TOS) is moved to the destination. The stack pointer is incremented by two afterwards.

Status Bits Status bits are not affected.

Example The contents of R7 and the status register are restored from the stack.

```
POP     R7      ; Restore R7
POP     SR      ; Restore status register
```

Example The contents of RAM byte LEO is restored from the stack.

```
POP.B   LEO     ; The low byte of the stack is moved to LEO.
```

Example The contents of R7 is restored from the stack.

```
POP.B   R7      ; The low byte of the stack is moved to R7,
                ; the high byte of R7 is 00h
```

Example The contents of the memory pointed to by R7 and the status register are restored from the stack.

```
POP.B   0(R7)   ; The low byte of the stack is moved to the
                ; the byte which is pointed to by R7
                ; Example:  R7 = 203h
                ;           Mem(R7) = low byte of system stack
                ; Example:  R7 = 20Ah
                ;           Mem(R7) = low byte of system stack
POP     SR      ; Last word on stack moved to the SR
```

NOTE: The System Stack Pointer

The system stack pinter (SP) is always incremented by two, independent of the byte suffix.

3.4.6.35 PUSH

PUSH[.W] Push word onto stack

PUSH.B Push byte onto stack

Syntax

```
PUSH src  or  PUSH.W src
PUSH.B src
```

Operation

SP - 2 → SP

src → @SP

Description The stack pointer is decremented by two, then the source operand is moved to the RAM word addressed by the stack pointer (TOS).

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The contents of the status register and R8 are saved on the stack.

```
PUSH     SR      ; save status register
PUSH     R8      ; save R8
```

Example The contents of the peripheral TCDAT is saved on the stack.

```
PUSH.B   &TCDAT  ; save data from 8-bit peripheral module,
                 ; address TCDAT, onto stack
```

NOTE: System Stack Pointer

The System stack pointer (SP) is always decremented by two, independent of the byte suffix.

3.4.6.36 RET

***RET**	Return from subroutine
Syntax	`RET`
Operation	@SP → PC SP + 2 → SP
Emulation	`MOV @SP+,PC`
Description	The return address pushed onto the stack by a CALL instruction is moved to the program counter. The program continues at the code address following the subroutine call.
Status Bits	Status bits are not affected.

3.4.6.37 RETI

RETI	Return from interrupt
Syntax	`RETI`
Operation	TOS → SR SP + 2 → SP TOS → PC SP + 2 → SP
Description	The status register is restored to the value at the beginning of the interrupt service routine by replacing the present SR contents with the TOS contents. The stack pointer (SP) is incremented by two. The program counter is restored to the value at the beginning of interrupt service. This is the consecutive step after the interrupted program flow. Restoration is performed by replacing the present PC contents with the TOS memory contents. The stack pointer (SP) is incremented.
Status Bits	N: Restored from system stack Z: Restored from system stack C: Restored from system stack V: Restored from system stack
Mode Bits	OSCOFF, CPUOFF, and GIE are restored from system stack.
Example	Figure 3-14 illustrates the main program interrupt.

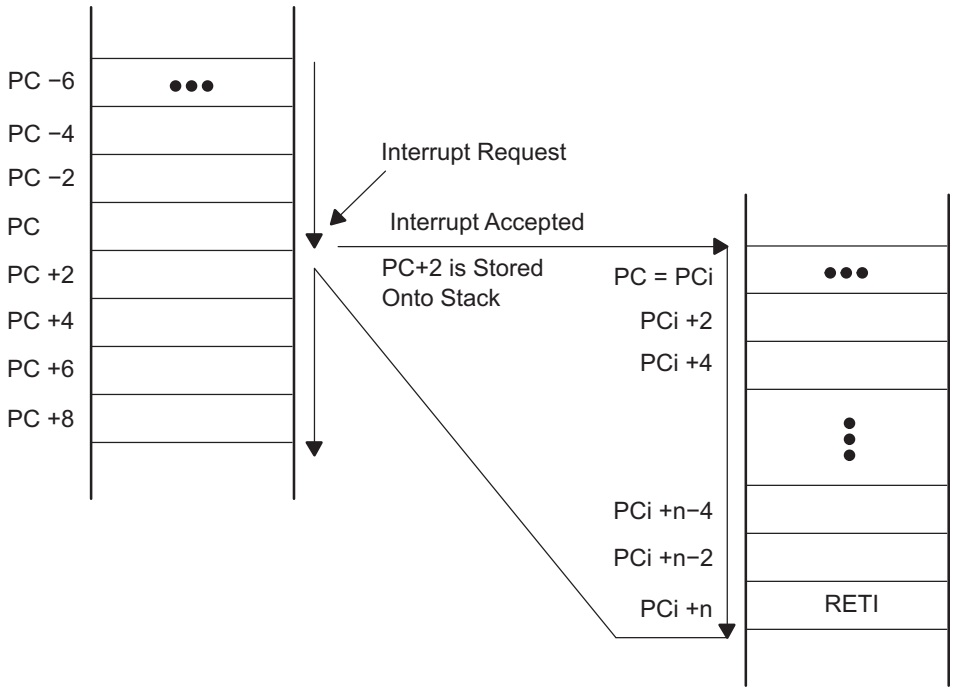


Figure 3-14. Main Program Interrupt

3.4.6.38 RLA

***RLA[.W]** Rotate left arithmetically

***RLA.B** Rotate left arithmetically

Syntax

```
RLA dst or RLA.W dst
RLA.B dst
```

Operation C <- MSB <- MSB-1 .... LSB+1 <- LSB <- 0

Emulation

```
ADD dst,dst
ADD.B dst,dst
```

Description The destination operand is shifted left one position as shown in Figure 3-15. The MSB is shifted into the carry bit (C) and the LSB is filled with 0. The RLA instruction acts as a signed multiplication by 2.

An overflow occurs if dst ≥ 04000h and dst < 0C000h before operation is performed: the result has changed sign.

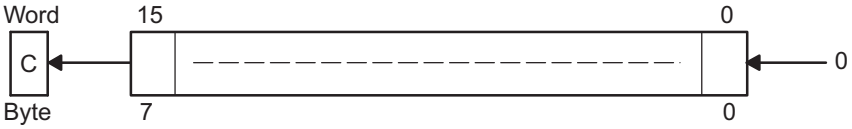


Figure 3-15. Destination Operand – Arithmetic Shift Left

An overflow occurs if dst ≥ 040h and dst < 0C0h before the operation is performed: the result has changed sign.

Status Bits N: Set if result is negative, reset if positive

Z: Set if result is zero, reset otherwise

C: Loaded from the MSB

V: Set if an arithmetic overflow occurs:

the initial value is 04000h ≤ dst < 0C000h; reset otherwise

Set if an arithmetic overflow occurs:

the initial value is 040h ≤ dst < 0C0h; reset otherwise

Mode Bits OSCOFF, CPUOFF,and GIE are not affected.

Example R7 is multiplied by 2.

```
RLA     R7   ; Shift left R7  (x 2)
```

Example The low byte of R7 is multiplied by 4.

```
RLA.B   R7   ; Shift left low byte of R7 (x 2)
RLA.B   R7   ; Shift left low byte of R7 (x 4)
```

NOTE: RLA Substitution

The assembler does not recognize the instruction:

```
RLA @R5+, RLA.B @R5+, or RLA(.B) @R5
```

It must be substituted by:

```
ADD @R5+,-2(R5), ADD.B @R5+,-1(R5), or ADD(.B) @R5
```

3.4.6.39 RLC

***RLC[.W]** Rotate left through carry

***RLC.B** Rotate left through carry

Syntax

```
RLC dst or RLC.W dst
RLC.B dst
```

Operation C <- MSB <- MSB-1 .... LSB+1 <- LSB <- C

Emulation

```
ADDC dst,dst
```

Description The destination operand is shifted left one position as shown in Figure 3-16. The carry bit (C) is shifted into the LSB and the MSB is shifted into the carry bit (C).

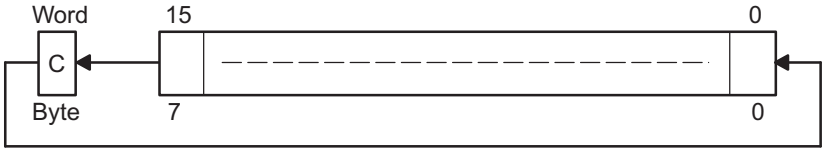


Figure 3-16. Destination Operand - Carry Left Shift

Status Bits

N: Set if result is negative, reset if positive

Z: Set if result is zero, reset otherwise

C: Loaded from the MSB

V: Set if an arithmetic overflow occurs

the initial value is 04000h ≤ dst < 0C000h; reset otherwise

Set if an arithmetic overflow occurs:

the initial value is 040h ≤ dst < 0C0h; reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R5 is shifted left one position.

```
RLC     R5          ; (R5 x 2) + C -> R5
```

Example The input P1IN.1 information is shifted into the LSB of R5.

```
BIT.B   #2,&P1IN    ; Information -> Carry
RLC     R5          ; Carry=P0in.1 -> LSB of R5
```

Example The MEM(LEO) content is shifted left one position.

```
RLC.B   LEO         ; Mem(LEO) x 2 + C -> Mem(LEO)
```

NOTE: RLC and RLC.B Substitution

The assembler does not recognize the instruction:

```
RLC @R5+, RLC @R5, or RLC(.B) @R5
```

It must be substitued by:

```
ADDC @R5+,-2(R5), ADDC.B @R5+,-1(R5), or ADDC(.B) @R5
```

3.4.6.40 RRA

RRA[.W] Rotate right arithmetically

RRA.B Rotate right arithmetically

Syntax

```
RRA dst  or  RRA.W dst
RRA.B dst
```

Operation MSB → MSB, MSB → MSB-1, ... LSB+1 → LSB, LSB → C

Description The destination operand is shifted right one position as shown in Figure 3-17. The MSB is shifted into the MSB, the MSB is shifted into the MSB-1, and the LSB+1 is shifted into the LSB.

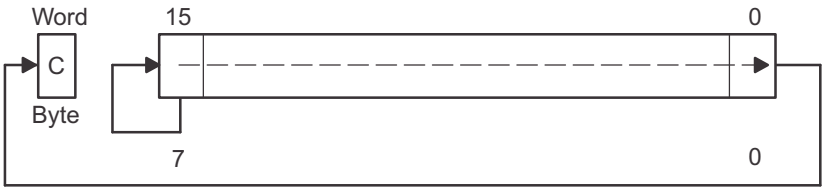


Figure 3-17. Destination Operand – Arithmetic Right Shift

Status Bits

N: Set if result is negative, reset if positive

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R5 is shifted right one position. The MSB retains the old value. It operates equal to an arithmetic division by 2.

```
RRA   R5   ; R5/2 -> R5
;   The value in R5 is multiplied by 0.75 (0.5 + 0.25).
;
PUSH    R5        ; Hold R5 temporarily using stack
RRA     R5        ; R5 x 0.5  ->  R5
ADD     @SP+,R5   ; R5 x 0.5 + R5 = 1.5 x R5  -> R5
RRA     R5        ; (1.5 x R5) x 0.5 = 0.75 x R5  -> R5
......
```

Example The low byte of R5 is shifted right one position. The MSB retains the old value. It operates equal to an arithmetic division by 2.

```
RRA.B    R5       ; R5/2 -> R5: operation is on low byte only
                  ; High byte of R5 is reset
PUSH.B   R5       ; R5 x 0.5  ->  TOS
RRA.B    @SP      ; TOS x 0.5 = 0.5 x R5 x 0.5 = 0.25 x R5  -> TOS
ADD.B    @SP+,R5  ; R5 x 0.5 + R5 x 0.25 = 0.75 x R5  -> R5
......
```

3.4.6.41 RRC

RRC[.W] Rotate right through carry

RRC.B Rotate right through carry

Syntax

```
RRC dst  or  RRC.W dst
RRC dst
```

Operation C → MSB → MSB-1 .... LSB+1 → LSB → C

Description The destination operand is shifted right one position as shown in Figure 3-18. The carry bit (C) is shifted into the MSB, the LSB is shifted into the carry bit (C).

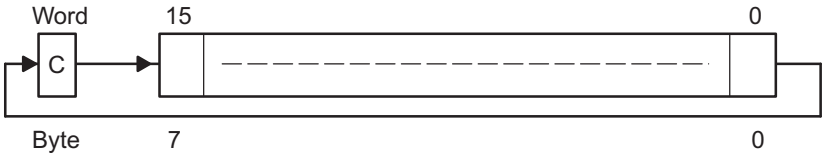


Figure 3-18. Destination Operand - Carry Right Shift

Status Bits

N: Set if result is negative, reset if positive

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIEare not affected.

Example R5 is shifted right one position. The MSB is loaded with 1.

```
SETC          ; Prepare carry for MSB
RRC     R5    ; R5/2 + 8000h -> R5
```

Example R5 is shifted right one position. The MSB is loaded with 1.

```
SETC          ; Prepare carry for MSB
RRC.B   R5    ; R5/2 + 80h -> R5; low byte of R5 is used
```

3.4.6.42 SBC

***SBC[.W]** Subtract source and borrow/.NOT. carry from destination

***SBC.B** Subtract source and borrow/.NOT. carry from destination

Syntax

```
SBC dst  or  SBC.W dst
SBC.B dst
```

Operation

dst + 0FFFFh + C → dst

dst + 0FFh + C → dst

Emulation

```
SUBC #0,dst
SUBC.B #0,dst
```

Description The carry bit (C) is added to the destination operand minus one. The previous contents of the destination are lost.

Status Bits

N: Set if result is negative, reset if positive

Z: Set if result is zero, reset otherwise

C: Set if there is a carry from the MSB of the result, reset otherwise.

Set to 1 if no borrow, reset if borrow.

V: Set if an arithmetic overflow occurs, reset otherwise.

Mode Bits OSCOFF, CPUOFF,and GIE are not affected.

Example The 16-bit counter pointed to by R13 is subtracted from a 32-bit counter pointed to by R12.

```
SUB     @R13,0(R12)   ; Subtract LSDs
SBC     2(R12)        ; Subtract carry from MSD
```

Example The 8-bit counter pointed to by R13 is subtracted from a 16-bit counter pointed to by R12.

```
SUB.B   @R13,0(R12)   ; Subtract LSDs
SBC.B   1(R12)        ; Subtract carry from MSD
```

NOTE: Borrow Implementation

The borrow is treated as a .NOT. carry:	Borrow	Carry bit
	Yes	0
	No	1

3.4.6.43 SETC

***SETC**	Set carry bit
Syntax	SETC
Operation	1 → C
Emulation	BIS #1,SR
Description	The carry bit (C) is set.
Status Bits	N: Not affected Z: Not affected C: Set V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	Emulation of the decimal subtraction: Subtract R5 from R6 decimally Assume that R5 = 03987h and R6 = 04137h

```
DSUB    ADD     #06666h,R5    ; Move content R5 from 0-9 to 6-0Fh
                              ; R5 = 03987h + 06666h = 09FEDh
        INV     R5            ; Invert this (result back to 0-9)
                              ; R5 = .NOT. R5 = 06012h
        SETC                  ; Prepare carry = 1
        DADD    R5,R6         ; Emulate subtraction by addition of:
                              ; (010000h - R5 - 1)
                              ; R6 = R6 + R5 + 1
                              ; R6 = 0150h
```

3.4.6.44 SETN

***SETN**	Set negative bit
Syntax	`SETN`
Operation	1 → N
Emulation	`BIS #4,SR`
Description	The negative bit (N) is set.
Status Bits	N: Set Z: Not affected C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.

3.4.6.45 SETZ

***SETZ**	Set zero bit
Syntax	`SETZ`
Operation	1 → Z
Emulation	`BIS #2,SR`
Description	The zero bit (Z) is set.
Status Bits	N: Not affected Z: Set C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.

3.4.6.46 SUB

SUB[.W]	Subtract source from destination
SUB.B	Subtract source from destination
Syntax	`SUB src,dst  or  SUB.W src,dst` `SUB.B src,dst`
Operation	dst + .NOT.src + 1 → dst or [(dst - src → dst)]
Description	The source operand is subtracted from the destination operand by adding the source operand's 1s complement and the constant 1. The source operand is not affected. The previous contents of the destination are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if result is zero, reset otherwise C: Set if there is a carry from the MSB of the result, reset otherwise. Set to 1 if no borrow, reset if borrow. V: Set if an arithmetic overflow occurs, otherwise reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	See example at the SBC instruction.
Example	See example at the SBC.B instruction.

NOTE: Borrow Is Treated as a .NOT.

The borrow is treated as a .NOT. carry:	Borrow	Carry bit
	Yes	0
	No	1

3.4.6.47 SUBC, SBB

SUBC[.W], SBB[.W] Subtract source and borrow/.NOT. carry from destination

SUBC.B, SBB.B Subtract source and borrow/.NOT. carry from destination

Syntax

```
SUBC     src,dst    or    SUBC.W   src,dst    or
SBB      src,dst    or    SBB.W    src,dst
SUBC.B   src,dst    or    SBB.B    src,dst
```

Operation

dst + .NOT.src + C → dst

or

(dst - src - 1 + C → dst)

Description The source operand is subtracted from the destination operand by adding the source operand's 1s complement and the carry bit (C). The source operand is not affected. The previous contents of the destination are lost.

Status Bits

N: Set if result is negative, reset if positive.

Z: Set if result is zero, reset otherwise.

C: Set if there is a carry from the MSB of the result, reset otherwise.

Set to 1 if no borrow, reset if borrow.

V: Set if an arithmetic overflow occurs, reset otherwise.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Two floating point mantissas (24 bits) are subtracted.

LSBs are in R13 and R10, MSBs are in R12 and R9.

```
SUB.W    R13,R10     ; 16-bit part, LSBs
SUBC.B   R12,R9      ; 8-bit part, MSBs
```

Example The 16-bit counter pointed to by R13 is subtracted from a 16-bit counter in R10 and R11(MSD).

```
SUB.B    @R13+,R10   ; Subtract LSDs without carry
SUBC.B   @R13,R11    ; Subtract MSDs with carry
...                  ; resulting from the LSDs
```

NOTE: Borrow Implementation

The borrow is treated as a .NOT. carry:	Borrow	Carry bit
	Yes	0
	No	1

3.4.6.48 SWPB

SWPB Swap bytes

Syntax `SWPB dst`

Operation Bits 15 to 8 ↔ bits 7 to 0

Description The destination operand high and low bytes are exchanged as shown in Figure 3-19.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

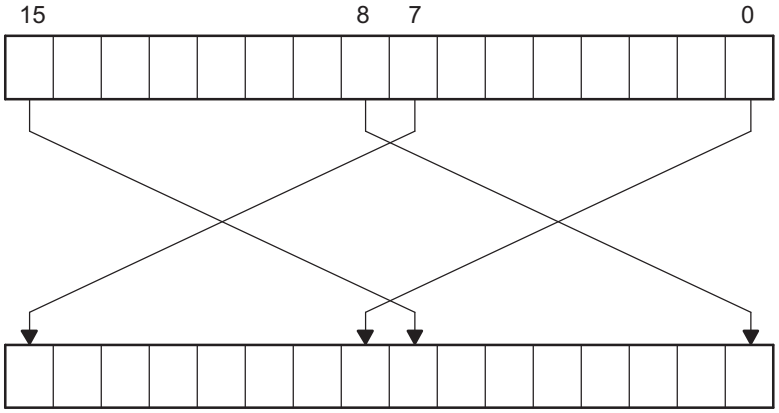


Figure 3-19. Destination Operand - Byte Swap

Example

```
MOV    #040BFh,R7   ; 0100000010111111 -> R7
SWPB   R7           ; 1011111101000000 in R7
```

Example The value in R5 is multiplied by 256. The result is stored in R5,R4.

```
SWPB   R5           ;
MOV    R5,R4        ; Copy the swapped value to R4
BIC    #0FF00h,R5   ; Correct the result
BIC    #00FFh,R4    ; Correct the result
```

3.4.6.49 SXT

SXT Extend Sign

Syntax `SXT dst`

Operation Bit 7 → Bit 8 ..... Bit 15

Description The sign of the low byte is extended into the high byte as shown in Figure 3-20.

Status Bits
N: Set if result is negative, reset if positive
Z: Set if result is zero, reset otherwise
C: Set if result is not zero, reset otherwise (.NOT. Zero)
V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

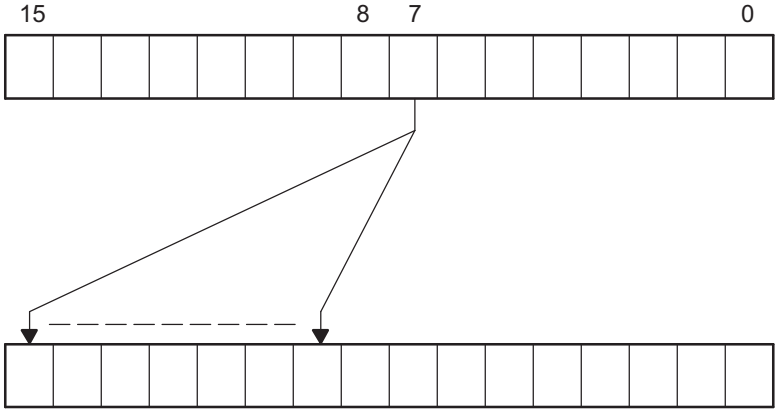


Figure 3-20. Destination Operand - Sign Extension

Example R7 is loaded with the P1IN value. The operation of the sign-extend instruction expands bit 8 to bit 15 with the value of bit 7.

R7 is then added to R6.

```
MOV.B   &P1IN,R7   ; P1IN = 080h:    .... .... 1000 0000
SXT     R7         ; R7 = 0FF80h:   1111 1111 1000 0000
```

3.4.6.50 TST

***TST[.W]**	Test destination
***TST.B**	Test destination
Syntax	`TST dst  or  TST.W dst` `TST.B dst`
Operation	dst + 0FFFFh + 1 dst + 0FFh + 1
Emulation	`CMP #0,dst` `CMP.B #0,dst`
Description	The destination operand is compared with zero. The status bits are set according to the result. The destination is not affected.
Status Bits	N: Set if destination is negative, reset if positive Z: Set if destination contains zero, reset otherwise C: Set V: Reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	R7 is tested. If it is negative, continue at R7NEG; if it is positive but not zero, continue at R7POS.

```
         TST     R7        ; Test R7
         JN      R7NEG     ; R7 is negative
         JZ      R7ZERO    ; R7 is zero
R7POS    ......            ; R7 is positive but not zero
R7NEG    ......            ; R7 is negative
R7ZERO   ......            ; R7 is zero
```

Example The low byte of R7 is tested. If it is negative, continue at R7NEG; if it is positive but not zero, continue at R7POS.

```
         TST.B   R7        ; Test low byte of R7
         JN      R7NEG     ; Low byte of R7 is negative
         JZ      R7ZERO    ; Low byte of R7 is zero
R7POS    ......            ; Low byte of R7 is positive but not zero
R7NEG    .....             ; Low byte of R7 is negative
R7ZERO   ......            ; Low byte of R7 is zero
```

3.4.6.51 XOR

XOR[.W]	Exclusive OR of source with destination
XOR.B	Exclusive OR of source with destination
Syntax	`XOR src,dst  or  XOR.W src,dst` `XOR.B src,dst`
Operation	src .XOR. dst → dst
Description	The source and destination operands are exclusive ORed. The result is placed into the destination. The source operand is not affected.
Status Bits	N: Set if result MSB is set, reset if not set Z: Set if result is zero, reset otherwise C: Set if result is not zero, reset otherwise (= .NOT. Zero) V: Set if both operands are negative
Mode Bits	OSCOFF, CPUOFF,and GIE are not affected.
Example	The bits set in R6 toggle the bits in the RAM word TONI. `XOR     R6,TONI  ; Toggle bits of word TONI on the bits set in R6`

Example	The bits set in R6 toggle the bits in the RAM byte TONI.
	`XOR.B   R6,TONI  ; Toggle bits of byte TONI on the bits set in`
	`                ; low byte of R6`

Example	Reset to 0 those bits in low byte of R7 that are different from bits in RAM byte EDE.
	`XOR.B   EDE,R7   ; Set different bit to "1s"`
	`INV.B   R7       ; Invert Lowbyte, Highbyte is 0h`

CPUX

This chapter describes the extended MSP430X 16-bit RISC CPU with 1-MB memory access, its addressing modes, and instruction set. The MSP430X CPU is implemented in all MSP430 devices that exceed 64-KB of address space.

Topic **Page**

4.1 CPU Introduction

The MSP430X CPU incorporates features specifically designed for modern programming techniques such as calculated branching, table processing and the use of high-level languages such as C. The MSP430X CPU can address a 1-MB address range without paging. In addition, the MSP430X CPU has fewer interrupt overhead cycles and fewer instruction cycles in some cases than the MSP430 CPU, while maintaining the same or better code density than the MSP430 CPU. The MSP430X CPU is backward compatible with the MSP430 CPU.

The MSP430X CPU features include:

- RISC architecture
- Orthogonal architecture
- Full register access including program counter, status register and stack pointer
- Single-cycle register operations
- Large register file reduces fetches to memory
- 20-bit address bus allows direct access and branching throughout the entire memory range without paging
- 16-bit data bus allows direct manipulation of word-wide arguments
- Constant generator provides the six most often used immediate values and reduces code size
- Direct memory-to-memory transfers without intermediate register holding
- Byte, word, and 20-bit address-word addressing

The block diagram of the MSP430X CPU is shown in Figure 4-1.

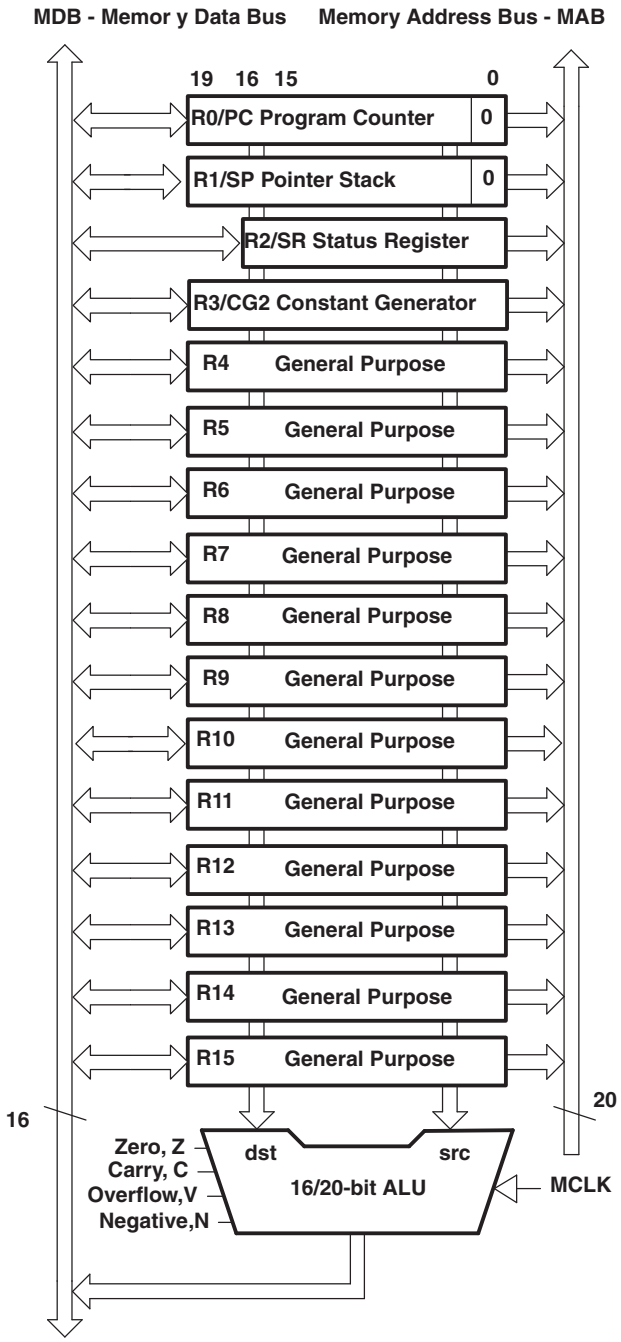


Figure 4-1. MSP430X CPU Block Diagram

4.2 Interrupts

The MSP430X uses the same interrupt structure as the MSP430:

- Vectored interrupts with no polling necessary
- Interrupt vectors are located downward from address 0FFFEh

Interrupt operation for both MSP430 and MSP430X CPUs is described in *Chapter 2 System Resets, Interrupts, and Operating modes, Section 2 Interrupts*. The interrupt vectors contain 16-bit addresses that point into the lower 64-KB memory. This means all interrupt handlers must start in the lower 64-KB memory, even in MSP430X devices.

During an interrupt, the program counter and the status register are pushed onto the stack as shown in Figure 4-2. The MSP430X architecture efficiently stores the complete 20-bit PC value by automatically appending the PC bits 19:16 to the stored SR value on the stack. When the RETI instruction is executed, the full 20-bit PC is restored making return from interrupt to any address in the memory range possible.

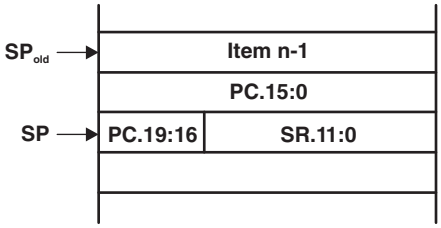


Figure 4-2. PC Storage on the Stack for Interrupts

4.3 CPU Registers

The CPU incorporates 16 registers (R0 through R15). Registers R0, R1, R2, and R3 have dedicated functions. Registers R4 through R15 are working registers for general use.

4.3.1 Program Counter (PC)

The 20-bit PC (PC/R0) points to the next instruction to be executed. Each instruction uses an even number of bytes (2, 4, 6, or 8 bytes), and the PC is incremented accordingly. Instruction accesses are performed on word boundaries, and the PC is aligned to even addresses. Figure 4-3 shows the PC.

Figure 4-3. Program Counter

The PC can be addressed with all instructions and addressing modes. A few examples:

```
MOV.W  #LABEL,PC  ; Branch to address LABEL (lower 64KB)

MOVA   #LABEL,PC  ; Branch to address LABEL (1MB memory)

MOV.W  LABEL,PC   ; Branch to address in word LABEL
                  ; (lower 64KB)

MOV.W  @R14,PC    ; Branch indirect to address in
                  ; R14 (lower 64KB)

ADDA   #4,PC      ; Skip two words (1MB memory)
```

The BR and CALL instructions reset the upper four PC bits to 0. Only addresses in the lower 64-KB address range can be reached with the BR or CALL instruction. When branching or calling, addresses beyond the lower 64-KB range can only be reached using the BRA or CALLA instructions. Also, any instruction to directly modify the PC does so according to the used addressing mode. For example, `MOV.W #value,PC` clears the upper four bits of the PC, because it is a .W instruction.

The PC is automatically stored on the stack with CALL (or CALLA) instructions and during an interrupt service routine. Figure 4-4 shows the storage of the PC with the return address after a CALLA instruction. A CALL instruction stores only bits 15:0 of the PC.

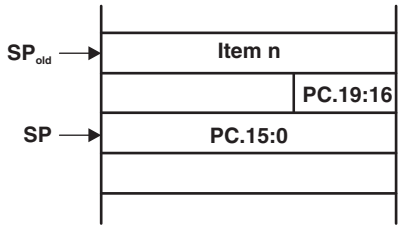


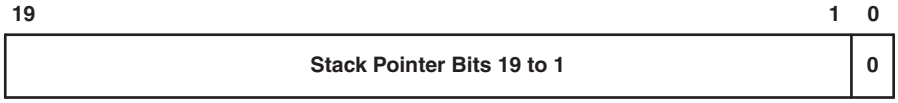
Figure 4-4. PC Storage on the Stack for CALLA

The RETA instruction restores bits 19:0 of the PC and adds 4 to the stack pointer (SP). The RET instruction restores bits 15:0 to the PC and adds 2 to the SP.

4.3.2 Stack Pointer (SP)

The 20-bit SP (SP/R1) is used by the CPU to store the return addresses of subroutine calls and interrupts. It uses a predecrement, postincrement scheme. In addition, the SP can be used by software with all instructions and addressing modes. Figure 4-5 shows the SP. The SP is initialized into RAM by the user, and is always aligned to even addresses.

Figure 4-6 shows the stack usage. Figure 4-7 shows the stack usage when 20-bit address words are pushed.




```
MOV.W   2(SP),R6      ; Copy Item I2 to R6
MOV.W   R7,0(SP)      ; Overwrite TOS with R7
PUSH    #0123h        ; Put 0123h on stack
POP     R8            ; R8 = 0123h
```

Figure 4-5. Stack Pointer

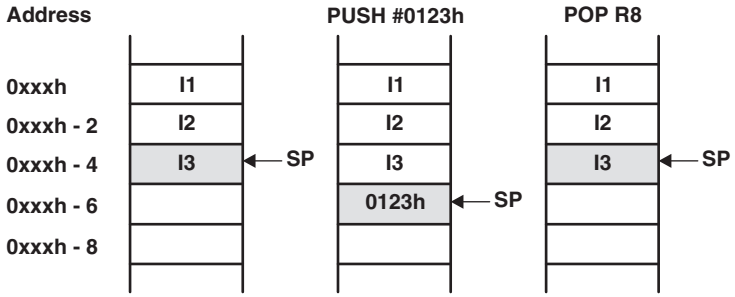


Figure 4-6. Stack Usage

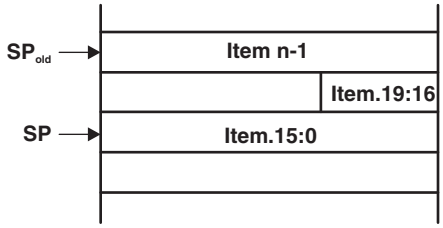


Figure 4-7. PUSHX.A Format on the Stack

The special cases of using the SP as an argument to the PUSH and POP instructions are described and shown in Figure 4-8.

The stack pointer is changed after a PUSH SP instruction.

The stack pointer is not changed after a POP SP instruction. The POP SP instruction places SP1 into the stack pointer SP (SP2 = SP1)

Figure 4-8. PUSH SP, POP SP Sequence

4.3.3 Status Register (SR)

The 16-bit SR (SR/R2), used as a source or destination register, can only be used in register mode addressed with word instructions. The remaining combinations of addressing modes are used to support the constant generator. Figure 4-9 shows the SR bits. Do not write 20-bit values to the SR. Unpredictable operation can result.

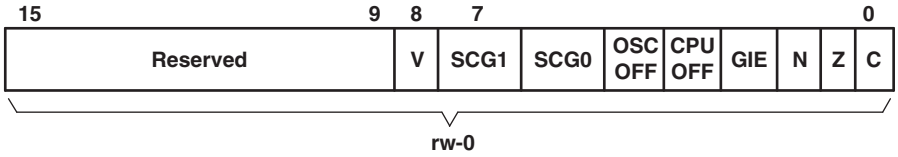


Figure 4-9. SR Bits

Table 4-1 describes the SR bits.

Table 4-1. SR Bit Description

Bit	Description	
Reserved	Reserved	
V	Overflow. This bit is set when the result of an arithmetic operation overflows the signed-variable range.	
	`ADD(.B), ADDX(.B,.A), ADDC(.B), ADDCX(.B.A), ADDA`	Set when: positive + positive = negative negative + negative = positive otherwise reset
	`SUB(.B), SUBX(.B,.A), SUBC(.B), SUBCX(.B,.A), SUBA, CMP(.B), CMPX(.B,.A), CMPA`	Set when: positive – negative = negative negative – positive = positive otherwise reset
SCG1	System clock generator 1. This bit may be to enable/disable functions in the clock system depending on the device family; for example, DCO bias enable/disable	
SCG0	System clock generator 0. This bit may be used to enable/disable functions in the clock system depending on the device family; for example, FLL disable/enable	
OSCOFF	Oscillator off. This bit, when set, turns off the LFXT1 crystal oscillator when LFXT1CLK is not used for MCLK or SMCLK.	
CPUOFF	CPU off. This bit, when set, turns off the CPU.	
GIE	General interrupt enable. This bit, when set, enables maskable interrupts. When reset, all maskable interrupts are disabled.	
N	Negative. This bit is set when the result of an operation is negative and cleared when the result is positive.	
Z	Zero. This bit is set when the result of an operation is 0 and cleared when the result is not 0.	
C	Carry. This bit is set when the result of an operation produced a carry and cleared when no carry occurred.	

4.3.4 Constant Generator Registers (CG1 and CG2)

Six commonly-used constants are generated with the constant generator registers R2 (CG1) and R3 (CG2), without requiring an additional 16-bit word of program code. The constants are selected with the source register addressing modes (As), as described in Table 4-2.

Table 4-2. Values of Constant Generators CG1, CG2

Register	As	Constant	Remarks
R2	00	–	Register mode
R2	01	(0)	Absolute address mode
R2	10	00004h	+4, bit processing
R2	11	00008h	+8, bit processing
R3	00	00000h	0, word processing
R3	01	00001h	+1
R3	10	00002h	+2, bit processing
R3	11	FFh, FFFFh, FFFFFh	–1, word processing

The constant generator advantages are:

- No special instructions required
- No additional code word for the six constants
- No code memory access required to retrieve the constant

The assembler uses the constant generator automatically if one of the six constants is used as an immediate source operand. Registers R2 and R3, used in the constant mode, cannot be addressed explicitly; they act as source-only registers.

4.3.4.1 Constant Generator – Expanded Instruction Set

The RISC instruction set of the MSP430 has only 27 instructions. However, the constant generator allows the MSP430 assembler to support 24 additional emulated instructions. For example, the single-operand instruction:

```
CLR dst
```

is emulated by the double-operand instruction with the same length:

```
MOV R3,dst
```

where the #0 is replaced by the assembler, and R3 is used with As = 00.

```
INC dst
```

is replaced by:

```
ADD #1,dst
```

4.3.5 General-Purpose Registers (R4 to R15)

The 12 CPU registers (R4 to R15) contain 8-bit, 16-bit, or 20-bit values. Any byte-write to a CPU register clears bits 19:8. Any word-write to a register clears bits 19:16. The only exception is the SXT instruction. The SXT instruction extends the sign through the complete 20-bit register.

The following figures show the handling of byte, word, and address-word data. Note the reset of the leading most significant bits (MSBs) if a register is the destination of a byte or word instruction.

Figure 4-10 shows byte handling (8-bit data, .B suffix). The handling is shown for a source register and a destination memory byte and for a source memory byte and a destination register.

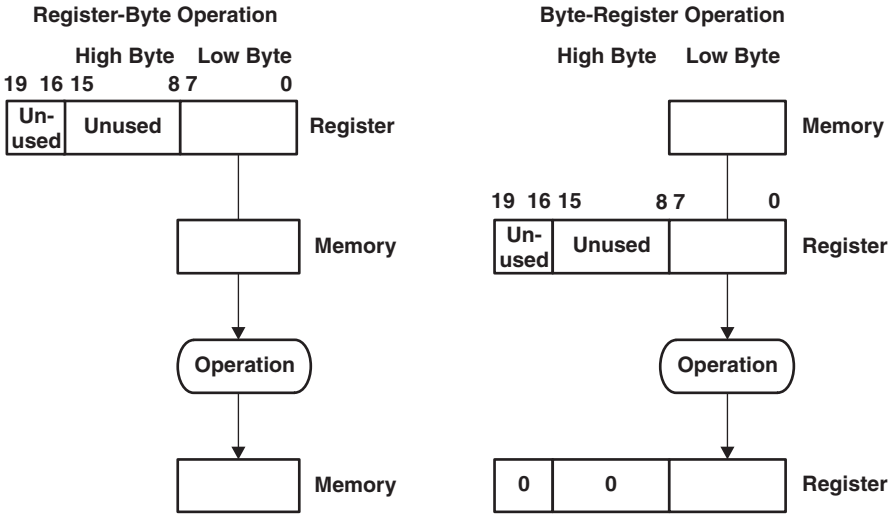


Figure 4-10. Register-Byte/Byte-Register Operation

Figure 4-11 and Figure 4-12 show 16-bit word handling (.W suffix). The handling is shown for a source register and a destination memory word and for a source memory word and a destination register.

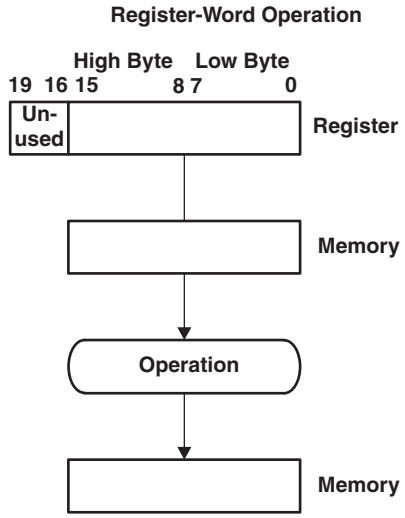


Figure 4-11. Register-Word Operation

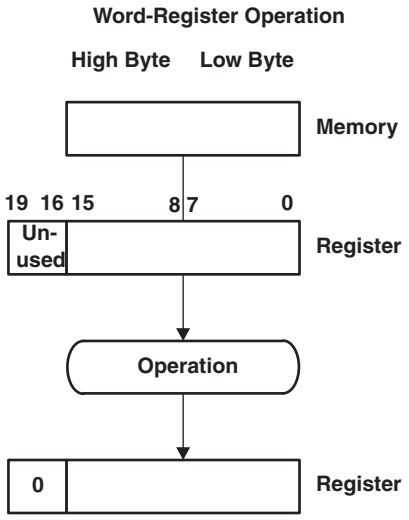


Figure 4-12. Word-Register Operation

Figure 4-13 and Figure 4-14 show 20-bit address-word handling (.A suffix). The handling is shown for a source register and a destination memory address-word and for a source memory address-word and a destination register.

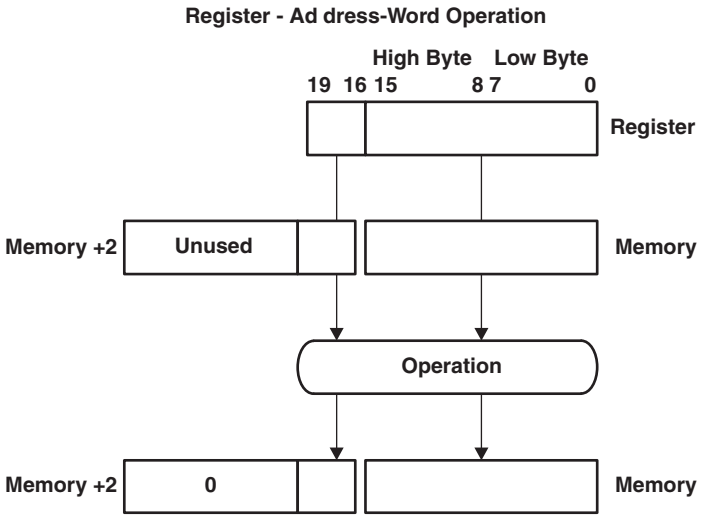


Figure 4-13. Register – Address-Word Operation

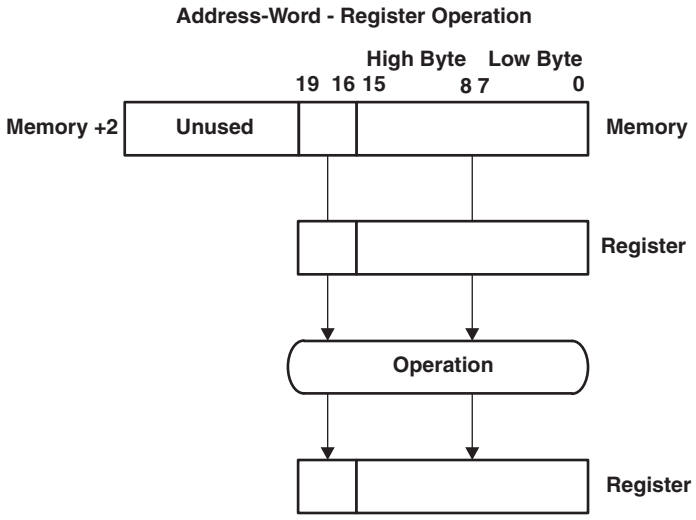


Figure 4-14. Address-Word – Register Operation

4.4 Addressing Modes

Seven addressing modes for the source operand and four addressing modes for the destination operand use 16-bit or 20-bit addresses (see Table 4-3). The MSP430 and MSP430X instructions are usable throughout the entire 1MB memory range.

Table 4-3. Source/Destination Addressing

As/Ad	Addressing Mode	Syntax	Description
00/0	Register	Rn	Register contents are operand.
01/1	Indexed	X(Rn)	(Rn + X) points to the operand. X is stored in the next word, or stored in combination of the preceding extension word and the next word.
01/1	Symbolic	ADDR	(PC + X) points to the operand. X is stored in the next word, or stored in combination of the preceding extension word and the next word. Indexed mode X(PC) is used.
01/1	Absolute	&ADDR	The word following the instruction contains the absolute address. X is stored in the next word, or stored in combination of the preceding extension word and the next word. Indexed mode X(SR) is used.
10/–	Indirect Register	@Rn	Rn is used as a pointer to the operand.
11/–	Indirect Autoincrement	@Rn+	Rn is used as a pointer to the operand. Rn is incremented afterwards by 1 for .B instructions. by 2 for .W instructions, and by 4 for .A instructions.
11/–	Immediate	#N	N is stored in the next word, or stored in combination of the preceding extension word and the next word. Indirect autoincrement mode @PC+ is used.

The seven addressing modes are explained in detail in the following sections. Most of the examples show the same addressing mode for the source and destination, but any valid combination of source and destination addressing modes is possible in an instruction.

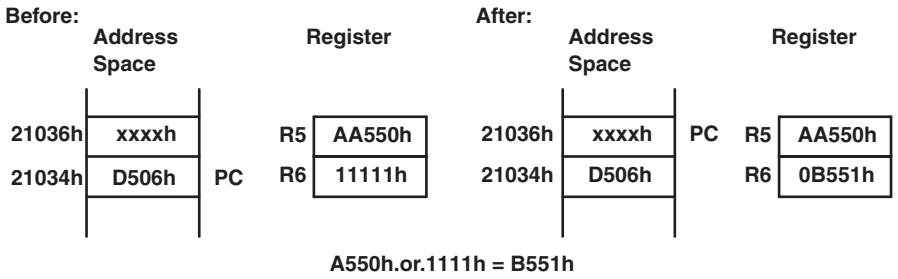
NOTE: Use of Labels EDE, TONI, TOM, and LEO

Throughout MSP430 documentation, EDE, TONI, TOM, and LEO are used as generic labels. They are only labels and have no special meaning.

4.4.1 Register Mode

Operation:	The operand is the 8-, 16-, or 20-bit content of the used CPU register.
Length:	One, two, or three words
Comment:	Valid for source and destination
Byte operation:	Byte operation reads only the eight least significant bits (LSBs) of the source register Rsrc and writes the result to the eight LSBs of the destination register Rdst. The bits Rdst.19:8 are cleared. The register Rsrc is not modified.
Word operation:	Word operation reads the 16 LSBs of the source register Rsrc and writes the result to the 16 LSBs of the destination register Rdst. The bits Rdst.19:16 are cleared. The register Rsrc is not modified.
Address-word operation:	Address-word operation reads the 20 bits of the source register Rsrc and writes the result to the 20 bits of the destination register Rdst. The register Rsrc is not modified
SXT exception:	The SXT instruction is the only exception for register operation. The sign of the low byte in bit 7 is extended to the bits Rdst.19:8.
Example:	`BIS.W R5,R6 ;`

This instruction logically ORs the 16-bit data contained in R5 with the 16-bit contents of R6. R6.19:16 is cleared.

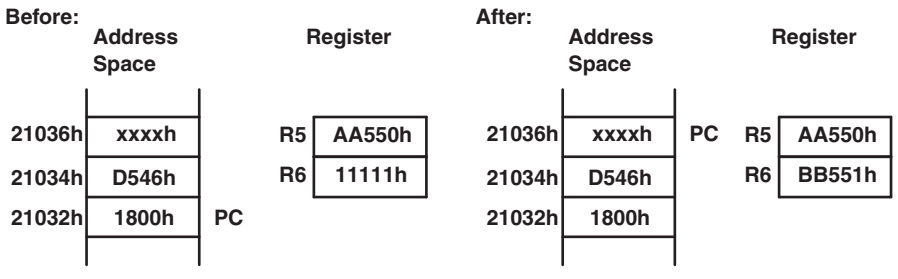


A550h.or.1111h = B551h

Example: `BISX.A R5,R6 ;`

This instruction logically ORs the 20-bit data contained in R5 with the 20-bit contents of R6.

The extension word contains the A/L bit for 20-bit data. The instruction word uses byte mode with bits A/L:B/W = 01. The result of the instruction is:



AA550h.or.11111h = BB551h

4.4.2 Indexed Mode

The Indexed mode calculates the address of the operand by adding the signed index to a CPU register. The Indexed mode has three addressing possibilities:

- Indexed mode in lower 64-KB memory
- MSP430 instruction with Indexed mode addressing memory above the lower 64-KB memory
- MSP430X instruction with Indexed mode

4.4.2.1 Indexed Mode in Lower 64-KB Memory

If the CPU register Rn points to an address in the lower 64KB of the memory range, the calculated memory address bits 19:16 are cleared after the addition of the CPU register Rn and the signed 16-bit index. This means the calculated memory address is always located in the lower 64KB and does not overflow or underflow out of the lower 64-KB memory space. The RAM and the peripheral registers can be accessed this way and existing MSP430 software is usable without modifications as shown in Figure 4-15.

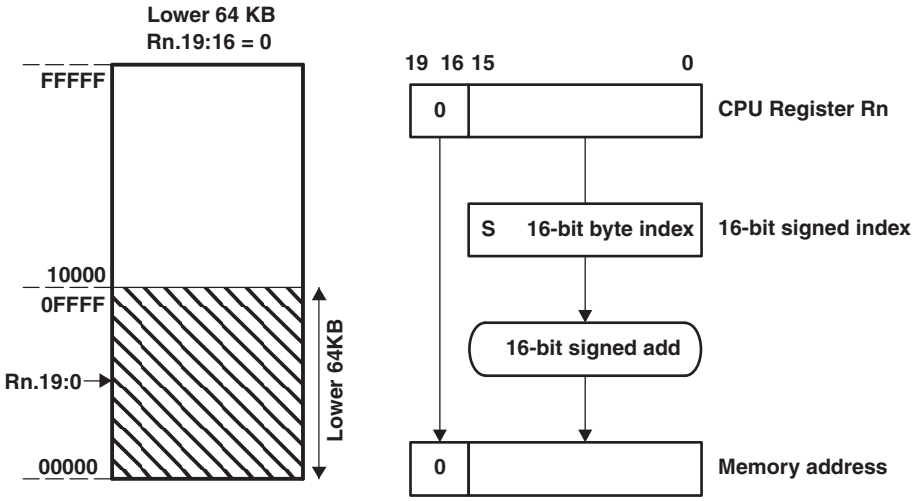
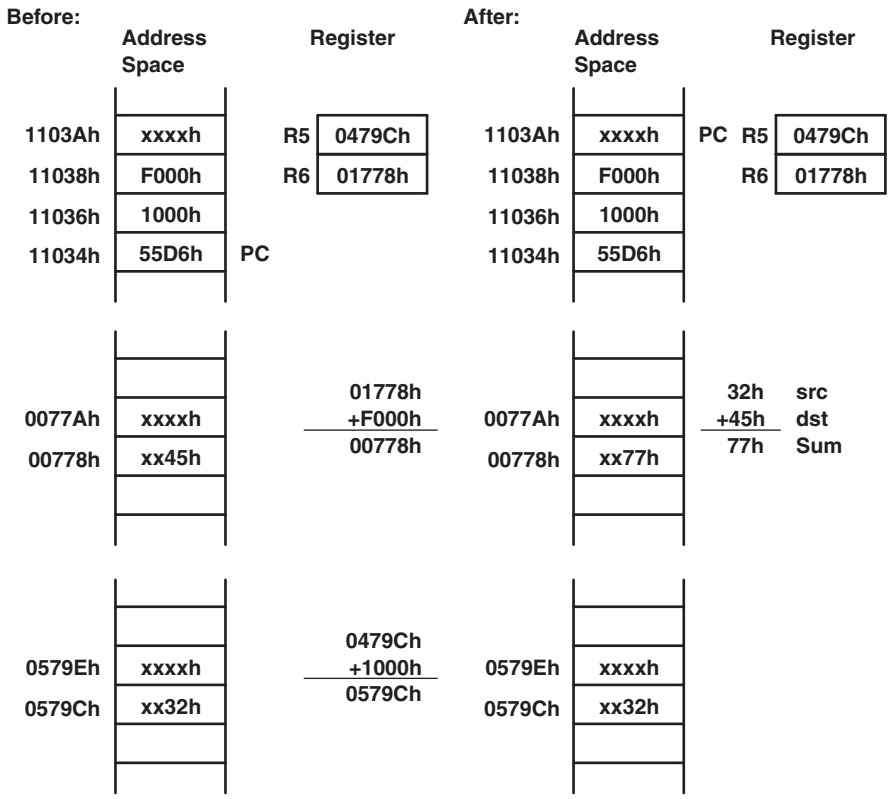


Figure 4-15. Indexed Mode in Lower 64KB

Length:	Two or three words
Operation:	The signed 16-bit index is located in the next word after the instruction and is added to the CPU register Rn. The resulting bits 19:16 are cleared giving a truncated 16-bit memory address, which points to an operand address in the range 00000h to 0FFFFh. The operand is the content of the addressed memory location.
Comment:	Valid for source and destination. The assembler calculates the register index and inserts it.
Example:	`ADD.B 1000h(R5),0F000h(R6);`
	This instruction adds the 8-bit data contained in source byte 1000h(R5) and the destination byte 0F000h(R6) and places the result into the destination byte. Source and destination bytes are both located in the lower 64KB due to the cleared bits 19:16 of registers R5 and R6.
Source:	The byte pointed to by R5 + 1000h results in address 0479Ch + 1000h = 0579Ch after truncation to a 16-bit address.
Destination:	The byte pointed to by R6 + F000h results in address 01778h + F000h = 00778h after truncation to a 16-bit address.



4.4.2.2 MSP430 Instruction With Indexed Mode in Upper Memory

If the CPU register Rn points to an address above the lower 64-KB memory, the Rn bits 19:16 are used for the address calculation of the operand. The operand may be located in memory in the range Rn ±32KB, because the index, X, is a signed 16-bit value. In this case, the address of the operand can overflow or underflow into the lower 64-KB memory space (see Figure 4-16 and Figure 4-17).

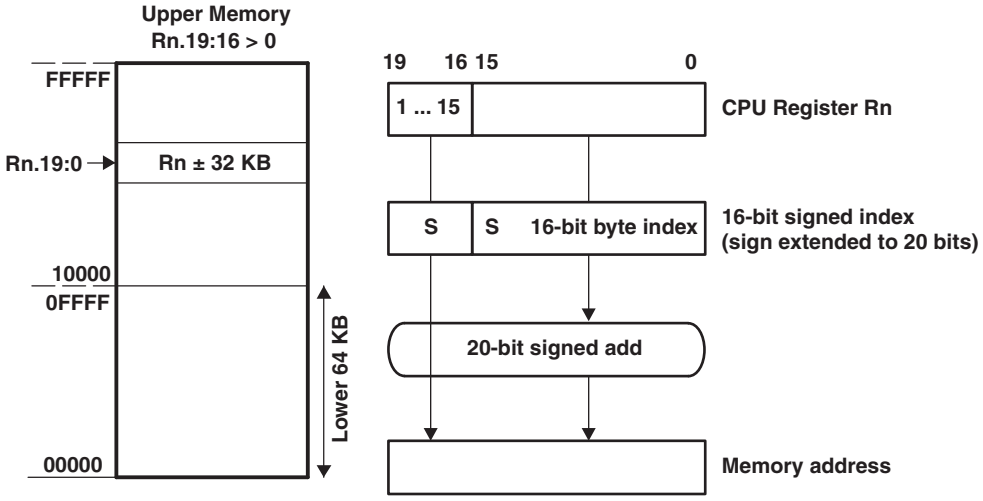


Figure 4-16. Indexed Mode in Upper Memory

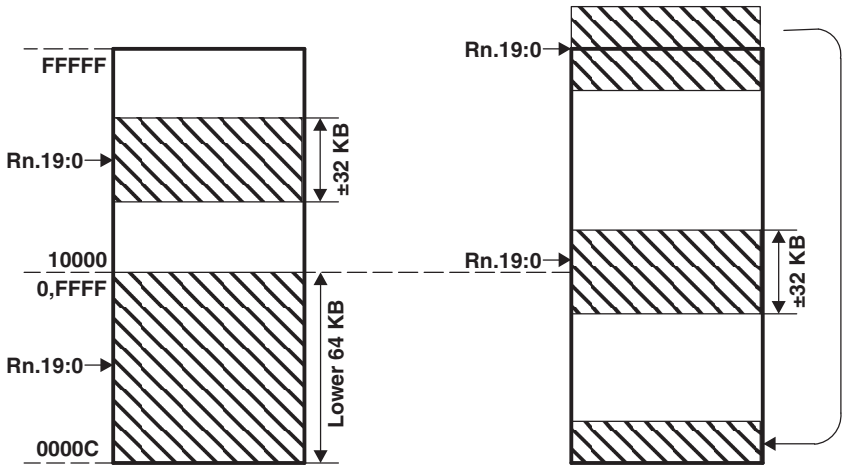
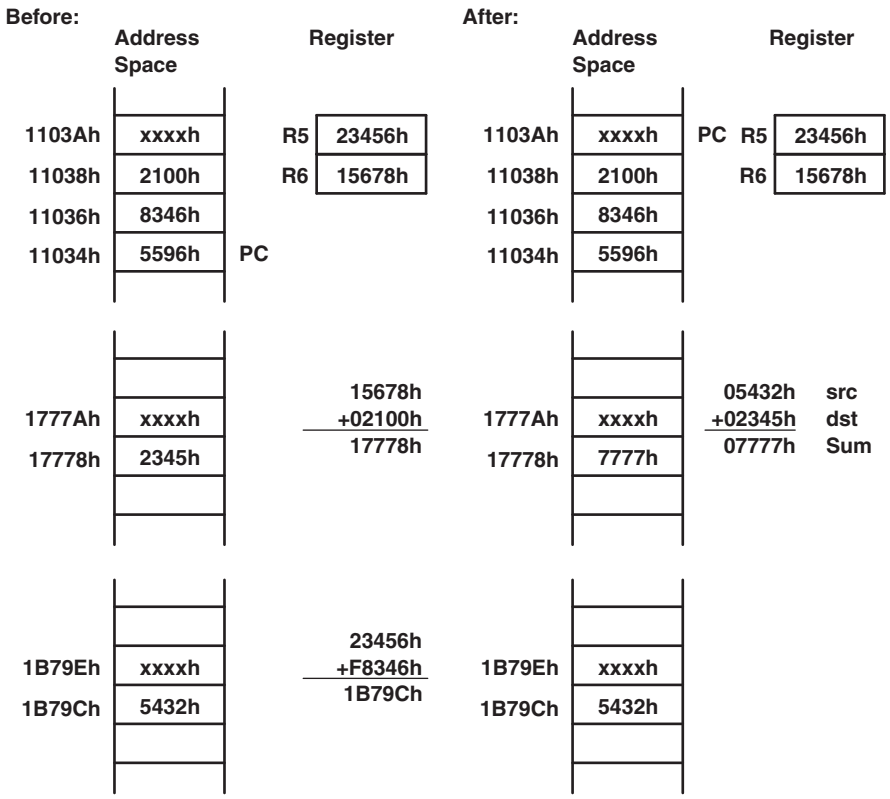


Figure 4-17. Overflow and Underflow for Indexed Mode

Length:	Two or three words
Operation:	The sign-extended 16-bit index in the next word after the instruction is added to the 20 bits of the CPU register Rn. This delivers a 20-bit address, which points to an address in the range 0 to FFFFFh. The operand is the content of the addressed memory location.
Comment:	Valid for source and destination. The assembler calculates the register index and inserts it.
Example:	`ADD.W 8346h(R5),2100h(R6) ;` This instruction adds the 16-bit data contained in the source and the destination addresses and places the 16-bit result into the destination. Source and destination operand can be located in the entire address range.
Source:	The word pointed to by R5 + 8346h. The negative index 8346h is sign extended, which results in address 23456h + F8346h = 1B79Ch.
Destination:	The word pointed to by R6 + 2100h results in address 15678h + 2100h = 17778h.

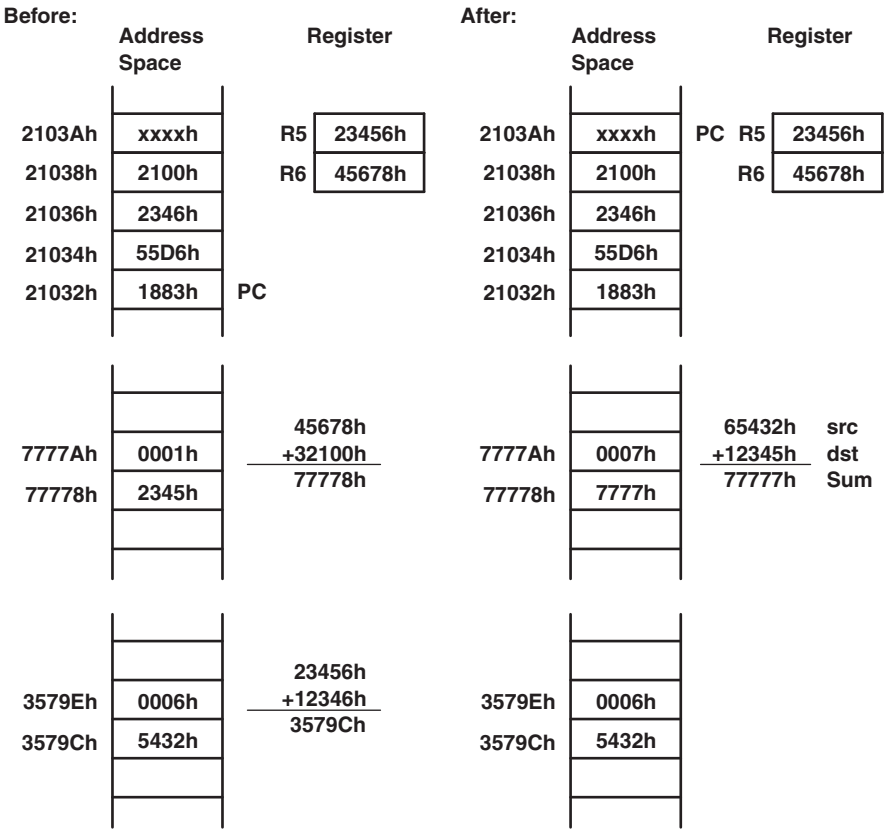


4.4.2.3 MSP430X Instruction With Indexed Mode

When using an MSP430X instruction with Indexed mode, the operand can be located anywhere in the range of Rn + 19 bits.

Length:	Three or four words
Operation:	The operand address is the sum of the 20-bit CPU register content and the 20-bit index. The 4 MSBs of the index are contained in the extension word; the 16 LSBs are contained in the word following the instruction. The CPU register is not modified
Comment:	Valid for source and destination. The assembler calculates the register index and inserts it.
Example:	`ADDX.A 12346h(R5),32100h(R6) ;` This instruction adds the 20-bit data contained in the source and the destination addresses and places the result into the destination.
Source:	Two words pointed to by R5 + 12346h which results in address 23456h + 12346h = 3579Ch.
Destination:	Two words pointed to by R6 + 32100h which results in address 45678h + 32100h = 77778h.

The extension word contains the MSBs of the source index and of the destination index and the A/L bit for 20-bit data. The instruction word uses byte mode due to the 20-bit data length with bits A/L:B/W = 01.



4.4.3 Symbolic Mode

The Symbolic mode calculates the address of the operand by adding the signed index to the PC. The Symbolic mode has three addressing possibilities:

- Symbolic mode in lower 64-KB memory
- MSP430 instruction with Symbolic mode addressing memory above the lower 64-KB memory.
- MSP430X instruction with Symbolic mode

4.4.3.1 Symbolic Mode in Lower 64KB

If the PC points to an address in the lower 64KB of the memory range, the calculated memory address bits 19:16 are cleared after the addition of the PC and the signed 16-bit index. This means the calculated memory address is always located in the lower 64KB and does not overflow or underflow out of the lower 64-KB memory space. The RAM and the peripheral registers can be accessed this way and existing MSP430 software is usable without modifications as shown in Figure 4-18.

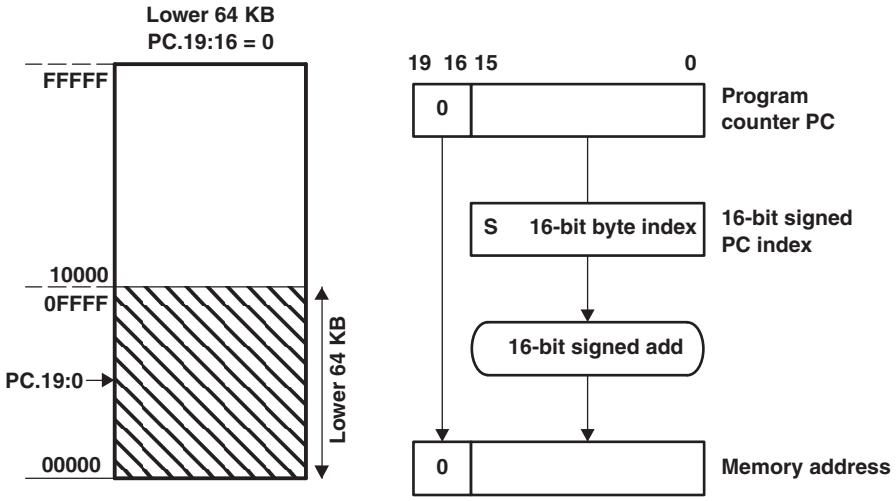
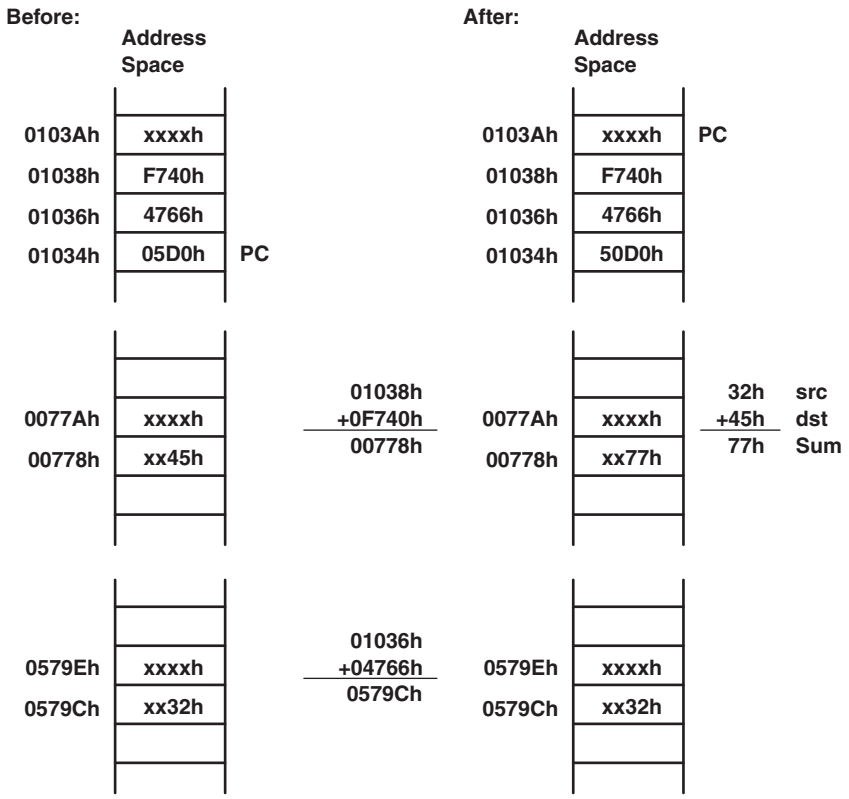


Figure 4-18. Symbolic Mode Running in Lower 64KB

Operation:	The signed 16-bit index in the next word after the instruction is added temporarily to the PC. The resulting bits 19:16 are cleared giving a truncated 16-bit memory address, which points to an operand address in the range 00000h to 0FFFFh. The operand is the content of the addressed memory location.
Length:	Two or three words
Comment:	Valid for source and destination. The assembler calculates the PC index and inserts it.
Example:	`ADD.B EDE,TONI ;` This instruction adds the 8-bit data contained in source byte EDE and destination byte TONI and places the result into the destination byte TONI. Bytes EDE and TONI and the program are located in the lower 64KB.
Source:	Byte EDE located at address 0579Ch, pointed to by PC + 4766h, where the PC index 4766h is the result of 0579Ch – 01036h = 04766h. Address 01036h is the location of the index for this example.
Destination:	Byte TONI located at address 00778h, pointed to by PC + F740h, is the truncated 16-bit result of 00778h – 1038h = FF740h. Address 01038h is the location of the index for this example.



4.4.3.2 MSP430 Instruction With Symbolic Mode in Upper Memory

If the PC points to an address above the lower 64-KB memory, the PC bits 19:16 are used for the address calculation of the operand. The operand may be located in memory in the range PC ± 32KB, because the index, X, is a signed 16-bit value. In this case, the address of the operand can overflow or underflow into the lower 64-KB memory space as shown in Figure 4-19 and Figure 4-20.

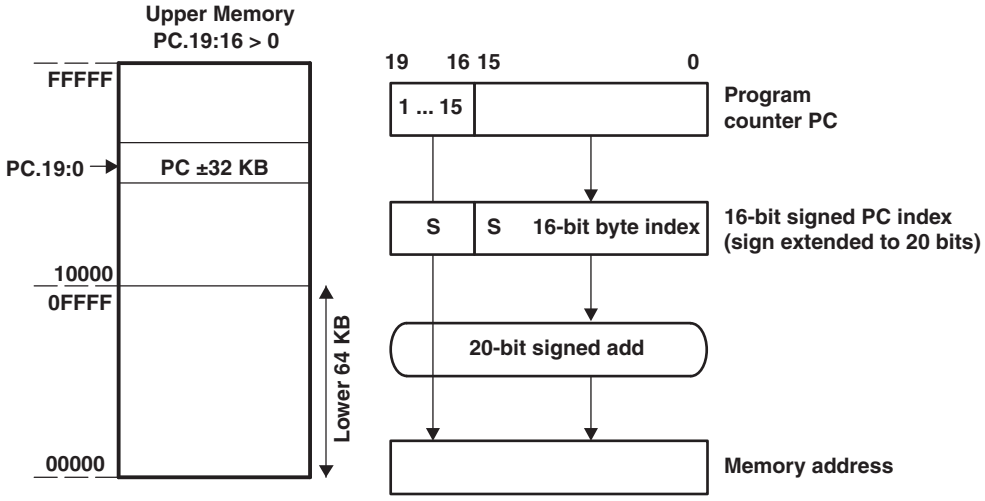


Figure 4-19. Symbolic Mode Running in Upper Memory

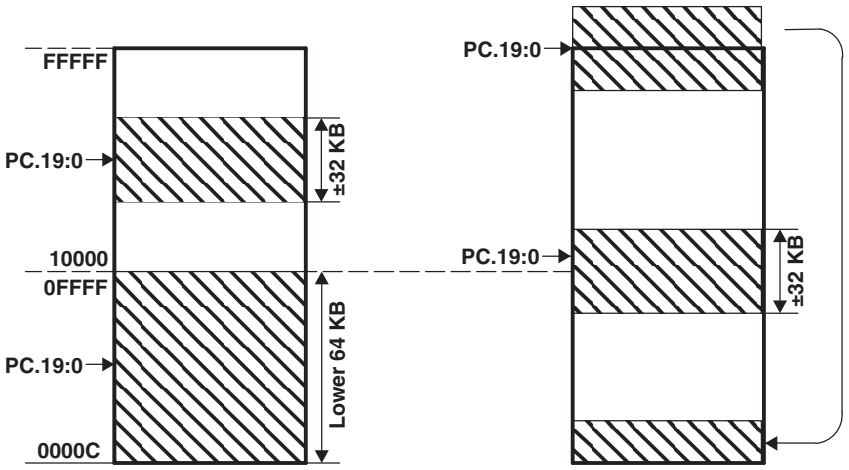
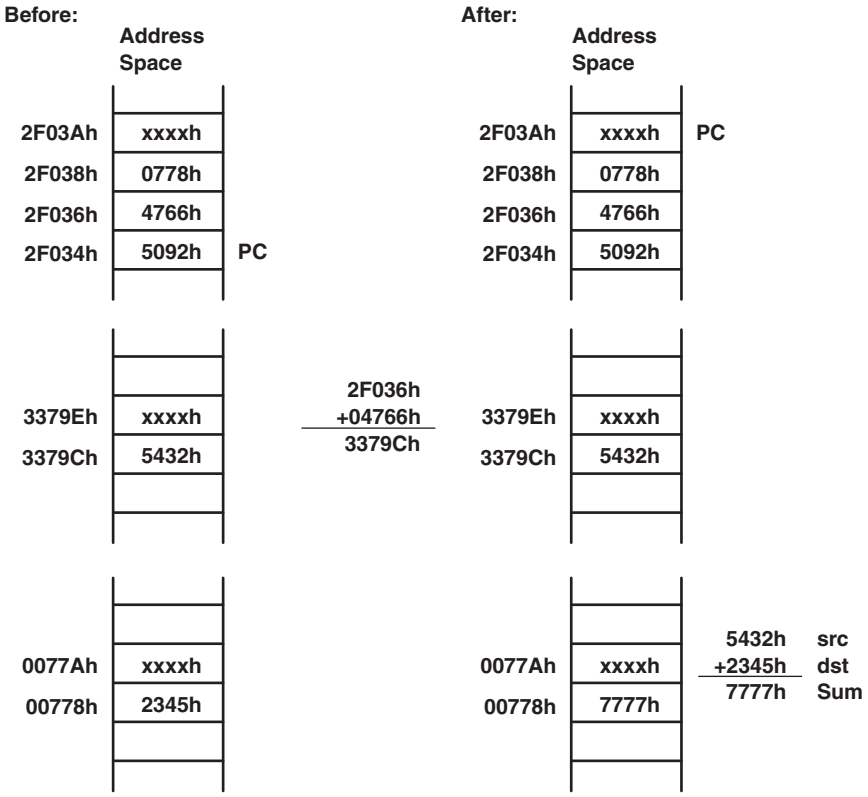


Figure 4-20. Overflow and Underflow for Symbolic Mode

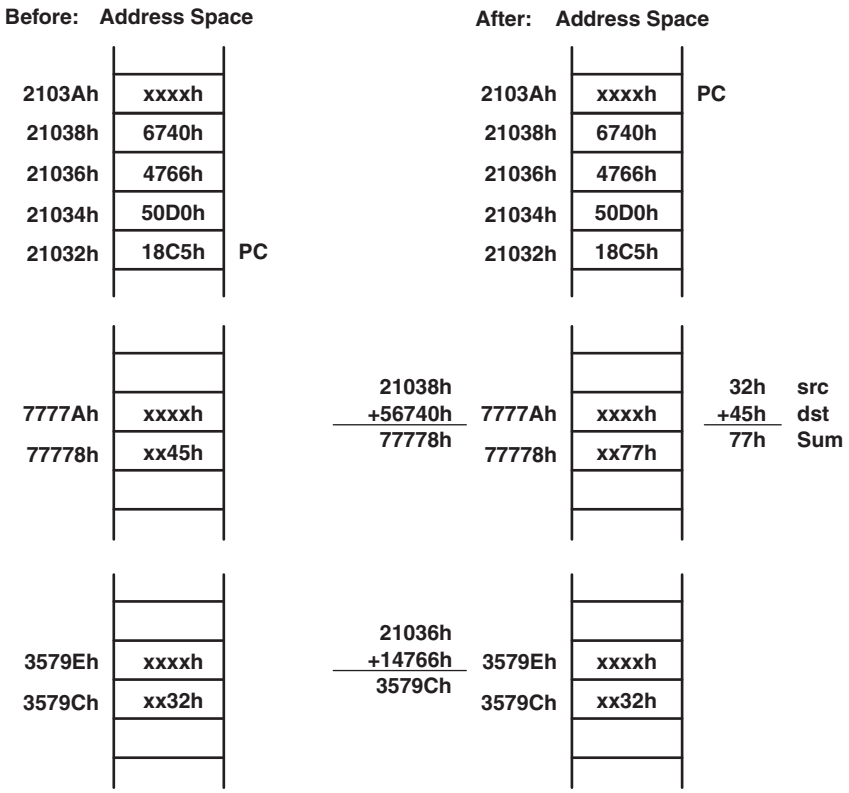
Length:	Two or three words
Operation:	The sign-extended 16-bit index in the next word after the instruction is added to the 20 bits of the PC. This delivers a 20-bit address, which points to an address in the range 0 to FFFFFh. The operand is the content of the addressed memory location.
Comment:	Valid for source and destination. The assembler calculates the PC index and inserts it
Example:	`ADD.W EDE,&TONI ;` This instruction adds the 16-bit data contained in source word EDE and destination word TONI and places the 16-bit result into the destination word TONI. For this example, the instruction is located at address 2F034h.
Source:	Word EDE at address 3379Ch, pointed to by PC + 4766h, which is the 16-bit result of 3379Ch – 2F036h = 04766h. Address 2F036h is the location of the index for this example.
Destination:	Word TONI located at address 00778h pointed to by the absolute address 00778h



4.4.3.3 MSP430X Instruction With Symbolic Mode

When using an MSP430X instruction with Symbolic mode, the operand can be located anywhere in the range of PC + 19 bits.

Length:	Three or four words
Operation:	The operand address is the sum of the 20-bit PC and the 20-bit index. The 4 MSBs of the index are contained in the extension word; the 16 LSBs are contained in the word following the instruction.
Comment:	Valid for source and destination. The assembler calculates the register index and inserts it.
Example:	`ADDX.B EDE,TONI ;`
	This instruction adds the 8-bit data contained in source byte EDE and destination byte TONI and places the result into the destination byte TONI.
Source:	Byte EDE located at address 3579Ch, pointed to by PC + 14766h, is the 20-bit result of 3579Ch – 21036h = 14766h. Address 21036h is the address of the index in this example.
Destination:	Byte TONI located at address 77778h, pointed to by PC + 56740h, is the 20-bit result of 77778h – 21038h = 56740h. Address 21038h is the address of the index in this example.



4.4.4 Absolute Mode

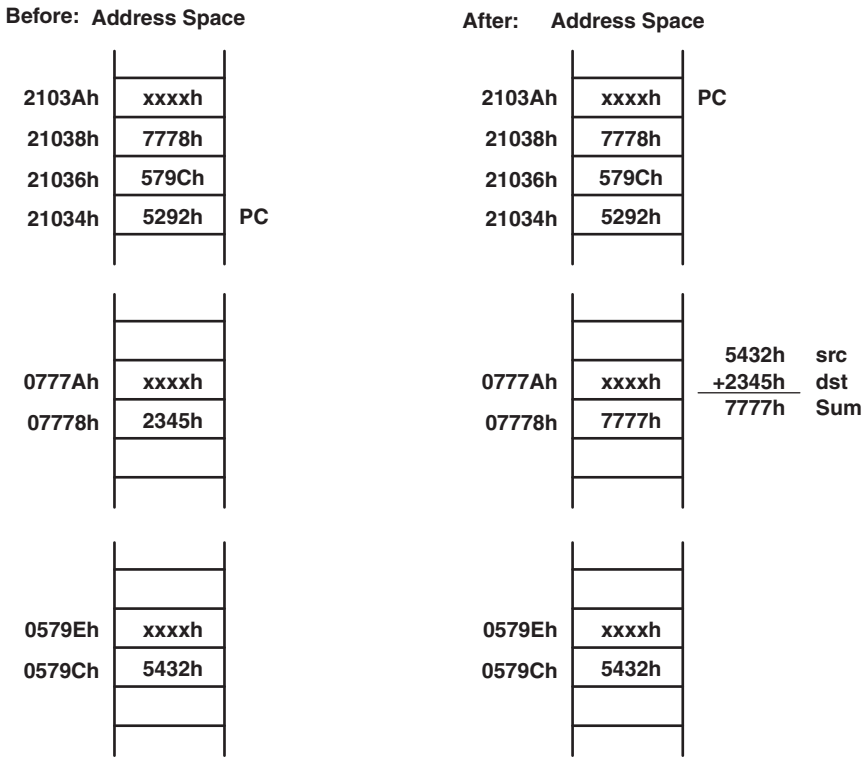
The Absolute mode uses the contents of the word following the instruction as the address of the operand. The Absolute mode has two addressing possibilities:

- Absolute mode in lower 64-KB memory
- MSP430X instruction with Absolute mode

4.4.4.1 Absolute Mode in Lower 64KB

If an MSP430 instruction is used with Absolute addressing mode, the absolute address is a 16-bit value and, therefore, points to an address in the lower 64KB of the memory range. The address is calculated as an index from 0 and is stored in the word following the instruction The RAM and the peripheral registers can be accessed this way and existing MSP430 software is usable without modifications.

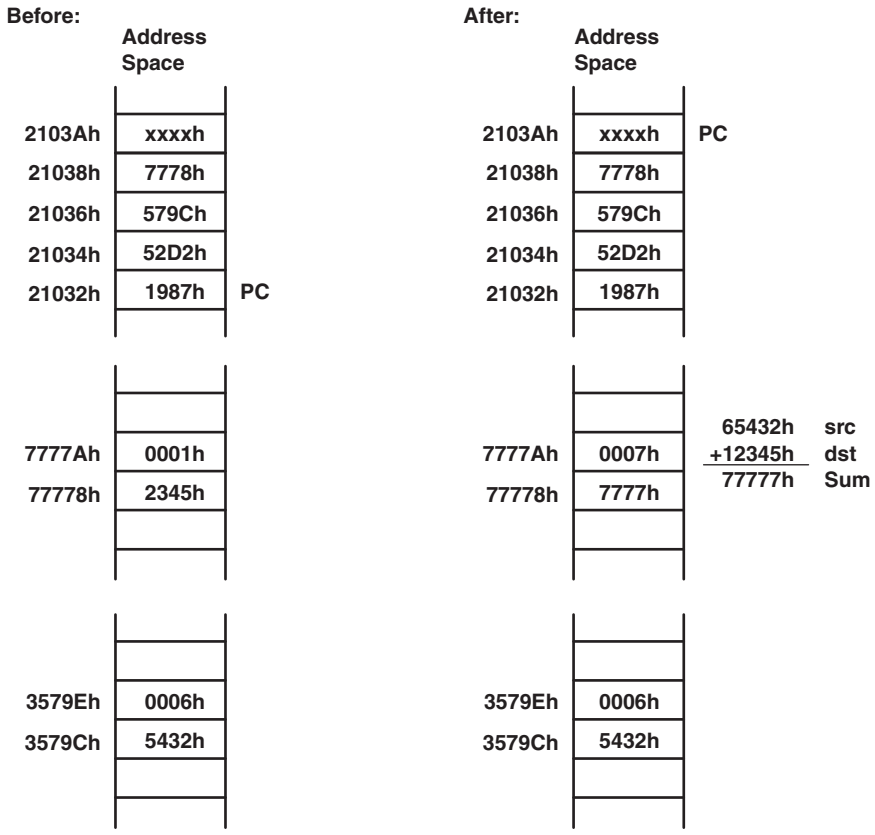
Length:	Two or three words
Operation:	The operand is the content of the addressed memory location.
Comment:	Valid for source and destination. The assembler calculates the index from 0 and inserts it.
Example:	`ADD.W &EDE,&TONI ;`
	This instruction adds the 16-bit data contained in the absolute source and destination addresses and places the result into the destination.
Source:	Word at address EDE
Destination:	Word at address TONI



4.4.4.2 MSP430X Instruction With Absolute Mode

If an MSP430X instruction is used with Absolute addressing mode, the absolute address is a 20-bit value and, therefore, points to any address in the memory range. The address value is calculated as an index from 0. The 4 MSBs of the index are contained in the extension word, and the 16 LSBs are contained in the word following the instruction.

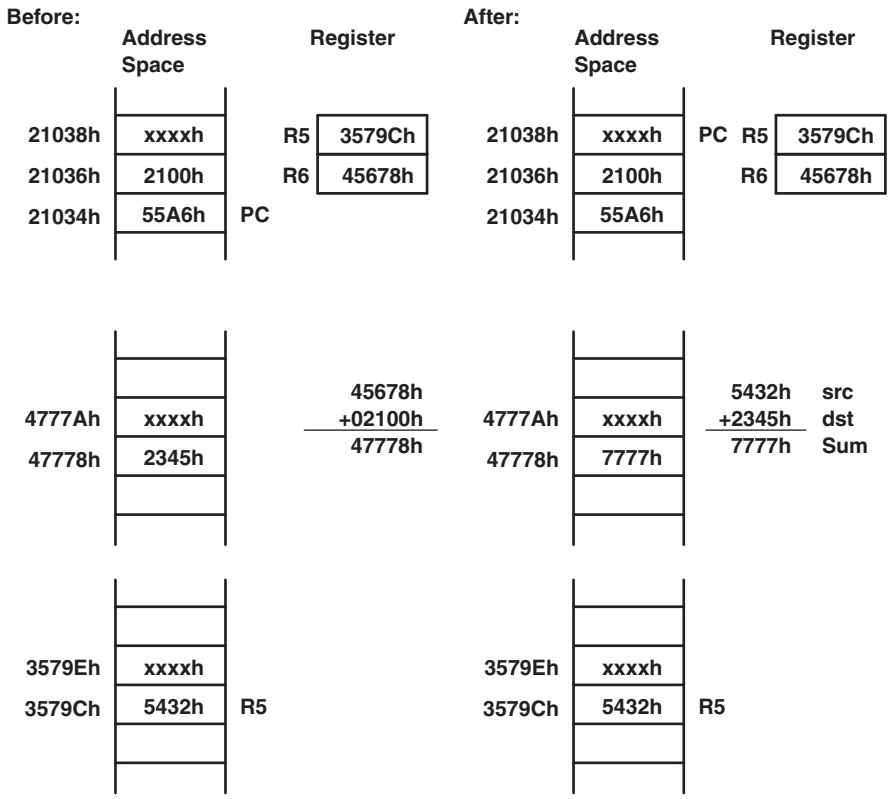
Length:	Three or four words
Operation:	The operand is the content of the addressed memory location.
Comment:	Valid for source and destination. The assembler calculates the index from 0 and inserts it.
Example:	`ADDX.A &EDE,&TONI ;`
	This instruction adds the 20-bit data contained in the absolute source and destination addresses and places the result into the destination.
Source:	Two words beginning with address EDE
Destination:	Two words beginning with address TONI



4.4.5 Indirect Register Mode

The Indirect Register mode uses the contents of the CPU register Rsrc as the source operand. The Indirect Register mode always uses a 20-bit address.

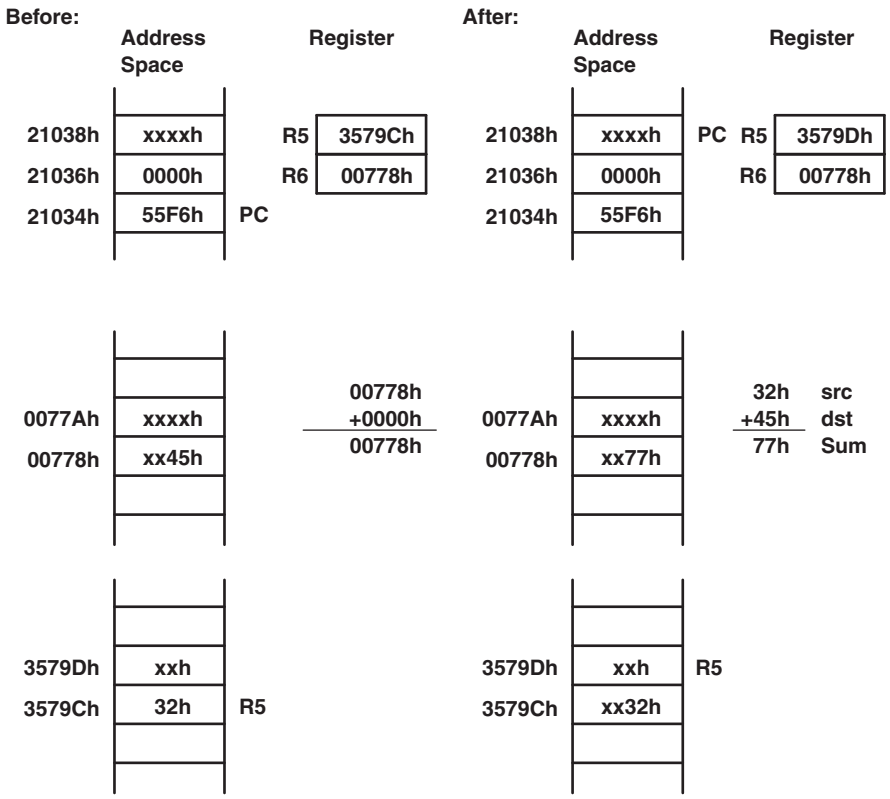
Length:	One, two, or three words
Operation:	The operand is the content the addressed memory location. The source register Rsrc is not modified.
Comment:	Valid only for the source operand. The substitute for the destination operand is 0(Rdst).
Example:	`ADDX.W @R5,2100h(R6)`
	This instruction adds the two 16-bit operands contained in the source and the destination addresses and places the result into the destination.
Source:	Word pointed to by R5. R5 contains address 3579Ch for this example.
Destination:	Word pointed to by R6 + 2100h, which results in address 45678h + 2100h = 7778h



4.4.6 Indirect Autoincrement Mode

The Indirect Autoincrement mode uses the contents of the CPU register Rsrc as the source operand. Rsrc is then automatically incremented by 1 for byte instructions, by 2 for word instructions, and by 4 for address-word instructions immediately after accessing the source operand. If the same register is used for source and destination, it contains the incremented address for the destination access. Indirect Autoincrement mode always uses 20-bit addresses.

Length:	One, two, or three words
Operation:	The operand is the content of the addressed memory location.
Comment:	Valid only for the source operand
Example:	`ADD.B @R5+,0(R6)`
	This instruction adds the 8-bit data contained in the source and the destination addresses and places the result into the destination.
Source:	Byte pointed to by R5. R5 contains address 3579Ch for this example.
Destination:	Byte pointed to by R6 + 0h, which results in address 0778h for this example



4.4.7 Immediate Mode

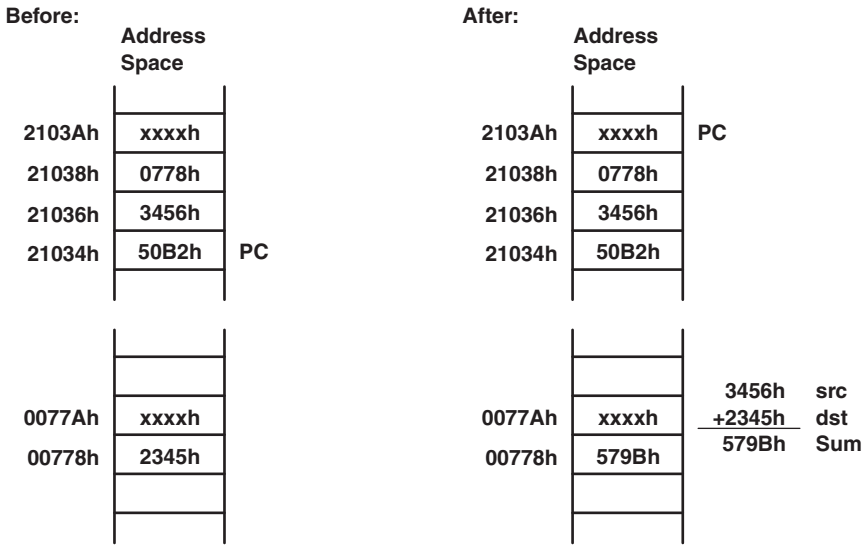
The Immediate mode allows accessing constants as operands by including the constant in the memory location following the instruction. The PC is used with the Indirect Autoincrement mode. The PC points to the immediate value contained in the next word. After the fetching of the immediate operand, the PC is incremented by 2 for byte, word, or address-word instructions. The Immediate mode has two addressing possibilities:

- 8-bit or 16-bit constants with MSP430 instructions
- 20-bit constants with MSP430X instruction

4.4.7.1 MSP430 Instructions With Immediate Mode

If an MSP430 instruction is used with Immediate addressing mode, the constant is an 8- or 16-bit value and is stored in the word following the instruction.

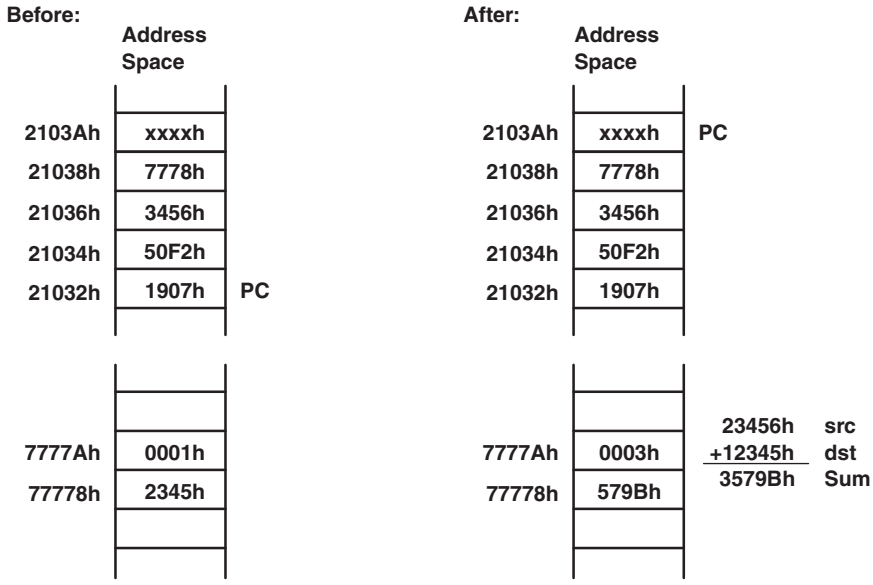
Length:	Two or three words. One word less if a constant of the constant generator can be used for the immediate operand.
Operation:	The 16-bit immediate source operand is used together with the 16-bit destination operand.
Comment:	Valid only for the source operand
Example:	`ADD #3456h,&TONI` This instruction adds the 16-bit immediate operand 3456h to the data in the destination address TONI.
Source:	16-bit immediate value 3456h
Destination:	Word at address TONI



4.4.7.2 MSP430X Instructions With Immediate Mode

If an MSP430X instruction is used with Immediate addressing mode, the constant is a 20-bit value. The 4 MSBs of the constant are stored in the extension word, and the 16 LSBs of the constant are stored in the word following the instruction.

Length:	Three or four words. One word less if a constant of the constant generator can be used for the immediate operand.
Operation:	The 20-bit immediate source operand is used together with the 20-bit destination operand.
Comment:	Valid only for the source operand
Example:	`ADDX.A #23456h,&TONI ;`
	This instruction adds the 20-bit immediate operand 23456h to the data in the destination address TONI.
Source:	20-bit immediate value 23456h
Destination:	Two words beginning with address TONI



4.5 MSP430 and MSP430X Instructions

MSP430 instructions are the 27 implemented instructions of the MSP430 CPU. These instructions are used throughout the 1MB memory range unless their 16-bit capability is exceeded. The MSP430X instructions are used when the addressing of the operands, or the data length exceeds the 16-bit capability of the MSP430 instructions.

There are three possibilities when choosing between an MSP430 and MSP430X instruction:

- To use only the MSP430 instructions – The only exceptions are the CALLA and the RETA instruction. This can be done if a few, simple rules are met:
  - Placement of all constants, variables, arrays, tables, and data in the lower 64KB. This allows the use of MSP430 instructions with 16-bit addressing for all data accesses. No pointers with 20-bit addresses are needed.
  - Placement of subroutine constants immediately after the subroutine code. This allows the use of the symbolic addressing mode with its 16-bit index to reach addresses within the range of PC + 32KB.
- To use only MSP430X instructions – The disadvantages of this method are the reduced speed due to the additional CPU cycles and the increased program space due to the necessary extension word for any double operand instruction.
- Use the best fitting instruction where needed.

The following sections list and describe the MSP430 and MSP430X instructions.

4.5.1 MSP430 Instructions

The MSP430 instructions can be used, regardless if the program resides in the lower 64KB or beyond it. The only exceptions are the instructions CALL and RET, which are limited to the lower 64-KB address range. CALLA and RETA instructions have been added to the MSP430X CPU to handle subroutines in the entire address range with no code size overhead.

4.5.1.1 MSP430 Double-Operand (Format I) Instructions

Figure 4-21 shows the format of the MSP430 double-operand instructions. Source and destination words are appended for the Indexed, Symbolic, Absolute, and Immediate modes. Table 4-4 lists the 12 MSP430 double-operand instructions.

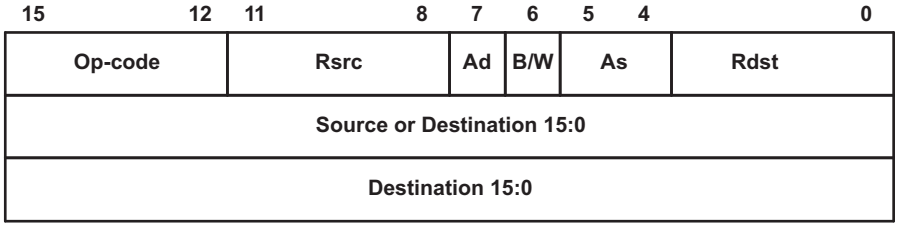


Figure 4-21. MSP430 Double-Operand Instruction Format

Table 4-4. MSP430 Double-Operand Instructions

Mnemonic	S-Reg, D-Reg	Operation	Status Bits[1]			
			V	N	Z	C
MOV(.B)	src,dst	src → dst	-	-	-	-
ADD(.B)	src,dst	src + dst → dst	*	*	*	*
ADDC(.B)	src,dst	src + dst + C → dst	*	*	*	*
SUB(.B)	src,dst	dst + .not.src + 1 → dst	*	*	*	*
SUBC(.B)	src,dst	dst + .not.src + C → dst	*	*	*	*
CMP(.B)	src,dst	dst → src	*	*	*	*
DADD(.B)	src,dst	src + dst + C → dst (decimally)	*	*	*	*
BIT(.B)	src,dst	src .and. dst	0	*	*	$\overline{Z}$
BIC(.B)	src,dst	.not.src .and. dst → dst	-	-	-	-
BIS(.B)	src,dst	src .or. dst → dst	-	-	-	-
XOR(.B)	src,dst	src .xor. dst → dst	*	*	*	$\overline{Z}$
AND(.B)	src,dst	src .and. dst → dst	0	*	*	$\overline{Z}$

(1) * = Status bit is affected.
- = Status bit is not affected.
0 = Status bit is cleared.
1 = Status bit is set.

4.5.1.2 MSP430 Single-Operand (Format II) Instructions

Figure 4-22 shows the format for MSP430 single-operand instructions, except RETI. The destination word is appended for the Indexed, Symbolic, Absolute, and Immediate modes. Table 4-5 lists the seven single-operand instructions.

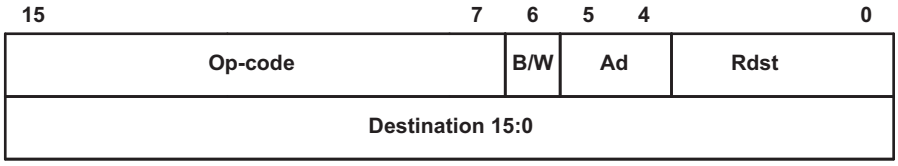


Figure 4-22. MSP430 Single-Operand Instructions

Table 4-5. MSP430 Single-Operand Instructions

Mnemonic	S-Reg, D-Reg	Operation	Status Bits [1]			
			V	N	Z	C
RRC(.B)	dst	C → MSB →.....LSB → C	*	*	*	*
RRA(.B)	dst	MSB → MSB →....LSB → C	0	*	*	*
PUSH(.B)	src	SP - 2 → SP, src → SP	–	–	–	–
SWPB	dst	bit 15...bit 8 ↔ bit 7...bit 0	–	–	–	–
CALL	dst	Call subroutine in lower 64KB	–	–	–	–
RETI		TOS → SR, SP + 2 → SP	*	*	*	*
		TOS → PC,SP + 2 → SP				
SXT	dst	Register mode: bit 7 → bit 8...bit 19 Other modes: bit 7 → bit 8...bit 15	0	*	*	$\overline{Z}$

(1) * = Status bit is affected.
– = Status bit is not affected.
0 = Status bit is cleared.
1 = Status bit is set.

4.5.1.3 Jump Instructions

Figure 4-23 shows the format for MSP430 and MSP430X jump instructions. The signed 10-bit word offset of the jump instruction is multiplied by two, sign-extended to a 20-bit address, and added to the 20-bit PC. This allows jumps in a range of –511 to +512 words relative to the PC in the full 20-bit address space. Jumps do not affect the status bits. Table 4-6 lists and describes the eight jump instructions.

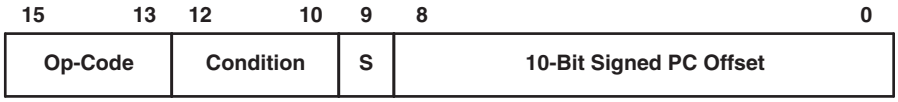


Figure 4-23. Format of Conditional Jump Instructions

Table 4-6. Conditional Jump Instructions

Mnemonic	S-Reg, D-Reg	Operation
JEQ/JZ	Label	Jump to label if zero bit is set
JNE/JNZ	Label	Jump to label if zero bit is reset
JC	Label	Jump to label if carry bit is set
JNC	Label	Jump to label if carry bit is reset
JN	Label	Jump to label if negative bit is set
JGE	Label	Jump to label if (N .XOR. V) = 0
JL	Label	Jump to label if (N .XOR. V) = 1
JMP	Label	Jump to label unconditionally

4.5.1.4 Emulated Instructions

In addition to the MSP430 and MSP430X instructions, emulated instructions are instructions that make code easier to write and read, but do not have op-codes themselves. Instead, they are replaced automatically by the assembler with a core instruction. There is no code or performance penalty for using emulated instructions. The emulated instructions are listed in Table 4-7.

Table 4-7. Emulated Instructions

Instruction	Explanation	Emulation	Status Bits (1)			
			V	N	Z	C
`ADC(.B) dst`	Add Carry to dst	`ADDC(.B) #0,dst`	*	*	*	*
`BR dst`	Branch indirectly dst	`MOV dst,PC`	–	–	–	–
`CLR(.B) dst`	Clear dst	`MOV(.B) #0,dst`	–	–	–	–
`CLRC`	Clear Carry bit	`BIC #1,SR`	–	–	–	0
`CLRN`	Clear Negative bit	`BIC #4,SR`	–	0	–	–
`CLRZ`	Clear Zero bit	`BIC #2,SR`	–	–	0	–
`DADC(.B) dst`	Add Carry to dst decimally	`DADD(.B) #0,dst`	*	*	*	*
`DEC(.B) dst`	Decrement dst by 1	`SUB(.B) #1,dst`	*	*	*	*
`DECD(.B) dst`	Decrement dst by 2	`SUB(.B) #2,dst`	*	*	*	*
`DINT`	Disable interrupt	`BIC #8,SR`	–	–	–	–
`EINT`	Enable interrupt	`BIS #8,SR`	–	–	–	–
`INC(.B) dst`	Increment dst by 1	`ADD(.B) #1,dst`	*	*	*	*
`INCD(.B) dst`	Increment dst by 2	`ADD(.B) #2,dst`	*	*	*	*

(1) * = Status bit is affected; – = Status bit is not affected; 0 = Status bit is cleared; 1 = Status bit is set.

Table 4-7. Emulated Instructions (continued)

Instruction	Explanation	Emulation	Status Bits [1]			
			V	N	Z	C
INV(.B) dst	Invert dst	XOR(.B) #–1,dst	*	*	*	*
NOP	No operation	MOV R3,R3	–	–	–	–
POP dst	Pop operand from stack	MOV @SP+,dst	–	–	–	–
RET	Return from subroutine	MOV @SP+,PC	–	–	–	–
RLA(.B) dst	Shift left dst arithmetically	ADD(.B) dst,dst	*	*	*	*
RLC(.B) dst	Shift left dst logically through Carry	ADDC(.B) dst,dst	*	*	*	*
SBC(.B) dst	Subtract Carry from dst	SUBC(.B) #0,dst	*	*	*	*
SETC	Set Carry bit	BIS #1,SR	–	–	–	1
SETN	Set Negative bit	BIS #4,SR	–	1	–	–
SETZ	Set Zero bit	BIS #2,SR	–	–	1	–
TST(.B) dst	Test dst (compare with 0)	CMP(.B) #0,dst	0	*	*	1

4.5.1.5 MSP430 Instruction Execution

The number of CPU clock cycles required for an instruction depends on the instruction format and the addressing modes used – not the instruction itself. The number of clock cycles refers to MCLK.

4.5.1.5.1 Instruction Cycles and Length for Interrupt, Reset, and Subroutines

Table 4-8 lists the length and the CPU cycles for reset, interrupts, and subroutines.

Table 4-8. Interrupt, Return, and Reset Cycles and Length

Action	Execution Time (MCLK Cycles)	Length of Instruction (Words)
Return from interrupt RETI	3 [1]	1
Return from subroutine RET	3	1
Interrupt request service (cycles needed before first instruction)	5 [2]	–
WDT reset	4	–
Reset ($\overline{\text{RST}}$/NMI)	4	–

(1) The cycle count in MSP430 CPU is 5.
(2) The cycle count in MSP430 CPU is 6.

4.5.1.5.2 Format II (Single-Operand) Instruction Cycles and Lengths

Table 4-9 lists the length and the CPU cycles for all addressing modes of the MSP430 single-operand instructions.

Table 4-9. MSP430 Format II Instruction Cycles and Length

Addressing Mode	No. of Cycles			Length of Instruction	Example
	RRA, RRC SWPB, SXT	PUSH	CALL		
Rn	1	3	3 [1]	1	SWPB R5
@Rn	3	3 [1]	4	1	RRC @R9
@Rn+	3	3 [1]	4 [2]	1	SWPB @R10+

(1) The cycle count in MSP430 CPU is 4.
(2) The cycle count in MSP430 CPU is 5. Also, the cycle count is 5 for X(Rn) addressing mode, when Rn = SP.

Table 4-9. MSP430 Format II Instruction Cycles and Length (continued)

Addressing Mode	No. of Cycles			Length of Instruction	Example
	RRA, RRC SWPB, SXT	PUSH	CALL		
#N	N/A	3 (1)	4 (2)	2	CALL #LABEL
X(Rn)	4	4 (2)	4 (2)	2	CALL 2(R7)
EDE	4	4 (2)	4 (2)	2	PUSH EDE
&EDE	4	4 (2)	4 (2)	2	SXT &EDE

4.5.1.5.3 Jump Instructions Cycles and Lengths

All jump instructions require one code word and take two CPU cycles to execute, regardless of whether the jump is taken or not.

4.5.1.5.4 Format I (Double-Operand) Instruction Cycles and Lengths

Table 4-10 lists the length and CPU cycles for all addressing modes of the MSP430 Format I instructions.

Table 4-10. MSP430 Format I Instructions Cycles and Length

Addressing Mode		No. of Cycles	Length of Instruction	Example	
Src	Dst				
Rn	Rm	1	1	MOV	R5,R8
	PC	2	1	BR	R9
	x(Rm)	4(1)	2	ADD	R5,4(R6)
	EDE	4(1)	2	XOR	R8,EDE
	&EDE	4(1)	2	MOV	R5,&EDE
@Rn	Rm	2	1	AND	@R4,R5
	PC	3	1	BR	@R8
	x(Rm)	5(1)	2	XOR	@R5,8(R6)
	EDE	5(1)	2	MOV	@R5,EDE
	&EDE	5(1)	2	XOR	@R5,&EDE
@Rn+	Rm	2	1	ADD	@R5+,R6
	PC	3	1	BR	@R9+
	x(Rm)	5(1)	2	XOR	@R5,8(R6)
	EDE	5(1)	2	MOV	@R9+,EDE
	&EDE	5(1)	2	MOV	@R9+,&EDE
#N	Rm	2	2	MOV	#20,R9
	PC	3	2	BR	#2AEh
	x(Rm)	5(1)	3	MOV	#0300h,0(SP)
	EDE	5(1)	3	ADD	#33,EDE
	&EDE	5(1)	3	ADD	#33,&EDE
x(Rn)	Rm	3	2	MOV	2(R5),R7
	PC	3	2	BR	2(R6)
	TONI	6(1)	3	MOV	4(R7),TONI
	x(Rm)	6(1)	3	ADD	4(R4),6(R9)
	&TONI	6(1)	3	MOV	2(R4),&TONI

(1) MOV, BIT, and CMP instructions execute in one fewer cycle.

Table 4-10. MSP430 Format I Instructions Cycles and Length (continued)

Addressing Mode		No. of Cycles	Length of Instruction	Example	
Src	Dst				
EDE	Rm	3	2	AND	EDE,R6
	PC	3	2	BR	EDE
	TONI	6(1)	3	CMP	EDE,TONI
	x(Rm)	6(1)	3	MOV	EDE,0(SP)
	&TONI	6(1)	3	MOV	EDE,&TONI
&EDE	Rm	3	2	MOV	&EDE,R8
	PC	3	2	BR	&EDE
	TONI	6(1)	3	MOV	&EDE,TONI
	x(Rm)	6(1)	3	MOV	&EDE,0(SP)
	&TONI	6(1)	3	MOV	&EDE,&TONI

4.5.2 MSP430X Extended Instructions

The extended MSP430X instructions give the MSP430X CPU full access to its 20-bit address space. Most MSP430X instructions require an additional word of op-code called the extension word. Some extended instructions do not require an additional word and are noted in the instruction description. All addresses, indexes, and immediate numbers have 20-bit values when preceded by the extension word.

There are two types of extension words:

- Register/register mode for Format I instructions and register mode for Format II instructions
- Extension word for all other address mode combinations

4.5.2.1 Register Mode Extension Word

The register mode extension word is shown in Figure 4-24 and described in Table 4-11. An example is shown in Figure 4-26.

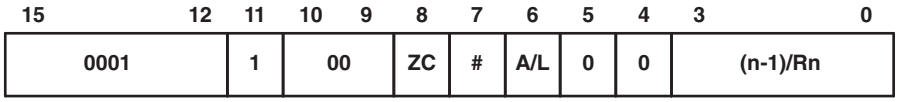


Figure 4-24. Extension Word for Register Modes

Table 4-11. Description of the Extension Word Bits for Register Mode

Bit	Description
15:11	Extension word op-code. Op-codes 1800h to 1FFFh are extension words.
10:9	Reserved
ZC	Zero carry 0 The executed instruction uses the status of the carry bit C. 1 The executed instruction uses the carry bit as 0. The carry bit is defined by the result of the final operation after instruction execution.
#	Repetition 0 The number of instruction repetitions is set by extension word bits 3:0. 1 The number of instruction repetitions is defined by the value of the four LSBs of Rn. See description for bits 3:0.

Table 4-11. Description of the Extension Word Bits for Register Mode (continued)

Bit	Description		
A/L	Data length extension. Together with the B/W bits of the following MSP430 instruction, the AL bit defines the used data length of the instruction.		
	A/L	**B/W**	**Comment**
	0	0	Reserved
	0	1	20-bit address word
	1	0	16-bit word
	1	1	8-bit byte
5:4	Reserved		
3:0	Repetition count		
	# = 0 These four bits set the repetition count n. These bits contain n – 1.		
	# = 1 These four bits define the CPU register whose bits 3:0 set the number of repetitions. Rn.3:0 contain n – 1.		

4.5.2.2 Non-Register Mode Extension Word

The extension word for non-register modes is shown in Figure 4-25 and described in Table 4-12. An example is shown in Figure 4-27.

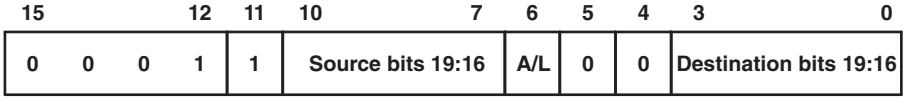


Figure 4-25. Extension Word for Non-Register Modes

Table 4-12. Description of Extension Word Bits for Non-Register Modes

Bit	Description		
15:11	Extension word op-code. Op-codes 1800h to 1FFFh are extension words.		
Source Bits 19:16	The four MSBs of the 20-bit source. Depending on the source addressing mode, these four MSBs may belong to an immediate operand, an index or to an absolute address.		
A/L	Data length extension. Together with the B/W bits of the following MSP430 instruction, the AL bit defines the used data length of the instruction.		
	A/L	**B/W**	**Comment**
	0	0	Reserved
	0	1	20-bit address word
	1	0	16-bit word
	1	1	8-bit byte
5:4	Reserved		
Destination Bits 19:16	The four MSBs of the 20-bit destination. Depending on the destination addressing mode, these four MSBs may belong to an index or to an absolute address.		

NOTE: B/W and A/L bit settings for SWPBX and SXTX

A/L	B/W	
0	0	SWPBX.A, SXTX.A
0	1	N/A
1	0	SWPB.W, SXTX.W
1	1	N/A

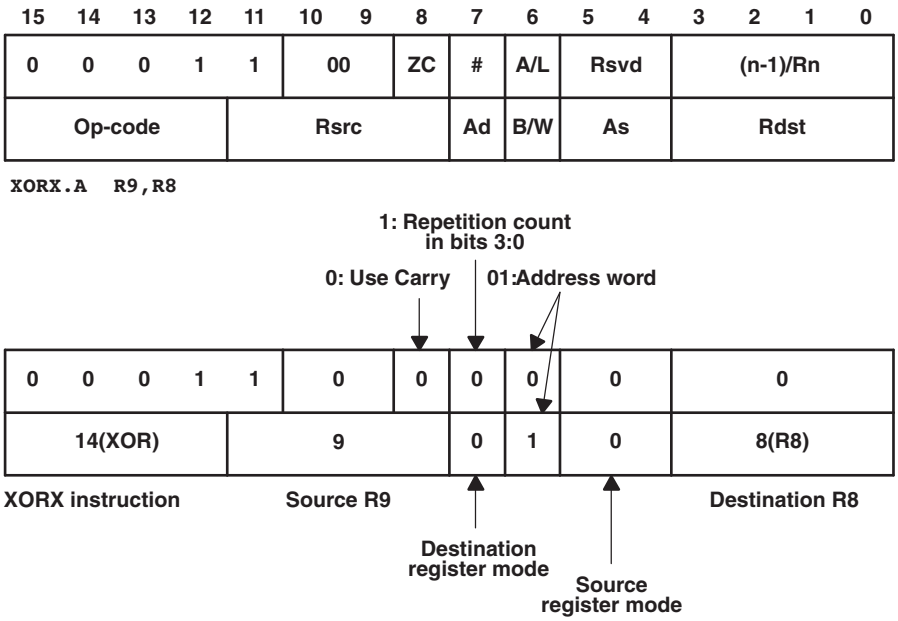


Figure 4-26. Example for Extended Register/Register Instruction

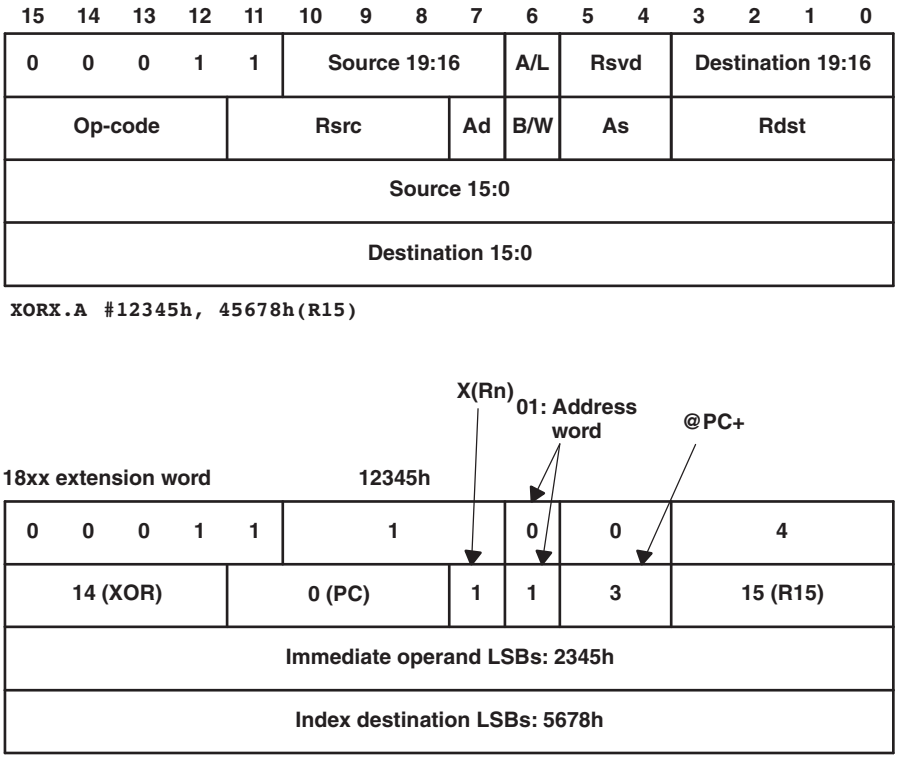


Figure 4-27. Example for Extended Immediate/Indexed Instruction

4.5.2.3 Extended Double-Operand (Format I) Instructions

All 12 double-operand instructions have extended versions as listed in Table 4-13.

Table 4-13. Extended Double-Operand Instructions

Mnemonic	Operands	Operation	Status Bits (1)			
			V	N	Z	C
MOVX(.B,.A)	src,dst	src → dst	–	–	–	–
ADDX(.B,.A)	src,dst	src + dst → dst	*	*	*	*
ADDCX(.B,.A)	src,dst	src + dst + C → dst	*	*	*	*
SUBX(.B,.A)	src,dst	dst + .not.src + 1 → dst	*	*	*	*
SUBCX(.B,.A)	src,dst	dst + .not.src + C → dst	*	*	*	*
CMPX(.B,.A)	src,dst	dst – src	*	*	*	*
DADDX(.B,.A)	src,dst	src + dst + C → dst (decimal)	*	*	*	*
BITX(.B,.A)	src,dst	src .and. dst	0	*	*	$\overline{Z}$
BICX(.B,.A)	src,dst	.not.src .and. dst → dst	–	–	–	–
BISX(.B,.A)	src,dst	src .or. dst → dst	–	–	–	–
XORX(.B,.A)	src,dst	src .xor. dst → dst	*	*	*	$\overline{Z}$
ANDX(.B,.A)	src,dst	src .and. dst → dst	0	*	*	$\overline{Z}$

(1) * = Status bit is affected.
– = Status bit is not affected.
0 = Status bit is cleared.
1 = Status bit is set.

The four possible addressing combinations for the extension word for Format I instructions are shown in Figure 4-28.

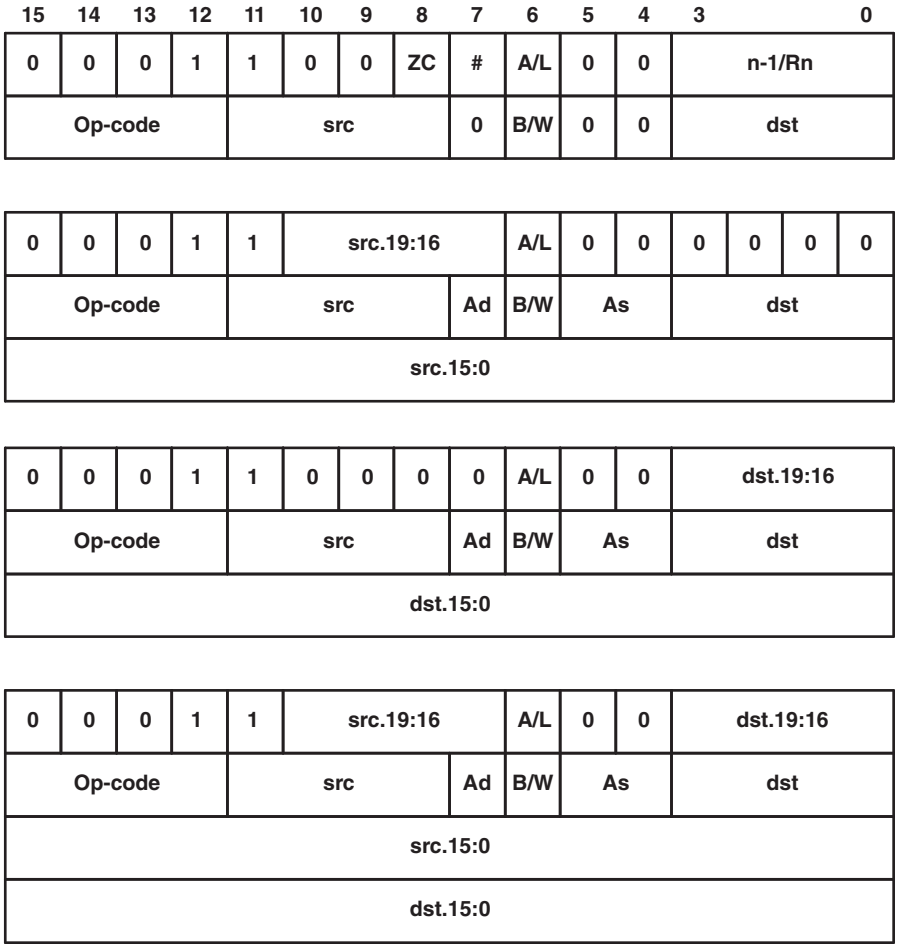


Figure 4-28. Extended Format I Instruction Formats

If the 20-bit address of a source or destination operand is located in memory, not in a CPU register, then two words are used for this operand as shown in Figure 4-29.

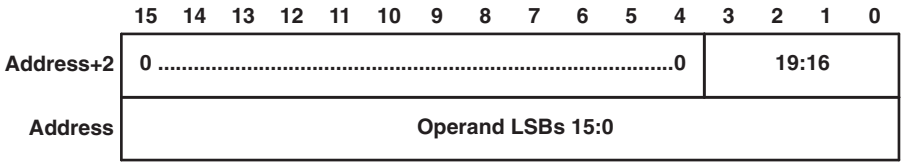


Figure 4-29. 20-Bit Addresses in Memory

4.5.2.4 Extended Single-Operand (Format II) Instructions

Extended MSP430X Format II instructions are listed in Table 4-14.

Table 4-14. Extended Single-Operand Instructions

Mnemonic	Operands	Operation	n	Status Bits (1)			
				V	N	Z	C
CALLA	dst	Call indirect to subroutine (20-bit address)		–	–	–	–
POPM.A	#n,Rdst	Pop n 20-bit registers from stack	1 to 16	–	–	–	–
POPM.W	#n,Rdst	Pop n 16-bit registers from stack	1 to 16	–	–	–	–
PUSHM.A	#n,Rsrc	Push n 20-bit registers to stack	1 to 16	–	–	–	–
PUSHM.W	#n,Rsrc	Push n 16-bit registers to stack	1 to 16	–	–	–	–
PUSHX(.B,.A)	src	Push 8/16/20-bit source to stack		–	–	–	–
RRCM(.A)	#n,Rdst	Rotate right Rdst n bits through carry (16-/20-bit register)	1 to 4	0	*	*	*
RRUM(.A)	#n,Rdst	Rotate right Rdst n bits unsigned (16-/20-bit register)	1 to 4	0	*	*	*
RRAM(.A)	#n,Rdst	Rotate right Rdst n bits arithmetically (16-/20-bit register)	1 to 4	*	*	*	*
RLAM(.A)	#n,Rdst	Rotate left Rdst n bits arithmetically (16-/20-bit register)	1 to 4	*	*	*	*
RRCX(.B,.A)	dst	Rotate right dst through carry (8-/16-/20-bit data)	1	0	*	*	*
RRUX(.B,.A)	Rdst	Rotate right dst unsigned (8-/16-/20-bit)	1	0	*	*	*
RRAX(.B,.A)	dst	Rotate right dst arithmetically	1	*	*	*	*
SWPBX(.A)	dst	Exchange low byte with high byte	1	–	–	–	–
SXTX(.A)	Rdst	Bit7 → bit8 ... bit19	1	0	*	*	*
SXTX(.A)	dst	Bit7 → bit8 ... MSB	1	0	*	*	*

(1) * = Status bit is affected.
– = Status bit is not affected.
0 = Status bit is cleared.
1 = Status bit is set.

The three possible addressing mode combinations for Format II instructions are shown in Figure 4-30.

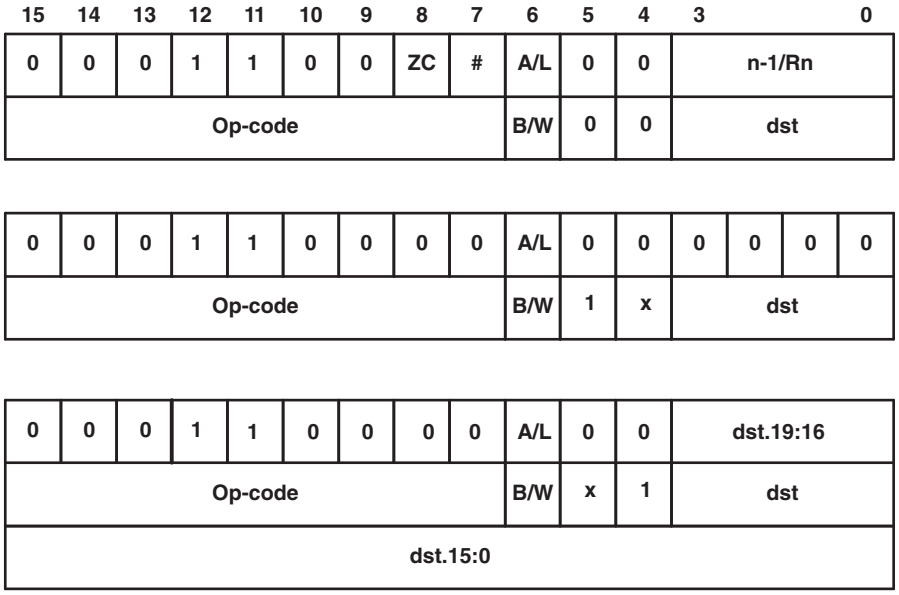


Figure 4-30. Extended Format II Instruction Format

4.5.2.4.1 Extended Format II Instruction Format Exceptions

Exceptions for the Format II instruction formats are shown in Figure 4-31 through Figure 4-34.

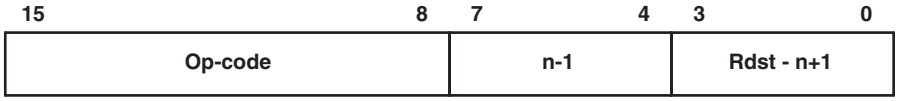


Figure 4-31. PUSHM/POPM Instruction Format

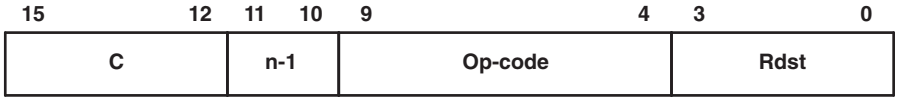


Figure 4-32. RRCM, RRAM, RRUM, and RLAM Instruction Format

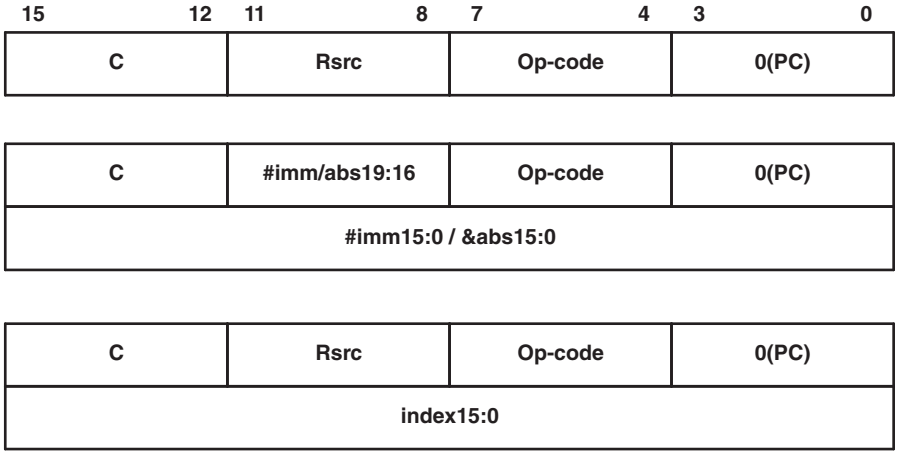


Figure 4-33. BRA Instruction Format

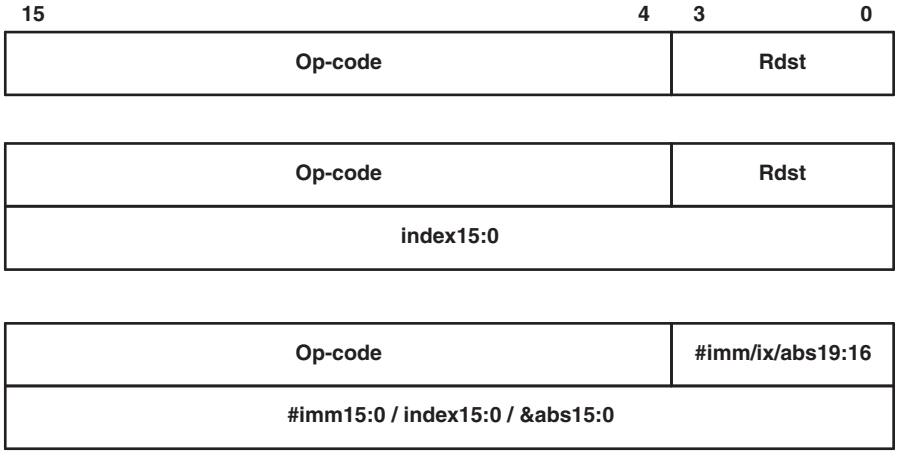


Figure 4-34. CALLA Instruction Format

4.5.2.5 Extended Emulated Instructions

The extended instructions together with the constant generator form the extended emulated instructions. Table 4-15 lists the emulated instructions.

Table 4-15. Extended Emulated Instructions

Instruction	Explanation	Emulation
ADCX(.B,.A) dst	Add carry to dst	ADDCX(.B,.A) #0,dst
BRA dst	Branch indirect dst	MOVA dst,PC
RETA	Return from subroutine	MOVA @SP+,PC
CLRA Rdst	Clear Rdst	MOV #0,Rdst
CLRX(.B,.A) dst	Clear dst	MOVX(.B,.A) #0,dst
DADCX(.B,.A) dst	Add carry to dst decimally	DADDX(.B,.A) #0,dst
DECX(.B,.A) dst	Decrement dst by 1	SUBX(.B,.A) #1,dst
DECDA Rdst	Decrement Rdst by 2	SUBA #2,Rdst
DECDX(.B,.A) dst	Decrement dst by 2	SUBX(.B,.A) #2,dst
INCX(.B,.A) dst	Increment dst by 1	ADDX(.B,.A) #1,dst
INCDA Rdst	Increment Rdst by 2	ADDA #2,Rdst
INCDX(.B,.A) dst	Increment dst by 2	ADDX(.B,.A) #2,dst
INVX(.B,.A) dst	Invert dst	XORX(.B,.A) #-1,dst
RLAX(.B,.A) dst	Shift left dst arithmetically	ADDX(.B,.A) dst,dst
RLCX(.B,.A) dst	Shift left dst logically through carry	ADDCX(.B,.A) dst,dst
SBCX(.B,.A) dst	Subtract carry from dst	SUBCX(.B,.A) #0,dst
TSTA Rdst	Test Rdst (compare with 0)	CMPA #0,Rdst
TSTX(.B,.A) dst	Test dst (compare with 0)	CMPX(.B,.A) #0,dst
POPX dst	Pop to dst	MOVX(.B, .A) @SP+,dst

4.5.2.6 MSP430X Address Instructions

MSP430X address instructions are instructions that support 20-bit operands but have restricted addressing modes. The addressing modes are restricted to the Register mode and the Immediate mode, except for the MOVA instruction as listed in Table 4-16. Restricting the addressing modes removes the need for the additional extension-word op-code improving code density and execution time. Address instructions should be used any time an MSP430X instruction is needed with the corresponding restricted addressing mode.

Table 4-16. Address Instructions, Operate on 20-Bit Register Data

Mnemonic	Operands	Operation	Status Bits (1)			
			V	N	Z	C
ADDA	Rsrc,Rdst	Add source to destination register	*	*	*	*
	#imm20,Rdst					
MOVA	Rsrc,Rdst	Move source to destination	–	–	–	–
	#imm20,Rdst					
	z16(Rsrc),Rdst					
	EDE,Rdst					
	&abs20,Rdst					
	@Rsrc,Rdst					
	@Rsrc+,Rdst					
	Rsrc,z16(Rdst)					
	Rsrc,&abs20					
CMPA	Rsrc,Rdst	Compare source to destination register	*	*	*	*
	#imm20,Rdst					
SUBA	Rsrc,Rdst	Subtract source from destination register	*	*	*	*
	#imm20,Rdst					

(1) * = Status bit is affected.
– = Status bit is not affected.
0 = Status bit is cleared.
1 = Status bit is set.

4.5.2.7 MSP430X Instruction Execution

The number of CPU clock cycles required for an MSP430X instruction depends on the instruction format and the addressing modes used, not the instruction itself. The number of clock cycles refers to MCLK.

4.5.2.7.1 MSP430X Format II (Single-Operand) Instruction Cycles and Lengths

Table 4-17 lists the length and the CPU cycles for all addressing modes of the MSP430X extended single-operand instructions.

Table 4-17. MSP430X Format II Instruction Cycles and Length

Instruction	Execution Cycles/Length of Instruction (Words)						
	Rn	@Rn	@Rn+	#N	X(Rn)	EDE	&EDE
RRAM	n/1	–	–	–	–	–	–
RRCM	n/1	–	–	–	–	–	–
RRUM	n/1	–	–	–	–	–	–
RLAM	n/1	–	–	–	–	–	–
PUSHM	2+n/1	–	–	–	–	–	–
PUSHM.A	2+2n/1	–	–	–	–	–	–
POPM	2+n/1	–	–	–	–	–	–
POPM.A	2+2n/1	–	–	–	–	–	–
CALLA	4/1	5/1	5/1	4/2	6 (1)/2	6/2	6/2
RRAX(.B)	1+n/2	4/2	4/2	–	5/3	5/3	5/3
RRAX.A	1+n/2	6/2	6/2	–	7/3	7/3	7/3
RRCX(.B)	1+n/2	4/2	4/2	–	5/3	5/3	5/3
RRCX.A	1+n/2	6/2	6/2	–	7/3	7/3	7/3
PUSHX(.B)	4/2	4/2	4/2	4/3	5 (1)/3	5/3	5/3
PUSHX.A	5/2	6/2	6/2	6/3	7 (1)/3	7/3	7/3
POPX(.B)	3/2	–	–	–	5/3	5/3	5/3
POPX.A	4/2	–	–	–	7/3	7/3	7/3

(1) Add one cycle when Rn = SP

4.5.2.7.2 MSP430X Format I (Double-Operand) Instruction Cycles and Lengths

Table 4-18 lists the length and CPU cycles for all addressing modes of the MSP430X extended Format I instructions.

Table 4-18. MSP430X Format I Instruction Cycles and Length

Addressing Mode		No. of Cycles		Length of Instruction	Examples
Source	Destination	.B/.W	.A	.B/.W/.A	
Rn	Rm[1]	2	2	2	BITX.B R5,R8
	PC	3	3	2	ADDX R9,PC
	X(Rm)	5[2]	7[3]	3	ANDX.A R5,4(R6)
	EDE	5[2]	7[3]	3	XORX R8,EDE
	&EDE	5[2]	7[3]	3	BITX.W R5,&EDE
@Rn	Rm	3	4	2	BITX @R5,R8
	PC	3	4	2	ADDX @R9,PC
	X(Rm)	6[2]	9[3]	3	ANDX.A @R5,4(R6)
	EDE	6[2]	9[3]	3	XORX @R8,EDE
	&EDE	6[2]	9[3]	3	BITX.B @R5,&EDE
@Rn+	Rm	3	4	2	BITX @R5+,R8
	PC	4	5	2	ADDX.A @R9+,PC
	X(Rm)	6[2]	9[3]	3	ANDX @R5+,4(R6)
	EDE	6[2]	9[3]	3	XORX.B @R8+,EDE
	&EDE	6[2]	9[3]	3	BITX @R5+,&EDE
#N	Rm	3	3	3	BITX #20,R8
	PC[4]	4	4	3	ADDX.A #FE000h,PC
	X(Rm)	6[2]	8[3]	4	ANDX #1234,4(R6)
	EDE	6[2]	8[3]	4	XORX #A5A5h,EDE
	&EDE	6[2]	8[3]	4	BITX.B #12,&EDE
X(Rn)	Rm	4	5	3	BITX 2(R5),R8
	PC[4]	5	6	3	SUBX.A 2(R6),PC
	X(Rm)	7[2]	10[3]	4	ANDX 4(R7),4(R6)
	EDE	7[2]	10[3]	4	XORX.B 2(R6),EDE
	&EDE	7[2]	10[3]	4	BITX 8(SP),&EDE
EDE	Rm	4	5	3	BITX.B EDE,R8
	PC[4]	5	6	3	ADDX.A EDE,PC
	X(Rm)	7[2]	10[3]	4	ANDX EDE,4(R6)
	EDE	7[2]	10[3]	4	ANDX EDE,TONI
	&TONI	7[2]	10[3]	4	BITX EDE,&TONI
&EDE	Rm	4	5	3	BITX &EDE,R8
	PC[4]	5	6	3	ADDX.A &EDE,PC
	X(Rm)	7[2]	10[3]	4	ANDX.B &EDE,4(R6)
	TONI	7[2]	10[3]	4	XORX &EDE,TONI
	&TONI	7[2]	10[3]	4	BITX &EDE,&TONI

(1) Repeat instructions require n + 1 cycles, where n is the number of times the instruction is executed.
(2) Reduce the cycle count by one for MOV, BIT, and CMP instructions.
(3) Reduce the cycle count by two for MOV, BIT, and CMP instructions.
(4) Reduce the cycle count by one for MOV, ADD, and SUB instructions.

4.5.2.7.3 MSP430X Address Instruction Cycles and Lengths

Table 4-19 lists the length and the CPU cycles for all addressing modes of the MSP430X address instructions.

Table 4-19. Address Instruction Cycles and Length

Addressing Mode		Execution Time (MCLK Cycles)		Length of Instruction (Words)		Example
Source	Destination	MOVA BRA	CMPA ADDA SUBA	MOVA	CMPA ADDA SUBA	
Rn	Rn	1	1	1	1	CMPA R5,R8
	PC	2	2	1	1	SUBA R9,PC
	x(Rm)	4	–	2	–	MOVA R5,4(R6)
	EDE	4	–	2	–	MOVA R8,EDE
	&EDE	4	–	2	–	MOVA R5,&EDE
@Rn	Rm	3	–	1	–	MOVA @R5,R8
	PC	3	–	1	–	MOVA @R9,PC
@Rn+	Rm	3	–	1	–	MOVA @R5+,R8
	PC	3	–	1	–	MOVA @R9+,PC
#N	Rm	2	3	2	2	CMPA #20,R8
	PC	3	3	2	2	SUBA #FE000h,PC
x(Rn)	Rm	4	–	2	–	MOVA 2(R5),R8
	PC	4	–	2	–	MOVA 2(R6),PC
EDE	Rm	4	–	2	–	MOVA EDE,R8
	PC	4	–	2	–	MOVA EDE,PC
&EDE	Rm	4	–	2	–	MOVA &EDE,R8
	PC	4	–	2	–	MOVA &EDE,PC

4.6 Instruction Set Description

Table 4-20 shows all available instructions:

Table 4-20. Instruction Map of MSP430X

	000	040	080	0C0	100	140	180	1C0	200	240	280	2C0	300	340	380	3C0
0xxx	MOVA, CMPA, ADDA, SUBA, RRCM, RRAM, RLAM, RRUM															
10xx	RRC	RRC.B	SWPB		RRA	RRA.B	SXT		PUSH	PUSH.B	CALL		RETI	CALLA		
14xx	PUSHM.A, POPM.A, PUSHM.W, POPM.W															
18xx	Extension word for Format I and Format II instructions															
1Cxx																
20xx	JNE/JNZ															
24xx	JEQ/JZ															
28xx	JNC															
2Cxx	JC															
30xx	JN															
34xx	JGE															
38xx	JL															
3Cxx	JMP															
4xxx	MOV, MOV.B															
5xxx	ADD, ADD.B															
6xxx	ADDC, ADDC.B															
7xxx	SUBC, SUBC.B															
8xxx	SUB, SUB.B															
9xxx	CMP, CMP.B															
Axxx	DADD, DADD.B															
Bxxx	BIT, BIT.B															
Cxxx	BIC, BIC.B															
Dxxx	BIS, BIS.B															
Exxx	XOR, XOR.B															
Fxxx	AND, AND.B															

4.6.1 Extended Instruction Binary Descriptions

Detailed MSP430X instruction binary descriptions are shown in the following tables.

Instruction	Instruction Group				src or data.19:16	Instruction Identifier				dst	
	15			12	11 8	7			4	3 0	
MOVA	0	0	0	0	src	0	0	0	0	dst	MOVA @Rsrc,Rdst
	0	0	0	0	src	0	0	0	1	dst	MOVA @Rsrc+,Rdst
	0	0	0	0	&abs.19:16	0	0	1	0	dst	MOVA &abs20,Rdst
	&abs.15:0										
	0	0	0	0	src	0	0	1	1	dst	MOVA x(Rsrc),Rdst
	x.15:0										±15-bit index x
	0	0	0	0	src	0	1	1	0	&abs.19:16	MOVA Rsrc,&abs20
	&abs.15:0										
	0	0	0	0	src	0	1	1	1	dst	MOVA Rsrc,X(Rdst)
	x.15:0										±15-bit index x
	0	0	0	0	imm.19:16	1	0	0	0	dst	MOVA #imm20,Rdst
	imm.15:0										
CMPA	0	0	0	0	imm.19:16	1	0	0	1	dst	CMPA #imm20,Rdst
	imm.15:0										
ADDA	0	0	0	0	imm.19:16	1	0	1	0	dst	ADDA #imm20,Rdst
	imm.15:0										
SUBA	0	0	0	0	imm.19:16	1	0	1	1	dst	SUBA #imm20,Rdst
	imm.15:0										
MOVA	0	0	0	0	src	1	1	0	0	dst	MOVA Rsrc,Rdst
CMPA	0	0	0	0	src	1	1	0	1	dst	CMPA Rsrc,Rdst
ADDA	0	0	0	0	src	1	1	1	0	dst	ADDA Rsrc,Rdst
SUBA	0	0	0	0	src	1	1	1	1	dst	SUBA Rsrc,Rdst

Instruction	Instruction Group				Bit Loc.	Inst. ID		Instruction Identifier				dst	
	15			12	11 10	9	8	7			4	3 0	
RRCM.A	0	0	0	0	n – 1	0	0	0	1	0	0	dst	RRCM.A #n,Rdst
RRAM.A	0	0	0	0	n – 1	0	1	0	1	0	0	dst	RRAM.A #n,Rdst
RLAM.A	0	0	0	0	n – 1	1	0	0	1	0	0	dst	RLAM.A #n,Rdst
RRUM.A	0	0	0	0	n – 1	1	1	0	1	0	0	dst	RRUM.A #n,Rdst
RRCM.W	0	0	0	0	n – 1	0	0	0	1	0	1	dst	RRCM.W #n,Rdst
RRAM.W	0	0	0	0	n – 1	0	1	0	1	0	1	dst	RRAM.W #n,Rdst
RLAM.W	0	0	0	0	n – 1	1	0	0	1	0	1	dst	RLAM.W #n,Rdst
RRUM.W	0	0	0	0	n – 1	1	1	0	1	0	1	dst	RRUM.W #n,Rdst

Instruction	Instruction Identifier												dst				
	15			12	11			8	7	6	5	4	3			0	
RETI	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	
CALLA	0	0	0	1	0	0	1	1	0	1	0	0	dst				CALLA Rdst
	0	0	0	1	0	0	1	1	0	1	0	1	dst				CALLA x(Rdst)
	x.15:0																
	0	0	0	1	0	0	1	1	0	1	1	0	dst				CALLA @Rdst
	0	0	0	1	0	0	1	1	0	1	1	1	dst				CALLA @Rdst+
	0	0	0	1	0	0	1	1	1	0	0	0	&abs.19:16				CALLA &abs20
	&abs.15:0																
	0	0	0	1	0	0	1	1	1	0	0	1	x.19:16				CALLA EDE
	x.15:0																CALLA x(PC)
	0	0	0	1	0	0	1	1	1	0	1	1	imm.19:16				CALLA #imm20
	imm.15:0																
Reserved	0	0	0	1	0	0	1	1	1	0	1	0	x	x	x	x	
Reserved	0	0	0	1	0	0	1	1	1	1	x	x	x	x	x	x	
PUSHM.A	0	0	0	1	0	1	0	0	n – 1				dst				PUSHM.A #n,Rdst
PUSHM.W	0	0	0	1	0	1	0	1	n – 1				dst				PUSHM.W #n,Rdst
POPM.A	0	0	0	1	0	1	1	0	n – 1				dst – n + 1				POPM.A #n,Rdst
POPM.W	0	0	0	1	0	1	1	1	n – 1				dst – n + 1				POPM.W #n,Rdst

4.6.2 MSP430 Instructions

The MSP430 instructions are described in the following sections.

See Section 4.6.3 for MSP430X extended instructions and Section 4.6.4 for MSP430X address instructions.

4.6.2.1 ADC

*** ADC[.W]** Add carry to destination

*** ADC.B** Add carry to destination

Syntax `ADC dst` or `ADC.W dst`

`ADC.B dst`

Operation dst + C → dst

Emulation `ADDC #0,dst`

`ADDC.B #0,dst`

Description The carry bit (C) is added to the destination operand. The previous contents of the destination are lost.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if result is zero, reset otherwise
- C: Set if dst was incremented from 0FFFFh to 0000, reset otherwise
  Set if dst was incremented from 0FFh to 00, reset otherwise
- V: Set if an arithmetic overflow occurs, otherwise reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 16-bit counter pointed to by R13 is added to a 32-bit counter pointed to by R12.

```
ADD     @R13,0(R12)      ; Add LSDs
ADC     2(R12)           ; Add carry to MSD
```

Example The 8-bit counter pointed to by R13 is added to a 16-bit counter pointed to by R12.

```
ADD.B   @R13,0(R12)     ; Add LSDs
ADC.B   1(R12)          ; Add carry to MSD
```

4.6.2.2 ADD

ADD[.W] Add source word to destination word

ADD.B Add source byte to destination byte

Syntax `ADD src,dst` or `ADD.W src,dst`

`ADD.B src,dst`

Operation src + dst → dst

Description The source operand is added to the destination operand. The previous content of the destination is lost.

Status Bits
- N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)
- Z: Set if result is zero, reset otherwise
- C: Set if there is a carry from the MSB of the result, reset otherwise
- V: Set if the result of two positive operands is negative, or if the result of two negative numbers is positive, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Ten is added to the 16-bit counter CNTR located in lower 64KB.

```
ADD.W   #10,&CNTR       ; Add 10 to 16-bit counter
```

Example A table word pointed to by R5 (20-bit address in R5) is added to R6. The jump to label TONI is performed on a carry.

```
ADD.W    @R5,R6         ; Add table word to R6. R6.19:16 = 0
JC       TONI           ; Jump if carry
...                     ; No carry
```

Example A table byte pointed to by R5 (20-bit address) is added to R6. The jump to label TONI is performed if no carry occurs. The table pointer is auto-incremented by 1. R6.19:8 = 0

```
ADD.B    @R5+,R6        ; Add byte to R6. R5 + 1. R6: 000xxh
JNC      TONI           ; Jump if no carry
...                     ; Carry occurred
```

4.6.2.3 ADDC

ADDC[.W] Add source word and carry to destination word

ADDC.B Add source byte and carry to destination byte

Syntax `ADDC src,dst` or `ADDC.W src,dst`

`ADDC.B src,dst`

Operation src + dst + C → dst

Description The source operand and the carry bit C are added to the destination operand. The previous content of the destination is lost.

Status Bits
- N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)
- Z: Set if result is zero, reset otherwise
- C: Set if there is a carry from the MSB of the result, reset otherwise
- V: Set if the result of two positive operands is negative, or if the result of two negative numbers is positive, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Constant value 15 and the carry of the previous instruction are added to the 16-bit counter CNTR located in lower 64KB.

```
ADDC.W    #15,&CNTR     ; Add 15 + C to 16-bit CNTR
```

Example A table word pointed to by R5 (20-bit address) and the carry C are added to R6. The jump to label TONI is performed on a carry. R6.19:16 = 0

```
ADDC.W    @R5,R6        ; Add table word + C to R6
JC        TONI          ; Jump if carry
...                     ; No carry
```

Example A table byte pointed to by R5 (20-bit address) and the carry bit C are added to R6. The jump to label TONI is performed if no carry occurs. The table pointer is auto-incremented by 1. R6.19:8 = 0

```
ADDC.B    @R5+,R6       ; Add table byte + C to R6. R5 + 1
JNC       TONI          ; Jump if no carry
...                     ; Carry occurred
```

4.6.2.4 AND

AND[.W] Logical AND of source word with destination word

AND.B Logical AND of source byte with destination byte

Syntax `AND src,dst` or `AND.W src,dst`

`AND.B src,dst`

Operation src .and. dst → dst

Description The source operand and the destination operand are logically ANDed. The result is placed into the destination. The source operand is not affected.

Status Bits
- N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)
- Z: Set if result is zero, reset otherwise
- C: Set if the result is not zero, reset otherwise. C = (.not. Z)
- V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The bits set in R5 (16-bit data) are used as a mask (AA55h) for the word TOM located in the lower 64KB. If the result is zero, a branch is taken to label TONI. R5.19:16 = 0

```
MOV     #AA55h,R5     ; Load 16-bit mask to R5
AND     R5,&TOM       ; TOM .and. R5 -> TOM
JZ      TONI          ; Jump if result 0
...                   ; Result > 0
```

or shorter:

```
AND     #AA55h,&TOM   ; TOM .and. AA55h -> TOM
JZ      TONI          ; Jump if result 0
```

Example A table byte pointed to by R5 (20-bit address) is logically ANDed with R6. R5 is incremented by 1 after the fetching of the byte. R6.19:8 = 0

```
AND.B   @R5+,R6       ; AND table byte with R6. R5 + 1
```

4.6.2.5 BIC

BIC[.W] Clear bits set in source word in destination word

BIC.B Clear bits set in source byte in destination byte

Syntax `BIC src,dst` or `BIC.W src,dst`

`BIC.B src,dst`

Operation (.not. src) .and. dst → dst

Description The inverted source operand and the destination operand are logically ANDed. The result is placed into the destination. The source operand is not affected.

Status Bits
- N: Not affected
- Z: Not affected
- C: Not affected
- V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The bits 15:14 of R5 (16-bit data) are cleared. R5.19:16 = 0

```
BIC     #0C000h,R5      ; Clear R5.19:14 bits
```

Example A table word pointed to by R5 (20-bit address) is used to clear bits in R7. R7.19:16 = 0

```
BIC.W   @R5,R7          ; Clear bits in R7 set in @R5
```

Example A table byte pointed to by R5 (20-bit address) is used to clear bits in Port1.

```
BIC.B   @R5,&P1OUT      ; Clear I/O port P1 bits set in @R5
```

4.6.2.6 BIS

BIS[.W] Set bits set in source word in destination word

BIS.B Set bits set in source byte in destination byte

Syntax `BIS src,dst` or `BIS.W src,dst`

`BIS.B src,dst`

Operation src .or. dst → dst

Description The source operand and the destination operand are logically ORed. The result is placed into the destination. The source operand is not affected.

Status Bits
N: Not affected
Z: Not affected
C: Not affected
V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Bits 15 and 13 of R5 (16-bit data) are set to one. R5.19:16 = 0

```
BIS     #A000h,R5       ; Set R5 bits
```

Example A table word pointed to by R5 (20-bit address) is used to set bits in R7. R7.19:16 = 0

```
BIS.W   @R5,R7          ; Set bits in R7
```

Example A table byte pointed to by R5 (20-bit address) is used to set bits in Port1. R5 is incremented by 1 afterwards.

```
BIS.B   @R5+,&P1OUT     ; Set I/O port P1 bits. R5 + 1
```

4.6.2.7 BIT

BIT[.W] Test bits set in source word in destination word

BIT.B Test bits set in source byte in destination byte

Syntax `BIT src,dst` or `BIT.W src,dst`

`BIT.B src,dst`

Operation src .and. dst

Description The source operand and the destination operand are logically ANDed. The result affects only the status bits in SR.

Register mode: the register bits Rdst.19:16 (.W) resp. Rdst. 19:8 (.B) are not cleared!

Status Bits

N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)

Z: Set if result is zero, reset otherwise

C: Set if the result is not zero, reset otherwise. C = (.not. Z)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Test if one (or both) of bits 15 and 14 of R5 (16-bit data) is set. Jump to label TONI if this is the case. R5.19:16 are not affected.

```
BIT     #C000h,R5       ; Test R5.15:14 bits
JNZ     TONI            ; At least one bit is set in R5
...                     ; Both bits are reset
```

Example A table word pointed to by R5 (20-bit address) is used to test bits in R7. Jump to label TONI if at least one bit is set. R7.19:16 are not affected.

```
BIT.W   @R5,R7          ; Test bits in R7
JC      TONI            ; At least one bit is set
...                     ; Both are reset
```

Example A table byte pointed to by R5 (20-bit address) is used to test bits in output Port1. Jump to label TONI if no bit is set. The next table byte is addressed.

```
BIT.B   @R5+,&P1OUT     ; Test I/O port P1 bits. R5 + 1
JNC     TONI            ; No corresponding bit is set
...                     ; At least one bit is set
```

4.6.2.8 BR, BRANCH

*** BR, BRANCH**	Branch to destination in lower 64K address space
Syntax	`BR dst`
Operation	dst → PC
Emulation	`MOV dst,PC`
Description	An unconditional branch is taken to an address anywhere in the lower 64K address space. All source addressing modes can be used. The branch instruction is a word instruction.
Status Bits	Status bits are not affected.
Example	Examples for all addressing modes are given.

```
BR      #EXEC    ; Branch to label EXEC or direct branch (e.g. #0A4h)
                 ; Core instruction MOV @PC+,PC

BR      EXEC     ; Branch to the address contained in EXEC
                 ; Core instruction MOV X(PC),PC
                 ; Indirect address

BR      &EXEC    ; Branch to the address contained in absolute
                 ; address EXEC
                 ; Core instruction MOV X(0),PC
                 ; Indirect address

BR      R5       ; Branch to the address contained in R5
                 ; Core instruction MOV R5,PC
                 ; Indirect R5

BR      @R5      ; Branch to the address contained in the word
                 ; pointed to by R5.
                 ; Core instruction MOV @R5,PC
                 ; Indirect, indirect R5

BR      @R5+     ; Branch to the address contained in the word pointed
                 ; to by R5 and increment pointer in R5 afterwards.
                 ; The next time-S/W flow uses R5 pointer-it can
                 ; alter program execution due to access to
                 ; next address in a table pointed to by R5
                 ; Core instruction MOV @R5,PC
                 ; Indirect, indirect R5 with autoincrement

BR      X(R5)    ; Branch to the address contained in the address
                 ; pointed to by R5 + X (e.g. table with address
                 ; starting at X). X can be an address or a label
                 ; Core instruction MOV X(R5),PC
                 ; Indirect, indirect R5 + X
```

4.6.2.9 CALL

CALL Call a subroutine in lower 64KB

Syntax `CALL dst`

Operation
dst → PC 16-bit dst is evaluated and stored
SP – 2 → SP
PC → @SP updated PC with return address to TOS
tmp → PC saved 16-bit dst to PC

Description A subroutine call is made from an address in the lower 64KB to a subroutine address in the lower 64KB. All seven source addressing modes can be used. The call instruction is a word instruction. The return is made with the RET instruction.

Status Bits
Status bits are not affected.
PC.19:16 cleared (address in lower 64KB)

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Examples Examples for all addressing modes are given.

Immediate Mode: Call a subroutine at label EXEC (lower 64KB) or call directly to address.

```
CALL   #EXEC              ; Start address EXEC
CALL   #0AA04h            ; Start address 0AA04h
```

Symbolic Mode: Call a subroutine at the 16-bit address contained in address EXEC. EXEC is located at the address (PC + X) where X is within PC + 32 K.

```
CALL   EXEC               ; Start address at @EXEC. z16(PC)
```

Absolute Mode: Call a subroutine at the 16-bit address contained in absolute address EXEC in the lower 64KB.

```
CALL   &EXEC              ; Start address at @EXEC
```

Register mode: Call a subroutine at the 16-bit address contained in register R5.15:0.

```
CALL   R5                 ; Start address at R5
```

Indirect Mode: Call a subroutine at the 16-bit address contained in the word pointed to by register R5 (20-bit address).

```
CALL   @R5                ; Start address at @R5
```

4.6.2.10 CLR

*** CLR[.W]** Clear destination

*** CLR.B** Clear destination

Syntax `CLR dst` or `CLR.W dst`
`CLR.B dst`

Operation 0 → dst

Emulation
```
MOV #0,dst
MOV.B #0,dst
```

Description The destination operand is cleared.

Status Bits Status bits are not affected.

Example RAM word TONI is cleared.

```
CLR     TONI      ; 0 -> TONI
```

Example Register R5 is cleared.

```
CLR     R5
```

Example RAM byte TONI is cleared.

```
CLR.B   TONI      ; 0 -> TONI
```

4.6.2.11 CLRC

*** CLRC**	Clear carry bit
Syntax	`CLRC`
Operation	0 → C
Emulation	`BIC #1,SR`
Description	The carry bit (C) is cleared. The clear carry instruction is a word instruction.
Status Bits	N: Not affected Z: Not affected C: Cleared V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The 16-bit decimal counter pointed to by R13 is added to a 32-bit counter pointed to by R12.

```
CLRC                    ; C=0: defines start
DADD   @R13,0(R12)      ; add 16-bit counter to low word of 32-bit counter
DADC   2(R12)           ; add carry to high word of 32-bit counter
```

4.6.2.12 CLRN

*** CLRN**	Clear negative bit
Syntax	`CLRN`
Operation	0 → N or (.NOT.src .AND. dst → dst)
Emulation	`BIC #4,SR`
Description	The constant 04h is inverted (0FFFBh) and is logically ANDed with the destination operand. The result is placed into the destination. The clear negative bit instruction is a word instruction.
Status Bits	N: Reset to 0 Z: Not affected C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The negative bit in the SR is cleared. This avoids special treatment with negative numbers of the subroutine called.

```
            CLRN
            CALL   SUBR
            ...
            ...
SUBR        JN     SUBRET     ; If input is negative: do nothing and return
            ...
            ...
            ...
SUBRET      RET
```

4.6.2.13 CLRZ

*** CLRZ**	Clear zero bit
Syntax	`CLRZ`
Operation	0 → Z or (.NOT.src .AND. dst → dst)
Emulation	`BIC #2,SR`
Description	The constant 02h is inverted (0FFFDh) and logically ANDed with the destination operand. The result is placed into the destination. The clear zero bit instruction is a word instruction.
Status Bits	N: Not affected Z: Reset to 0 C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The zero bit in the SR is cleared.

```
CLRZ
```

Indirect, Auto-Increment mode: Call a subroutine at the 16-bit address contained in the word pointed to by register R5 (20-bit address) and increment the 16-bit address in R5 afterwards by 2. The next time the software uses R5 as a pointer, it can alter the program execution due to access to the next word address in the table pointed to by R5.

```
CALL   @R5+          ; Start address at @R5. R5 + 2
```

Indexed mode: Call a subroutine at the 16-bit address contained in the 20-bit address pointed to by register (R5 + X), for example, a table with addresses starting at X. The address is within the lower 64KB. X is within +32KB.

```
CALL   X(R5)         ; Start address at @(R5+X). z16(R5)
```

4.6.2.14 CMP

CMP[.W] Compare source word and destination word

CMP.B Compare source byte and destination byte

Syntax `CMP src,dst` or `CMP.W src,dst`

`CMP.B src,dst`

Operation (.not.src) + 1 + dst
or
dst – src

Emulation `BIC #2,SR`

Description The source operand is subtracted from the destination operand. This is made by adding the 1s complement of the source + 1 to the destination. The result affects only the status bits in SR.

Register mode: the register bits Rdst.19:16 (.W) resp. Rdst. 19:8 (.B) are not cleared.

Status Bits

N: Set if result is negative (src > dst), reset if positive (src = dst)

Z: Set if result is zero (src = dst), reset otherwise (src ≠ dst)

C: Set if there is a carry from the MSB, reset otherwise

V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow).

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Compare word EDE with a 16-bit constant 1800h. Jump to label TONI if EDE equals the constant. The address of EDE is within PC + 32 K.

```
CMP     #01800h,EDE     ; Compare word EDE with 1800h
JEQ     TONI            ; EDE contains 1800h
...                     ; Not equal
```

Example A table word pointed to by (R5 + 10) is compared with R7. Jump to label TONI if R7 contains a lower, signed 16-bit number. R7.19:16 is not cleared. The address of the source operand is a 20-bit address in full memory range.

```
CMP.W   10(R5),R7       ; Compare two signed numbers
JL      TONI            ; R7 < 10(R5)
...                     ; R7 >= 10(R5)
```

Example A table byte pointed to by R5 (20-bit address) is compared to the value in output Port1. Jump to label TONI if values are equal. The next table byte is addressed.

```
CMP.B   @R5+,&P1OUT     ; Compare P1 bits with table. R5 + 1
JEQ     TONI            ; Equal contents
...                     ; Not equal
```

4.6.2.15 DADC

*** DADC[.W]** Add carry decimally to destination

*** DADC.B** Add carry decimally to destination

Syntax `DADC dst` or `DADC.W dst`
`DADC.B dst`

Operation dst + C → dst (decimally)

Emulation
```
DADD #0,dst
DADD.B #0,dst
```

Description The carry bit (C) is added decimally to the destination.

Status Bits
- N: Set if MSB is 1
- Z: Set if dst is 0, reset otherwise
- C: Set if destination increments from 9999 to 0000, reset otherwise
  Set if destination increments from 99 to 00, reset otherwise
- V: Undefined

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The four-digit decimal number contained in R5 is added to an eight-digit decimal number pointed to by R8.

```
CLRC                ; Reset carry
                    ; next instruction's start condition is defined
DADD   R5,0(R8)     ; Add LSDs + C
DADC   2(R8)        ; Add carry to MSD
```

Example The two-digit decimal number contained in R5 is added to a four-digit decimal number pointed to by R8.

```
CLRC                ; Reset carry
                    ; next instruction's start condition is defined
DADD.B   R5,0(R8)   ; Add LSDs + C
DADC     1(R8)      ; Add carry to MSDs
```

4.6.2.16 DADD

*** DADD[.W]** Add source word and carry decimally to destination word

*** DADD.B** Add source byte and carry decimally to destination byte

Syntax `DADD src,dst` or `DADD.W src,dst`
`DADD.B src,dst`

Operation src + dst + C → dst (decimally)

Description The source operand and the destination operand are treated as two (.B) or four (.W) binary coded decimals (BCD) with positive signs. The source operand and the carry bit C are added decimally to the destination operand. The source operand is not affected. The previous content of the destination is lost. The result is not defined for non-BCD numbers.

Status Bits
N: Set if MSB of result is 1 (word > 7999h, byte > 79h), reset if MSB is 0
Z: Set if result is zero, reset otherwise
C: Set if the BCD result is too large (word > 9999h, byte > 99h), reset otherwise
V: Undefined

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Decimal 10 is added to the 16-bit BCD counter DECCNTR.

```
DADD   #10h,&DECCNTR   ; Add 10 to 4-digit BCD counter
```

Example The eight-digit BCD number contained in 16-bit RAM addresses BCD and BCD+2 is added decimally to an eight-digit BCD number contained in R4 and R5 (BCD+2 and R5 contain the MSDs). The carry C is added, and cleared.

```
CLRC                   ; Clear carry
DADD.W   &BCD,R4       ; Add LSDs. R4.19:16 = 0
DADD.W   &BCD+2,R5     ; Add MSDs with carry. R5.19:16 = 0
JC       OVERFLOW      ; Result >9999,9999: go to error routine
...                    ; Result ok
```

Example The two-digit BCD number contained in word BCD (16-bit address) is added decimally to a two-digit BCD number contained in R4. The carry C is added, also. R4.19:8 = 0CLRC ; Clear carryDADD.B &BCD,R4 ; Add BCD to R4 decimally. R4: 0,00ddh

```
CLRC                   ; Clear carry
DADD.B   &BCD,R4       ; Add BCD to R4 decimally.
                         R4: 0,00ddh
```

4.6.2.17 DEC

*** DEC[.W]**	Decrement destination
*** DEC.B**	Decrement destination
Syntax	`DEC dst` or `DEC.W dst` `DEC.B dst`
Operation	dst – 1 → dst
Emulation	`SUB #1,dst` `SUB.B #1,dst`
Description	The destination operand is decremented by one. The original contents are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if dst contained 1, reset otherwise C: Reset if dst contained 0, set otherwise V: Set if an arithmetic overflow occurs, otherwise reset. Set if initial value of destination was 08000h, otherwise reset. Set if initial value of destination was 080h, otherwise reset.
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	R10 is decremented by 1.

```
        DEC     R10                 ; Decrement R10

; Move a block of 255 bytes from memory location starting with EDE to
; memory location starting with TONI. Tables should not overlap: start of
; destination address TONI must not be within the range EDE to EDE+0FEh

        MOV     #EDE,R6
        MOV     #510,R10
L$1     MOV     @R6+,TONI-EDE-1(R6)
        DEC     R10
        JNZ     L$1
```

Do not transfer tables using the routine above with the overlap shown in Figure 4-35.

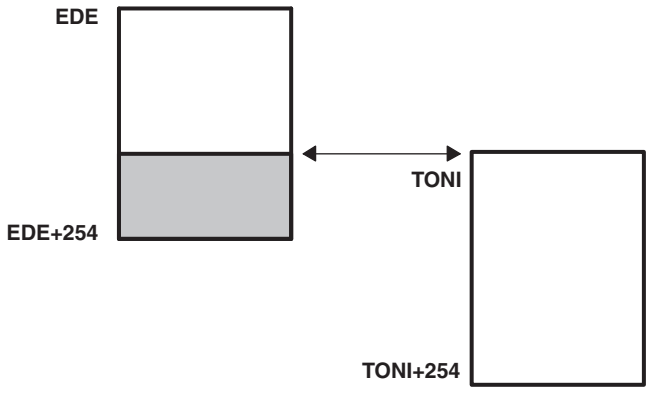


Figure 4-35. Decrement Overlap

4.6.2.18 DECD

*** DECD[.W]** Double-decrement destination

*** DECD.B** Double-decrement destination

Syntax `DECD dst` or `DECD.W dst`
`DECD.B dst`

Operation dst – 2 → dst

Emulation
```
SUB #2,dst
SUB.B #2,dst
```

Description The destination operand is decremented by two. The original contents are lost.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if dst contained 2, reset otherwise
- C: Reset if dst contained 0 or 1, set otherwise
- V: Set if an arithmetic overflow occurs, otherwise reset
  Set if initial value of destination was 08001 or 08000h, otherwise reset
  Set if initial value of destination was 081 or 080h, otherwise reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R10 is decremented by 2.

```
        DECD    R10             ; Decrement R10 by two
```

```
; Move a block of 255 bytes from memory location starting with EDE to
; memory location starting with TONI.
; Tables should not overlap: start of destination address TONI must not
; be within the range EDE to EDE+0FEh

        MOV     #EDE,R6
        MOV     #255,R10
L$1     MOV.B   @R6+,TONI-EDE-2(R6)
        DECD    R10
        JNZ     L$1
```

Example Memory at location LEO is decremented by two.

```
        DECD.B  LEO             ; Decrement MEM(LEO)
```

Decrement status byte STATUS by two

```
        DECD.B  STATUS
```

4.6.2.19 DINT

*** DINT**	Disable (general) interrupts
Syntax	`DINT`
Operation	0 → GIE or (0FFF7h .AND. SR → SR / .NOT. src .AND. dst → dst)
Emulation	`BIC #8,SR`
Description	All interrupts are disabled. The constant 08h is inverted and logically ANDed with the SR. The result is placed into the SR.
Status Bits	Status bits are not affected.
Mode Bits	GIE is reset. OSCOFF and CPUOFF are not affected.
Example	The general interrupt enable (GIE) bit in the SR is cleared to allow a nondisrupted move of a 32-bit counter. This ensures that the counter is not modified during the move by any interrupt.

```
DINT                ; All interrupt events using the GIE bit are disabled
NOP
MOV    COUNTHI,R5   ; Copy counter
MOV    COUNTLO,R6
EINT                ; All interrupt events using the GIE bit are enabled
```

NOTE: Disable interrupt

If any code sequence needs to be protected from interruption, DINT should be executed at least one instruction before the beginning of the uninterruptible sequence, or it should be followed by a NOP instruction.

4.6.2.20 EINT

*** EINT**	Enable (general) interrupts
Syntax	`EINT`
Operation	1 → GIE or (0008h .OR. SR → SR / .src .OR. dst → dst)
Emulation	`BIS #8,SR`
Description	All interrupts are enabled. The constant #08h and the SR are logically ORed. The result is placed into the SR.
Status Bits	Status bits are not affected.
Mode Bits	GIE is set. OSCOFF and CPUOFF are not affected.
Example	The general interrupt enable (GIE) bit in the SR is set.

```
; Interrupt routine of ports P1.2 to P1.7
; P1IN is the address of the register where all port bits are read.
; P1IFG is the address of the register where all interrupt events are latched.

          PUSH.B   &P1IN
          BIC.B    @SP,&P1IFG  ; Reset only accepted flags
          EINT                 ; Preset port 1 interrupt flags stored on stack
                               ; other interrupts are allowed
          BIT      #Mask,@SP
          JEQ      MaskOK      ; Flags are present identically to mask: jump
          ...
          ...
MaskOK    BIC      #Mask,@SP
          ...
          ...
          INCD     SP          ; Housekeeping: inverse to PUSH instruction
                               ; at the start of interrupt subroutine. Corrects
                               ; the stack pointer.
          RETI
```

NOTE: Enable interrupt

The instruction following the enable interrupt instruction (EINT) is always executed, even if an interrupt service request is pending when the interrupts are enabled.

4.6.2.21 INC

*** INC[.W]** Increment destination

*** INC.B** Increment destination

Syntax `INC dst` or `INC.W dst`

`INC.B dst`

Operation dst + 1 → dst

Emulation `ADD #1,dst`

Description The destination operand is incremented by one. The original contents are lost.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if dst contained 0FFFFh, reset otherwise
  Set if dst contained 0FFh, reset otherwise
- C: Set if dst contained 0FFFFh, reset otherwise
  Set if dst contained 0FFh, reset otherwise
- V: Set if dst contained 07FFFh, reset otherwise
  Set if dst contained 07Fh, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The status byte, STATUS, of a process is incremented. When it is equal to 11, a branch to OVFL is taken.

```
INC.B   STATUS
CMP.B   #11,STATUS
JEQ     OVFL
```

4.6.2.22 INCD

*** INCD[.W]** Double-increment destination

*** INCD.B** Double-increment destination

Syntax `INCD dst` or `INCD.W dst`

`INCD.B dst`

Operation dst + 2 → dst

Emulation `ADD #2,dst`

`ADD.B #2,dst`

Description The destination operand is incremented by two. The original contents are lost.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if dst contained 0FFFEh, reset otherwise
  Set if dst contained 0FEh, reset otherwise
- C: Set if dst contained 0FFFEh or 0FFFFh, reset otherwise
  Set if dst contained 0FEh or 0FFh, reset otherwise
- V: Set if dst contained 07FFEh or 07FFFh, reset otherwise
  Set if dst contained 07Eh or 07Fh, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The item on the top of the stack (TOS) is removed without using a register.

```
.......
PUSH    R5       ; R5 is the result of a calculation, which is stored
                 ; in the system stack
INCD    SP       ; Remove TOS by double-increment from stack
                 ; Do not use INCD.B, SP is a word-aligned register
RET
```

Example The byte on the top of the stack is incremented by two.

```
INCD.B   0(SP)   ; Byte on TOS is increment by two
```

4.6.2.23 INV

*** INV[.W]** Invert destination

*** INV.B** Invert destination

Syntax `INV dst` or `INV.W dst`

`INV.B dst`

Operation .not.dst → dst

Emulation `XOR #0FFFFh,dst`

`XOR.B #0FFh,dst`

Description The destination operand is inverted. The original contents are lost.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if dst contained 0FFFFh, reset otherwise
  Set if dst contained 0FFh, reset otherwise
- C: Set if result is not zero, reset otherwise (= .NOT. Zero)
- V: Set if initial destination operand was negative, otherwise reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Content of R5 is negated (2s complement).

```
MOV     #00AEh,R5    ;                      R5 = 000AEh
INV     R5           ; Invert R5,           R5 = 0FF51h
INC     R5           ; R5 is now negated,   R5 = 0FF52h
```

Example Content of memory byte LEO is negated.

```
MOV.B   #0AEh,LEO    ;                      MEM(LEO) = 0AEh
INV.B   LEO          ; Invert LEO,          MEM(LEO) = 051h
INC.B   LEO          ; MEM(LEO) is negated, MEM(LEO) = 052h
```

4.6.2.24 JC, JHS

JC Jump if carry

JHS Jump if higher or same (unsigned)

Syntax

```
JC label
JHS label
```

Operation

If C = 1: PC + (2 × Offset) → PC
If C = 0: execute the following instruction

Description The carry bit C in the SR is tested. If it is set, the signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit PC. This means a jump in the range –511 to +512 words relative to the PC in the full memory range. If C is reset, the instruction after the jump is executed.

JC is used for the test of the carry bit C.

JHS is used for the comparison of unsigned numbers.

Status Bits Status bits are not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The state of the port 1 pin P1IN.1 bit defines the program flow.

```
BIT.B   #2,&P1IN      ; Port 1, bit 1 set? Bit -> C
JC      Label1        ; Yes, proceed at Label1
...                   ; No, continue
```

Example If R5 ≥ R6 (unsigned), the program continues at Label2.

```
CMP     R6,R 5        ; Is R5 >= R6? Info to C
JHS     Label2        ; Yes, C = 1
...                   ; No, R5 < R6. Continue
```

Example If R5 ≥ 12345h (unsigned operands), the program continues at Label2.

```
CMPA    #12345h,R5    ; Is R5 >= 12345h? Info to C
JHS     Label2        ; Yes, 12344h < R5 <= F,FFFFh. C = 1
...                   ; No, R5 < 12345h. Continue
```

4.6.2.25 JEQ, JZ

JEQ Jump if equal

JZ Jump if zero

Syntax
```
JEQ label
JZ label
```

Operation If Z = 1: PC + (2 × Offset) → PC
If Z = 0: execute following instruction

Description The zero bit Z in the SR is tested. If it is set, the signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit PC. This means a jump in the range –511 to +512 words relative to the PC in the full memory range. If Z is reset, the instruction after the jump is executed.

JZ is used for the test of the zero bit Z.

JEQ is used for the comparison of operands.

Status Bits Status bits are not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The state of the P2IN.0 bit defines the program flow.

```
BIT.B   #1,&P2IN     ; Port 2, bit 0 reset?
JZ      Label1       ; Yes, proceed at Label1
...                  ; No, set, continue
```

Example If R5 = 15000h (20-bit data), the program continues at Label2.

```
CMPA    #15000h,R5   ; Is R5 = 15000h? Info to SR
JEQ     Label2       ; Yes, R5 = 15000h. Z = 1
...                  ; No, R5 not equal 15000h. Continue
```

Example R7 (20-bit counter) is incremented. If its content is zero, the program continues at Label4.

```
ADDA    #1,R7        ; Increment R7
JZ      Label4       ; Zero reached: Go to Label4
...                  ; R7 not equal 0. Continue here.
```

4.6.2.26 JGE

JGE Jump if greater or equal (signed)

Syntax `JGE label`

Operation If (N .xor. V) = 0: PC + (2 × Offset) → PC
If (N .xor. V) = 1: execute following instruction

Description The negative bit N and the overflow bit V in the SR are tested. If both bits are set or both are reset, the signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit PC. This means a jump in the range -511 to +512 words relative to the PC in full Memory range. If only one bit is set, the instruction after the jump is executed.

JGE is used for the comparison of signed operands: also for incorrect results due to overflow, the decision made by the JGE instruction is correct.

Note: JGE emulates the nonimplemented JP (jump if positive) instruction if used after the instructions AND, BIT, RRA, SXTX, and TST. These instructions clear the V bit.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example If byte EDE (lower 64KB) contains positive data, go to Label1. Software can run in the full memory range.

```
TST.B   &EDE            ; Is EDE positive? V <- 0
JGE     Label1          ; Yes, JGE emulates JP
...                     ; No, 80h <= EDE <= FFh
```

Example If the content of R6 is greater than or equal to the memory pointed to by R7, the program continues a Label5. Signed data. Data and program in full memory range.

```
CMP     @R7,R6          ; Is R6 >= @R7?
JGE     Label5          ; Yes, go to Label5
...                     ; No, continue here
```

Example If R5 ≥ 12345h (signed operands), the program continues at Label2. Program in full memory range.

```
CMPA    #12345h,R5      ; Is R5 >= 12345h?
JGE     Label2          ; Yes, 12344h < R5 <= 7FFFFh
...                     ; No, 80000h <= R5 < 12345h
```

4.6.2.27 JL

JL Jump if less (signed)

Syntax `JL label`

Operation If (N .xor. V) = 1: PC + (2 × Offset) → PC
If (N .xor. V) = 0: execute following instruction

Description The negative bit N and the overflow bit V in the SR are tested. If only one is set, the signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit PC. This means a jump in the range –511 to +512 words relative to the PC in full memory range. If both bits N and V are set or both are reset, the instruction after the jump is executed.

JL is used for the comparison of signed operands: also for incorrect results due to overflow, the decision made by the JL instruction is correct.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example If byte EDE contains a smaller, signed operand than byte TONI, continue at Label1. The address EDE is within PC ± 32 K.

```
CMP.B   &TONI,EDE     ; Is EDE < TONI
JL      Label1        ; Yes
...                   ; No, TONI <= EDE
```

Example If the signed content of R6 is less than the memory pointed to by R7 (20-bit address), the program continues at Label5. Data and program in full memory range.

```
CMP     @R7,R6        ; Is R6 < @R7?
JL      Label5        ; Yes, go to Label5
...                   ; No, continue here
```

Example If R5 < 12345h (signed operands), the program continues at Label2. Data and program in full memory range.

```
CMPA    #12345h,R5    ; Is R5 < 12345h?
JL      Label2        ; Yes, 80000h =< R5 < 12345h
...                   ; No, 12344h < R5 <= 7FFFFh
```

4.6.2.28 JMP

JMP	Jump unconditionally
Syntax	`JMP label`
Operation	PC + (2 × Offset) → PC
Description	The signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit PC. This means an unconditional jump in the range –511 to +512 words relative to the PC in the full memory. The JMP instruction may be used as a BR or BRA instruction within its limited range relative to the PC.
Status Bits	Status bits are not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The byte STATUS is set to 10. Then a jump to label MAINLOOP is made. Data in lower 64KB, program in full memory range.

```
MOV.B   #10,&STATUS     ; Set STATUS to 10
JMP     MAINLOOP        ; Go to main loop
```

Example The interrupt vector TAIV of Timer_A3 is read and used for the program flow. Program in full memory range, but interrupt handlers always starts in lower 64KB.

```
ADD     &TAIV,PC        ; Add Timer_A interrupt vector to PC
RETI                    ; No Timer_A interrupt pending
JMP     IHCCR1          ; Timer block 1 caused interrupt
JMP     IHCCR2          ; Timer block 2 caused interrupt
RETI                    ; No legal interrupt, return
```

4.6.2.29 JN

JN Jump if negative

Syntax `JN label`

Operation If N = 1: PC + (2 × Offset) → PC
If N = 0: execute following instruction

Description The negative bit N in the SR is tested. If it is set, the signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit program PC. This means a jump in the range -511 to +512 words relative to the PC in the full memory range. If N is reset, the instruction after the jump is executed.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The byte COUNT is tested. If it is negative, program execution continues at Label0. Data in lower 64KB, program in full memory range.

```
TST.B   &COUNT      ; Is byte COUNT negative?
JN      Label0      ; Yes, proceed at Label0
...                 ; COUNT >= 0
```

Example R6 is subtracted from R5. If the result is negative, program continues at Label2. Program in full memory range.

```
SUB     R6,R5       ; R5 - R6 -> R5
JN      Label2      ; R5 is negative: R6 > R5 (N = 1)
...                 ; R5 >= 0. Continue here.
```

Example R7 (20-bit counter) is decremented. If its content is below zero, the program continues at Label4. Program in full memory range.

```
SUBA    #1,R7       ; Decrement R7
JN      Label4      ; R7 < 0: Go to Label4
...                 ; R7 >= 0. Continue here.
```

4.6.2.30 JNC, JLO

JNC Jump if no carry

JLO Jump if lower (unsigned)

Syntax

```
JNC label
JLO label
```

Operation If C = 0: PC + (2 × Offset) → PC
If C = 1: execute following instruction

Description The carry bit C in the SR is tested. If it is reset, the signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit PC. This means a jump in the range –511 to +512 words relative to the PC in the full memory range. If C is set, the instruction after the jump is executed.

JNC is used for the test of the carry bit C.

JLO is used for the comparison of unsigned numbers.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example If byte EDE < 15, the program continues at Label2. Unsigned data. Data in lower 64KB, program in full memory range.

```
CMP.B   #15,&EDE     ; Is EDE < 15? Info to C
JLO     Label2       ; Yes, EDE < 15. C = 0
...                  ; No, EDE >= 15. Continue
```

Example The word TONI is added to R5. If no carry occurs, continue at Label0. The address of TONI is within PC ± 32 K.

```
ADD     TONI,R5      ; TONI + R5 -> R5. Carry -> C
JNC     Label0       ; No carry
...                  ; Carry = 1: continue here
```

4.6.2.31 JNZ, JNE

JNZ Jump if not zero

JNE Jump if not equal

Syntax

```
JNZ label
JNE label
```

Operation If Z = 0: PC + (2 × Offset) → PC
If Z = 1: execute following instruction

Description The zero bit Z in the SR is tested. If it is reset, the signed 10-bit word offset contained in the instruction is multiplied by two, sign extended, and added to the 20-bit PC. This means a jump in the range –511 to +512 words relative to the PC in the full memory range. If Z is set, the instruction after the jump is executed.

JNZ is used for the test of the zero bit Z.

JNE is used for the comparison of operands.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The byte STATUS is tested. If it is not zero, the program continues at Label3. The address of STATUS is within PC ± 32 K.

```
TST.B   STATUS          ; Is STATUS = 0?
JNZ     Label3          ; No, proceed at Label3
...                     ; Yes, continue here
```

Example If word EDE ≠ 1500, the program continues at Label2. Data in lower 64KB, program in full memory range.

```
CMP     #1500,&EDE      ; Is EDE = 1500? Info to SR
JNE     Label2          ; No, EDE not equal 1500.
...                     ; Yes, R5 = 1500. Continue
```

Example R7 (20-bit counter) is decremented. If its content is not zero, the program continues at Label4. Program in full memory range.

```
SUBA    #1,R7           ; Decrement R7
JNZ     Label4          ; Zero not reached: Go to Label4
...                     ; Yes, R7 = 0. Continue here.
```

4.6.2.32 MOV

MOV[.W] Move source word to destination word

MOV.B Move source byte to destination byte

Syntax `MOV src,dst` or `MOV.W src,dst`

`MOV.B src,dst`

Operation src → dst

Description The source operand is copied to the destination. The source operand is not affected.

Status Bits
- N: Not affected
- Z: Not affected
- C: Not affected
- V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Move a 16-bit constant 1800h to absolute address-word EDE (lower 64KB)

```
MOV     #01800h,&EDE            ; Move 1800h to EDE
```

Example The contents of table EDE (word data, 16-bit addresses) are copied to table TOM. The length of the tables is 030h words. Both tables reside in the lower 64KB.

```
        MOV     #EDE,R10                ; Prepare pointer (16-bit address)
Loop    MOV     @R10+,TOM-EDE-2(R10)    ; R10 points to both tables.
                                        ; R10+2
        CMP     #EDE+60h,R10            ; End of table reached?
        JLO     Loop                    ; Not yet
        ...                             ; Copy completed
```

Example The contents of table EDE (byte data, 16-bit addresses) are copied to table TOM. The length of the tables is 020h bytes. Both tables may reside in full memory range, but must be within R10 ± 32 K.

```
        MOVA    #EDE,R10                ; Prepare pointer (20-bit)
        MOV     #20h,R9                 ; Prepare counter
Loop    MOV.B   @R10+,TOM-EDE-1(R10)    ; R10 points to both tables.
                                        ; R10+1
        DEC     R9                      ; Decrement counter
        JNZ     Loop                    ; Not yet done
        ...                             ; Copy completed
```

4.6.2.33 NOP

*** NOP**	No operation
Syntax	`NOP`
Operation	None
Emulation	`MOV #0, R3`
Description	No operation is performed. The instruction may be used for the elimination of instructions during the software check or for defined waiting times.
Status Bits	Status bits are not affected.

4.6.2.34 POP

*** POP[.W]** Pop word from stack to destination

*** POP.B** Pop byte from stack to destination

Syntax
```
POP dst
POP.B dst
```

Operation
@SP → temp
SP + 2 → SP
temp → dst

Emulation `MOV @SP+,dst` or `MOV.W @SP+,dst`
`MOV.B @SP+,dst`

Description The stack location pointed to by the SP (TOS) is moved to the destination. The SP is incremented by two afterwards.

Status Bits Status bits are not affected.

Example The contents of R7 and the SR are restored from the stack.

```
POP     R7      ; Restore R7
POP     SR      ; Restore status register
```

Example The contents of RAM byte LEO is restored from the stack.

```
POP.B   LEO     ; The low byte of the stack is moved to LEO.
```

Example The contents of R7 is restored from the stack.

```
POP.B   R7      ; The low byte of the stack is moved to R7,
                ; the high byte of R7 is 00h
```

Example The contents of the memory pointed to by R7 and the SR are restored from the stack.

```
POP.B   0(R7)   ; The low byte of the stack is moved to the
                ; the byte which is pointed to by R7
                : Example:   R7 = 203h
                ;            Mem(R7) = low byte of system stack
                : Example:   R7 = 20Ah
                ;            Mem(R7) = low byte of system stack
POP     SR      ; Last word on stack moved to the SR
```

NOTE: System stack pointer

The system SP is always incremented by two, independent of the byte suffix.

4.6.2.35 PUSH

PUSH[.W] Save a word on the stack

PUSH.B Save a byte on the stack

Syntax `PUSH dst` or `PUSH.W dst`
`PUSH.B dst`

Operation SP – 2 → SP
dst → @SP

Description The 20-bit SP SP is decremented by two. The operand is then copied to the RAM word addressed by the SP. A pushed byte is stored in the low byte; the high byte is not affected.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Save the two 16-bit registers R9 and R10 on the stack

```
PUSH    R9      ; Save R9 and R10 XXXXh
PUSH    R10     ; YYYYh
```

Example Save the two bytes EDE and TONI on the stack. The addresses EDE and TONI are within PC ± 32 K.

```
PUSH.B  EDE     ; Save EDE   xxXXh
PUSH.B  TONI    ; Save TONI   xxYYh
```

4.6.2.36 RET

RET	Return from subroutine
Syntax	RET
Operation	@SP →PC.15:0 Saved PC to PC.15:0. PC.19:16 ← 0 SP + 2 → SP
Description	The 16-bit return address (lower 64KB), pushed onto the stack by a CALL instruction is restored to the PC. The program continues at the address following the subroutine call. The four MSBs of the PC.19:16 are cleared.
Status Bits	Status bits are not affected. PC.19:16: Cleared
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	Call a subroutine SUBR in the lower 64KB and return to the address in the lower 64KB after the CALL.

```
        CALL    #SUBR     ; Call subroutine starting at SUBR
        ...               ; Return by RET to here
SUBR    PUSH    R14       ; Save R14 (16 bit data)
        ...               ; Subroutine code
        POP     R14       ; Restore R14
        RET               ; Return to lower 64KB
```

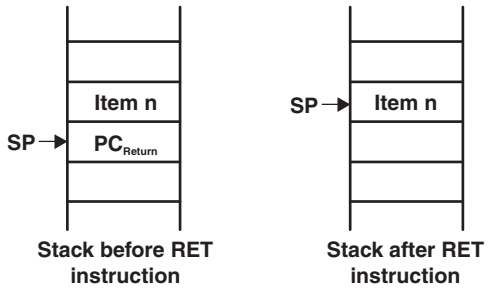


Figure 4-36. Stack After a RET Instruction

4.6.2.37 RETI

RETI	Return from interrupt
Syntax	`RETI`
Operation	@SP → SR.15:0 Restore saved SR with PC.19:16 SP + 2 → SP @SP → PC.15:0 Restore saved PC.15:0 SP + 2 → SP Housekeeping
Description	The SR is restored to the value at the beginning of the interrupt service routine. This includes the four MSBs of the PC.19:16. The SP is incremented by two afterward. The 20-bit PC is restored from PC.19:16 (from same stack location as the status bits) and PC.15:0. The 20-bit PC is restored to the value at the beginning of the interrupt service routine. The program continues at the address following the last executed instruction when the interrupt was granted. The SP is incremented by two afterward.
Status Bits	N: Restored from stack C: Restored from stack Z: Restored from stack V: Restored from stack
Mode Bits	OSCOFF, CPUOFF, and GIE are restored from stack.
Example	Interrupt handler in the lower 64KB. A 20-bit return address is stored on the stack.

```
INTRPT  PUSHM.A   #2,R14    ; Save R14 and R13 (20-bit data)
        ...                 ; Interrupt handler code
        POPM.A    #2,R14    ; Restore R13 and R14 (20-bit data)
        RETI                ; Return to 20-bit address in full memory range
```

4.6.2.38 RLA

*** RLA[.W]** Rotate left arithmetically

*** RLA.B** Rotate left arithmetically

Syntax
```
RLA dst or          RLA.W dst
RLA.B dst
```

Operation C ← MSB ← MSB-1 .... LSB+1 ← LSB ← 0

Emulation
```
ADD dst,dst
ADD.B dst,dst
```

Description The destination operand is shifted left one position as shown in Figure 4-37. The MSB is shifted into the carry bit (C) and the LSB is filled with 0. The RLA instruction acts as a signed multiplication by 2.

An overflow occurs if dst ≥ 04000h and dst < 0C000h before operation is performed; the result has changed sign.

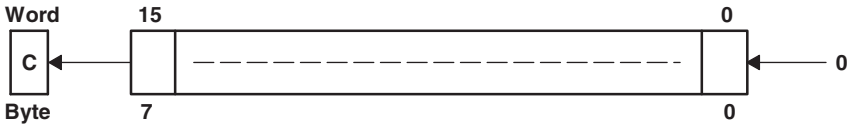


Figure 4-37. Destination Operand—Arithmetic Shift Left

An overflow occurs if dst ≥ 040h and dst < 0C0h before the operation is performed; the result has changed sign.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if result is zero, reset otherwise
- C: Loaded from the MSB
- V: Set if an arithmetic overflow occurs; the initial value is 04000h ≤ dst < 0C000h, reset otherwise

  Set if an arithmetic overflow occurs; the initial value is 040h ≤ dst < 0C0h, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R7 is multiplied by 2.

```
RLA     R7    ; Shift left R7  (x 2)
```

Example The low byte of R7 is multiplied by 4.

```
RLA.B   R7    ; Shift left low byte of R7  (x 2)
RLA.B   R7    ; Shift left low byte of R7  (x 4)
```

NOTE: RLA substitution

The assembler does not recognize the instructions:

```
RLA  @R5+          RLA.B  @R5+          RLA(.B) @R5
```

They must be substituted by:

```
ADD  @R5+,-2(R5)   ADD.B  @R5+,-1(R5)   ADD(.B) @R5
```

4.6.2.39 RLC

*** RLC[.W]** Rotate left through carry

*** RLC.B** Rotate left through carry

Syntax `RLC dst` or `RLC.W dst`

`RLC.B dst`

Operation C ← MSB ← MSB-1 .... LSB+1 ← LSB ← C

Emulation `ADDC dst,dst`

Description The destination operand is shifted left one position as shown in Figure 4-38. The carry bit (C) is shifted into the LSB, and the MSB is shifted into the carry bit (C).

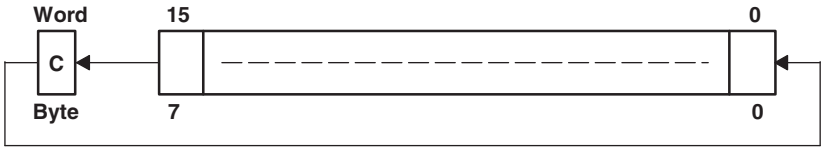


Figure 4-38. Destination Operand—Carry Left Shift

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if result is zero, reset otherwise
- C: Loaded from the MSB
- V: Set if an arithmetic overflow occurs; the initial value is 04000h ≤ dst < 0C000h, reset otherwise
  Set if an arithmetic overflow occurs; the initial value is 040h ≤ dst < 0C0h, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R5 is shifted left one position.

```
RLC     R5          ; (R5 x 2) + C -> R5
```

Example The input P1IN.1 information is shifted into the LSB of R5.

```
BIT.B   #2,&P1IN    ; Information -> Carry
RLC     R5          ; Carry=P0in.1 -> LSB of R5
```

Example The MEM(LEO) content is shifted left one position.

```
RLC.B   LEO         ; Mem(LEO) x 2 + C -> Mem(LEO)
```

NOTE: RLA substitution

The assembler does not recognize the instructions:

`RLC @R5+` `RLC.B @R5+` `RLC(.B) @R5`

They must be substituted by:

`ADDC @R5+,-2(R5)` `ADDC.B @R5+,-1(R5)` `ADDC(.B) @R5`

4.6.2.40 RRA

RRA[.W] Rotate right arithmetically destination word

RRA.B Rotate right arithmetically destination byte

Syntax `RRA.B dst` or `RRA.W dst`

Operation MSB → MSB → MSB–1 → ... LSB+1 → LSB → C

Description The destination operand is shifted right arithmetically by one bit position as shown in Figure 4-39. The MSB retains its value (sign). RRA operates equal to a signed division by 2. The MSB is retained and shifted into the MSB–1. The LSB+1 is shifted into the LSB. The previous LSB is shifted into the carry bit C.

Status Bits
- N: Set if result is negative (MSB = 1), reset otherwise (MSB = 0)
- Z: Set if result is zero, reset otherwise
- C: Loaded from the LSB
- V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The signed 16-bit number in R5 is shifted arithmetically right one position.

```
RRA     R5              ; R5/2 -> R5
```

Example The signed RAM byte EDE is shifted arithmetically right one position.

```
RRA.B   EDE             ; EDE/2 -> EDE
```

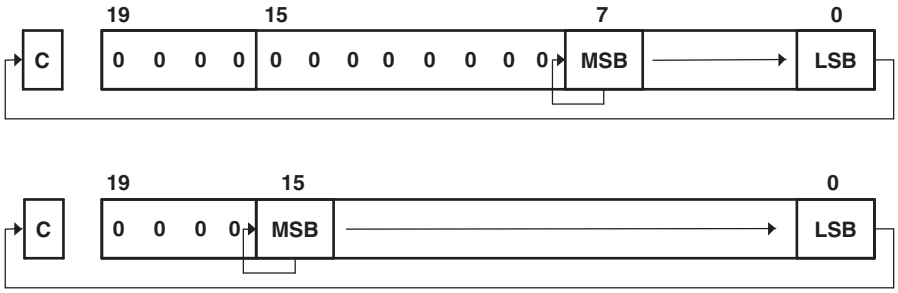


Figure 4-39. Rotate Right Arithmetically RRA.B and RRA.W

4.6.2.41 RRC

RRC[.W]	Rotate right through carry destination word
RRC.B	Rotate right through carry destination byte
Syntax	`RRC dst` or `RRC.W dst` `RRC.B dst`
Operation	C → MSB → MSB–1 → ... LSB+1 → LSB → C
Description	The destination operand is shifted right by one bit position as shown in Figure 4-40. The carry bit C is shifted into the MSB and the LSB is shifted into the carry bit C.
Status Bits	N: Set if result is negative (MSB = 1), reset otherwise (MSB = 0) Z: Set if result is zero, reset otherwise C: Loaded from the LSB V: Reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	RAM word EDE is shifted right one bit position. The MSB is loaded with 1.

```
SETC            ; Prepare carry for MSB
RRC     EDE     ; EDE = EDE >> 1 + 8000h
```

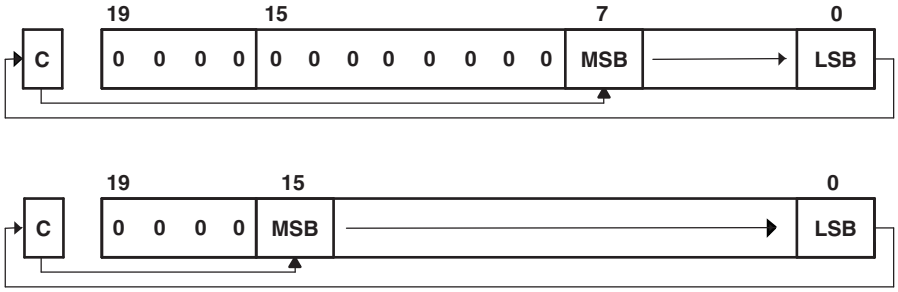


Figure 4-40. Rotate Right Through Carry RRC.B and RRC.W

4.6.2.42 SBC

*** SBC[.W]** Subtract borrow (.NOT. carry) from destination

*** SBC.B** Subtract borrow (.NOT. carry) from destination

Syntax `SBC dst` or `SBC.W dst`

`SBC.B dst`

Operation dst + 0FFFFh + C → dst

dst + 0FFh + C → dst

Emulation `SUBC #0,dst`

`SUBC.B #0,dst`

Description The carry bit (C) is added to the destination operand minus one. The previous contents of the destination are lost.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if result is zero, reset otherwise
- C: Set if there is a carry from the MSB of the result, reset otherwise
  Set to 1 if no borrow, reset if borrow
- V: Set if an arithmetic overflow occurs, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 16-bit counter pointed to by R13 is subtracted from a 32-bit counter pointed to by R12.

```
SUB     @R13,0(R12)    ; Subtract LSDs
SBC     2(R12)         ; Subtract carry from MSD
```

Example The 8-bit counter pointed to by R13 is subtracted from a 16-bit counter pointed to by R12.

```
SUB.B   @R13,0(R12)    ; Subtract LSDs
SBC.B   1(R12)         ; Subtract carry from MSD
```

NOTE: Borrow implementation

The borrow is treated as a .NOT. carry:

Borrow	Carry Bit
Yes	0
No	1

4.6.2.43 SETC

*** SETC**	Set carry bit
Syntax	SETC
Operation	1 → C
Emulation	BIS #1,SR
Description	The carry bit (C) is set.
Status Bits	N: Not affected Z: Not affected C: Set V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	Emulation of the decimal subtraction: Subtract R5 from R6 decimally. Assume that R5 = 03987h and R6 = 04137h.

```
DSUB    ADD     #06666h,R5      ; Move content R5 from 0-9 to 6-0Fh
                                ; R5 = 03987h + 06666h = 09FEDh
        INV     R5              ; Invert this (result back to 0-9)
                                ; R5 = .NOT. R5 = 06012h
        SETC                    ; Prepare carry = 1
        DADD    R5,R6           ; Emulate subtraction by addition of:
                                ; (010000h - R5 - 1)
                                ; R6 = R6 + R5 + 1
                                ; R6 = 0150h
```

4.6.2.44 SETN

*** SETN**	Set negative bit
Syntax	`SETN`
Operation	1 → N
Emulation	`BIS #4,SR`
Description	The negative bit (N) is set.
Status Bits	N: Set Z: Not affected C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.

4.6.2.45 SETZ

*** SETZ**	Set zero bit
Syntax	`SETZ`
Operation	1 → N
Emulation	`BIS #2,SR`
Description	The zero bit (Z) is set.
Status Bits	N: Not affected Z: Set C: Not affected V: Not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.

4.6.2.46 SUB

SUB[.W] Subtract source word from destination word

SUB.B Subtract source byte from destination byte

Syntax `SUB src,dst` or `SUB.W src,dst`

`SUB.B src,dst`

Operation (.not.src) + 1 + dst → dst or dst – src → dst

Description The source operand is subtracted from the destination operand. This is made by adding the 1s complement of the source + 1 to the destination. The source operand is not affected, the result is written to the destination operand.

Status Bits

N: Set if result is negative (src > dst), reset if positive (src ≤ dst)

Z: Set if result is zero (src = dst), reset otherwise (src ≠ dst)

C: Set if there is a carry from the MSB, reset otherwise

V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow)

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example A 16-bit constant 7654h is subtracted from RAM word EDE.

```
SUB     #7654h,&EDE     ; Subtract 7654h from EDE
```

Example A table word pointed to by R5 (20-bit address) is subtracted from R7. Afterwards, if R7 contains zero, jump to label TONI. R5 is then auto-incremented by 2. R7.19:16 = 0.

```
SUB     @R5+,R7         ; Subtract table number from R7. R5 + 2
JZ      TONI            ; R7 = @R5 (before subtraction)
...                     ; R7 <> @R5 (before subtraction)
```

Example Byte CNT is subtracted from byte R12 points to. The address of CNT is within PC ± 32K. The address R12 points to is in full memory range.

```
SUB.B   CNT,0(R12)      ; Subtract CNT from @R12
```

4.6.2.47 SUBC

SUBC[.W] Subtract source word with carry from destination word

SUBC.B Subtract source byte with carry from destination byte

Syntax `SUBC src,dst` or `SUBC.W src,dst`

`SUBC.B src,dst`

Operation (.not.src) + C + dst → dst or dst – (src – 1) + C → dst

Description The source operand is subtracted from the destination operand. This is done by adding the 1s complement of the source + carry to the destination. The source operand is not affected, the result is written to the destination operand. Used for 32, 48, and 64-bit operands.

Status Bits

N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)

Z: Set if result is zero, reset otherwise

C: Set if there is a carry from the MSB, reset otherwise

V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow)

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example A 16-bit constant 7654h is subtracted from R5 with the carry from the previous instruction. R5.19:16 = 0

```
SUBC.W   #7654h,R5       ; Subtract 7654h + C from R5
```

Example A 48-bit number (3 words) pointed to by R5 (20-bit address) is subtracted from a 48-bit counter in RAM, pointed to by R7. R5 points to the next 48-bit number afterwards. The address R7 points to is in full memory range.

```
SUB      @R5+,0(R7)      ; Subtract LSBs. R5 + 2
SUBC     @R5+,2(R7)      ; Subtract MIDs with C. R5 + 2
SUBC     @R5+,4(R7)      ; Subtract MSBs with C. R5 + 2
```

Example Byte CNT is subtracted from the byte, R12 points to. The carry of the previous instruction is used. The address of CNT is in lower 64KB.

```
SUBC.B   &CNT,0(R12)     ; Subtract byte CNT from @R12
```

4.6.2.48 SWPB

SWPB	Swap bytes
Syntax	`SWPB dst`
Operation	dst.15:8 ↔ dst.7:0
Description	The high and the low byte of the operand are exchanged. PC.19:16 bits are cleared in register mode.
Status Bits	Status bits are not affected
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	Exchange the bytes of RAM word EDE (lower 64KB)

```
MOV    #1234h,&EDE      ; 1234h -> EDE
SWPB   &EDE             ; 3412h -> EDE
```

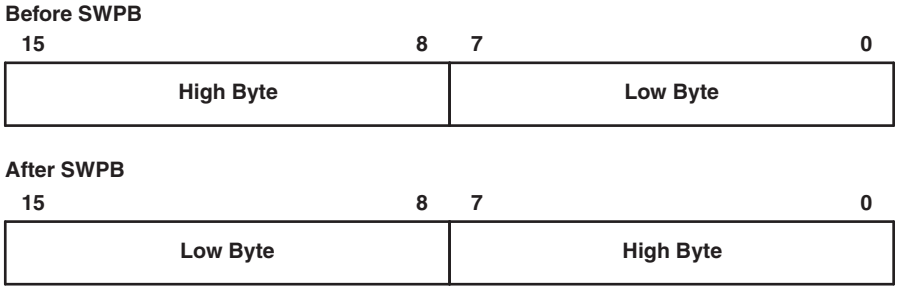


Figure 4-41. Swap Bytes in Memory

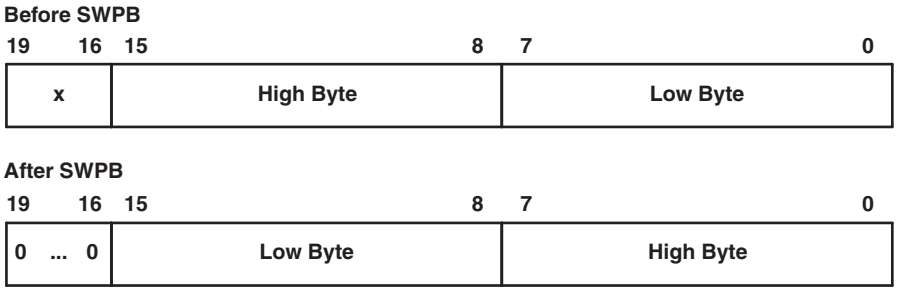


Figure 4-42. Swap Bytes in a Register

4.6.2.49 SXT

SXT Extend sign

Syntax `SXT dst`

Operation dst.7 → dst.15:8, dst.7 → dst.19:8 (register mode)

Description Register mode: the sign of the low byte of the operand is extended into the bits Rdst.19:8.

Rdst.7 = 0: Rdst.19:8 = 000h afterwards

Rdst.7 = 1: Rdst.19:8 = FFFh afterwards

Other modes: the sign of the low byte of the operand is extended into the high byte.

dst.7 = 0: high byte = 00h afterwards

dst.7 = 1: high byte = FFh afterwards

Status Bits

N: Set if result is negative, reset otherwise

Z: Set if result is zero, reset otherwise

C: Set if result is not zero, reset otherwise (C = .not.Z)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The signed 8-bit data in EDE (lower 64KB) is sign extended and added to the 16-bit signed data in R7.

```
MOV.B   &EDE,R5      ; EDE -> R5. 00XXh
SXT     R5           ; Sign extend low byte to R5.19:8
ADD     R5,R7        ; Add signed 16-bit values
```

Example The signed 8-bit data in EDE (PC +32 K) is sign extended and added to the 20-bit data in R7.

```
MOV.B   EDE,R5       ; EDE -> R5. 00XXh
SXT     R5           ; Sign extend low byte to R5.19:8
ADDA    R5,R7        ; Add signed 20-bit values
```

4.6.2.50 TST

*** TST[.W]** Test destination

*** TST.B** Test destination

Syntax `TST dst` or `TST.W dst`

`TST.B dst`

Operation dst + 0FFFFh + 1

dst + 0FFh + 1

Emulation `CMP #0,dst`

`CMP.B #0,dst`

Description The destination operand is compared with zero. The status bits are set according to the result. The destination is not affected.

Status Bits N: Set if destination is negative, reset if positive

Z: Set if destination contains zero, reset otherwise

C: Set

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R7 is tested. If it is negative, continue at R7NEG; if it is positive but not zero, continue at R7POS.

```
            TST     R7        ; Test R7
            JN      R7NEG     ; R7 is negative
            JZ      R7ZERO    ; R7 is zero
R7POS       ......            ; R7 is positive but not zero
R7NEG       ......            ; R7 is negative
R7ZERO      ......            ; R7 is zero
```

Example The low byte of R7 is tested. If it is negative, continue at R7NEG; if it is positive but not zero, continue at R7POS.

```
            TST.B   R7        ; Test low byte of R7
            JN      R7NEG     ; Low byte of R7 is negative
            JZ      R7ZERO    ; Low byte of R7 is zero
R7POS       ......            ; Low byte of R7 is positive but not zero
R7NEG       .....             ; Low byte of R7 is negative
R7ZERO      ......            ; Low byte of R7 is zero
```

4.6.2.51 XOR

XOR[.W] Exclusive OR source word with destination word

XOR.B Exclusive OR source byte with destination byte

Syntax `XOR src,dst` or `XOR.W src,dst`

`XOR.B src,dst`

Operation src .xor. dst → dst

Description The source and destination operands are exclusively ORed. The result is placed into the destination. The source operand is not affected. The previous content of the destination is lost.

Status Bits
- N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)
- Z: Set if result is zero, reset otherwise
- C: Set if result is not zero, reset otherwise (C = .not. Z)
- V: Set if both operands are negative before execution, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Toggle bits in word CNTR (16-bit data) with information (bit = 1) in address-word TONI. Both operands are located in lower 64KB.

```
XOR     &TONI,&CNTR     ; Toggle bits in CNTR
```

Example A table word pointed to by R5 (20-bit address) is used to toggle bits in R6. R6.19:16 = 0.

```
XOR     @R5,R6          ; Toggle bits in R6
```

Example Reset to zero those bits in the low byte of R7 that are different from the bits in byte EDE. R7.19:8 = 0. The address of EDE is within PC ± 32 K.

```
XOR.B   EDE,R7          ; Set different bits to 1 in R7.
INV.B   R7              ; Invert low byte of R7, high byte is 0h
```

4.6.3 MSP430X Extended Instructions

The MSP430X extended instructions give the MSP430X CPU full access to its 20-bit address space. MSP430X instructions require an additional word of op-code called the extension word. All addresses, indexes, and immediate numbers have 20-bit values when preceded by the extension word. The MSP430X extended instructions are described in the following sections. For MSP430X instructions that do not require the extension word, it is noted in the instruction description.

See Section 4.6.2 for standard MSP430 instructions and Section 4.6.4 for MSP430X address instructions.

4.6.3.1 ADCX

*** ADCX.A** Add carry to destination address-word

*** ADCX.[W]** Add carry to destination word

*** ADCX.B** Add carry to destination byte

Syntax

```
ADCX.A dst
ADCX dst or          ADCX.W dst
ADCX.B dst
```

Operation dst + C → dst

Emulation

```
ADDCX.A #0,dst
ADDCX #0,dst
ADDCX.B #0,dst
```

Description The carry bit (C) is added to the destination operand. The previous contents of the destination are lost.

Status Bits

N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)

Z: Set if result is zero, reset otherwise

C: Set if there is a carry from the MSB of the result, reset otherwise

V: Set if the result of two positive operands is negative, or if the result of two negative numbers is positive, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 40-bit counter, pointed to by R12 and R13, is incremented.

```
INCX.A   @R12     ; Increment lower 20 bits
ADCX.A   @R13     ; Add carry to upper 20 bits
```

4.6.3.2 ADDX

ADDX.A Add source address-word to destination address-word

ADDX.[W] Add source word to destination word

ADDX.B Add source byte to destination byte

Syntax `ADDX.A src,dst`

`ADDX src,dst` or `ADDX.W src,dst`

`ADDX.B src,dst`

Operation src + dst → dst

Description The source operand is added to the destination operand. The previous contents of the destination are lost. Both operands can be located in the full address space.

Status Bits
- N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)
- Z: Set if result is zero, reset otherwise
- C: Set if there is a carry from the MSB of the result, reset otherwise
- V: Set if the result of two positive operands is negative, or if the result of two negative numbers is positive, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Ten is added to the 20-bit pointer CNTR located in two words CNTR (LSBs) and CNTR+2 (MSBs).

```
ADDX.A   #10,CNTR    ; Add 10 to 20-bit pointer
```

Example A table word (16-bit) pointed to by R5 (20-bit address) is added to R6. The jump to label TONI is performed on a carry.

```
ADDX.W   @R5,R6      ; Add table word to R6
JC       TONI        ; Jump if carry
...                  ; No carry
```

Example A table byte pointed to by R5 (20-bit address) is added to R6. The jump to label TONI is performed if no carry occurs. The table pointer is auto-incremented by 1.

```
ADDX.B   @R5+,R6     ; Add table byte to R6. R5 + 1. R6: 000xxh
JNC      TONI        ; Jump if no carry
...                  ; Carry occurred
```

Note: Use ADDA for the following two cases for better code density and execution.

```
ADDX.A   Rsrc,Rdst
ADDX.A   #imm20,Rdst
```

4.6.3.3 ADDCX

ADDCX.A Add source address-word and carry to destination address-word

ADDCX.[W] Add source word and carry to destination word

ADDCX.B Add source byte and carry to destination byte

Syntax

`ADDCX.A src,dst`

`ADDCX src,dst` or `ADDCX.W src,dst`

`ADDCX.B src,dst`

Operation src + dst + C → dst

Description The source operand and the carry bit C are added to the destination operand. The previous contents of the destination are lost. Both operands may be located in the full address space.

Status Bits

N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)

Z: Set if result is zero, reset otherwise

C: Set if there is a carry from the MSB of the result, reset otherwise

V: Set if the result of two positive operands is negative, or if the result of two negative numbers is positive, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Constant 15 and the carry of the previous instruction are added to the 20-bit counter CNTR located in two words.

```
ADDCX.A   #15,&CNTR   ; Add 15 + C to 20-bit CNTR
```

Example A table word pointed to by R5 (20-bit address) and the carry C are added to R6. The jump to label TONI is performed on a carry.

```
ADDCX.W   @R5,R6      ; Add table word + C to R6
JC        TONI        ; Jump if carry
...                   ; No carry
```

Example A table byte pointed to by R5 (20-bit address) and the carry bit C are added to R6. The jump to label TONI is performed if no carry occurs. The table pointer is auto-incremented by 1.

```
ADDCX.B   @R5+,R6     ; Add table byte + C to R6. R5 + 1
JNC       TONI        ; Jump if no carry
...                   ; Carry occurred
```

4.6.3.4 ANDX

ANDX.A Logical AND of source address-word with destination address-word

ANDX.[W] Logical AND of source word with destination word

ANDX.B Logical AND of source byte with destination byte

Syntax

```
ANDX.A src,dst
ANDX src,dst or ANDX.W src,dst
ANDX.B src,dst
```

Operation src .and. dst → dst

Description The source operand and the destination operand are logically ANDed. The result is placed into the destination. The source operand is not affected. Both operands may be located in the full address space.

Status Bits

N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)

Z: Set if result is zero, reset otherwise

C: Set if the result is not zero, reset otherwise. C = (.not. Z)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The bits set in R5 (20-bit data) are used as a mask (AAA55h) for the address-word TOM located in two words. If the result is zero, a branch is taken to label TONI.

```
MOVA    #AAA55h,R5      ; Load 20-bit mask to R5
ANDX.A  R5,TOM          ; TOM .and. R5 -> TOM
JZ      TONI            ; Jump if result 0
...                     ; Result > 0
```

or shorter:

```
ANDX.A  #AAA55h,TOM     ; TOM .and. AAA55h -> TOM
JZ      TONI            ; Jump if result 0
```

Example A table byte pointed to by R5 (20-bit address) is logically ANDed with R6. R6.19:8 = 0. The table pointer is auto-incremented by 1.

```
ANDX.B  @R5+,R6         ; AND table byte with R6. R5 + 1
```

4.6.3.5 BICX

BICX.A Clear bits set in source address-word in destination address-word

BICX.[W] Clear bits set in source word in destination word

BICX.B Clear bits set in source byte in destination byte

Syntax

```
BICX.A src,dst
BICX src,dst or BICX.W src,dst
BICX.B src,dst
```

Operation (.not. src) .and. dst → dst

Description The inverted source operand and the destination operand are logically ANDed. The result is placed into the destination. The source operand is not affected. Both operands may be located in the full address space.

Status Bits

N: Not affected

Z: Not affected

C: Not affected

V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The bits 19:15 of R5 (20-bit data) are cleared.

```
BICX.A   #0F8000h,R5     ; Clear R5.19:15 bits
```

Example A table word pointed to by R5 (20-bit address) is used to clear bits in R7. R7.19:16 = 0.

```
BICX.W   @R5,R7          ; Clear bits in R7
```

Example A table byte pointed to by R5 (20-bit address) is used to clear bits in output Port1.

```
BICX.B   @R5,&P1OUT      ; Clear I/O port P1 bits
```

4.6.3.6 BISX

BISX.A Set bits set in source address-word in destination address-word

BISX.[W] Set bits set in source word in destination word

BISX.B Set bits set in source byte in destination byte

Syntax
```
BISX.A src,dst
BISX src,dst or BISX.W src,dst
BISX.B src,dst
```

Operation src .or. dst → dst

Description The source operand and the destination operand are logically ORed. The result is placed into the destination. The source operand is not affected. Both operands may be located in the full address space.

Status Bits
N: Not affected
Z: Not affected
C: Not affected
V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Bits 16 and 15 of R5 (20-bit data) are set to one.

```
BISX.A   #018000h,R5   ; Set R5.16:15 bits
```

Example A table word pointed to by R5 (20-bit address) is used to set bits in R7.

```
BISX.W   @R5,R7        ; Set bits in R7
```

Example A table byte pointed to by R5 (20-bit address) is used to set bits in output Port1.

```
BISX.B   @R5,&P1OUT    ; Set I/O port P1 bits
```

4.6.3.7 BITX

BITX.A Test bits set in source address-word in destination address-word

BITX.[W] Test bits set in source word in destination word

BITX.B Test bits set in source byte in destination byte

Syntax `BITX.A src,dst`

`BITX src,dst` or `BITX.W src,dst`

`BITX.B src,dst`

Operation src .and. dst → dst

Description The source operand and the destination operand are logically ANDed. The result affects only the status bits. Both operands may be located in the full address space.

Status Bits
- N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)
- Z: Set if result is zero, reset otherwise
- C: Set if the result is not zero, reset otherwise. C = (.not. Z)
- V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Test if bit 16 or 15 of R5 (20-bit data) is set. Jump to label TONI if so.

```
BITX.A   #018000h,R5   ; Test R5.16:15 bits
JNZ      TONI          ; At least one bit is set
...                    ; Both are reset
```

Example A table word pointed to by R5 (20-bit address) is used to test bits in R7. Jump to label TONI if at least one bit is set.

```
BITX.W   @R5,R7        ; Test bits in R7: C = .not.Z
JC       TONI          ; At least one is set
...                    ; Both are reset
```

Example A table byte pointed to by R5 (20-bit address) is used to test bits in input Port1. Jump to label TONI if no bit is set. The next table byte is addressed.

```
BITX.B   @R5+,&P1IN    ; Test input P1 bits. R5 + 1
JNC      TONI          ; No corresponding input bit is set
...                    ; At least one bit is set
```

4.6.3.8 CLRX

*** CLRX.A** Clear destination address-word
*** CLRX.[W]** Clear destination word
*** CLRX.B** Clear destination byte

Syntax
```
CLRX.A dst
CLRX dst or          CLRX.W dst
CLRX.B dst
```

Operation 0 → dst

Emulation
```
MOVX.A #0,dst
MOVX #0,dst
MOVX.B #0,dst
```

Description The destination operand is cleared.

Status Bits Status bits are not affected.

Example RAM address-word TONI is cleared.

```
CLRX.A   TONI   ; 0 -> TONI
```

4.6.3.9 CMPX

CMPX.A Compare source address-word and destination address-word

CMPX.[W] Compare source word and destination word

CMPX.B Compare source byte and destination byte

Syntax `CMPX.A src,dst`

`CMPX src,dst` or `CMPX.W src,dst`

`CMPX.B src,dst`

Operation (.not. src) + 1 + dst or dst – src

Description The source operand is subtracted from the destination operand by adding the 1s complement of the source + 1 to the destination. The result affects only the status bits. Both operands may be located in the full address space.

Status Bits

N: Set if result is negative (src > dst), reset if positive (src ≤ dst)

Z: Set if result is zero (src = dst), reset otherwise (src ≠ dst)

C: Set if there is a carry from the MSB, reset otherwise

V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow)

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Compare EDE with a 20-bit constant 18000h. Jump to label TONI if EDE equals the constant.

```
CMPX.A   #018000h,EDE     ; Compare EDE with 18000h
JEQ      TONI             ; EDE contains 18000h
...                       ; Not equal
```

Example A table word pointed to by R5 (20-bit address) is compared with R7. Jump to label TONI if R7 contains a lower, signed, 16-bit number.

```
CMPX.W   @R5,R7           ; Compare two signed numbers
JL       TONI             ; R7 < @R5
...                       ; R7 >= @R5
```

Example A table byte pointed to by R5 (20-bit address) is compared to the input in I/O Port1. Jump to label TONI if the values are equal. The next table byte is addressed.

```
CMPX.B   @R5+,&P1IN       ; Compare P1 bits with table. R5 + 1
JEQ      TONI             ; Equal contents
...                       ; Not equal
```

Note: Use CMPA for the following two cases for better density and execution.

```
CMPA     Rsrc,Rdst
CMPA     #imm20,Rdst
```

4.6.3.10 DADCX

*** DADCX.A** Add carry decimally to destination address-word

*** DADCX.[W]** Add carry decimally to destination word

*** DADCX.B** Add carry decimally to destination byte

Syntax

```
DADCX.A dst
DADCX dst or          DADCX.W dst
DADCX.B dst
```

Operation dst + C → dst (decimally)

Emulation

```
DADDX.A #0,dst
DADDX #0,dst
DADDX.B #0,dst
```

Description The carry bit (C) is added decimally to the destination.

Status Bits

- N: Set if MSB of result is 1 (address-word > 79999h, word > 7999h, byte > 79h), reset if MSB is 0
- Z: Set if result is zero, reset otherwise
- C: Set if the BCD result is too large (address-word > 99999h, word > 9999h, byte > 99h), reset otherwise
- V: Undefined

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 40-bit counter, pointed to by R12 and R13, is incremented decimally.

```
DADDX.A   #1,0(R12)     ; Increment lower 20 bits
DADCX.A   0(R13)        ; Add carry to upper 20 bits
```

4.6.3.11 DADDX

DADDX.A Add source address-word and carry decimally to destination address-word

DADDX.[W] Add source word and carry decimally to destination word

DADDX.B Add source byte and carry decimally to destination byte

Syntax

```
DADDX.A src,dst
DADDX src,dst or DADDX.W src,dst
DADDX.B src,dst
```

Operation src + dst + C → dst (decimally)

Description The source operand and the destination operand are treated as two (.B), four (.W), or five (.A) binary coded decimals (BCD) with positive signs. The source operand and the carry bit C are added decimally to the destination operand. The source operand is not affected. The previous contents of the destination are lost. The result is not defined for non-BCD numbers. Both operands may be located in the full address space.

Status Bits

N: Set if MSB of result is 1 (address-word > 79999h, word > 7999h, byte > 79h), reset if MSB is 0.

Z: Set if result is zero, reset otherwise

C: Set if the BCD result is too large (address-word > 99999h, word > 9999h, byte > 99h), reset otherwise

V: Undefined

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Decimal 10 is added to the 20-bit BCD counter DECCNTR located in two words.

```
DADDX.A   #10h,&DECCNTR     ; Add 10 to 20-bit BCD counter
```

Example The eight-digit BCD number contained in 20-bit addresses BCD and BCD+2 is added decimally to an eight-digit BCD number contained in R4 and R5 (BCD+2 and R5 contain the MSDs).

```
CLRC                        ; Clear carry
DADDX.W   BCD,R4            ; Add LSDs
DADDX.W   BCD+2,R5          ; Add MSDs with carry
JC        OVERFLOW          ; Result >99999999: go to error routine
...                         ;    Result ok
```

Example The two-digit BCD number contained in 20-bit address BCD is added decimally to a two-digit BCD number contained in R4.

```
CLRC                        ; Clear carry
DADDX.B   BCD,R4            ; Add BCD to R4 decimally.
                            ; R4: 000ddh
```

4.6.3.12 DECX

*** DECX.A** Decrement destination address-word

*** DECX.[W]** Decrement destination word

*** DECX.B** Decrement destination byte

Syntax
```
DECX.A dst
DECX dst or          DECX.W dst
DECX.B dst
```

Operation dst – 1 → dst

Emulation
```
SUBX.A #1,dst
SUBX #1,dst
SUBX.B #1,dst
```

Description The destination operand is decremented by one. The original contents are lost.

Status Bits
- N: Set if result is negative, reset if positive
- Z: Set if dst contained 1, reset otherwise
- C: Reset if dst contained 0, set otherwise
- V: Set if an arithmetic overflow occurs, otherwise reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example RAM address-word TONI is decremented by one.

```
DECX.A   TONI     ; Decrement TONI
```

4.6.3.13 DECDX

*** DECDX.A** Double-decrement destination address-word
*** DECDX.[W]** Double-decrement destination word
*** DECDX.B** Double-decrement destination byte

Syntax
```
DECDX.A dst
DECDX dst or          DECDX.W dst
DECDX.B dst
```

Operation dst – 2 → dst

Emulation
```
SUBX.A #2,dst
SUBX #2,dst
SUBX.B #2,dst
```

Description The destination operand is decremented by two. The original contents are lost.

Status Bits
N: Set if result is negative, reset if positive
Z: Set if dst contained 2, reset otherwise
C: Reset if dst contained 0 or 1, set otherwise
V: Set if an arithmetic overflow occurs, otherwise reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example RAM address-word TONI is decremented by two.

```
DECDX.A   TONI     ; Decrement TONI
```

4.6.3.14 INCX

*** INCX.A** Increment destination address-word
*** INCX.[W]** Increment destination word
*** INCX.B** Increment destination byte

Syntax
```
INCX.A dst
INCX dst or          INCX.W dst
INCX.B dst
```

Operation dst + 1 → dst

Emulation
```
ADDX.A #1,dst
ADDX #1,dst
ADDX.B #1,dst
```

Description The destination operand is incremented by one. The original contents are lost.

Status Bits
N: Set if result is negative, reset if positive
Z: Set if dst contained 0FFFFFh, reset otherwise
Set if dst contained 0FFFFh, reset otherwise
Set if dst contained 0FFh, reset otherwise
C: Set if dst contained 0FFFFFh, reset otherwise
Set if dst contained 0FFFFh, reset otherwise
Set if dst contained 0FFh, reset otherwise
V: Set if dst contained 07FFFh, reset otherwise
Set if dst contained 07FFFh, reset otherwise
Set if dst contained 07Fh, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example RAM address-word TONI is incremented by one.

```
INCX.A   TONI     ; Increment TONI (20-bits)
```

4.6.3.15 INCDX

*** INCDX.A** Double-increment destination address-word
*** INCDX.[W]** Double-increment destination word
*** INCDX.B** Double-increment destination byte

Syntax
```
INCDX.A dst
INCDX dst or          INCDX.W dst
INCDX.B dst
```

Operation dst + 2 → dst

Emulation
```
ADDX.A #2,dst
ADDX #2,dst
ADDX.B #2,dst
```

Description The destination operand is incremented by two. The original contents are lost.

Status Bits
N: Set if result is negative, reset if positive
Z: Set if dst contained 0FFFFEh, reset otherwise
Set if dst contained 0FFFEh, reset otherwise
Set if dst contained 0FEh, reset otherwise
C: Set if dst contained 0FFFFEh or 0FFFFFh, reset otherwise
Set if dst contained 0FFFEh or 0FFFFh, reset otherwise
Set if dst contained 0FEh or 0FFh, reset otherwise
V: Set if dst contained 07FFFEh or 07FFFFh, reset otherwise
Set if dst contained 07FFEh or 07FFFh, reset otherwise
Set if dst contained 07Eh or 07Fh, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example RAM byte LEO is incremented by two; PC points to upper memory.

```
INCDX.B   LEO     ; Increment LEO by two
```

4.6.3.16 INVX

*** INVX.A** Invert destination
*** INVX.[W]** Invert destination
*** INVX.B** Invert destination

Syntax
```
INVX.A dst
INVX dst or          INVX.W dst
INVX.B dst
```

Operation .NOT.dst → dst

Emulation
```
XORX.A #0FFFFFh,dst
XORX #0FFFFh,dst
XORX.B #0FFh,dst
```

Description The destination operand is inverted. The original contents are lost.

Status Bits
N: Set if result is negative, reset if positive
Z: Set if dst contained 0FFFFFh, reset otherwise
Set if dst contained 0FFFFh, reset otherwise
Set if dst contained 0FFh, reset otherwise
C: Set if result is not zero, reset otherwise (= .NOT. Zero)
V: Set if initial destination operand was negative, otherwise reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example 20-bit content of R5 is negated (2s complement).

```
INVX.A   R5      ; Invert R5
INCX.A   R5      ; R5 is now negated
```

Example Content of memory byte LEO is negated. PC is pointing to upper memory.

```
INVX.B   LEO     ; Invert LEO
INCX.B   LEO     ; MEM(LEO) is negated
```

4.6.3.17 MOVX

MOVX.A Move source address-word to destination address-word

MOVX.[W] Move source word to destination word

MOVX.B Move source byte to destination byte

Syntax `MOVX.A src,dst`

`MOVX src,dst` or `MOVX.W src,dst`

`MOVX.B src,dst`

Operation src → dst

Description The source operand is copied to the destination. The source operand is not affected. Both operands may be located in the full address space.

Status Bits
N: Not affected
Z: Not affected
C: Not affected
V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Move a 20-bit constant 18000h to absolute address-word EDE

```
MOVX.A   #018000h,&EDE          ; Move 18000h to EDE
```

Example The contents of table EDE (word data, 20-bit addresses) are copied to table TOM. The length of the table is 030h words.

```
       MOVA     #EDE,R10               ; Prepare pointer (20-bit address)
Loop   MOVX.W   @R10+,TOM-EDE-2(R10)   ; R10 points to both tables.
                                       ; R10+2
       CMPA     #EDE+60h,R10           ; End of table reached?
       JLO      Loop                   ; Not yet
       ...                             ; Copy completed
```

Example The contents of table EDE (byte data, 20-bit addresses) are copied to table TOM. The length of the table is 020h bytes.

```
       MOVA     #EDE,R10               ; Prepare pointer (20-bit)
       MOV      #20h,R9                ; Prepare counter
Loop   MOVX.W   @R10+,TOM-EDE-2(R10)   ; R10 points to both tables.
                                       ; R10+1
       DEC      R9                     ; Decrement counter
       JNZ      Loop                   ; Not yet done
       ...                             ; Copy completed
```

Ten of the 28 possible addressing combinations of the MOVX.A instruction can use the MOVA instruction. This saves two bytes and code cycles. Examples for the addressing combinations are:

```
MOVX.A   Rsrc,Rdst          MOVA   Rsrc,Rdst        ; Reg/Reg
MOVX.A   #imm20,Rdst        MOVA   #imm20,Rdst      ; Immediate/Reg
MOVX.A   &abs20,Rdst        MOVA   &abs20,Rdst      ; Absolute/Reg
MOVX.A   @Rsrc,Rdst         MOVA   @Rsrc,Rdst       ; Indirect/Reg
MOVX.A   @Rsrc+,Rdst        MOVA   @Rsrc+,Rdst      ; Indirect,Auto/Reg
MOVX.A   Rsrc,&abs20        MOVA   Rsrc,&abs20      ; Reg/Absolute
```

The next four replacements are possible only if 16-bit indexes are sufficient for the addressing:

```
MOVX.A   z20(Rsrc),Rdst     MOVA   z16(Rsrc),Rdst   ; Indexed/Reg
MOVX.A   Rsrc,z20(Rdst)     MOVA   Rsrc,z16(Rdst)   ; Reg/Indexed
MOVX.A   symb20,Rdst        MOVA   symb16,Rdst      ; Symbolic/Reg
MOVX.A   Rsrc,symb20        MOVA   Rsrc,symb16      ; Reg/Symbolic
```

4.6.3.18 POPM

POPM.A Restore n CPU registers (20-bit data) from the stack

POPM.[W] Restore n CPU registers (16-bit data) from the stack

Syntax

`POPM.A #n,Rdst` 1 ≤ n ≤ 16

`POPM.W #n,Rdst` or `POPM #n,Rdst` 1 ≤ n ≤ 16

Operation POPM.A: Restore the register values from stack to the specified CPU registers. The SP is incremented by four for each register restored from stack. The 20-bit values from stack (two words per register) are restored to the registers.

POPM.W: Restore the 16-bit register values from stack to the specified CPU registers. The SP is incremented by two for each register restored from stack. The 16-bit values from stack (one word per register) are restored to the CPU registers.

Note : This instruction does not use the extension word.

Description POPM.A: The CPU registers pushed on the stack are moved to the extended CPU registers, starting with the CPU register (Rdst – n + 1). The SP is incremented by (n × 4) after the operation.

POPM.W: The 16-bit registers pushed on the stack are moved back to the CPU registers, starting with CPU register (Rdst – n + 1). The SP is incremented by (n × 2) after the instruction. The MSBs (Rdst.19:16) of the restored CPU registers are cleared.

Status Bits Status bits are not affected, except SR is included in the operation.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Restore the 20-bit registers R9, R10, R11, R12, R13 from the stack

```
POPM.A   #5,R13     ; Restore R9, R10, R11, R12, R13
```

Example Restore the 16-bit registers R9, R10, R11, R12, R13 from the stack.

```
POPM.W   #5,R13     ; Restore R9, R10, R11, R12, R13
```

4.6.3.19 PUSHM

PUSHM.A Save n CPU registers (20-bit data) on the stack

PUSHM.[W] Save n CPU registers (16-bit words) on the stack

Syntax

`PUSHM.A #n,Rdst` 1 ≤ n ≤ 16

`PUSHM.W #n,Rdst` or `PUSHM #n,Rdst` 1 ≤ n ≤ 16

Operation PUSHM.A: Save the 20-bit CPU register values on the stack. The SP is decremented by four for each register stored on the stack. The MSBs are stored first (higher address).

PUSHM.W: Save the 16-bit CPU register values on the stack. The SP is decremented by two for each register stored on the stack.

Description PUSHM.A: The n CPU registers, starting with Rdst backwards, are stored on the stack. The SP is decremented by (n × 4) after the operation. The data (Rn.19:0) of the pushed CPU registers is not affected.

PUSHM.W: The n registers, starting with Rdst backwards, are stored on the stack. The SP is decremented by (n × 2) after the operation. The data (Rn.19:0) of the pushed CPU registers is not affected.

Note : This instruction does not use the extension word.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Save the five 20-bit registers R9, R10, R11, R12, R13 on the stack

```
PUSHM.A   #5,R13     ; Save R13, R12, R11, R10, R9
```

Example Save the five 16-bit registers R9, R10, R11, R12, R13 on the stack

```
PUSHM.W   #5,R13     ; Save R13, R12, R11, R10, R9
```

4.6.3.20 POPX

*** POPX.A**	Restore single address-word from the stack
*** POPX.[W]**	Restore single word from the stack
*** POPX.B**	Restore single byte from the stack

Syntax	`POPX.A dst`
	`POPX dst` or `POPX.W dst`
	`POPX.B dst`

Operation	Restore the 8-/16-/20-bit value from the stack to the destination. 20-bit addresses are possible. The SP is incremented by two (byte and word operands) and by four (address-word operand).
Emulation	`MOVX(.B,.A) @SP+,dst`
Description	The item on TOS is written to the destination operand. Register mode, Indexed mode, Symbolic mode, and Absolute mode are possible. The SP is incremented by two or four. Note: The SP is incremented by two also for byte operations.
Status Bits	Status bits are not affected.
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	Write the 16-bit value on TOS to the 20-bit address &EDE

```
POPX.W   &EDE   ; Write word to address EDE
```

Example Write the 20-bit value on TOS to R9

```
POPX.A   R9     ; Write address-word to R9
```

4.6.3.21 PUSHX

PUSHX.A Save single address-word to the stack

PUSHX.[W] Save single word to the stack

PUSHX.B Save single byte to the stack

Syntax

```
PUSHX.A src
PUSHX src or          PUSHX.W src
PUSHX.B src
```

Operation Save the 8-/16-/20-bit value of the source operand on the TOS. 20-bit addresses are possible. The SP is decremented by two (byte and word operands) or by four (address-word operand) before the write operation.

Description The SP is decremented by two (byte and word operands) or by four (address-word operand). Then the source operand is written to the TOS. All seven addressing modes are possible for the source operand.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Save the byte at the 20-bit address &EDE on the stack

```
PUSHX.B   &EDE     ; Save byte at address EDE
```

Example Save the 20-bit value in R9 on the stack.

```
PUSHX.A   R9       ; Save address-word in R9
```

4.6.3.22 RLAM

RLAM.A Rotate left arithmetically the 20-bit CPU register content

RLAM.[W] Rotate left arithmetically the 16-bit CPU register content

Syntax

`RLAM.A #n,Rdst` 1 ≤ n ≤ 4

`RLAM.W #n,Rdst` or `RLAM #n,Rdst` 1 ≤ n ≤ 4

Operation C ← MSB ← MSB-1 .... LSB+1 ← LSB ← 0

Description The destination operand is shifted arithmetically left one, two, three, or four positions as shown in Figure 4-43. RLAM works as a multiplication (signed and unsigned) with 2, 4, 8, or 16. The word instruction RLAM.W clears the bits Rdst.19:16.

Note : This instruction does not use the extension word.

Status Bits

N: Set if result is negative
.A: Rdst.19 = 1, reset if Rdst.19 = 0
.W: Rdst.15 = 1, reset if Rdst.15 = 0

Z: Set if result is zero, reset otherwise

C: Loaded from the MSB (n = 1), MSB-1 (n = 2), MSB-2 (n = 3), MSB-3 (n = 4)

V: Undefined

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 20-bit operand in R5 is shifted left by three positions. It operates equal to an arithmetic multiplication by 8.

```
RLAM.A   #3,R5      ; R5 = R5 x 8
```

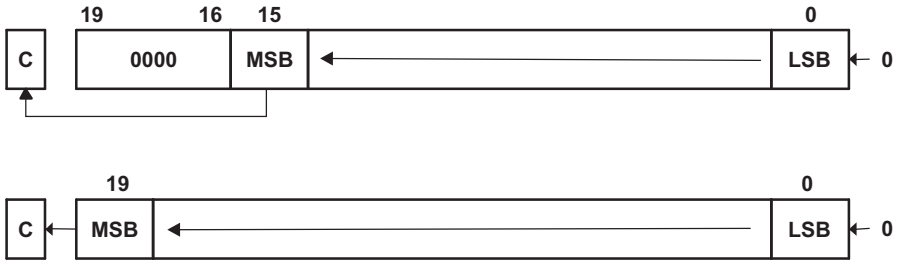


Figure 4-43. Rotate Left Arithmetically—RLAM[.W] and RLAM.A

4.6.3.23 RLAX

*** RLAX.A** Rotate left arithmetically address-word

*** RLAX.[W]** Rotate left arithmetically word

*** RLAX.B** Rotate left arithmetically byte

Syntax

```
RLAX.A dst
RLAX dst or          RLAX.W dst
RLAX.B dst
```

Operation C ← MSB ← MSB-1 .... LSB+1 ← LSB ← 0

Emulation

```
ADDX.A dst,dst
ADDX dst,dst
ADDX.B dst,dst
```

Description The destination operand is shifted left one position as shown in Figure 4-44. The MSB is shifted into the carry bit (C) and the LSB is filled with 0. The RLAX instruction acts as a signed multiplication by 2.

Status Bits

N: Set if result is negative, reset if positive

Z: Set if result is zero, reset otherwise

C: Loaded from the MSB

V: Set if an arithmetic overflow occurs: the initial value is 040000h ≤ dst < 0C0000h; reset otherwise

Set if an arithmetic overflow occurs: the initial value is 04000h ≤ dst < 0C000h; reset otherwise

Set if an arithmetic overflow occurs: the initial value is 040h ≤ dst < 0C0h; reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 20-bit value in R7 is multiplied by 2

```
RLAX.A   R7     ; Shift left R7 (20-bit)
```

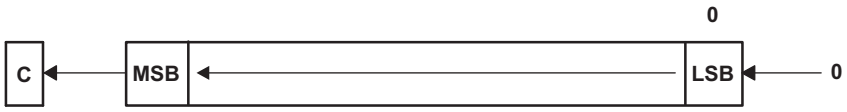


Figure 4-44. Destination Operand-Arithmetic Shift Left

4.6.3.24 RLCX

*** RLCX.A** Rotate left through carry address-word

*** RLCX.[W]** Rotate left through carry word

*** RLCX.B** Rotate left through carry byte

Syntax

```
RLCX.A dst
RLCX dst or          RLCX.W dst
RLCX.B dst
```

Operation C ← MSB ← MSB-1 .... LSB+1 ← LSB ← C

Emulation

```
ADDCX.A dst,dst
ADDCX dst,dst
ADDCX.B dst,dst
```

Description The destination operand is shifted left one position as shown in Figure 4-45. The carry bit (C) is shifted into the LSB and the MSB is shifted into the carry bit (C).

Status Bits

N: Set if result is negative, reset if positive

Z: Set if result is zero, reset otherwise

C: Loaded from the MSB

V: Set if an arithmetic overflow occurs: the initial value is 040000h ≤ dst < 0C0000h; reset otherwise

Set if an arithmetic overflow occurs: the initial value is 04000h ≤ dst < 0C000h; reset otherwise

Set if an arithmetic overflow occurs: the initial value is 040h ≤ dst < 0C0h; reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 20-bit value in R5 is shifted left one position.

```
RLCX.A   R5     ; (R5 x 2) + C -> R5
```

Example The RAM byte LEO is shifted left one position. PC is pointing to upper memory.

```
RLCX.B   LEO    ; RAM(LEO) x 2 + C -> RAM(LEO)
```

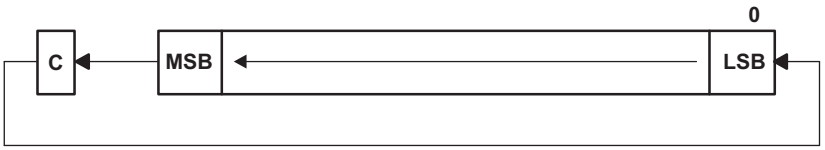


Figure 4-45. Destination Operand-Carry Left Shift

4.6.3.25 RRAM

RRAM.A Rotate right arithmetically the 20-bit CPU register content

RRAM.[W] Rotate right arithmetically the 16-bit CPU register content

Syntax

`RRAM.A #n,Rdst` 1 ≤ n ≤ 4

`RRAM.W #n,Rdst` or `RRAM #n,Rdst` 1 ≤ n ≤ 4

Operation MSB → MSB → MSB–1 ... LSB+1 → LSB → C

Description The destination operand is shifted right arithmetically by one, two, three, or four bit positions as shown in Figure 4-46. The MSB retains its value (sign). RRAM operates equal to a signed division by 2/4/8/16. The MSB is retained and shifted into MSB-1. The LSB+1 is shifted into the LSB, and the LSB is shifted into the carry bit C. The word instruction RRAM.W clears the bits Rdst.19:16.

Note : This instruction does not use the extension word.

Status Bits

N: Set if result is negative
.A: Rdst.19 = 1, reset if Rdst.19 = 0
.W: Rdst.15 = 1, reset if Rdst.15 = 0

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB (n = 1), LSB+1 (n = 2), LSB+2 (n = 3), or LSB+3 (n = 4)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The signed 20-bit number in R5 is shifted arithmetically right two positions.

```
RRAM.A   #2,R5          ; R5/4 -> R5
```

Example The signed 20-bit value in R15 is multiplied by 0.75. (0.5 + 0.25) × R15.

```
PUSHM.A   #1,R15        ; Save extended R15 on stack
RRAM.A    #1,R15        ; R15 y 0.5 -> R15
ADDX.A    @SP+,R15      ; R15 y 0.5 + R15 = 1.5 y R15 -> R15
RRAM.A    #1,R15        ; (1.5 y R15) y 0.5 = 0.75 y R15 -> R15
```

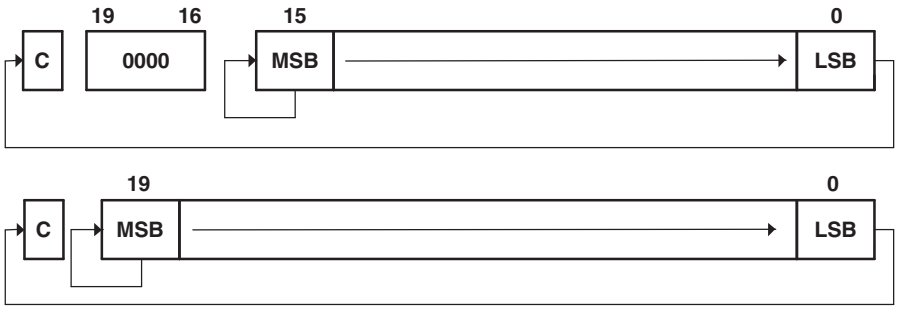


Figure 4-46. Rotate Right Arithmetically RRAM[.W] and RRAM.A

4.6.3.26 RRAX

RRAX.A Rotate right arithmetically the 20-bit operand

RRAX.[W] Rotate right arithmetically the 16-bit operand

RRAX.B Rotate right arithmetically the 8-bit operand

Syntax

```
RRAX.A Rdst
RRAX.W Rdst
RRAX Rdst
RRAX.B Rdst
RRAX.A dst
RRAX dst or          RRAX.W dst
RRAX.B dst
```

Operation MSB → MSB → MSB–1 ... LSB+1 → LSB → C

Description Register mode for the destination: the destination operand is shifted right by one bit position as shown in Figure 4-47. The MSB retains its value (sign). The word instruction RRAX.W clears the bits Rdst.19:16, the byte instruction RRAX.B clears the bits Rdst.19:8. The MSB retains its value (sign), the LSB is shifted into the carry bit. RRAX here operates equal to a signed division by 2.

All other modes for the destination: the destination operand is shifted right arithmetically by one bit position as shown in Figure 4-48. The MSB retains its value (sign), the LSB is shifted into the carry bit. RRAX here operates equal to a signed division by 2. All addressing modes, with the exception of the Immediate mode, are possible in the full memory.

Status Bits

N: Set if result is negative, reset if positive
- .A: dst.19 = 1, reset if dst.19 = 0
- .W: dst.15 = 1, reset if dst.15 = 0
- .B: dst.7 = 1, reset if dst.7 = 0

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The signed 20-bit number in R5 is shifted arithmetically right four positions.

```
RPT      #4
RRAX.A   R5        ; R5/16 -> R5
```

Example The signed 8-bit value in EDE is multiplied by 0.5.

```
RRAX.B   &EDE       ; EDE/2 -> EDE
```

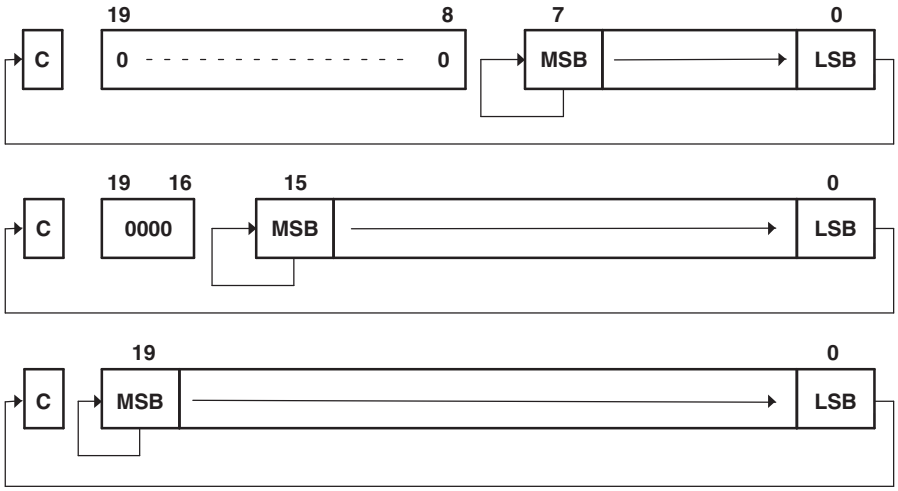


Figure 4-47. Rotate Right Arithmetically RRAX(.B,.A) – Register Mode

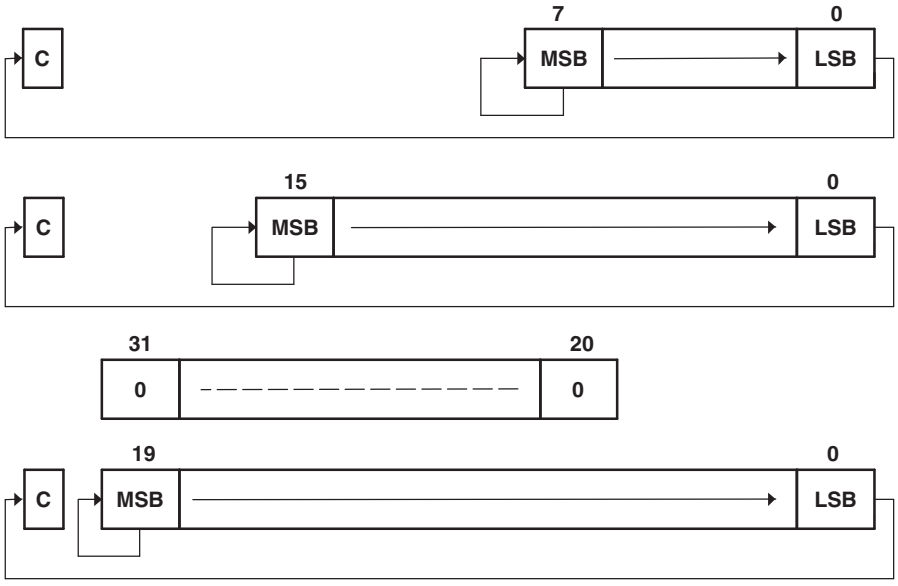


Figure 4-48. Rotate Right Arithmetically RRAX(.B,.A) – Non-Register Mode

4.6.3.27 RRCM

RRCM.A Rotate right through carry the 20-bit CPU register content

RRCM.[W] Rotate right through carry the 16-bit CPU register content

Syntax

`RRCM.A #n,Rdst` 1 ≤ n ≤ 4

`RRCM.W #n,Rdst` or `RRCM #n,Rdst` 1 ≤ n ≤ 4

Operation C → MSB → MSB–1 ... LSB+1 → LSB → C

Description The destination operand is shifted right by one, two, three, or four bit positions as shown in Figure 4-49. The carry bit C is shifted into the MSB, the LSB is shifted into the carry bit. The word instruction RRCM.W clears the bits Rdst.19:16.

Note : This instruction does not use the extension word.

Status Bits

N: Set if result is negative
.A: Rdst.19 = 1, reset if Rdst.19 = 0
.W: Rdst.15 = 1, reset if Rdst.15 = 0

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB (n = 1), LSB+1 (n = 2), LSB+2 (n = 3), or LSB+3 (n = 4)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The address-word in R5 is shifted right by three positions. The MSB–2 is loaded with 1.

```
SETC                ; Prepare carry for MSB-2
RRCM.A   #3,R5      ; R5 = R5 » 3 + 20000h
```

Example The word in R6 is shifted right by two positions. The MSB is loaded with the LSB. The MSB–1 is loaded with the contents of the carry flag.

```
RRCM.W   #2,R6      ; R6 = R6 » 2. R6.19:16 = 0
```

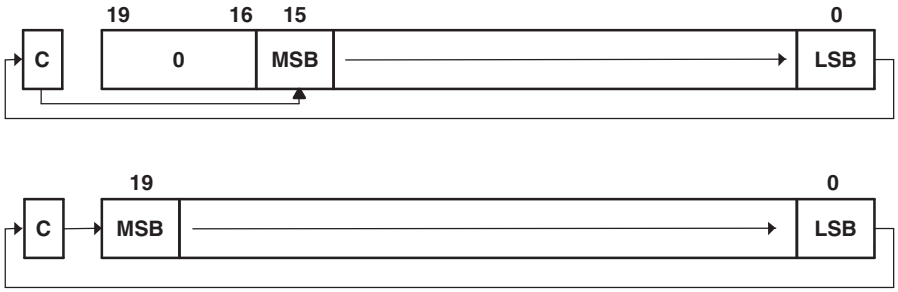


Figure 4-49. Rotate Right Through Carry RRCM[.W] and RRCM.A

4.6.3.28 RRCX

RRCX.A Rotate right through carry the 20-bit operand

RRCX.[W] Rotate right through carry the 16-bit operand

RRCX.B Rotate right through carry the 8-bit operand

Syntax

```
RRCX.A Rdst
RRCX.W Rdst
RRCX Rdst
RRCX.B Rdst
RRCX.A dst
RRCX dst or          RRCX.W dst
RRCX.B dst
```

Operation C → MSB → MSB–1 ... LSB+1 → LSB → C

Description Register mode for the destination: the destination operand is shifted right by one bit position as shown in Figure 4-50. The word instruction RRCX.W clears the bits Rdst.19:16, the byte instruction RRCX.B clears the bits Rdst.19:8. The carry bit C is shifted into the MSB, the LSB is shifted into the carry bit.

All other modes for the destination: the destination operand is shifted right by one bit position as shown in Figure 4-51. The carry bit C is shifted into the MSB, the LSB is shifted into the carry bit. All addressing modes, with the exception of the Immediate mode, are possible in the full memory.

Status Bits

N: Set if result is negative
- .A: dst.19 = 1, reset if dst.19 = 0
- .W: dst.15 = 1, reset if dst.15 = 0
- .B: dst.7 = 1, reset if dst.7 = 0

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 20-bit operand at address EDE is shifted right by one position. The MSB is loaded with 1.

```
SETC              ; Prepare carry for MSB
RRCX.A   EDE      ; EDE = EDE » 1 + 80000h
```

Example The word in R6 is shifted right by 12 positions.

```
RPT      #12
RRCX.W   R6       ; R6 = R6 » 12. R6.19:16 = 0
```

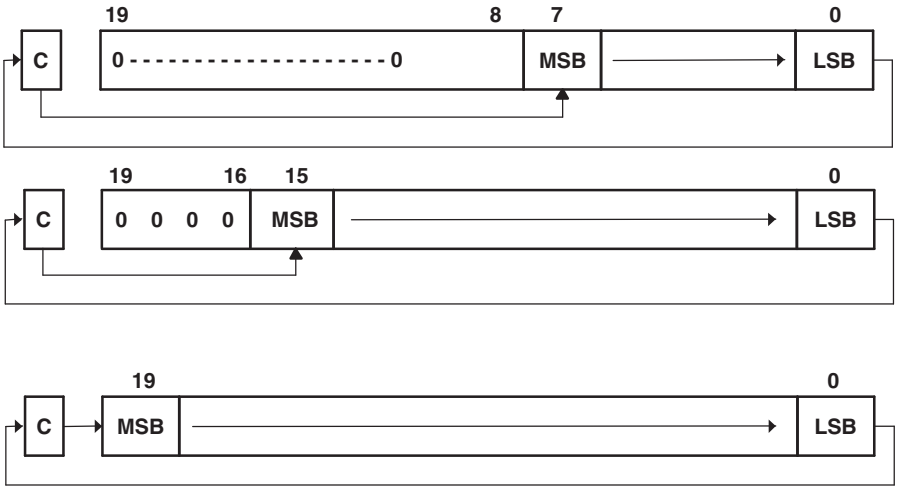


Figure 4-50. Rotate Right Through Carry RRCX(.B,.A) – Register Mode

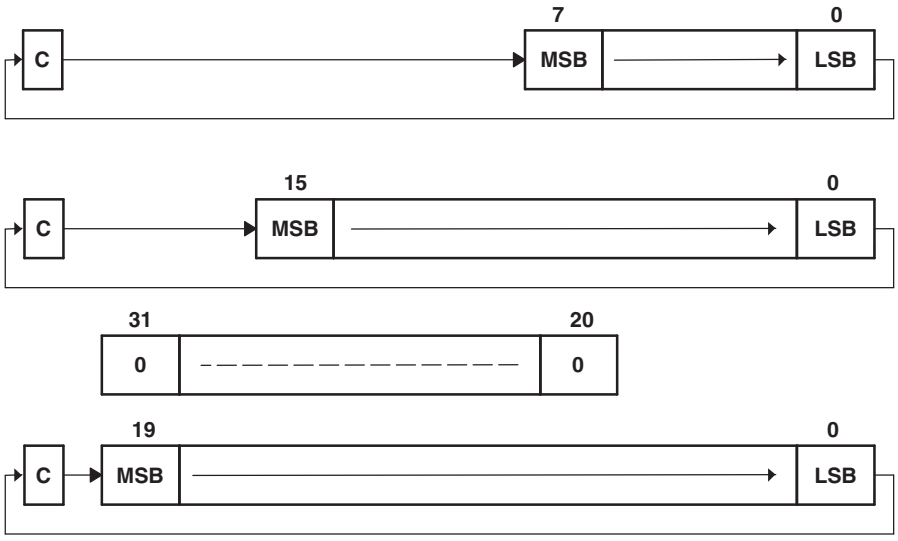


Figure 4-51. Rotate Right Through Carry RRCX(.B,.A) – Non-Register Mode

4.6.3.29 RRUM

RRUM.A Rotate right through carry the 20-bit CPU register content

RRUM.[W] Rotate right through carry the 16-bit CPU register content

Syntax

`RRUM.A #n,Rdst` 1 ≤ n ≤ 4

`RRUM.W #n,Rdst` or `RRUM #n,Rdst` 1 ≤ n ≤ 4

Operation 0 → MSB → MSB–1 ... LSB+1 → LSB → C

Description The destination operand is shifted right by one, two, three, or four bit positions as shown in Figure 4-52. Zero is shifted into the MSB, the LSB is shifted into the carry bit. RRUM works like an unsigned division by 2, 4, 8, or 16. The word instruction RRUM.W clears the bits Rdst.19:16.

Note : This instruction does not use the extension word.

Status Bits

N: Set if result is negative
.A: Rdst.19 = 1, reset if Rdst.19 = 0
.W: Rdst.15 = 1, reset if Rdst.15 = 0

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB (n = 1), LSB+1 (n = 2), LSB+2 (n = 3), or LSB+3 (n = 4)

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The unsigned address-word in R5 is divided by 16.

```
RRUM.A   #4,R5      ; R5 = R5 » 4. R5/16
```

Example The word in R6 is shifted right by one bit. The MSB R6.15 is loaded with 0.

```
RRUM.W   #1,R6      ; R6 = R6/2. R6.19:15 = 0
```

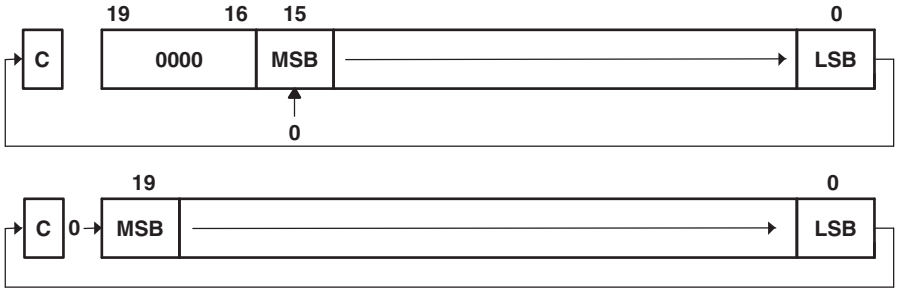


Figure 4-52. Rotate Right Unsigned RRUM[.W] and RRUM.A

4.6.3.30 RRUX

RRUX.A Shift right unsigned the 20-bit CPU register content

RRUX.[W] Shift right unsigned the 16-bit CPU register content

RRUX.B Shift right unsigned the 8-bit CPU register content

Syntax

```
RRUX.A Rdst
RRUX.W Rdst
RRUX Rdst
RRUX.B Rdst
```

Operation C=0 → MSB → MSB–1 ... LSB+1 → LSB → C

Description RRUX is valid for register mode only: the destination operand is shifted right by one bit position as shown in Figure 4-53. The word instruction RRUX.W clears the bits Rdst.19:16. The byte instruction RRUX.B clears the bits Rdst.19:8. Zero is shifted into the MSB, the LSB is shifted into the carry bit.

Status Bits

N: Set if result is negative
- .A: dst.19 = 1, reset if dst.19 = 0
- .W: dst.15 = 1, reset if dst.15 = 0
- .B: dst.7 = 1, reset if dst.7 = 0

Z: Set if result is zero, reset otherwise

C: Loaded from the LSB

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The word in R6 is shifted right by 12 positions.

```
RPT      #12
RRUX.W   R6       ; R6 = R6 » 12. R6.19:16 = 0
```

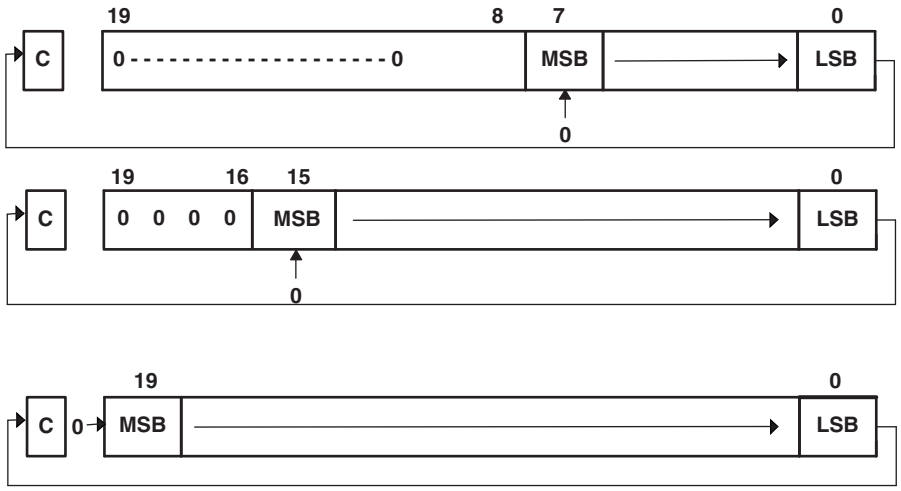


Figure 4-53. Rotate Right Unsigned RRUX(.B,.A) – Register Mode

4.6.3.31 SBCX

*** SBCX.A** Subtract borrow (.NOT. carry) from destination address-word

*** SBCX.[W]** Subtract borrow (.NOT. carry) from destination word

*** SBCX.B** Subtract borrow (.NOT. carry) from destination byte

Syntax
```
SBCX.A dst
SBCX dst or          SBCX.W dst
SBCX.B dst
```

Operation
dst + 0FFFFFh + C → dst
dst + 0FFFFh + C → dst
dst + 0FFh + C → dst

Emulation
```
SBCX.A #0,dst
SBCX #0,dst
SBCX.B #0,dst
```

Description The carry bit (C) is added to the destination operand minus one. The previous contents of the destination are lost.

Status Bits
N: Set if result is negative, reset if positive
Z: Set if result is zero, reset otherwise
C: Set if there is a carry from the MSB of the result, reset otherwise
Set to 1 if no borrow, reset if borrow
V: Set if an arithmetic overflow occurs, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 8-bit counter pointed to by R13 is subtracted from a 16-bit counter pointed to by R12.

```
SUBX.B   @R13,0(R12)      ; Subtract LSDs
SBCX.B   1(R12)           ; Subtract carry from MSD
```

NOTE: Borrow implementation

The borrow is treated as a .NOT. carry:

Borrow	Carry Bit
Yes	0
No	1

4.6.3.32 SUBX

SUBX.A Subtract source address-word from destination address-word

SUBX.[W] Subtract source word from destination word

SUBX.B Subtract source byte from destination byte

Syntax

```
SUBX.A src,dst
SUBX src,dst or SUBX.W src,dst
SUBX.B src,dst
```

Operation (.not. src) + 1 + dst → dst or dst – src → dst

Description The source operand is subtracted from the destination operand. This is done by adding the 1s complement of the source + 1 to the destination. The source operand is not affected. The result is written to the destination operand. Both operands may be located in the full address space.

Status Bits

N: Set if result is negative (src > dst), reset if positive (src ≤ dst)

Z: Set if result is zero (src = dst), reset otherwise (src ≠ dst)

C: Set if there is a carry from the MSB, reset otherwise

V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow)

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example A 20-bit constant 87654h is subtracted from EDE (LSBs) and EDE+2 (MSBs).

```
SUBX.A   #87654h,EDE     ; Subtract 87654h from EDE+2|EDE
```

Example A table word pointed to by R5 (20-bit address) is subtracted from R7. Jump to label TONI if R7 contains zero after the instruction. R5 is auto-incremented by two. R7.19:16 = 0.

```
SUBX.W   @R5+,R7         ; Subtract table number from R7. R5 + 2
JZ       TONI            ; R7 = @R5 (before subtraction)
...                      ; R7 <> @R5 (before subtraction)
```

Example Byte CNT is subtracted from the byte R12 points to in the full address space. Address of CNT is within PC ± 512 K.

```
SUBX.B   CNT,0(R12)      ; Subtract CNT from @R12
```

Note: Use SUBA for the following two cases for better density and execution.

```
SUBX.A   Rsrc,Rdst
SUBX.A   #imm20,Rdst
```

4.6.3.33 SUBCX

SUBCX.A Subtract source address-word with carry from destination address-word

SUBCX.[W] Subtract source word with carry from destination word

SUBCX.B Subtract source byte with carry from destination byte

Syntax

`SUBCX.A src,dst`

`SUBCX src,dst` or `SUBCX.W src,dst`

`SUBCX.B src,dst`

Operation (.not. src) + C + dst → dst or dst – (src – 1) + C → dst

Description The source operand is subtracted from the destination operand. This is made by adding the 1s complement of the source + carry to the destination. The source operand is not affected, the result is written to the destination operand. Both operands may be located in the full address space.

Status Bits

N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)

Z: Set if result is zero, reset otherwise

C: Set if there is a carry from the MSB, reset otherwise

V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow).

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example A 20-bit constant 87654h is subtracted from R5 with the carry from the previous instruction.

```
SUBCX.A   #87654h,R5      ; Subtract 87654h + C from R5
```

Example A 48-bit number (3 words) pointed to by R5 (20-bit address) is subtracted from a 48-bit counter in RAM, pointed to by R7. R5 auto-increments to point to the next 48-bit number.

```
SUBX.W    @R5+,0(R7)      ; Subtract LSBs. R5 + 2
SUBCX.W   @R5+,2(R7)      ; Subtract MIDs with C. R5 + 2
SUBCX.W   @R5+,4(R7)      ; Subtract MSBs with C. R5 + 2
```

Example Byte CNT is subtracted from the byte R12 points to. The carry of the previous instruction is used. 20-bit addresses.

```
SUBCX.B   &CNT,0(R12)     ; Subtract byte CNT from @R12
```

4.6.3.34 SWPBX

SWPBX.A Swap bytes of lower word

SWPBX.[W] Swap bytes of word

Syntax `SWPBX.A dst`

`SWPBX dst` or `SWPBX.W dst`

Operation dst.15:8 ↔ dst.7:0

Description Register mode: Rn.15:8 are swapped with Rn.7:0. When the .A extension is used, Rn.19:16 are unchanged. When the .W extension is used, Rn.19:16 are cleared.

Other modes: When the .A extension is used, bits 31:20 of the destination address are cleared, bits 19:16 are left unchanged, and bits 15:8 are swapped with bits 7:0. When the .W extension is used, bits 15:8 are swapped with bits 7:0 of the addressed word.

Status Bits Status bits are not affected.

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Exchange the bytes of RAM address-word EDE

```
MOVX.A    #23456h,&EDE      ; 23456h -> EDE
SWPBX.A   EDE               ; 25634h -> EDE
```

Example Exchange the bytes of R5

```
MOVA      #23456h,R5        ; 23456h -> R5
SWPBX.W   R5                ; 05634h -> R5
```

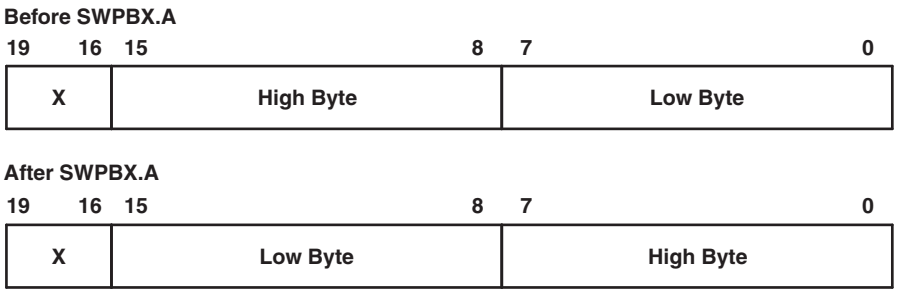


Figure 4-54. Swap Bytes SWPBX.A Register Mode

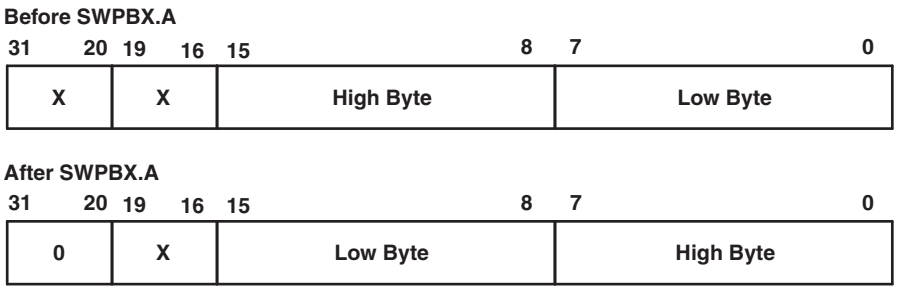


Figure 4-55. Swap Bytes SWPBX.A In Memory

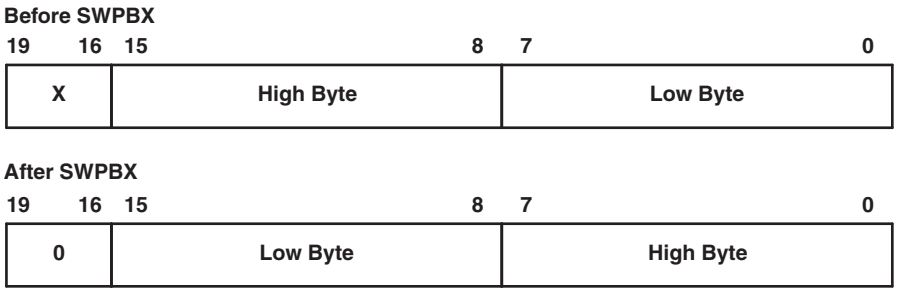


Figure 4-56. Swap Bytes SWPBX[.W] Register Mode

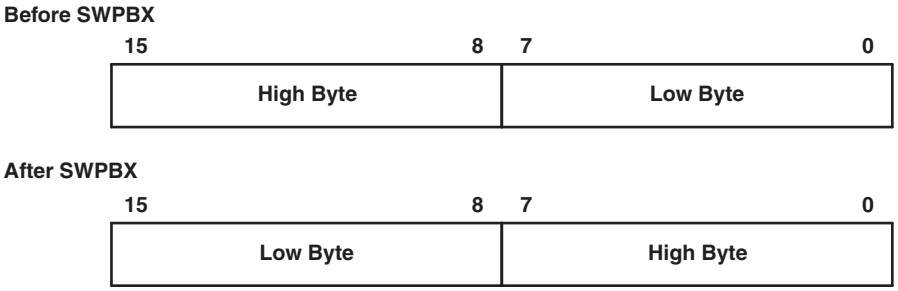


Figure 4-57. Swap Bytes SWPBX[.W] In Memory

4.6.3.35 SXTX

SXTX.A	Extend sign of lower byte to address-word
SXTX.[W]	Extend sign of lower byte to word
Syntax	`SXTX.A dst` `SXTX dst` or `SXTX.W dst`
Operation	dst.7 → dst.15:8, Rdst.7 → Rdst.19:8 (Register mode)
Description	Register mode: The sign of the low byte of the operand (Rdst.7) is extended into the bits Rdst.19:8. Other modes: SXTX.A: the sign of the low byte of the operand (dst.7) is extended into dst.19:8. The bits dst.31:20 are cleared. SXTX[.W]: the sign of the low byte of the operand (dst.7) is extended into dst.15:8.
Status Bits	N: Set if result is negative, reset otherwise Z: Set if result is zero, reset otherwise C: Set if result is not zero, reset otherwise (C = .not.Z) V: Reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The signed 8-bit data in EDE.7:0 is sign extended to 20 bits: EDE.19:8. Bits 31:20 located in EDE+2 are cleared.

```
SXTX.A      &EDE            ; Sign extended EDE -> EDE+2/EDE
```

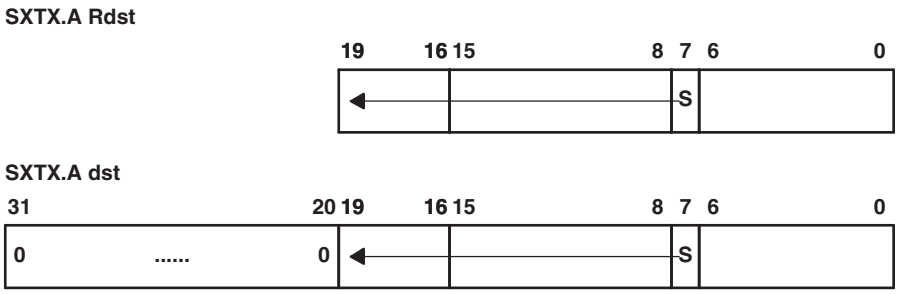


Figure 4-58. Sign Extend SXTX.A

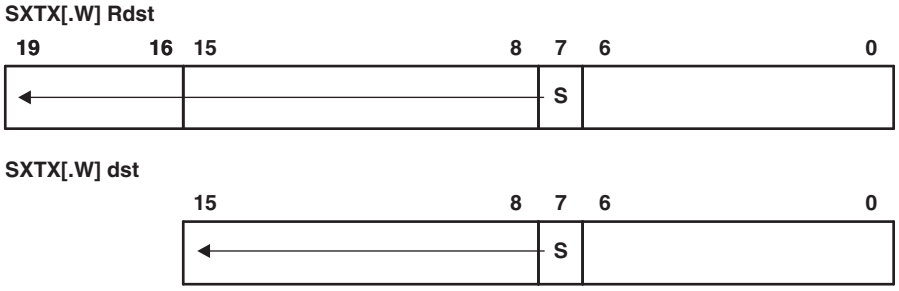


Figure 4-59. Sign Extend SXTX[.W]

4.6.3.36 TSTX

*** TSTX.A** Test destination address-word

*** TSTX.[W]** Test destination word

*** TSTX.B** Test destination byte

Syntax
```
TSTX.A dst
TSTX dst or          TSTX.W dst
TSTX.B dst
```

Operation
dst + 0FFFFFh + 1
dst + 0FFFFh + 1
dst + 0FFh + 1

Emulation
```
CMPX.A #0,dst
CMPX #0,dst
CMPX.B #0,dst
```

Description The destination operand is compared with zero. The status bits are set according to the result. The destination is not affected.

Status Bits
N: Set if destination is negative, reset if positive
Z: Set if destination contains zero, reset otherwise
C: Set
V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example RAM byte LEO is tested; PC is pointing to upper memory. If it is negative, continue at LEONEG; if it is positive but not zero, continue at LEOPOS.

```
            TSTX.B   LEO          ; Test LEO
            JN       LEONEG       ; LEO is negative
            JZ       LEOZERO      ; LEO is zero
LEOPOS      ......                ; LEO is positive but not zero
LEONEG      ......                ; LEO is negative
LEOZERO     ......                ; LEO is zero
```

4.6.3.37 XORX

XORX.A Exclusive OR source address-word with destination address-word

XORX.[W] Exclusive OR source word with destination word

XORX.B Exclusive OR source byte with destination byte

Syntax

`XORX.A src,dst`

`XORX src,dst` or `XORX.W src,dst`

`XORX.B src,dst`

Operation src .xor. dst → dst

Description The source and destination operands are exclusively ORed. The result is placed into the destination. The source operand is not affected. The previous contents of the destination are lost. Both operands may be located in the full address space.

Status Bits

N: Set if result is negative (MSB = 1), reset if positive (MSB = 0)

Z: Set if result is zero, reset otherwise

C: Set if result is not zero, reset otherwise (carry = .not. Zero)

V: Set if both operands are negative (before execution), reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Toggle bits in address-word CNTR (20-bit data) with information in address-word TONI (20-bit address)

```
XORX.A   TONI,&CNTR      ; Toggle bits in CNTR
```

Example A table word pointed to by R5 (20-bit address) is used to toggle bits in R6.

```
XORX.W   @R5,R6          ; Toggle bits in R6. R6.19:16 = 0
```

Example Reset to zero those bits in the low byte of R7 that are different from the bits in byte EDE (20-bit address)

```
XORX.B   EDE,R7          ; Set different bits to 1 in R7
INV.B    R7              ; Invert low byte of R7. R7.19:8 = 0.
```

4.6.4 MSP430X Address Instructions

MSP430X address instructions are instructions that support 20-bit operands but have restricted addressing modes. The addressing modes are restricted to the Register mode and the Immediate mode, except for the MOVA instruction. Restricting the addressing modes removes the need for the additional extension-word op-code, which improves code density and execution time. The MSP430X address instructions are described in the following sections.

See Section 4.6.3 for MSP430X extended instructions and Section 4.6.2 for standard MSP430 instructions.

4.6.4.1 ADDA

ADDA Add 20-bit source to a 20-bit destination register

Syntax
```
ADDA Rsrc,Rdst
ADDA #imm20,Rdst
```

Operation src + Rdst → Rdst

Description The 20-bit source operand is added to the 20-bit destination CPU register. The previous contents of the destination are lost. The source operand is not affected.

Status Bits
- N: Set if result is negative (Rdst.19 = 1), reset if positive (Rdst.19 = 0)
- Z: Set if result is zero, reset otherwise
- C: Set if there is a carry from the 20-bit result, reset otherwise
- V: Set if the result of two positive operands is negative, or if the result of two negative numbers is positive, reset otherwise

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example R5 is increased by 0A4320h. The jump to TONI is performed if a carry occurs.

```
ADDA   #0A4320h,R5      ; Add A4320h to 20-bit R5
JC     TONI             ; Jump on carry
...                     ; No carry occurred
```

4.6.4.2 BRA

*** BRA** Branch to destination

Syntax `BRA dst`

Operation dst → PC

Emulation `MOVA dst,PC`

Description An unconditional branch is taken to a 20-bit address anywhere in the full address space. All seven source addressing modes can be used. The branch instruction is an address-word instruction. If the destination address is contained in a memory location X, it is contained in two ascending words: X (LSBs) and (X + 2) (MSBs).

Status Bits
N: Not affected
Z: Not affected
C: Not affected
V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Examples Examples for all addressing modes are given.

Immediate mode: Branch to label EDE located anywhere in the 20-bit address space or branch directly to address.

```
BRA     #EDE          ; MOVA   #imm20,PC
BRA     #01AA04h
```

Symbolic mode: Branch to the 20-bit address contained in addresses EXEC (LSBs) and EXEC+2 (MSBs). EXEC is located at the address (PC + X) where X is within +32 K. Indirect addressing.

```
BRA     EXEC          ; MOVA   z16(PC),PC
```

Note: If the 16-bit index is not sufficient, a 20-bit index may be used with the following instruction.

```
MOVX.A  EXEC,PC       ; 1M byte range with 20-bit index
```

Absolute mode: Branch to the 20-bit address contained in absolute addresses EXEC (LSBs) and EXEC+2 (MSBs). Indirect addressing.

```
BRA     &EXEC         ; MOVA   &abs20,PC
```

Register mode: Branch to the 20-bit address contained in register R5. Indirect R5.

```
BRA     R5            ; MOVA   R5,PC
```

Indirect mode: Branch to the 20-bit address contained in the word pointed to by register R5 (LSBs). The MSBs have the address (R5 + 2). Indirect, indirect R5.

```
BRA     @R5           ; MOVA   @R5,PC
```

Indirect, Auto-Increment mode: Branch to the 20-bit address contained in the words pointed to by register R5 and increment the address in R5 afterwards by 4. The next time the S/W flow uses R5 as a pointer, it can alter the program execution due to access to the next address in the table pointed to by R5. Indirect, indirect R5.

```
BRA      @R5+          ; MOVA   @R5+,PC. R5 + 4
```

Indexed mode: Branch to the 20-bit address contained in the address pointed to by register (R5 + X) (for example, a table with addresses starting at X). (R5 + X) points to the LSBs, (R5 + X + 2) points to the MSBs of the address. X is within R5 + 32 K. Indirect, indirect (R5 + X).

```
BRA      X(R5)         ; MOVA   z16(R5),PC
```

Note: If the 16-bit index is not sufficient, a 20-bit index X may be used with the following instruction:

```
MOVX.A   X(R5),PC      ; 1M byte range with 20-bit index
```

4.6.4.3 CALLA

CALLA Call a subroutine

Syntax `CALLA dst`

Operation
dst → tmp 20-bit dst is evaluated and stored
SP – 2 → SP
PC.19:16 → @SP updated PC with return address to TOS (MSBs)
SP – 2 → SP
PC.15:0 → @SP updated PC to TOS (LSBs)
tmp → PC saved 20-bit dst to PC

Description A subroutine call is made to a 20-bit address anywhere in the full address space. All seven source addressing modes can be used. The call instruction is an address-word instruction. If the destination address is contained in a memory location X, it is contained in two ascending words, X (LSBs) and (X + 2) (MSBs). Two words on the stack are needed for the return address. The return is made with the instruction RETA.

Status Bits
N: Not affected
Z: Not affected
C: Not affected
V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Examples Examples for all addressing modes are given.

Immediate mode: Call a subroutine at label EXEC or call directly an address.

```
CALLA   #EXEC          ; Start address EXEC
CALLA   #01AA04h       ; Start address 01AA04h
```

Symbolic mode: Call a subroutine at the 20-bit address contained in addresses EXEC (LSBs) and EXEC+2 (MSBs). EXEC is located at the address (PC + X) where X is within +32 K. Indirect addressing.

```
CALLA   EXEC           ; Start address at @EXEC. z16(PC)
```

Absolute mode: Call a subroutine at the 20-bit address contained in absolute addresses EXEC (LSBs) and EXEC+2 (MSBs). Indirect addressing.

```
CALLA   &EXEC          ; Start address at @EXEC
```

Register mode: Call a subroutine at the 20-bit address contained in register R5. Indirect R5.

```
CALLA   R5             ; Start address at @R5
```

Indirect mode: Call a subroutine at the 20-bit address contained in the word pointed to by register R5 (LSBs). The MSBs have the address (R5 + 2). Indirect, indirect R5.

```
CALLA   @R5            ; Start address at @R5
```

Indirect, Auto-Increment mode: Call a subroutine at the 20-bit address contained in the words pointed to by register R5 and increment the 20-bit address in R5 afterwards by 4. The next time the S/W flow uses R5 as a pointer, it can alter the program execution due to access to the next word address in the table pointed to by R5. Indirect, indirect R5.

```
CALLA   @R5+          ; Start address at @R5. R5 + 4
```

Indexed mode: Call a subroutine at the 20-bit address contained in the address pointed to by register (R5 + X); for example, a table with addresses starting at X. (R5 + X) points to the LSBs, (R5 + X + 2) points to the MSBs of the word address. X is within R5 + 32 K. Indirect, indirect (R5 + X).

```
CALLA   X(R5)         ; Start address at @(R5+X). z16(R5)
```

4.6.4.4 CLRA

*** CLRA**	Clear 20-bit destination register
Syntax	`CLRA Rdst`
Operation	0 → Rdst
Emulation	`MOVA #0,Rdst`
Description	The destination register is cleared.
Status Bits	Status bits are not affected.
Example	The 20-bit value in R10 is cleared.

```
CLRA   R10      ; 0 -> R10
```

4.6.4.5 CMPA

CMPA Compare the 20-bit source with a 20-bit destination register

Syntax
```
CMPA Rsrc,Rdst
CMPA #imm20,Rdst
```

Operation (.not. src) + 1 + Rdst or Rdst – src

Description The 20-bit source operand is subtracted from the 20-bit destination CPU register. This is made by adding the 1s complement of the source + 1 to the destination register. The result affects only the status bits.

Status Bits
- N: Set if result is negative (src > dst), reset if positive (src ≤ dst)
- Z: Set if result is zero (src = dst), reset otherwise (src ≠ dst)
- C: Set if there is a carry from the MSB, reset otherwise
- V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow)

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example A 20-bit immediate operand and R6 are compared. If they are equal, the program continues at label EQUAL.

```
CMPA   #12345h,R6      ; Compare R6 with 12345h
JEQ    EQUAL           ; R5 = 12345h
...                    ; Not equal
```

Example The 20-bit values in R5 and R6 are compared. If R5 is greater than (signed) or equal to R6, the program continues at label GRE.

```
CMPA   R6,R5           ; Compare R6 with R5 (R5 - R6)
JGE    GRE             ; R5 >= R6
...                    ; R5 < R6
```

4.6.4.6 DECDA

*** DECDA**	Double-decrement 20-bit destination register
Syntax	`DECDA Rdst`
Operation	Rdst – 2 → Rdst
Emulation	`SUBA #2,Rdst`
Description	The destination register is decremented by two. The original contents are lost.
Status Bits	N: Set if result is negative, reset if positive Z: Set if Rdst contained 2, reset otherwise C: Reset if Rdst contained 0 or 1, set otherwise V: Set if an arithmetic overflow occurs, otherwise reset
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The 20-bit value in R5 is decremented by 2.

```
DECDA   R5      ; Decrement R5 by two
```

4.6.4.7 INCDA

*** INCDA**	Double-increment 20-bit destination register
Syntax	`INCDA Rdst`
Operation	Rdst + 2 → Rdst
Emulation	`ADDA #2,Rdst`
Description	The destination register is incremented by two. The original contents are lost.
Status Bits	N: Set if result is negative, reset if positive
	Z: Set if Rdst contained 0FFFFEh, reset otherwise
	Set if Rdst contained 0FFFEh, reset otherwise
	Set if Rdst contained 0FEh, reset otherwise
	C: Set if Rdst contained 0FFFFEh or 0FFFFFh, reset otherwise
	Set if Rdst contained 0FFFEh or 0FFFFh, reset otherwise
	Set if Rdst contained 0FEh or 0FFh, reset otherwise
	V: Set if Rdst contained 07FFFEh or 07FFFFh, reset otherwise
	Set if Rdst contained 07FFEh or 07FFFh, reset otherwise
	Set if Rdst contained 07Eh or 07Fh, reset otherwise
Mode Bits	OSCOFF, CPUOFF, and GIE are not affected.
Example	The 20-bit value in R5 is incremented by two.

```
INCDA   R5      ; Increment R5 by two
```

4.6.4.8 MOVA

MOVA Move the 20-bit source to the 20-bit destination

Syntax

```
MOVA Rsrc,Rdst
MOVA #imm20,Rdst
MOVA z16(Rsrc),Rdst
MOVA EDE,Rdst
MOVA &abs20,Rdst
MOVA @Rsrc,Rdst
MOVA @Rsrc+,Rdst
MOVA Rsrc,z16(Rdst)
MOVA Rsrc,&abs20
```

Operation

src → Rdst

Rsrc → dst

Description The 20-bit source operand is moved to the 20-bit destination. The source operand is not affected. The previous content of the destination is lost.

Status Bits

N: Not affected

Z: Not affected

C: Not affected

V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Examples Copy 20-bit value in R9 to R8

```
MOVA   R9,R8          ; R9 -> R8
```

Write 20-bit immediate value 12345h to R12

```
MOVA   #12345h,R12    ; 12345h -> R12
```

Copy 20-bit value addressed by (R9 + 100h) to R8. Source operand in addresses (R9 + 100h) LSBs and (R9 + 102h) MSBs.

```
MOVA   100h(R9),R8       ; Index: + 32 K. 2 words transferred
```

Move 20-bit value in 20-bit absolute addresses EDE (LSBs) and EDE+2 (MSBs) to R12

```
MOVA   &EDE,R12          ; &EDE -> R12. 2 words transferred
```

Move 20-bit value in 20-bit addresses EDE (LSBs) and EDE+2 (MSBs) to R12. PC index ± 32 K.

```
MOVA   EDE,R12           ; EDE -> R12. 2 words transferred
```

Copy 20-bit value R9 points to (20 bit address) to R8. Source operand in addresses @R9 LSBs and @(R9 + 2) MSBs.

```
MOVA   @R9,R8            ; @R9 -> R8. 2 words transferred
```

Copy 20-bit value R9 points to (20 bit address) to R8. R9 is incremented by four afterwards. Source operand in addresses @R9 LSBs and @(R9 + 2) MSBs.

```
MOVA    @R9+,R8          ; @R9 -> R8. R9 + 4. 2 words transferred.
```

Copy 20-bit value in R8 to destination addressed by (R9 + 100h). Destination operand in addresses @(R9 + 100h) LSBs and @(R9 + 102h) MSBs.

```
MOVA    R8,100h(R9)      ; Index: +- 32 K. 2 words transferred
```

Move 20-bit value in R13 to 20-bit absolute addresses EDE (LSBs) and EDE+2 (MSBs)

```
MOVA    R13,&EDE         ; R13 -> EDE. 2 words transferred
```

Move 20-bit value in R13 to 20-bit addresses EDE (LSBs) and EDE+2 (MSBs). PC index ± 32 K.

```
MOVA    R13,EDE          ; R13 -> EDE. 2 words transferred
```

4.6.4.9 RETA

*** RETA** Return from subroutine

Syntax `RETA`

Operation
@SP → PC.15:0 LSBs (15:0) of saved PC to PC.15:0
SP + 2 → SP
@SP → PC.19:16 MSBs (19:16) of saved PC to PC.19:16
SP + 2 → SP

Emulation `MOVA @SP+,PC`

Description The 20-bit return address information, pushed onto the stack by a CALLA instruction, is restored to the PC. The program continues at the address following the subroutine call. The SR bits SR.11:0 are not affected. This allows the transfer of information with these bits.

Status Bits
N: Not affected
Z: Not affected
C: Not affected
V: Not affected

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example Call a subroutine SUBR from anywhere in the 20-bit address space and return to the address after the CALLA

```
        CALLA     #SUBR       ; Call subroutine starting at SUBR
        ...                   ; Return by RETA to here
SUBR    PUSHM.A   #2,R14      ; Save R14 and R13 (20 bit data)
        ...                   ; Subroutine code
        POPM.A    #2,R14      ; Restore R13 and R14 (20 bit data)
        RETA                  ; Return (to full address space)
```

4.6.4.10 TSTA

*** TSTA** Test 20-bit destination register

Syntax `TSTA Rdst`

Operation dst + 0FFFFFh + 1

dst + 0FFFFh + 1

dst + 0FFh + 1

Emulation `CMPA #0,Rdst`

Description The destination register is compared with zero. The status bits are set according to the result. The destination register is not affected.

Status Bits N: Set if destination register is negative, reset if positive

Z: Set if destination register contains zero, reset otherwise

C: Set

V: Reset

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 20-bit value in R7 is tested. If it is negative, continue at R7NEG; if it is positive but not zero, continue at R7POS.

```
            TSTA   R7          ; Test R7
            JN     R7NEG       ; R7 is negative
            JZ     R7ZERO      ; R7 is zero
R7POS       ......             ; R7 is positive but not zero
R7NEG       ......             ; R7 is negative
R7ZERO      ......             ; R7 is zero
```

4.6.4.11 SUBA

SUBA Subtract 20-bit source from 20-bit destination register

Syntax
```
SUBA Rsrc,Rdst
SUBA #imm20,Rdst
```

Operation (.not.src) + 1 + Rdst → Rdst or Rdst – src → Rdst

Description The 20-bit source operand is subtracted from the 20-bit destination register. This is made by adding the 1s complement of the source + 1 to the destination. The result is written to the destination register, the source is not affected.

Status Bits
- N: Set if result is negative (src > dst), reset if positive (src ≤ dst)
- Z: Set if result is zero (src = dst), reset otherwise (src ≠ dst)
- C: Set if there is a carry from the MSB (Rdst.19), reset otherwise
- V: Set if the subtraction of a negative source operand from a positive destination operand delivers a negative result, or if the subtraction of a positive source operand from a negative destination operand delivers a positive result, reset otherwise (no overflow)

Mode Bits OSCOFF, CPUOFF, and GIE are not affected.

Example The 20-bit value in R5 is subtracted from R6. If a carry occurs, the program continues at label TONI.

```
SUBA   R5,R6      ; R6 - R5 -> R6
JC    TONI        ; Carry occurred
...               ; No carry
```

Basic Clock Module+

The basic clock module+ provides the clocks for MSP430x2xx devices. This chapter describes the operation of the basic clock module+ of the MSP430x2xx device family.

Topic **Page**

5.1 Basic Clock Module+ Introduction

The basic clock module+ supports low system cost and ultralow power consumption. Using three internal clock signals, the user can select the best balance of performance and low power consumption. The basic clock module+ can be configured to operate without any external components, with one external resistor, with one or two external crystals, or with resonators, under full software control.

The basic clock module+ includes two, three or four clock sources:

- LFXT1CLK: Low-frequency/high-frequency oscillator that can be used with low-frequency watch crystals or external clock sources of 32768 Hz or with standard crystals, resonators, or external clock sources in the 400-kHz to 16-MHz range.
- XT2CLK: Optional high-frequency oscillator that can be used with standard crystals, resonators, or external clock sources in the 400-kHz to 16-MHz range.
- DCOCLK: Internal digitally controlled oscillator (DCO).
- VLOCLK: Internal very low power, low frequency oscillator with 12-kHz typical frequency.

Three clock signals are available from the basic clock module+:

- ACLK: Auxiliary clock. ACLK is software selectable as LFXT1CLK or VLOCLK. ACLK is divided by 1, 2, 4, or 8. ACLK is software selectable for individual peripheral modules.
- MCLK: Master clock. MCLK is software selectable as LFXT1CLK, VLOCLK, XT2CLK (if available on-chip), or DCOCLK. MCLK is divided by 1, 2, 4, or 8. MCLK is used by the CPU and system.
- SMCLK: Sub-main clock. SMCLK is software selectable as LFXT1CLK, VLOCLK, XT2CLK (if available on-chip), or DCOCLK. SMCLK is divided by 1, 2, 4, or 8. SMCLK is software selectable for individual peripheral modules.

The block diagram of the basic clock module+ in the MSP430F2xx devices is shown in Figure 5-1.

The block diagram of the basic clock module+ in the MSP430AFE2xx devices is shown in Figure 5-2.

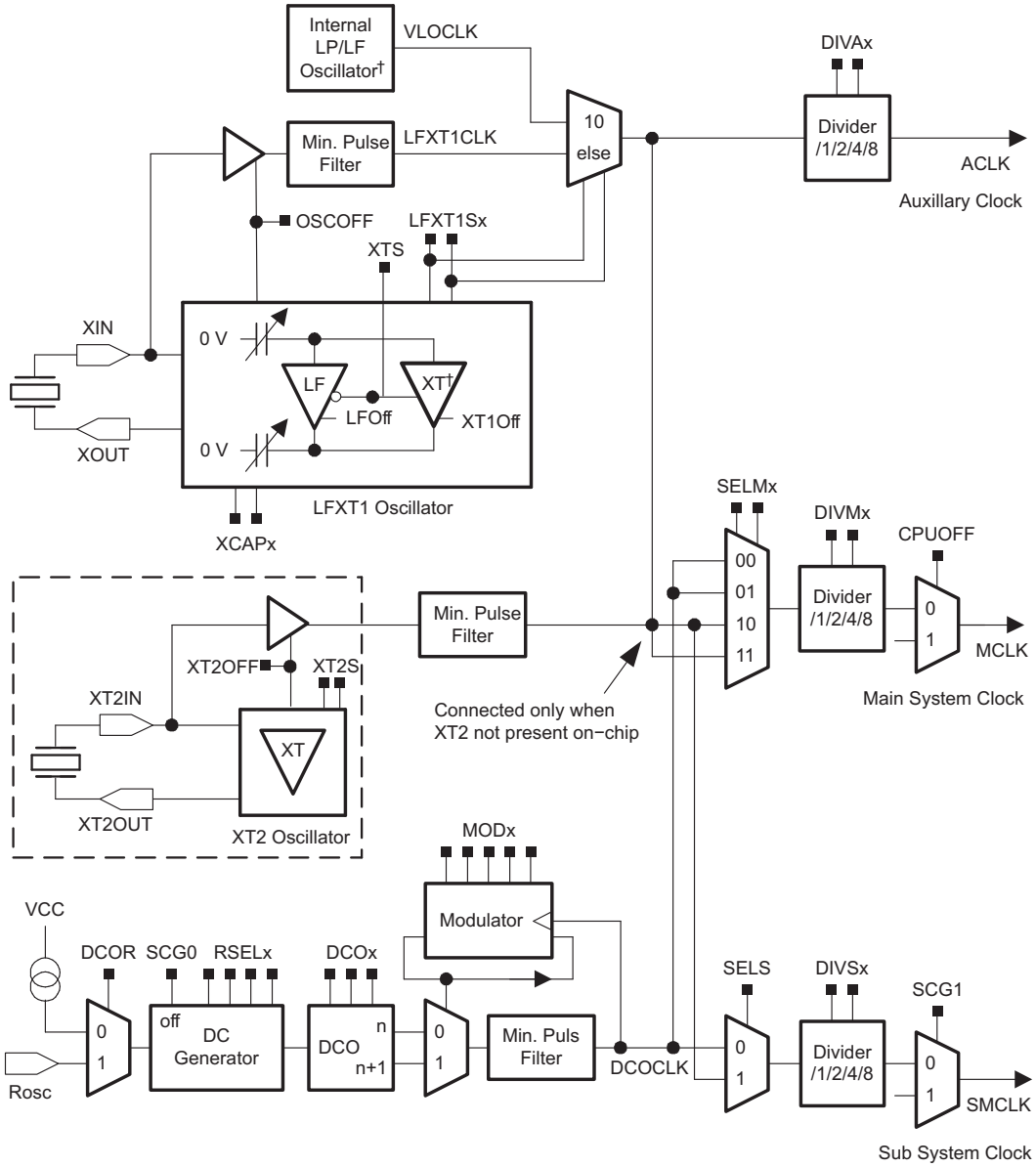


Figure 5-1. Basic Clock Module+ Block Diagram − MSP430F2xx

NOTE: † Device-Specific Clock Variations

Not all clock features are available on all MSP430x2xx devices:
MSP430G22x0: LFXT1 is not present, XT2 is not present, ROSC is not supported.

MSP430F20xx, MSP430G2xx1, MSP430G2xx2, MSP430G2xx3: LFXT1 does not support HF mode, XT2 is not present, ROSC is not supported.
MSP430x21x1: Internal LP/LF oscillator is not present, XT2 is not present, ROSC is not supported.
MSP430x21x2: XT2 is not present.
MSP430F22xx, MSP430x23x0: XT2 is not present.

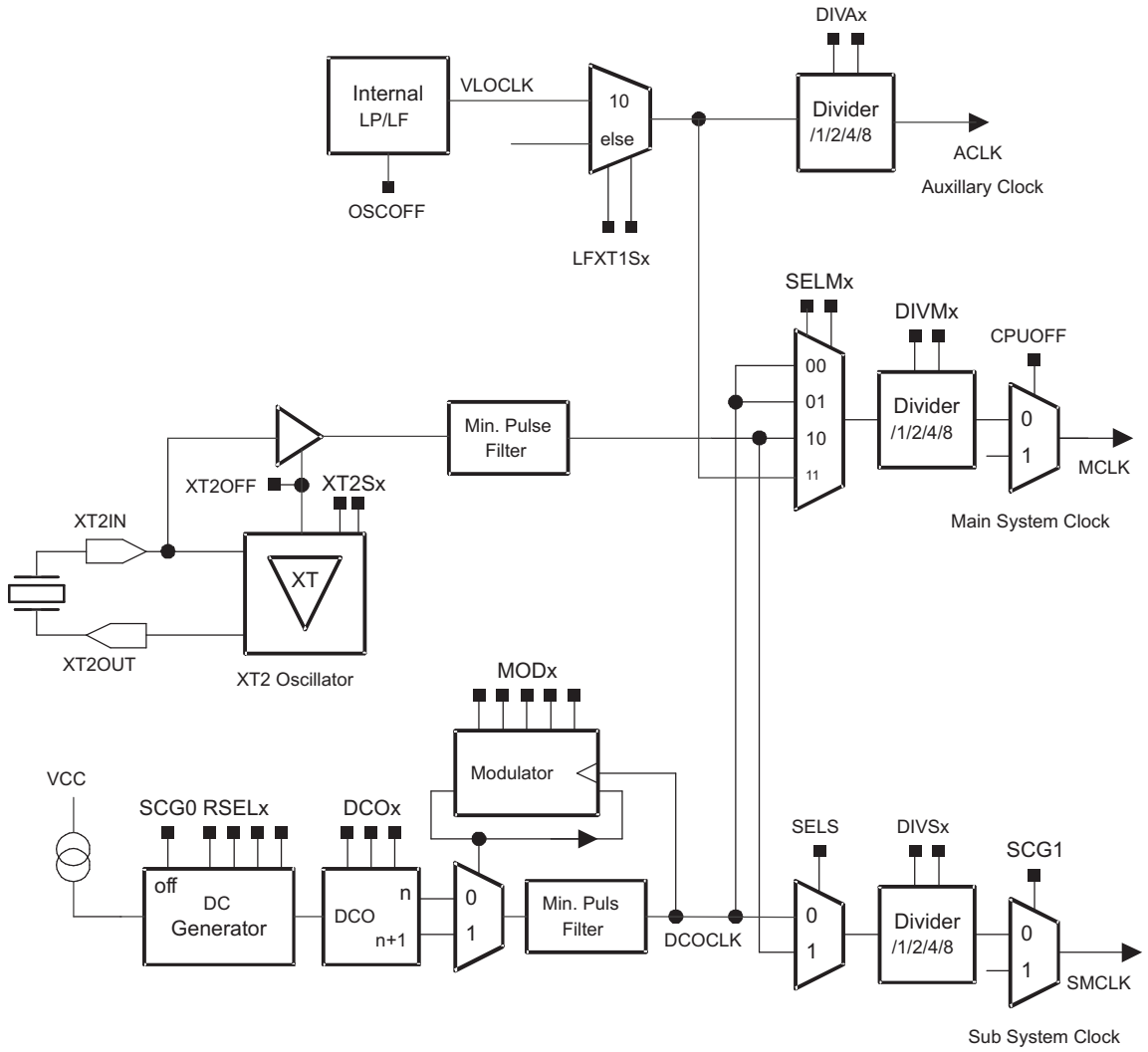


Figure 5-2. Basic Clock Module+ Block Diagram − MSP430AFE2xx

NOTE: LFXT1 is not present in MSP430AFE2xx devices.

5.2 Basic Clock Module+ Operation

After a PUC, MCLK and SMCLK are sourced from DCOCLK at ~1.1 MHz (see the device-specific data sheet for parameters) and ACLK is sourced from LFXT1CLK in LF mode with an internal load capacitance of 6 pF.

Status register control bits SCG0, SCG1, OSCOFF, and CPUOFF configure the MSP430 operating modes and enable or disable portions of the basic clock module+ (see the *System Resets, Interrupts and Operating Modes* chapter). The DCOCTL, BCSCTL1, BCSCTL2, and BCSCTL3 registers configure the basic clock module+.

The basic clock module+ can be configured or reconfigured by software at any time during program execution, for example:

```
CLR.B   &DCOCTL                     ; Select lowest DCOx
                                    ; and MODx settings
BIS.B   #RSEL2+RSEL1+RSEL0,&BCSCTL1 ; Select range 7
BIS.B   #DCO2+DCO1+DCO0,&DCOCTL     ; Select max DCO tap
```

5.2.1 Basic Clock Module+ Features for Low-Power Applications

Conflicting requirements typically exist in battery-powered applications:

- Low clock frequency for energy conservation and time keeping
- High clock frequency for fast reaction to events and fast burst processing capability
- Clock stability over operating temperature and supply voltage

The basic clock module+ addresses the above conflicting requirements by allowing the user to select from the three available clock signals: ACLK, MCLK, and SMCLK. For optimal low-power performance, ACLK can be sourced from a low-power 32768-Hz watch crystal (if available), providing a stable time base for the system and low-power standby operation, or from the internal low-frequency oscillator when crystal-accurate time keeping is not required. The MCLK can be configured to operate from the on-chip DCO that can be activated when requested by interrupt-driven events. The SMCLK can be configured to operate from a crystal or the DCO, depending on peripheral requirements. A flexible clock distribution and divider system is provided to fine tune the individual clock requirements.

5.2.2 Internal Very-Low-Power Low-Frequency Oscillator (VLO)

The internal very-low-power low-frequency oscillator (VLO) provides a typical frequency of 12 kHz (see device-specific data sheet for parameters) without requiring a crystal. VLOCLK source is selected by setting LFXT1Sx = 10 when XTS = 0. The OSCOFF bit disables the VLO for LPM4. The LFXT1 crystal oscillators are disabled when the VLO is selected reducing current consumption. The VLO consumes no power when not being used.

Devices without LFXT1 (for example, the MSP430G22x0) should be configured to use the VLO as ACLK.

5.2.3 LFXT1 Oscillator

The LFXT1 oscillator is not implemented in the MSP430G22x0 device family.

The LFXT1 oscillator supports ultra-low current consumption using a 32768-Hz watch crystal in LF mode (XTS = 0). A watch crystal connects to XIN and XOUT without any other external components. The software-selectable XCAPx bits configure the internally provided load capacitance for the LFXT1 crystal in LF mode. This capacitance can be selected as 1 pF, 6 pF, 10 pF, or 12.5 pF typical. Additional external capacitors can be added if necessary.

The LFXT1 oscillator also supports high-speed crystals or resonators when in HF mode (XTS = 1, XCAPx = 00). The high-speed crystal or resonator connects to XIN and XOUT and requires external capacitors on both terminals. These capacitors should be sized according to the crystal or resonator specifications. When LFXT1 is in HF mode, the LFXT1Sx bits select the range of operation.

LFXT1 may be used with an external clock signal on the XIN pin in either LF or HF mode when LFXT1Sx = 11, OSCOFF = 0, and XCAPx = 00. When used with an external signal, the external frequency must meet the data sheet parameters for the chosen mode. When the input frequency is below the specified lower limit, the LFXT1OF bit may be set preventing the CPU from being clocked with LFXT1CLK.

Software can disable LFXT1 by setting OSCOFF, if LFXT1CLK does not source SMCLK or MCLK, as shown in Figure 5-3.

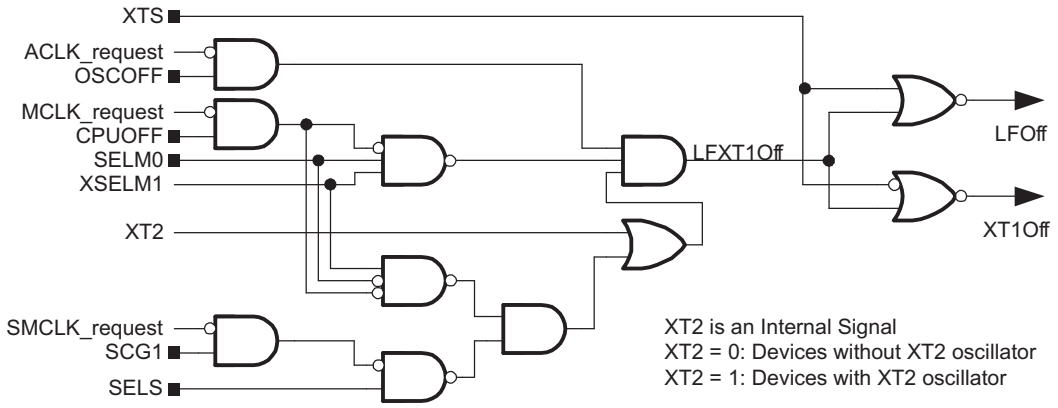


Figure 5-3. Off Signals for the LFXT1 Oscillator

NOTE: LFXT1 Oscillator Characteristics

Low-frequency crystals often require hundreds of milliseconds to start up, depending on the crystal.

Ultralow-power oscillators such as the LFXT1 in LF mode should be guarded from noise coupling from other sources. The crystal should be placed as close as possible to the MSP430 with the crystal housing grounded and the crystal traces guarded with ground traces.

5.2.4 XT2 Oscillator

Some devices have a second crystal oscillator, XT2. XT2 sources XT2CLK and its characteristics are identical to LFXT1 in HF mode. The XT2Sx bits select the range of operation of XT2. The XT2OFF bit disables the XT2 oscillator if XT2CLK is not used for MCLK or SMCLK as shown in Figure 5-4.

XT2 may be used with external clock signals on the XT2IN pin when XT2Sx = 11 and XT2OFF = 0. When used with an external signal, the external frequency must meet the data sheet parameters for XT2. When the input frequency is below the specified lower limit, the XT2OF bit may be set to prevent the CPU from being clocked with XT2CLK.

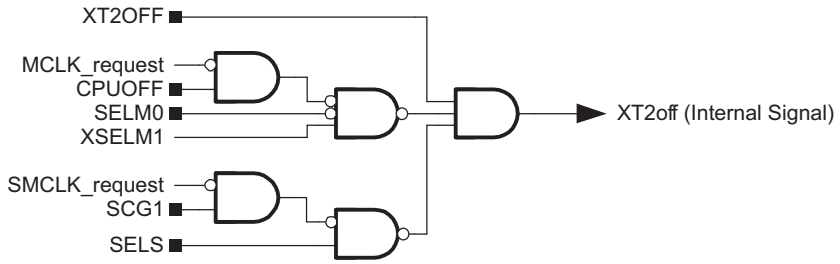


Figure 5-4. Off Signals for Oscillator XT2

5.2.5 Digitally-Controlled Oscillator (DCO)

The DCO is an integrated digitally controlled oscillator. The DCO frequency can be adjusted by software using the DCOx, MODx, and RSELx bits.

5.2.5.1 Disabling the DCO

Software can disable DCOCLK by setting SCG0 when it is not used to source SMCLK or MCLK in active mode, as shown in Figure 5-5.

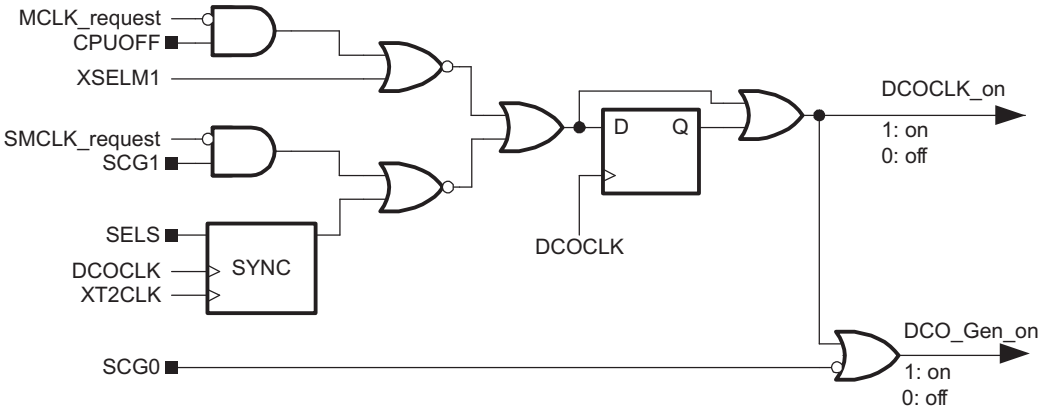


Figure 5-5. On/Off Control of DCO

5.2.5.2 Adjusting the DCO Frequency

After a PUC, RSELx = 7 and DCOx = 3, allowing the DCO to start at a mid-range frequency. MCLK and SMCLK are sourced from DCOCLK. Because the CPU executes code from MCLK, which is sourced from the fast-starting DCO, code execution typically begins from PUC in less than 2 µs. The typical DCOx and RSELx ranges and steps are shown in Figure 5-6.

The frequency of DCOCLK is set by the following functions:

- The four RSELx bits select one of sixteen nominal frequency ranges for the DCO. These ranges are defined for an individual device in the device-specific data sheet.
- The three DCOx bits divide the DCO range selected by the RSELx bits into 8 frequency steps, separated by approximately 10%.
- The five MODx bits, switch between the frequency selected by the DCOx bits and the next higher frequency set by DCOx+1. When DCOx = 07h, the MODx bits have no effect because the DCO is already at the highest setting for the selected RSELx range.

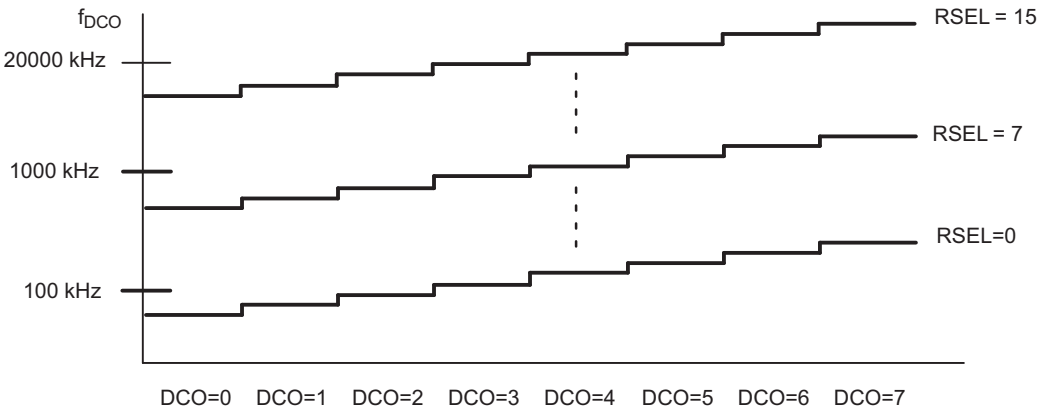


Figure 5-6. Typical DCOx Range and RSELx Steps

Each MSP430F2xx device (and most MSP430G2xx devices; see device-specific data sheets) has calibrated DCOCTL and BCSCTL1 register settings for specific frequencies stored in information memory segment A. To use the calibrated settings, the information is copied into the DCOCTL and BCSCTL1 registers. The calibrated settings affect the DCOx, MODx, and RSELx bits, and clear all other bits, except XT2OFF which remains set. The remaining bits of BCSCTL1 can be set or cleared as needed with BIS.B or BIC.B instructions.

```
; Set DCO to 1 MHz:
CLR.B   &DCOCTL                 ; Select lowest DCOx
                                ; and MODx settings
```

```
MOV.B   &CALBC1_1MHZ,&BCSCTL1   ; Set range
MOV.B   &CALDCO_1MHZ,&DCOCTL    ; Set DCO step + modulation
```

5.2.5.3 Using an External Resistor (R_{OSC}) for the DCO

Some MSP430F2xx devices provide the option to source the DCO current through an external resistor, R_{OSC}, tied to $DV_{CC,}$ when DCOR = 1. In this case, the DCO has the same characteristics as MSP430x1xx devices, and the RSELx setting is limited to 0 to 7 with the RSEL3 ignored. This option provides an additional method to tune the DCO frequency by varying the resistor value. See the device-specific data sheet for parameters.

5.2.6 DCO Modulator

The modulator mixes two DCO frequencies, f_{DCO} and f_{DCO+1} to produce an intermediate effective frequency between f_{DCO} and f_{DCO+1} and spread the clock energy, reducing electromagnetic interference (EMI). The modulator mixes f_{DCO} and f_{DCO+1} for 32 DCOCLK clock cycles and is configured with the MODx bits. When MODx = 0 the modulator is off.

The modulator mixing formula is:

$$t = (32 - MODx) \times t_{DCO} + MODx \times t_{DCO+1}$$

Because f_{DCO} is lower than the effective frequency and f_{DCO+1} is higher than the effective frequency, the error of the effective frequency integrates to zero. It does not accumulate. The error of the effective frequency is zero every 32 DCOCLK cycles. Figure 5-7 shows the modulator operation.

The modulator settings and DCO control are configured with software. The DCOCLK can be compared to a stable frequency of known value and adjusted with the DCOx, RSELx, and MODx bits. See http://www.msp430.com for application notes and example code on configuring the DCO.

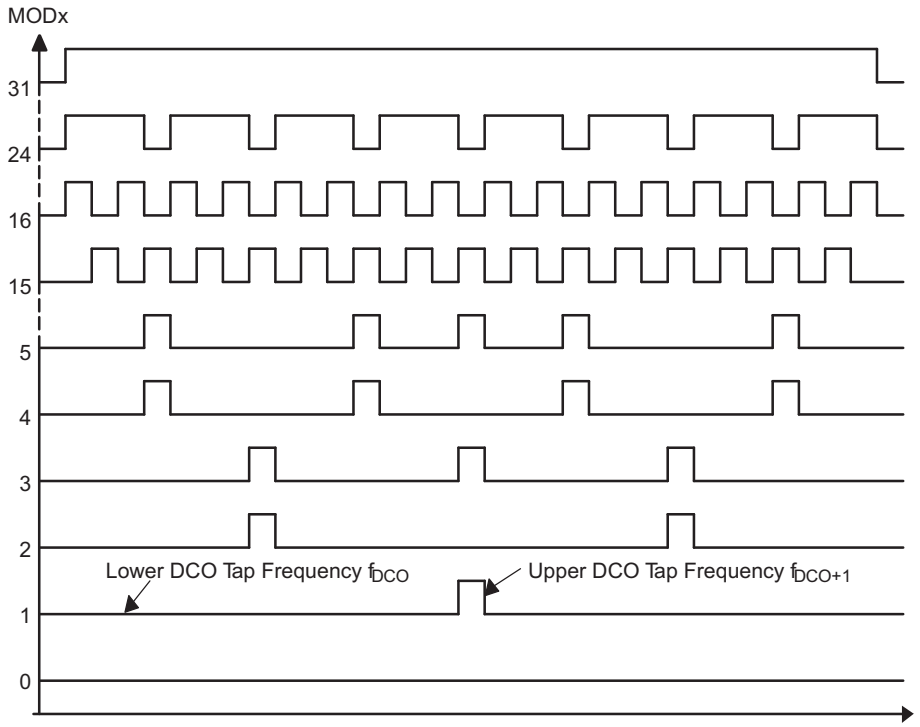


Figure 5-7. Modulator Patterns

5.2.7 Basic Clock Module+ Fail-Safe Operation

The basic clock module+ incorporates an oscillator-fault fail-safe feature. This feature detects an oscillator fault for LFXT1 and XT2 as shown in Figure 5-8. The available fault conditions are:

- Low-frequency oscillator fault (LFXT1OF) for LFXT1 in LF mode

- High-frequency oscillator fault (LFXT1OF) for LFXT1 in HF mode
- High-frequency oscillator fault (XT2OF) for XT2

The crystal oscillator fault bits LFXT1OF, and XT2OF are set if the corresponding crystal oscillator is turned on and not operating properly. The fault bits remain set as long as the fault condition exists and are automatically cleared if the enabled oscillators function normally.

The OFIFG oscillator-fault flag is set and latched at POR or when an oscillator fault (LFXT1OF, or XT2OF) is detected. When OFIFG is set, MCLK is sourced from the DCO, and if OFIE is set, the OFIFG requests an NMI interrupt. When the interrupt is granted, the OFIE is reset automatically. The OFIFG flag must be cleared by software. The source of the fault can be identified by checking the individual fault bits.

If a fault is detected for the crystal oscillator sourcing the MCLK, the MCLK is automatically switched to the DCO for its clock source. This does not change the SELMx bit settings. This condition must be handled by user software.

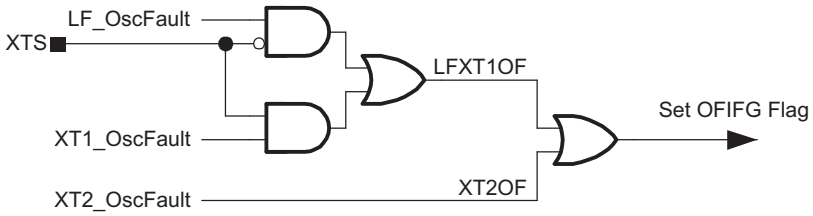


Figure 5-8. Oscillator-Fault Logic

5.2.7.1 Sourcing MCLK from a Crystal

After a PUC, the basic clock module+ uses DCOCLK for MCLK. If required, MCLK may be sourced from LFXT1 or XT2 - if available.

The sequence to switch the MCLK source from the DCO clock to the crystal clock (LFXT1CLK or XT2CLK) is:

1. Turn on the crystal oscillator and select the appropriate mode
2. Clear the OFIFG flag
3. Wait at least 50 µs
4. Test OFIFG, and repeat steps 2 through 4 until OFIFG remains cleared.

```
; Select LFXT1 (HF mode) for MCLK
     BIC.W   #OSCOFF,SR                ; Turn on osc.
     BIS.B   #XTS,&BCSCTL1             ; HF mode
     MOV.B   #LFXT1S0,&BCSCTL3         ; 1-3MHz Crystal
L1   BIC.B   #OFIFG,&IFG1              ; Clear OFIFG
     MOV.W   #0FFh,R15                 ; Delay
L2   DEC.W   R15                       ;
     JNZ     L2                        ;
     BIT.B   #OFIFG,&IFG1              ; Re-test OFIFG
     JNZ     L1                        ; Repeat test if needed
     BIS.B   #SELM1+SELM0,&BCSCTL2     ; Select LFXT1CLK
```

5.2.8 Synchronization of Clock Signals

When switching MCLK or SMCLK from one clock source to another, the switch is synchronized to avoid critical race conditions as shown in Figure 5-9:

- The current clock cycle continues until the next rising edge.
- The clock remains high until the next rising edge of the new clock.
- The new clock source is selected and continues with a full high period.

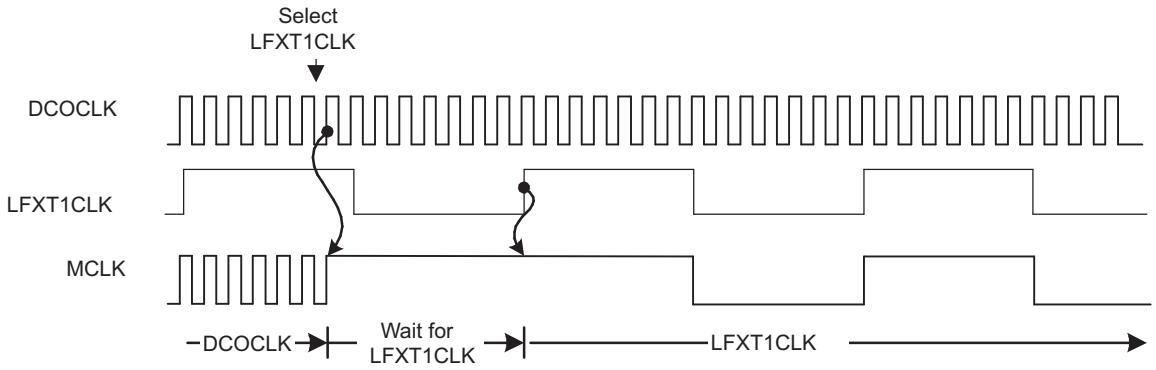


Figure 5-9. Switch MCLK from DCOCLK to LFXT1CLK

5.3 Basic Clock Module+ Registers

The basic clock module+ registers are listed in Table 5-1.

Table 5-1. Basic Clock Module+ Registers

Register	Short Form	Register Type	Address	Initial State
DCO control register	DCOCTL	Read/write	056h	060h with PUC
Basic clock system control 1	BCSCTL1	Read/write	057h	087h with POR(1)
Basic clock system control 2	BCSCTL2	Read/write	058h	Reset with PUC
Basic clock system control 3	BCSCTL3	Read/write	053h	005h with PUC(2)
SFR interrupt enable register 1	IE1	Read/write	000h	Reset with PUC
SFR interrupt flag register 1	IFG1	Read/write	002h	Reset with PUC

(1) Some of the register bits are also PUC initialized (see Section 5.3.2).
(2) The initial state of BCSCTL3 is 000h in the MSP430AFE2xx devices.

5.3.1 DCOCTL, DCO Control Register

7	6	5	4	3	2	1	0
DCOx			MODx				
rw-0	rw-1	rw-1	rw-0	rw-0	rw-0	rw-0	rw-0

DCOx	Bits 7-5	DCO frequency select. These bits select which of the eight discrete DCO frequencies within the range defined by the RSELx setting is selected.
MODx	Bits 4-0	Modulator selection. These bits define how often the f_{DCO+1} frequency is used within a period of 32 DCOCLK cycles. During the remaining clock cycles (32-MOD) the f_{DCO} frequency is used. Not useable when DCOx = 7.

5.3.2 BCSCTL1, Basic Clock System Control Register 1

7	6	5	4	3	2	1	0
XT2OFF	XTS[1][2]	DIVAx		RSELx			
rw-(1)	rw-(0)	rw-(0)	rw-(0)	rw-0	rw-1	rw-1	rw-1

XT2OFF	Bit 7	XT2 off. This bit turns off the XT2 oscillator
		0 XT2 is on
		1 XT2 is off if it is not used for MCLK or SMCLK.
XTS	Bit 6	LFXT1 mode select.
		0 Low-frequency mode
		1 High-frequency mode
DIVAx	Bits 5-4	Divider for ACLK
		00 /1
		01 /2
		10 /4
		11 /8
RSELx	Bits 3-0	Range select. Sixteen different frequency ranges are available. The lowest frequency range is selected by setting RSELx = 0. RSEL3 is ignored when DCOR = 1.

(1) XTS = 1 is not supported in MSP430x20xx and MSP430G2xx devices (see Figure 5-1 and Figure 5-2 for details on supported settings for all devices).

(2) This bit is reserved in the MSP430AFE2xx devices.

5.3.3 BCSCTL2, Basic Clock System Control Register 2

7	6	5	4	3	2	1	0
SELMx		**DIVMx**		**SELS**	**DIVSx**		**DCOR**[1][2]
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

SELMx	Bits 7-6	Select MCLK. These bits select the MCLK source.	
		00	DCOCLK
		01	DCOCLK
		10	XT2CLK when XT2 oscillator present on-chip. LFXT1CLK or VLOCLK when XT2 oscillator not present on-chip.
		11	LFXT1CLK or VLOCLK
DIVMx	Bits 5-4	Divider for MCLK	
		00	/1
		01	/2
		10	/4
		11	/8
SELS	Bit 3	Select SMCLK. This bit selects the SMCLK source.	
		0	DCOCLK
		1	XT2CLK when XT2 oscillator present. LFXT1CLK or VLOCLK when XT2 oscillator not present
DIVSx	Bits 2-1	Divider for SMCLK	
		00	/1
		01	/2
		10	/4
		11	/8
DCOR	Bit 0	DCO resistor select. Not available in all devices. See the device-specific data sheet.	
		0	Internal resistor
		1	External resistor

(1) Does not apply to MSP430x20xx or MSP430x21xx devices.
(2) This bit is reserved in the MSP430AFE2xx devices.

5.3.4 BCSCTL3, Basic Clock System Control Register 3

7	6	5	4	3	2	1	0
XT2Sx		LFXT1Sx(1)		XCAPx(2)		XT2OF(3)	LFXT1OF(2)
rw-0	rw-0	rw-0	rw-0	rw-0	rw-1	r0	r-(1)

XT2Sx Bits 7-6 XT2 range select. These bits select the frequency range for XT2.

00 0.4- to 1-MHz crystal or resonator

01 1- to 3-MHz crystal or resonator

10 3- to 16-MHz crystal or resonator

11 Digital external 0.4- to 16-MHz clock source

LFXT1Sx Bits 5-4 Low-frequency clock select and LFXT1 range select. These bits select between LFXT1 and VLO when XTS = 0, and select the frequency range for LFXT1 when XTS = 1.

When XTS = 0:

00 32768-Hz crystal on LFXT1

01 Reserved

10 VLOCLK (Reserved in MSP430F21x1 devices)

11 Digital external clock source

When XTS = 1 (Not applicable for MSP430x20xx devices, MSP430G2xx1/2/3)

00 0.4- to 1-MHz crystal or resonator

01 1- to 3-MHz crystal or resonator

10 3- to 16-MHz crystal or resonator

11 Digital external 0.4- to 16-MHz clock source

LFXT1Sx definition for MSP430AFE2xx devices:

00 Reserved

01 Reserved

10 VLOCLK

11 Reserved

XCAPx Bits 3-2 Oscillator capacitor selection. These bits select the effective capacitance seen by the LFXT1 crystal when XTS = 0. If XTS = 1 or if LFXT1Sx = 11 XCAPx should be 00.

00 ~1 pF

01 ~6 pF

10 ~10 pF

11 ~12.5 pF

XT2OF Bit 1 XT2 oscillator fault

0 No fault condition present

1 Fault condition present

LFXT1OF Bit 0 LFXT1 oscillator fault

0 No fault condition present

1 Fault condition present

(1) MSP430G22x0: The LFXT1Sx bits should be programmed to 10b during the initialization and start-up code to select VLOCLK (for more details refer to Digital I/O chapter). The other bits are reserved and should not be altered.

(2) This bit is reserved in the MSP430AFE2xx devices.

(3) Does not apply to MSP430x2xx, MSP430x21xx, or MSP430x22xx devices.

5.3.5 IE1, Interrupt Enable Register 1

7	6	5	4	3	2	1	0
						OFIE[1]	
						rw-0	

	Bits 7-2	These bits may be used by other modules. See device-specific data sheet.
OFIE	Bit 1	Oscillator fault interrupt enable. This bit enables the OFIFG interrupt. Because other bits in IE1 may be used for other modules, it is recommended to set or clear this bit using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions. 0 Interrupt not enabled 1 Interrupt enabled
	Bits 0	This bit may be used by other modules. See device-specific data sheet.

(1) MSP430G22x0: This bit should not be set.

5.3.6 IFG1, Interrupt Flag Register 1

7	6	5	4	3	2	1	0
						OFIFG[1]	
						rw-1	

	Bits 7-2	These bits may be used by other modules. See device-specific data sheet.
OFIFG	Bit 1	Oscillator fault interrupt flag. Because other bits in IFG1 may be used for other modules, it is recommended to set or clear this bit using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions. 0 No interrupt pending 1 Interrupt pending
	Bits 0	This bit may be used by other modules. See device-specific data sheet.

(1) MSP430G22x0: The LFXT1 oscillator pins are not available in this device. The oscillator fault flag will always be set by hardware. The interrupt enable bit should not be set.

DMA Controller

The DMA controller module transfers data from one address to another without CPU intervention. This chapter describes the operation of the DMA controller of the MSP430x2xx device family.

Topic **Page**

6.1 DMA Introduction

The direct memory access (DMA) controller transfers data from one address to another, without CPU intervention, across the entire address range. For example, the DMA controller can move data from the ADC12 conversion memory to RAM.

Devices that contain a DMA controller may have one, two, or three DMA channels available. Therefore, depending on the number of DMA channels available, some features described in this chapter are not applicable to all devices.

Using the DMA controller can increase the throughput of peripheral modules. It can also reduce system power consumption by allowing the CPU to remain in a low-power mode without having to awaken to move data to or from a peripheral.

The DMA controller features include:

- Up to three independent transfer channels
- Configurable DMA channel priorities
- Requires only two MCLK clock cycles per transfer
- Byte or word and mixed byte/word transfer capability
- Block sizes up to 65535 bytes or words
- Configurable transfer trigger selections
- Selectable edge or level-triggered transfer
- Four addressing modes
- Single, block, or burst-block transfer modes

The DMA controller block diagram is shown in Figure 6-1.

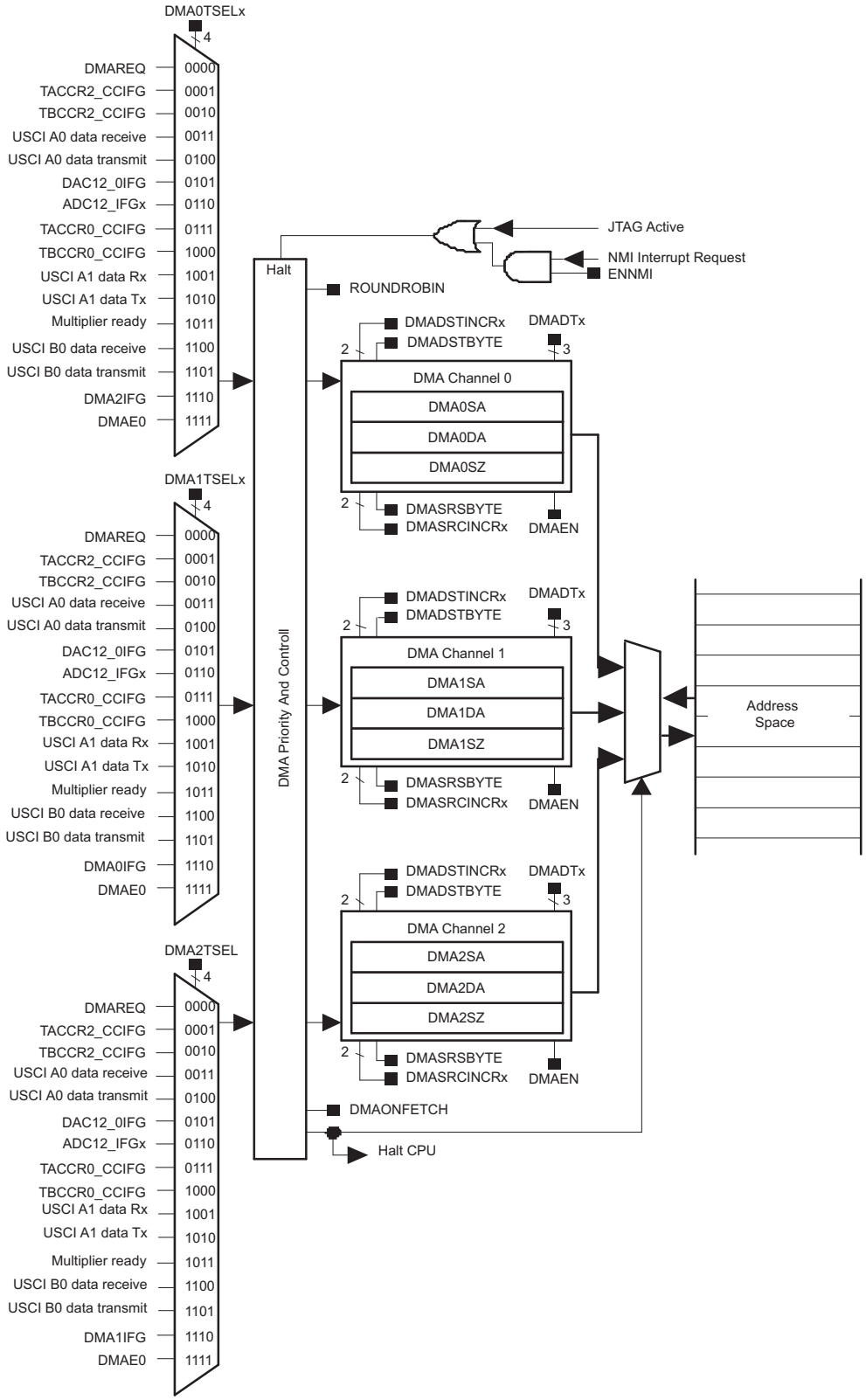


Figure 6-1. DMA Controller Block Diagram

6.2 DMA Operation

The DMA controller is configured with user software. The setup and operation of the DMA is discussed in the following sections.

6.2.1 DMA Addressing Modes

The DMA controller has four addressing modes. The addressing mode for each DMA channel is independently configurable. For example, channel 0 may transfer between two fixed addresses, while channel 1 transfers between two blocks of addresses. The addressing modes are shown in Figure 6-2. The addressing modes are:

- Fixed address to fixed address
- Fixed address to block of addresses
- Block of addresses to fixed address
- Block of addresses to block of addresses

The addressing modes are configured with the DMASRCINCRx and DMADSTINCRx control bits. The DMASRCINCRx bits select if the source address is incremented, decremented, or unchanged after each transfer. The DMADSTINCRx bits select if the destination address is incremented, decremented, or unchanged after each transfer.

Transfers may be byte-to-byte, word-to-word, byte-to-word, or word-to-byte. When transferring word-to-byte, only the lower byte of the source-word transfers. When transferring byte-to-word, the upper byte of the destination-word is cleared when the transfer occurs.

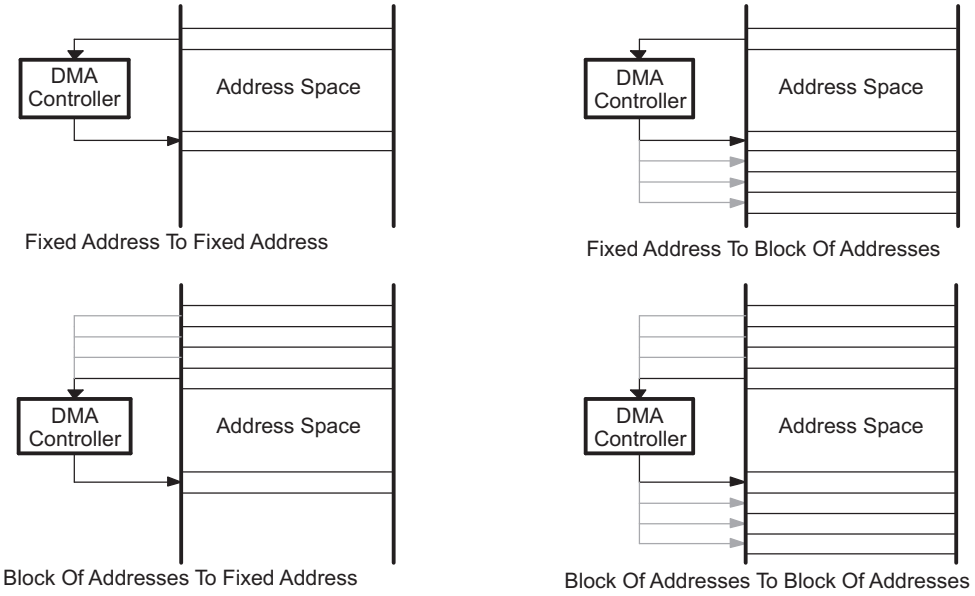


Figure 6-2. DMA Addressing Modes

6.2.2 DMA Transfer Modes

The DMA controller has six transfer modes selected by the DMADTx bits as listed in Table 6-1. Each channel is individually configurable for its transfer mode. For example, channel 0 may be configured in single transfer mode, while channel 1 is configured for burst-block transfer mode, and channel 2 operates in repeated block mode. The transfer mode is configured independently from the addressing mode. Any addressing mode can be used with any transfer mode.

Two types of data can be transferred selectable by the DMAxCTL DSTBYTE and SRCBYTE fields. The source and/or destination location can be either byte or word data. It is also possible to transfer byte to byte, word to word or any combination.

Table 6-1. DMA Transfer Modes

DMADTx	Transfer Mode	Description
000	Single transfer	Each transfer requires a trigger. DMAEN is automatically cleared when DMAxSZ transfers have been made.
001	Block transfer	A complete block is transferred with one trigger. DMAEN is automatically cleared at the end of the block transfer.
010, 011	Burst-block transfer	CPU activity is interleaved with a block transfer. DMAEN is automatically cleared at the end of the burst-block transfer.
100	Repeated single transfer	Each transfer requires a trigger. DMAEN remains enabled.
101	Repeated block transfer	A complete block is transferred with one trigger. DMAEN remains enabled.
110, 111	Repeated burst-block transfer	CPU activity is interleaved with a block transfer. DMAEN remains enabled.

6.2.2.1 Single Transfer

In single transfer mode, each byte/word transfer requires a separate trigger. The single transfer state diagram is shown in Figure 6-3.

The DMAxSZ register is used to define the number of transfers to be made. The DMADSTINCRx and DMASRCINCRx bits select if the destination address and the source address are incremented or decremented after each transfer. If DMAxSZ = 0, no transfers occur.

The DMAxSA, DMAxDA, and DMAxSZ registers are copied into temporary registers. The temporary values of DMAxSA and DMAxDA are incremented or decremented after each transfer. The DMAxSZ register is decremented after each transfer. When the DMAxSZ register decrements to zero it is reloaded from its temporary register and the corresponding DMAIFG flag is set. When DMADTx = 0, the DMAEN bit is cleared automatically when DMAxSZ decrements to zero and must be set again for another transfer to occur.

In repeated single transfer mode, the DMA controller remains enabled with DMAEN = 1, and a transfer occurs every time a trigger occurs.

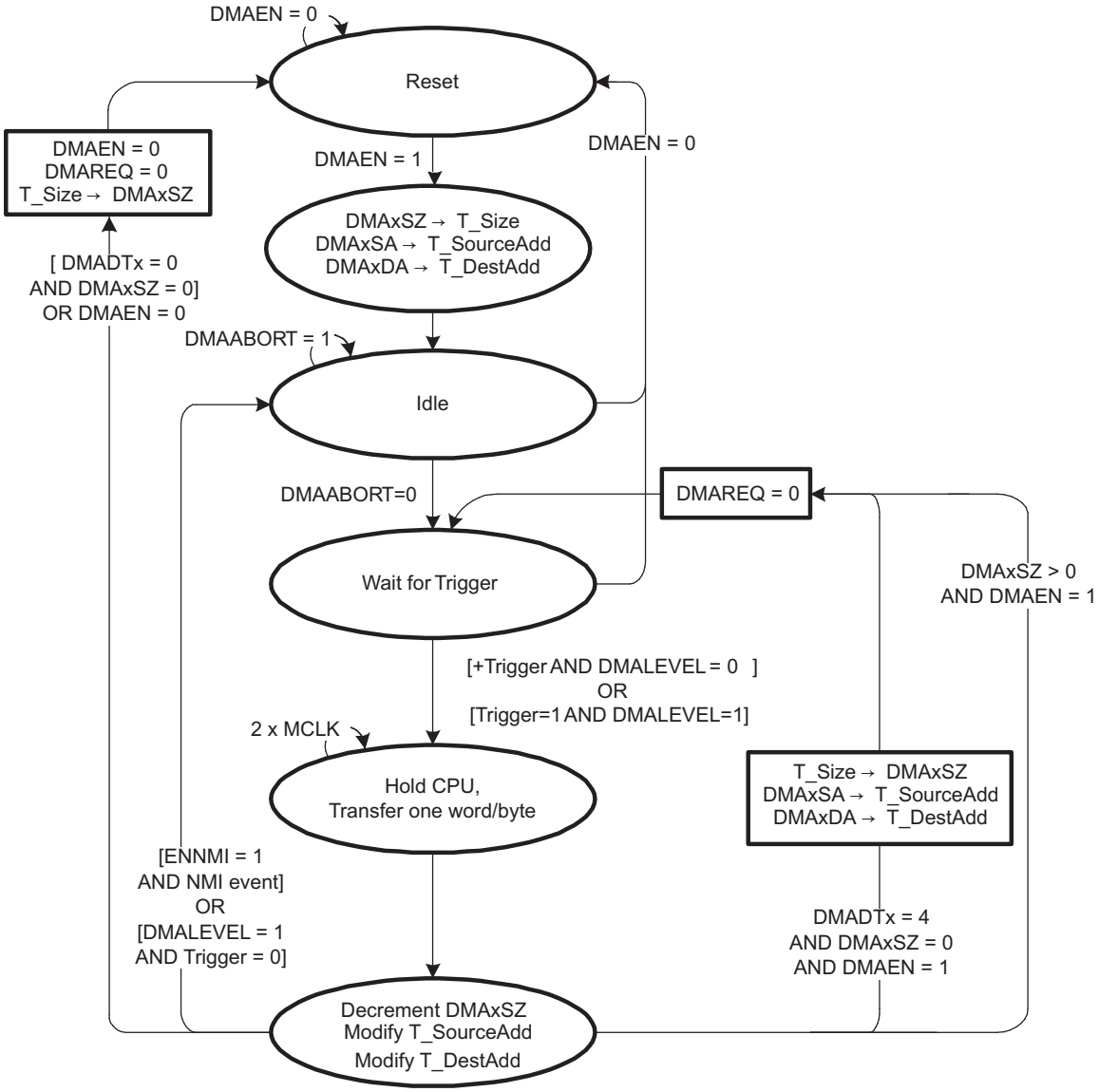


Figure 6-3. DMA Single Transfer State Diagram

6.2.2.2 Block Transfers

In block transfer mode, a transfer of a complete block of data occurs after one trigger. When DMADTx = 1, the DMAEN bit is cleared after the completion of the block transfer and must be set again before another block transfer can be triggered. After a block transfer has been triggered, further trigger signals occurring during the block transfer are ignored. The block transfer state diagram is shown in Figure 6-4.

The DMAxSZ register is used to define the size of the block and the DMADSTINCRx and DMASRCINCRx bits select if the destination address and the source address are incremented or decremented after each transfer of the block. If DMAxSZ = 0, no transfers occur.

The DMAxSA, DMAxDA, and DMAxSZ registers are copied into temporary registers. The temporary values of DMAxSA and DMAxDA are incremented or decremented after each transfer in the block. The DMAxSZ register is decremented after each transfer of the block and shows the number of transfers remaining in the block. When the DMAxSZ register decrements to zero it is reloaded from its temporary register and the corresponding DMAIFG flag is set.

During a block transfer, the CPU is halted until the complete block has been transferred. The block transfer takes 2 x MCLK x DMAxSZ clock cycles to complete. CPU execution resumes with its previous state after the block transfer is complete.

In repeated block transfer mode, the DMAEN bit remains set after completion of the block transfer. The next trigger after the completion of a repeated block transfer triggers another block transfer.

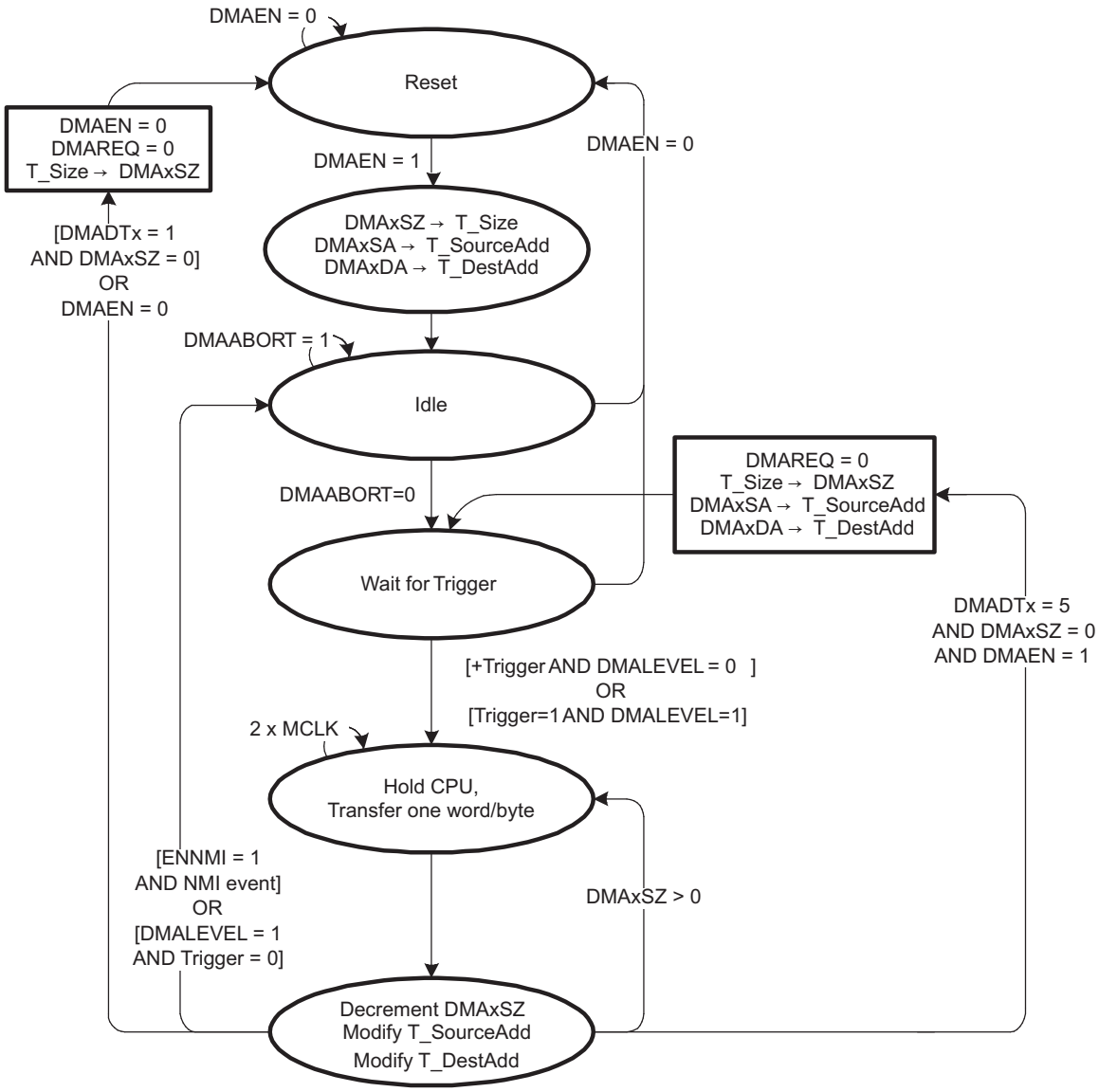


Figure 6-4. DMA Block Transfer State Diagram

6.2.2.3 Burst-Block Transfers

In burst-block mode, transfers are block transfers with CPU activity interleaved. The CPU executes 2 MCLK cycles after every four byte/word transfers of the block resulting in 20% CPU execution capacity. After the burst-block, CPU execution resumes at 100% capacity and the DMAEN bit is cleared. DMAEN must be set again before another burst-block transfer can be triggered. After a burst-block transfer has been triggered, further trigger signals occurring during the burst-block transfer are ignored. The burst-block transfer state diagram is shown in Figure 6-5.

The DMAxSZ register is used to define the size of the block and the DMADSTINCRx and DMASRCINCRx bits select if the destination address and the source address are incremented or decremented after each transfer of the block. If DMAxSZ = 0, no transfers occur.

The DMAxSA, DMAxDA, and DMAxSZ registers are copied into temporary registers. The temporary values of DMAxSA and DMAxDA are incremented or decremented after each transfer in the block. The DMAxSZ register is decremented after each transfer of the block and shows the number of transfers remaining in the block. When the DMAxSZ register decrements to zero it is reloaded from its temporary register and the corresponding DMAIFG flag is set.

In repeated burst-block mode the DMAEN bit remains set after completion of the burst-block transfer and no further trigger signals are required to initiate another burst-block transfer. Another burst-block transfer begins immediately after completion of a burst-block transfer. In this case, the transfers must be stopped by clearing the DMAEN bit, or by an NMI interrupt when ENNMI is set. In repeated burst-block mode the CPU executes at 20% capacity continuously until the repeated burst-block transfer is stopped.

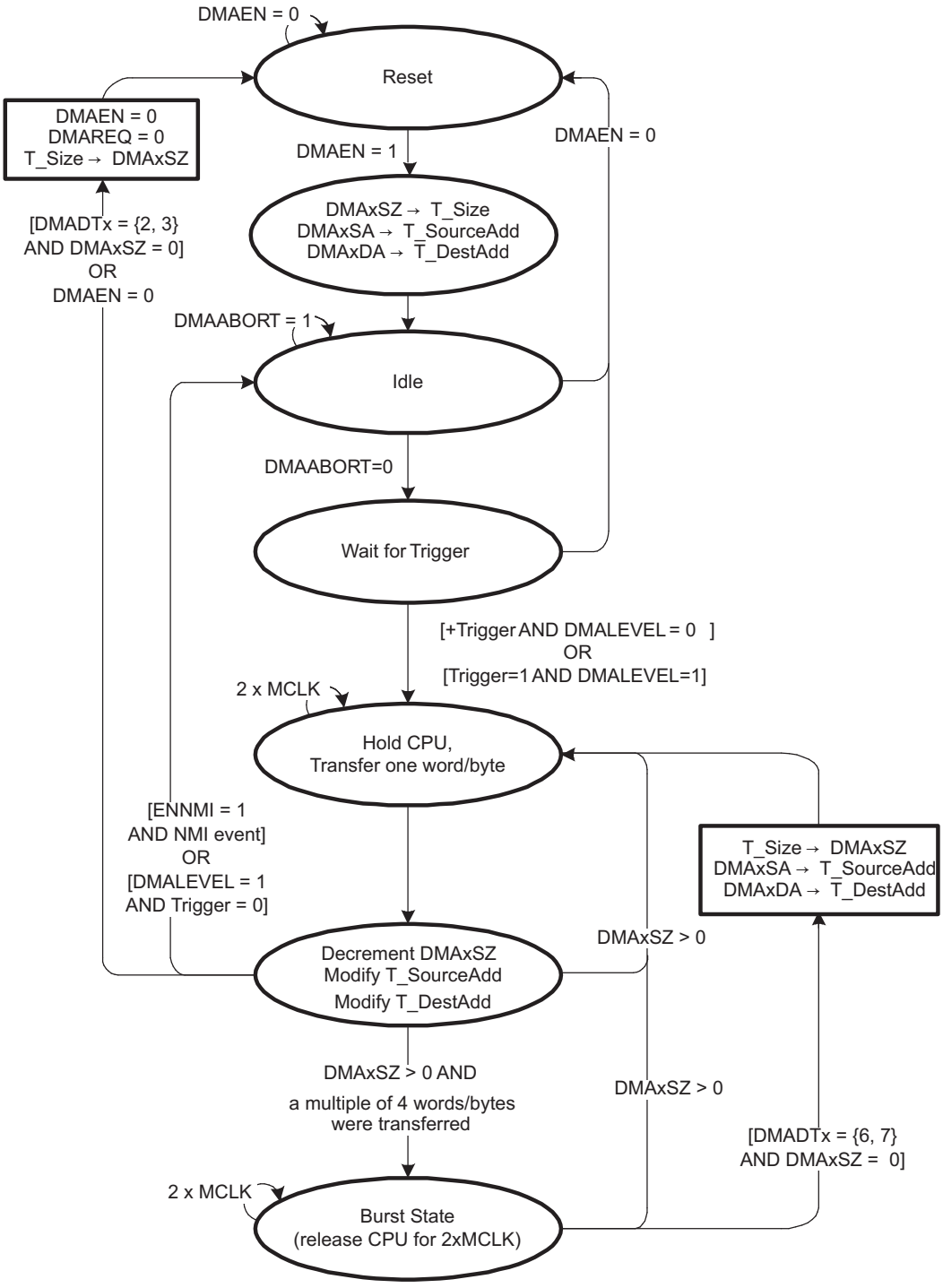


Figure 6-5. DMA Burst-Block Transfer State Diagram

6.2.3 Initiating DMA Transfers

Each DMA channel is independently configured for its trigger source with the DMAxTSELx bits as described in Table 6-2. The DMAxTSELx bits should be modified only when the DMACTLx DMAEN bit is 0. Otherwise, unpredictable DMA triggers may occur.

When selecting the trigger, the trigger must not have already occurred, or the transfer will not take place. For example, if the TACCR2 CCIFG bit is selected as a trigger, and it is already set, no transfer will occur until the next time the TACCR2 CCIFG bit is set.

6.2.3.1 Edge-Sensitive Triggers

When DMALEVEL = 0, edge-sensitive triggers are used and the rising edge of the trigger signal initiates the transfer. In single-transfer mode, each transfer requires its own trigger. When using block or burst-block modes, only one trigger is required to initiate the block or burst-block transfer.

6.2.3.2 Level-Sensitive Triggers

When DMALEVEL = 1, level-sensitive triggers are used. For proper operation, level-sensitive triggers can only be used when external trigger DMAE0 is selected as the trigger. DMA transfers are triggered as long as the trigger signal is high and the DMAEN bit remains set.

The trigger signal must remain high for a block or burst-block transfer to complete. If the trigger signal goes low during a block or burst-block transfer, the DMA controller is held in its current state until the trigger goes back high or until the DMA registers are modified by software. If the DMA registers are not modified by software, when the trigger signal goes high again, the transfer resumes from where it was when the trigger signal went low.

When DMALEVEL = 1, transfer modes selected when DMADTx = {0, 1, 2, 3} are recommended because the DMAEN bit is automatically reset after the configured transfer.

6.2.3.3 Halting Executing Instructions for DMA Transfers

The DMAONFETCH bit controls when the CPU is halted for a DMA transfer. When DMAONFETCH = 0, the CPU is halted immediately and the transfer begins when a trigger is received. When DMAONFETCH = 1, the CPU finishes the currently executing instruction before the DMA controller halts the CPU and the transfer begins.

NOTE: DMAONFETCH Must Be Used When The DMA Writes To Flash

If the DMA controller is used to write to flash memory, the DMAONFETCH bit must be set. Otherwise, unpredictable operation can result.

Table 6-2. DMA Trigger Operation

DMAxTSELx	Operation
0000	A transfer is triggered when the DMAREQ bit is set. The DMAREQ bit is automatically reset when the transfer starts
0001	A transfer is triggered when the TACCR2 CCIFG flag is set. The TACCR2 CCIFG flag is automatically reset when the transfer starts. If the TACCR2 CCIE bit is set, the TACCR2 CCIFG flag will not trigger a transfer.
0010	A transfer is triggered when the TBCCR2 CCIFG flag is set. The TBCCR2 CCIFG flag is automatically reset when the transfer starts. If the TBCCR2 CCIE bit is set, the TBCCR2 CCIFG flag will not trigger a transfer.
0011	A transfer is triggered when serial interface receives new data. Devices with USCI_A0 module: A transfer is triggered when USCI_A0 receives new data. UCA0RXIFG is automatically reset when the transfer starts. If UCA0RXIE is set, the UCA0RXIFG flag will not trigger a transfer.
0100	A transfer is triggered when serial interface is ready to transmit new data. Devices with USCI_A0 module: A transfer is triggered when USCI_A0 is ready to transmit new data. UCA0TXIFG is automatically reset when the transfer starts. If UCA0TXIE is set, the UCA0TXIFG flag will not trigger a transfer.

Table 6-2. DMA Trigger Operation (continued)

DMAxTSELx	Operation
0101	A transfer is triggered when the DAC12_0CTL DAC12IFG flag is set. The DAC12_0CTL DAC12IFG flag is automatically cleared when the transfer starts. If the DAC12_0CTL DAC12IE bit is set, the DAC12_0CTL DAC12IFG flag will not trigger a transfer.
0110	A transfer is triggered by an ADC12IFGx flag. When single-channel conversions are performed, the corresponding ADC12IFGx is the trigger. When sequences are used, the ADC12IFGx for the last conversion in the sequence is the trigger. A transfer is triggered when the conversion is completed and the ADC12IFGx is set. Setting the ADC12IFGx with software will not trigger a transfer. All ADC12IFGx flags are automatically reset when the associated ADC12MEMx register is accessed by the DMA controller.
0111	A transfer is triggered when the TACCR0 CCIFG flag is set. The TACCR0 CCIFG flag is automatically reset when the transfer starts. If the TACCR0 CCIE bit is set, the TACCR0 CCIFG flag will not trigger a transfer.
1000	A transfer is triggered when the TBCCR0 CCIFG flag is set. The TBCCR0 CCIFG flag is automatically reset when the transfer starts. If the TBCCR0 CCIE bit is set, the TBCCR0 CCIFG flag will not trigger a transfer.
1001	A transfer is triggered when the UCA1RXIFG flag is set. UCA1RXIFG is automatically reset when the transfer starts. If URXIE1 is set, the UCA1RXIFG flag will not trigger a transfer.
1010	A transfer is triggered when the UCA1TXIFG flag is set. UCA1TXIFG is automatically reset when the transfer starts. If UTXIE1 is set, the UCA1TXIFG flag will not trigger a transfer.
1011	A transfer is triggered when the hardware multiplier is ready for a new operand.
1100	No transfer is triggered. Devices with USCI_B0 module: A transfer is triggered when USCI_B0 receives new data. UCB0RXIFG is automatically reset when the transfer starts. If UCB0RXIE is set, the UCB0RXIFG flag will not trigger a transfer.
1101	No transfer is triggered. Devices with USCI_B0 module: A transfer is triggered when USCI_B0 is ready to transmit new data. UCB0TXIFG is automatically reset when the transfer starts. If UCB0TXIE is set, the UCB0TXIFG flag will not trigger a transfer.
1110	A transfer is triggered when the DMAxIFG flag is set. DMA0IFG triggers channel 1, DMA1IFG triggers channel 2, and DMA2IFG triggers channel 0. None of the DMAxIFG flags are automatically reset when the transfer starts.
1111	A transfer is triggered by the external trigger DMAE0.

6.2.4 Stopping DMA Transfers

There are two ways to stop DMA transfers in progress:

- A single, block, or burst-block transfer may be stopped with an NMI interrupt, if the ENNMI bit is set in register DMACTL1.
- A burst-block transfer may be stopped by clearing the DMAEN bit.

6.2.5 DMA Channel Priorities

The default DMA channel priorities are DMA0-DMA1-DMA2. If two or three triggers happen simultaneously or are pending, the channel with the highest priority completes its transfer (single, block or burst-block transfer) first, then the second priority channel, then the third priority channel. Transfers in progress are not halted if a higher priority channel is triggered. The higher priority channel waits until the transfer in progress completes before starting.

The DMA channel priorities are configurable with the ROUNDROBIN bit. When the ROUNDROBIN bit is set, the channel that completes a transfer becomes the lowest priority. The *order* of the priority of the channels always stays the same, DMA0-DMA1-DMA2 (see Table 6-3).

Table 6-3. Channel Priorities

DMA Priority	Transfer Occurs	New DMA Priority
DMA0 - DMA1 - DMA2	DMA1	DMA2 - DMA0 - DMA1
DMA2 - DMA0 - DMA1	DMA2	DMA0 - DMA1 - DMA2
DMA0 - DMA1 - DMA2	DMA0	DMA1 - DMA2 - DMA0

When the ROUNDROBIN bit is cleared the channel priority returns to the default priority.

6.2.6 DMA Transfer Cycle Time

The DMA controller requires one or two MCLK clock cycles to synchronize before each single transfer or complete block or burst-block transfer. Each byte/word transfer requires two MCLK cycles after synchronization, and one cycle of wait time after the transfer. Because the DMA controller uses MCLK, the DMA cycle time is dependent on the MSP430 operating mode and clock system setup.

If the MCLK source is active, but the CPU is off, the DMA controller will use the MCLK source for each transfer, without re-enabling the CPU. If the MCLK source is off, the DMA controller will temporarily restart MCLK, sourced with DCOCLK, for the single transfer or complete block or burst-block transfer. The CPU remains off, and after the transfer completes, MCLK is turned off. The maximum DMA cycle time for all operating modes is shown in Table 6-4.

Table 6-4. Maximum Single-Transfer DMA Cycle Time

CPU Operating Mode	Clock Source	Maximum DMA Cycle Time
Active mode	MCLK = DCOCLK	4 MCLK cycles
Active mode	MCLK = LFXT1CLK	4 MCLK cycles
Low-power mode LPM0/1	MCLK = DCOCLK	5 MCLK cycles
Low-power mode LPM3/4	MCLK = DCOCLK	5 MCLK cycles + 6 µs(1)
Low-power mode LPM0/1	MCLK = LFXT1CLK	5 MCLK cycles
Low-power mode LPM3	MCLK = LFXT1CLK	5 MCLK cycles
Low-power mode LPM4	MCLK = LFXT1CLK	5 MCLK cycles + 6 µs(1)

(1) The additional 6 µs are needed to start the DCOCLK. It is the $t_{(LPMx)}$ parameter in the data sheet.

6.2.7 Using DMA With System Interrupts

DMA transfers are not interruptible by system interrupts. System interrupts remain pending until the completion of the transfer. NMI interrupts can interrupt the DMA controller if the ENNMI bit is set.

System interrupt service routines are interrupted by DMA transfers. If an interrupt service routine or other routine must execute with no interruptions, the DMA controller should be disabled prior to executing the routine.

6.2.8 DMA Controller Interrupts

Each DMA channel has its own DMAIFG flag. Each DMAIFG flag is set in any mode, when the corresponding DMAxSZ register counts to zero. If the corresponding DMAIE and GIE bits are set, an interrupt request is generated.

All DMAIFG flags source only one DMA controller interrupt vector and, on some devices, the interrupt vector may be shared with other modules. Please refer to the device specific datasheet for further details. For these devices, software must check the DMAIFG and respective module flags to determine the source of the interrupt. The DMAIFG flags are not reset automatically and must be reset by software.

Additionally, some devices utilize the DMAIV register. All DMAIFG flags are prioritized, with DMA0IFG being the highest, and combined to source a single interrupt vector. The highest priority enabled interrupt generates a number in the DMAIV register. This number can be evaluated or added to the program counter to automatically enter the appropriate software routine. Disabled DMA interrupts do not affect the DMAIV value.

Any access, read or write, of the DMAIV register automatically resets the highest pending interrupt flag. If another interrupt flag is set, another interrupt is immediately generated after servicing the initial interrupt. For example, assume that DMA0 has the highest priority. If the DMA0IFG and DMA2IFG flags are set when the interrupt service routine accesses the DMAIV register, DMA0IFG is reset automatically. After the RETI instruction of the interrupt service routine is executed, the DMA2IFG will generate another interrupt.

The following software example shows the recommended use of DMAIV and the handling overhead. The DMAIV value is added to the PC to automatically jump to the appropriate routine.

The numbers at the right margin show the necessary CPU cycles for each instruction. The software overhead for different interrupt sources includes interrupt latency and return-from-interrupt cycles, but not the task handling itself.

Example 6-1. DMAIV Software Example

```
;Interrupt handler for DMA0IFG, DMA1IFG, DMA2IFG     Cycles
DMA_HND  ...              ; Interrupt latency           6
         ADD   &DMAIV,PC  ; Add offset to Jump table    3
         RETI             ; Vector  0: No interrupt     5
         JMP   DMA0_HND   ; Vector  2: DMA channel 0    2
         JMP   DMA1_HND   ; Vector  4: DMA channel 1    2
         JMP   DMA2_HND   ; Vector  6: DMA channel 2    2
         RETI             ; Vector  8: Reserved         5
         RETI             ; Vector 10: Reserved         5
         RETI             ; Vector 12: Reserved         5
         RETI             ; Vector 14: Reserved         5

DMA2_HND                  ; Vector 6: DMA channel 2
         ...              ; Task starts here
         RETI             ; Back to main program        5

DMA1_HND                  ; Vector 4: DMA channel 1
         ...              ; Task starts here
         RETI             ; Back to main program        5

DMA0_HND                  ; Vector 2: DMA channel 0
         ...              ; Task starts here
         RETI             ; Back to main program        5
```

6.2.9 Using the USCI_B I²C Module with the DMA Controller

The USCI_B I²C module provides two trigger sources for the DMA controller. The USCI_B I²C module can trigger a transfer when new I²C data is received and when data is needed for transmit.

A transfer is triggered if UCB0RXIFG is set. The UCB0RXIFG is cleared automatically when the DMA controller acknowledges the transfer. If UCB0RXIE is set, UCB0RXIFG will not trigger a transfer.

A transfer is triggered if UCB0TXIFG is set. The UCB0TXIFG is cleared automatically when the DMA controller acknowledges the transfer. If UCB0TXIE is set, UCB0TXIFG will not trigger a transfer.

6.2.10 Using ADC12 with the DMA Controller

MSP430 devices with an integrated DMA controller can automatically move data from any ADC12MEMx register to another location. DMA transfers are done without CPU intervention and independently of any low-power modes. The DMA controller increases throughput of the ADC12 module, and enhances low-power applications allowing the CPU to remain off while data transfers occur.

DMA transfers can be triggered from any ADC12IFGx flag. When CONSEQx = {0,2} the ADC12IFGx flag for the ADC12MEMx used for the conversion can trigger a DMA transfer. When CONSEQx = {1,3}, the ADC12IFGx flag for the last ADC12MEMx in the sequence can trigger a DMA transfer. Any ADC12IFGx flag is automatically cleared when the DMA controller accesses the corresponding ADC12MEMx.

6.2.11 Using DAC12 With the DMA Controller

MSP430 devices with an integrated DMA controller can automatically move data to the DAC12_xDAT register. DMA transfers are done without CPU intervention and independently of any low-power modes. The DMA controller increases throughput to the DAC12 module, and enhances low-power applications allowing the CPU to remain off while data transfers occur.

Applications requiring periodic waveform generation can benefit from using the DMA controller with the DAC12. For example, an application that produces a sinusoidal waveform may store the sinusoid values in a table. The DMA controller can continuously and automatically transfer the values to the DAC12 at specific intervals creating the sinusoid with zero CPU execution. The DAC12_xCTL DAC12IFG flag is automatically cleared when the DMA controller accesses the DAC12_xDAT register.

6.2.12 Writing to Flash With the DMA Controller

MSP430 devices with an integrated DMA controller can automatically move data to the Flash memory. DMA transfers are done without CPU intervention and independent of any low-power modes. The DMA controller performs the move of the data word/byte to the Flash. The write timing control is done by the Flash controller. Write transfers to the Flash memory succeed if the Flash controller is set up prior to the DMA transfer and if the Flash is not busy. To set up the Flash controller for write accesses, see the *Flash Memory Controller* chapter.

6.3 DMA Registers

The DMA registers are listed in Table 6-5.

Table 6-5. DMA Registers

Register	Short Form	Register Type	Address	Initial State
DMA control 0	DMACTL0	Read/write	0122h	Reset with POR
DMA control 1	DMACTL1	Read/write	0124h	Reset with POR
DMA interrupt vector	DMAIV	Read only	0126h	Reset with POR
DMA channel 0 control	DMA0CTL	Read/write	01D0h	Reset with POR
DMA channel 0 source address	DMA0SA	Read/write	01D2h	Unchanged
DMA channel 0 destination address	DMA0DA	Read/write	01D6h	Unchanged
DMA channel 0 transfer size	DMA0SZ	Read/write	01DAh	Unchanged
DMA channel 1 control	DMA1CTL	Read/write	01DCh	Reset with POR
DMA channel 1 source address	DMA1SA	Read/write	01DEh	Unchanged
DMA channel 1 destination address	DMA1DA	Read/write	01E2h	Unchanged
DMA channel 1 transfer size	DMA1SZ	Read/write	01E6h	Unchanged
DMA channel 2 control	DMA2CTL	Read/write	01E8h	Reset with POR
DMA channel 2 source address	DMA2SA	Read/write	01EAh	Unchanged
DMA channel 2 destination address	DMA2DA	Read/write	01EEh	Unchanged
DMA-channel 2 transfer size	DMA2SZ	Read/write	01F2h	Unchanged

6.3.1 DMACTL0, DMA Control Register 0

15	14	13	12	11	10	9	8
Reserved				**DMA2TSELx**			
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
DMA1TSELx				**DMA0TSELx**			
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Reserved Bits 15-12 Reserved

DMA2TSELx Bits 11-8 DMA trigger select. These bits select the DMA transfer trigger.

0000	DMAREQ bit (software trigger)
0001	TACCR2 CCIFG bit
0010	TBCCR2 CCIFG bit
0011	Serial data received UCA0RXIFG
0100	Serial data transmit ready UCA0TXIFG
0101	DAC12_0CTL DAC12IFG bit
0110	ADC12 ADC12IFGx bit
0111	TACCR0 CCIFG bit
1000	TBCCR0 CCIFG bit
1001	Serial data received UCA1RXIFG
1010	Serial data transmit ready UCA1TXIFG
1011	Multiplier ready
1100	Serial data received UCB0RXIFG
1101	Serial data transmit ready UCB0TXIFG
1110	DMA0IFG bit triggers DMA channel 1 DMA1IFG bit triggers DMA channel 2 DMA2IFG bit triggers DMA channel 0
1111	External trigger DMAE0

DMA1TSELx Bits 7-4 Same as DMA2TSELx

DMA0TSELx Bits 3-0 Same as DMA2TSELx

6.3.2 DMACTL1, DMA Control Register 1

15	14	13	12	11	10	9	8
0	**0**	**0**	**0**	**0**	**0**	**0**	**0**
r0	r0	r0	r0	r0	r0	r0	r0
7	6	5	4	3	2	1	0
0	**0**	**0**	**0**	**0**	**DMAON FETCH**	**ROUND ROBIN**	**ENNMI**
r0	r0	r0	r0	r0	rw-(0)	rw-(0)	rw-(0)

Reserved Bits 15-3 Reserved. Read only. Always read as 0.

DMAONFETCH Bit 2 DMA on fetch

0	The DMA transfer occurs immediately.
1	The DMA transfer occurs on next instruction fetch after the trigger.

ROUNDROBIN Bit 1 Round robin. This bit enables the round-robin DMA channel priorities.

0	DMA channel priority is DMA0 - DMA1 - DMA2
1	DMA channel priority changes with each transfer

ENNMI Bit 0 Enable NMI. This bit enables the interruption of a DMA transfer by an NMI interrupt. When an NMI interrupts a DMA transfer, the current transfer is completed normally, further transfers are stopped, and DMAABORT is set.

0	NMI interrupt does not interrupt DMA transfer
1	NMI interrupt interrupts a DMA transfer

6.3.3 DMAxCTL, DMA Channel x Control Register

15	14	13	12	11	10	9	8
Reserved	**DMADTx**			**DMADSTINCRx**		**DMASRCINCRx**	
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
DMADST BYTE	**DMASRC BYTE**	**DMALEVEL**	**DMAEN**	**DMAIFG**	**DMAIE**	**DMAABORT**	**DMAREQ**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Reserved Bit 15 Reserved

DMADTx Bits 14-12 DMA Transfer mode.

000 Single transfer
001 Block transfer
010 Burst-block transfer
011 Burst-block transfer
100 Repeated single transfer
101 Repeated block transfer
110 Repeated burst-block transfer
111 Repeated burst-block transfer

DMADSTINCRx Bits 11-10 DMA destination increment. This bit selects automatic incrementing or decrementing of the destination address after each byte or word transfer. When DMADSTBYTE = 1, the destination address increments/decrements by one. When DMADSTBYTE = 0, the destination address increments/decrements by two. The DMAxDA is copied into a temporary register and the temporary register is incremented or decremented. DMAxDA is not incremented or decremented.

00 Destination address is unchanged
01 Destination address is unchanged
10 Destination address is decremented
11 Destination address is incremented

DMASRCINCRx Bits 9-8 DMA source increment. This bit selects automatic incrementing or decrementing of the source address for each byte or word transfer. When DMASRCBYTE = 1, the source address increments/decrements by one. When DMASRCBYTE = 0, the source address increments/decrements by two. The DMAxSA is copied into a temporary register and the temporary register is incremented or decremented. DMAxSA is not incremented or decremented.

00 Source address is unchanged
01 Source address is unchanged
10 Source address is decremented
11 Source address is incremented

DMADSTBYTE Bit 7 DMA destination byte. This bit selects the destination as a byte or word.

0 Word
1 Byte

DMASRCBYTE Bit 6 DMA source byte. This bit selects the source as a byte or word.

0 Word
1 Byte

DMALEVEL Bit 5 DMA level. This bit selects between edge-sensitive and level-sensitive triggers.

0 Edge sensitive (rising edge)
1 Level sensitive (high level)

DMAEN Bit 4 DMA enable

0 Disabled
1 Enabled

DMAIFG Bit 3 DMA interrupt flag

0 No interrupt pending
1 Interrupt pending

DMAIE Bit 2 DMA interrupt enable

0 Disabled
1 Enabled

DMAABORT	Bit 1	DMA Abort. This bit indicates if a DMA transfer was interrupt by an NMI. 0 DMA transfer not interrupted 1 DMA transfer was interrupted by NMI
DMAREQ	Bit 0	DMA request. Software-controlled DMA start. DMAREQ is reset automatically. 0 No DMA start 1 Start DMA

6.3.4 DMAxSA, DMA Source Address Register

15	14	13	12	11	10	9	8
Reserved							
r0	r0	r0	r0	r0	r0	r0	r0
7	6	5	4	3	2	1	0
Reserved				**DMAxSAx**			
r0	r0	r0	r0	rw	rw	rw	rw
15	14	13	12	11	10	9	8
DMAxSAx							
rw	rw	rw	rw	rw	rw	rw	rw
7	6	5	4	3	2	1	0
DMAxSAx							
rw	rw	rw	rw	rw	rw	rw	rw

DMAxSA	Bits 15-0	DMA source address The source address register points to the DMA source address for single transfers or the first source address for block transfers. The source address register remains unchanged during block and burst-block transfers. Devices that have addressable memory range 64 KB or below contain a single word for the DMAxSA. The upper word is automatically cleared when writing using word operations. Reads from this location are always read as zero. Devices that have addressable memory range beyond 64 KB contain an additional word for the source address. Bits 15-4 of this additional word are reserved and always read as zero. When writing to DMAxSA with word formats, this additional word is automatically cleared. Reads of this additional word using word formats, are always read as zero.

6.3.5 DMAxDA, DMA Destination Address Register

15	14	13	12	11	10	9	8
Reserved							
r0	r0	r0	r0	r0	r0	r0	r0
7	6	5	4	3	2	1	0
Reserved				DMAxDAx			
r0	r0	r0	r0	rw	rw	rw	rw
15	14	13	12	11	10	9	8
DMAxDAx							
rw	rw	rw	rw	rw	rw	rw	rw
7	6	5	4	3	2	1	0
DMAxDAx							
rw	rw	rw	rw	rw	rw	rw	rw

DMAxDA Bits 15-0 DMA destination address

The destination address register points to the DMA destination address for single transfers or the first destination address for block transfers. The destination address register remains unchanged during block and burst-block transfers.

Devices that have addressable memory range 64 KB or below contain a single word for the DMAxDA.

Devices that have addressable memory range beyond 64 KB contain an additional word for the destination address. Bits 15-4 of this additional word are reserved and always read as zero. When writing to DMAxDA with word formats, this additional word is automatically cleared. Reads of this additional word using word formats, are always read as zero.

6.3.6 DMAxSZ, DMA Size Address Register

15	14	13	12	11	10	9	8
DMAxSZx							
rw	rw	rw	rw	rw	rw	rw	rw
7	6	5	4	3	2	1	0
DMAxSZx							
rw	rw	rw	rw	rw	rw	rw	rw

DMAxSZx Bits 15-0 DMA size. The DMA size register defines the number of byte/word data per block transfer. DMAxSZ register decrements with each word or byte transfer. When DMAxSZ decrements to 0, it is immediately and automatically reloaded with its previously initialized value.

00000h	Transfer is disabled
00001h	One byte or word to be transferred
00002h	Two bytes or words have to be transferred
⋮	
0FFFFh	65535 bytes or words have to be transferred

6.3.7 DMAIV, DMA Interrupt Vector Register

15	14	13	12	11	10	9	8
0	**0**	**0**	**0**	**0**	**0**	**0**	**0**
r0	r0	r0	r0	r0	r0	r0	r0

7	6	5	4	3	2	1	0
0	**0**	**0**	**0**	**DMAIVx**			**0**
r0	r0	r0	r0	r--(0)	r--(0)	r--(0)	r0

DMAIVx Bits 15-0 DMA interrupt vector value

DMAIV Contents	Interrupt Source	Interrupt Flag	Interrupt Priority
00h	No interrupt pending	-	
02h	DMA channel 0	DMA0IFG	Highest
04h	DMA channel 1	DMA1IFG	
06h	DMA channel 2	DMA2IFG	
08h	Reserved	-	
0Ah	Reserved	-	
0Ch	Reserved	-	
0Eh	Reserved	-	Lowest

Flash Memory Controller

This chapter describes the operation of the MSP430x2xx flash memory controller.

Topic **Page**

7.1 Flash Memory Introduction

The MSP430 flash memory is bit-, byte-, and word-addressable and programmable. The flash memory module has an integrated controller that controls programming and erase operations. The controller has four registers, a timing generator, and a voltage generator to supply program and erase voltages.

MSP430 flash memory features include:

- Internal programming voltage generation
- Bit, byte, or word programmable
- Ultralow-power operation
- Segment erase and mass erase
- Marginal 0 and marginal 1 read mode (optional, see the device-specific data sheet)

Figure 7-1 shows the block diagram of the flash memory and controller.

NOTE: Minimum V_{cc} during flash write or erase

The minimum V_{cc} voltage during a flash write or erase operation is 2.2 V. If V_{cc} falls below 2.2 V during write or erase, the result of the write or erase is unpredictable.

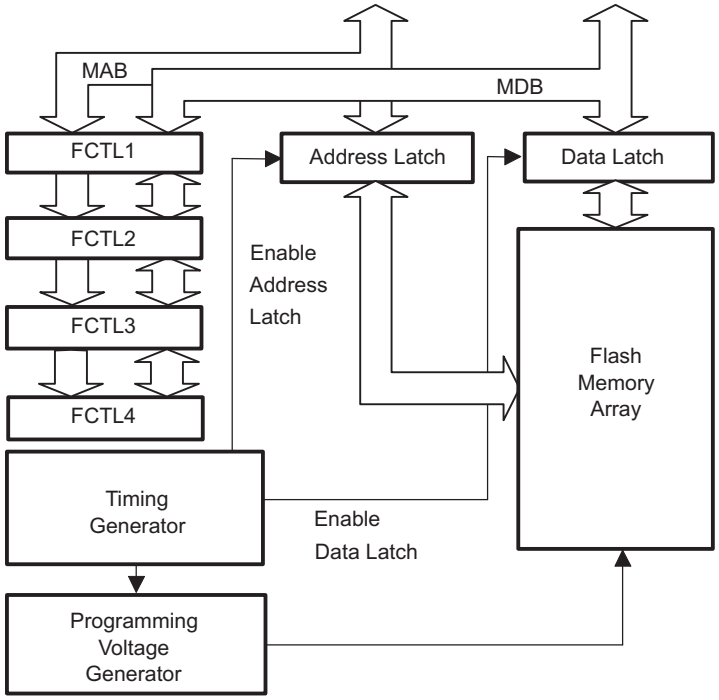


Figure 7-1. Flash Memory Module Block Diagram

7.2 Flash Memory Segmentation

MSP430 flash memory is partitioned into segments. Single bits, bytes, or words can be written to flash memory, but the segment is the smallest size of flash memory that can be erased.

The flash memory is partitioned into main and information memory sections. There is no difference in the operation of the main and information memory sections. Code or data can be located in either section. The differences between the two sections are the segment size and the physical addresses.

The information memory has four 64-byte segments. The main memory has one or more 512-byte segments. See the device-specific data sheet for the complete memory map of a device.

The segments are further divided into blocks.

Figure 7-2 shows the flash segmentation using an example of 32-KB flash that has eight main segments and four information segments.

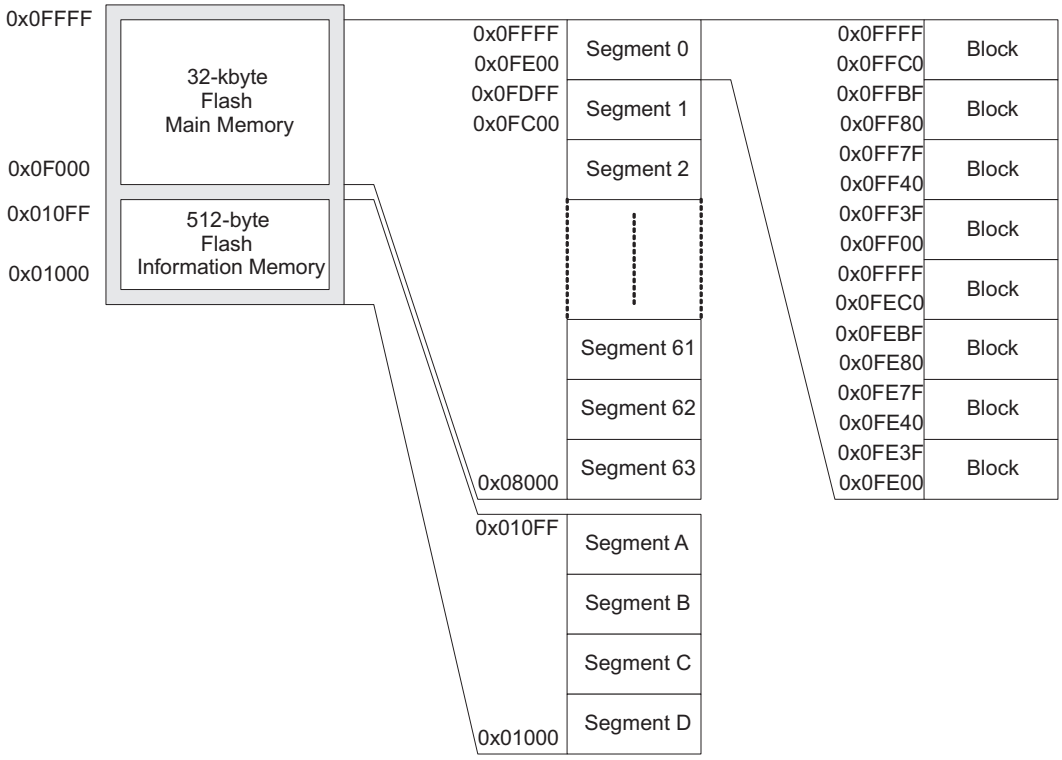


Figure 7-2. Flash Memory Segments, 32-KB Example

7.2.1 SegmentA

SegmentA of the information memory is locked separately from all other segments with the LOCKA bit. When LOCKA = 1, SegmentA cannot be written or erased and all information memory is protected from erasure during a mass erase or production programming. When LOCKA = 0, SegmentA can be erased and written as any other flash memory segment, and all information memory is erased during a mass erase or production programming.

The state of the LOCKA bit is toggled when a 1 is written to it. Writing a 0 to LOCKA has no effect. This allows existing flash programming routines to be used unchanged.

```
; Unlock SegmentA
   BIT   #LOCKA,&FCTL3          ; Test LOCKA
   JZ    SEGA_UNLOCKED          ; Already unlocked?
   MOV   #FWKEY+LOCKA,&FCTL3    ; No, unlock SegmentA
SEGA_UNLOCKED                   ; Yes, continue
; SegmentA is unlocked

; Lock SegmentA
   BIT   #LOCKA,&FCTL3          ; Test LOCKA
   JNZ   SEGA_LOCKED            ; Already locked?
   MOV   #FWKEY+LOCKA,&FCTL3    ; No, lock SegmentA
SEGA_LOCKED                     ; Yes, continue
; SegmentA is locked
```

7.3 Flash Memory Operation

The default mode of the flash memory is read mode. In read mode, the flash memory is not being erased or written, the flash timing generator and voltage generator are off, and the memory operates identically to ROM.

MSP430 flash memory is in-system programmable (ISP) without the need for additional external voltage. The CPU can program its own flash memory. The flash memory write and erase modes are selected with the BLKWRT, WRT, MERAS, and ERASE bits and are:

- Byte or word write
- Block write
- Segment erase
- Mass erase (all main memory segments)
- All erase (all segments)

Reading from or writing to flash memory while it is being programmed or erased is prohibited. If CPU execution is required during the write or erase, the code to be executed must be in RAM. Any flash update can be initiated from within flash memory or RAM.

7.3.1 Flash Memory Timing Generator

Write and erase operations are controlled by the flash timing generator shown in Figure 7-3. The flash timing generator operating frequency, f_{FTG}, must be in the range from approximately 257 kHz to approximately 476 kHz (see device-specific data sheet).

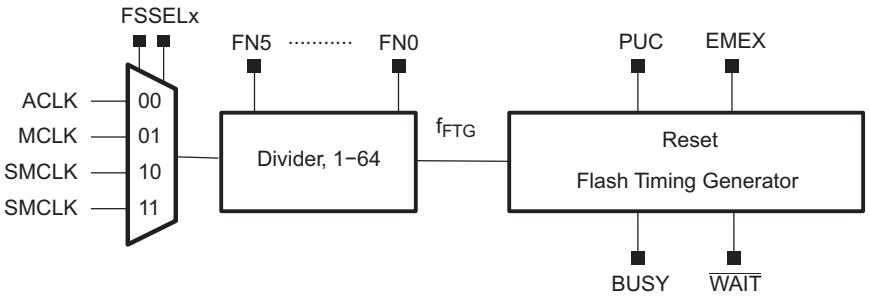


Figure 7-3. Flash Memory Timing Generator Block Diagram

7.3.1.1 Flash Timing Generator Clock Selection

The flash timing generator can be sourced from ACLK, SMCLK, or MCLK. The selected clock source should be divided using the FNx bits to meet the frequency requirements for f_{FTG}. If the f_{FTG} frequency deviates from the specification during the write or erase operation, the result of the write or erase may be unpredictable, or the flash memory may be stressed above the limits of reliable operation.

If a clock failure is detected during a write or erase operation, the operation is aborted, the FAIL flag is set, and the result of the operation is unpredictable.

While a write or erase operation is active the selected clock source can not be disabled by putting the MSP430 into a low-power mode. The selected clock source remains active until the operation is completed before being disabled.

7.3.2 Erasing Flash Memory

The erased level of a flash memory bit is 1. Each bit can be programmed from 1 to 0 individually but to reprogram from 0 to 1 requires an erase cycle. The smallest amount of flash that can be erased is a segment. There are three erase modes selected with the ERASE and MERAS bits listed in Table 7-1.

Table 7-1. Erase Modes

MERAS	ERASE	Erase Mode
0	1	Segment erase
1	0	Mass erase (all main memory segments)
1	1	LOCKA = 0: Erase main and information flash memory. LOCKA = 1: Erase only main flash memory.

Any erase is initiated by a dummy write into the address range to be erased. The dummy write starts the flash timing generator and the erase operation. Figure 7-4 shows the erase cycle timing. The BUSY bit is set immediately after the dummy write and remains set throughout the erase cycle. BUSY, MERAS, and ERASE are automatically cleared when the cycle completes. The erase cycle timing is not dependent on the amount of flash memory present on a device. Erase cycle times are equivalent for all MSP430F2xx and MSP430G2xx devices.

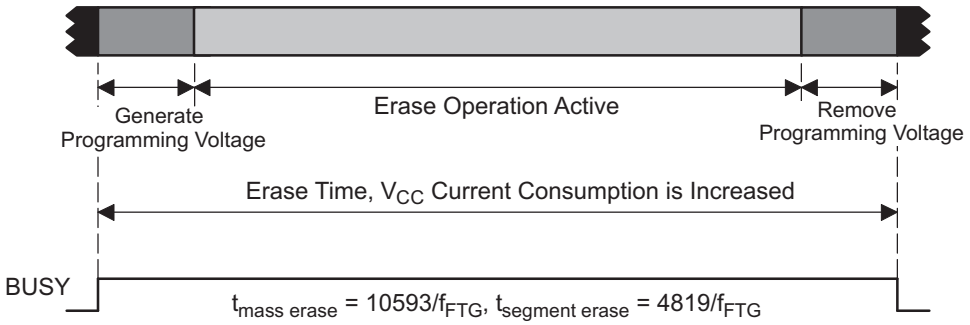


Figure 7-4. Erase Cycle Timing

A dummy write to an address not in the range to be erased does not start the erase cycle, does not affect the flash memory, and is not flagged in any way. This errant dummy write is ignored.

7.3.2.1 Initiating an Erase from Within Flash Memory

Any erase cycle can be initiated from within flash memory or from RAM. When a flash segment erase operation is initiated from within flash memory, all timing is controlled by the flash controller, and the CPU is held while the erase cycle completes. After the erase cycle completes, the CPU resumes code execution with the instruction following the dummy write.

When initiating an erase cycle from within flash memory, it is possible to erase the code needed for execution after the erase. If this occurs, CPU execution is unpredictable after the erase cycle.

The flow to initiate an erase from flash is shown in Figure 7-5.

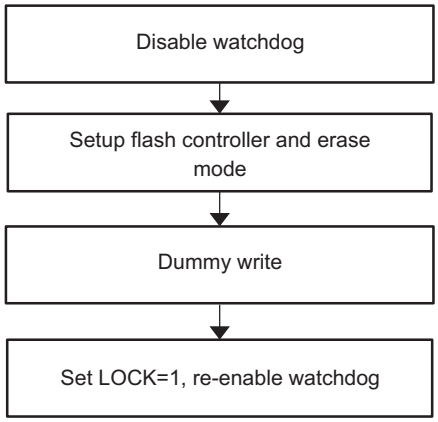


Figure 7-5. Erase Cycle from Within Flash Memory

```
; Segment Erase from flash. 514 kHz < SMCLK < 952 kHz
; Assumes ACCVIE = NMIIE = OFIE = 0.
   MOV      #WDTPW+WDTHOLD,&WDTCTL     ; Disable WDT
   MOV      #FWKEY+FSSEL1+FN0,&FCTL2   ; SMCLK/2
   MOV      #FWKEY, &FCTL3             ; Clear LOCK
   MOV      #FWKEY+ERASE, &FCTL1       ; Enable segment erase
   CLR      &0FC10h                    ; Dummy write, erase S1
   MOV      #FWKEY+LOCK, &FCTL3        ; Done, set LOCK
   ...                                 ; Re-enable WDT?
```

7.3.2.2 Initiating an Erase from RAM

Any erase cycle may be initiated from RAM. In this case, the CPU is not held and can continue to execute code from RAM. The BUSY bit must be polled to determine the end of the erase cycle before the CPU can access any flash address again. If a flash access occurs while BUSY = 1, it is an access violation, ACCVIFG is set, and the erase results are unpredictable.

The flow to initiate an erase from flash from RAM is shown in Figure 7-6.

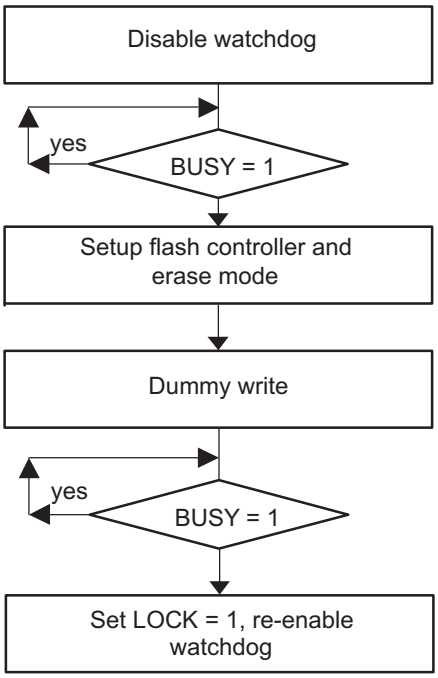


Figure 7-6. Erase Cycle from Within RAM

```
; Segment Erase from RAM. 514 kHz < SMCLK < 952 kHz
; Assumes ACCVIE = NMIIE = OFIE = 0.
     MOV   #WDTPW+WDTHOLD,&WDTCTL      ; Disable WDT
L1   BIT   #BUSY, &FCTL3               ; Test BUSY
     JNZ   L1                          ; Loop while busy
     MOV   #FWKEY+FSSEL1+FN0, &FCTL2   ; SMCLK/2
     MOV   #FWKEY&FCTL3                ; Clear LOCK
     MOV   #FWKEY+ERASE, &FCTL1        ; Enable erase
     CLR   &0FC10h                     ; Dummy write, erase S1
L2   BIT   #BUSY, &FCTL3               ; Test BUSY
     JNZ   L2                          ; Loop while busy
     MOV   #FWKEY+LOCK&FCTL3           ; Done, set LOCK
     ...                               ; Re-enable WDT?
```

7.3.3 Writing Flash Memory

The write modes, selected by the WRT and BLKWRT bits, are listed in Table 7-2.

Table 7-2. Write Modes

BLKWRT	WRT	Write Mode
0	1	Byte or word write
1	1	Block write

Both write modes use a sequence of individual write instructions, but using the block write mode is approximately twice as fast as byte or word mode, because the voltage generator remains on for the complete block write. Any instruction that modifies a destination can be used to modify a flash location in either byte or word write mode or block write mode. A flash word (low and high bytes) must not be written more than twice between erasures. Otherwise, damage can occur.

The BUSY bit is set while a write operation is active and cleared when the operation completes. If the write operation is initiated from RAM, the CPU must not access flash while BUSY = 1. Otherwise, an access violation occurs, ACCVIFG is set, and the flash write is unpredictable.

7.3.3.1 Byte or Word Write

A byte or word write operation can be initiated from within flash memory or from RAM. When initiating from within flash memory, all timing is controlled by the flash controller, and the CPU is held while the write completes. After the write completes, the CPU resumes code execution with the instruction following the write. The byte or word write timing is shown in Figure 7-7.

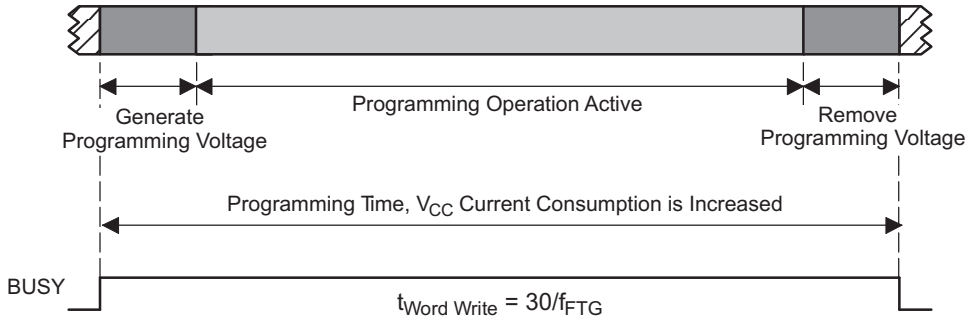


Figure 7-7. Byte or Word Write Timing

When a byte or word write is executed from RAM, the CPU continues to execute code from RAM. The BUSY bit must be zero before the CPU accesses flash again, otherwise an access violation occurs, ACCVIFG is set, and the write result is unpredictable.

In byte or word mode, the internally-generated programming voltage is applied to the complete 64-byte block, each time a byte or word is written, for 27 of the 30 f_{FTG} cycles. With each byte or word write, the amount of time the block is subjected to the programming voltage accumulates. The cumulative programming time, t_{CPT}, must not be exceeded for any block. If the cumulative programming time is met, the block must be erased before performing any further writes to any address within the block. See the device-specific data sheet for specifications.

7.3.3.2 Initiating a Byte or Word Write From Within Flash Memory

The flow to initiate a byte or word write from flash is shown in Figure 7-8.

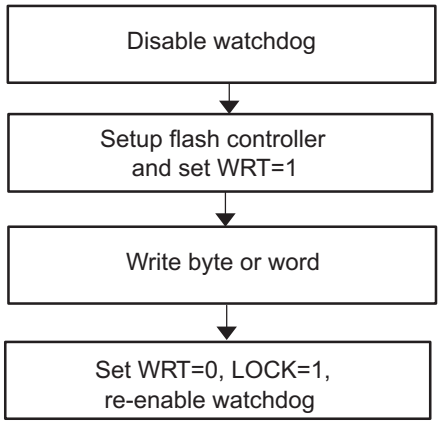


Figure 7-8. Initiating a Byte or Word Write From Flash

```
; Byte/word write from flash. 514 kHz < SMCLK < 952 kHz
; Assumes 0FF1Eh is already erased
; Assumes ACCVIE = NMIIE = OFIE = 0.
   MOV   #WDTPW+WDTHOLD,&WDTCTL     ; Disable WDT
   MOV   #FWKEY+FSSEL1+FN0,&FCTL2   ; SMCLK/2
   MOV   #FWKEY,&FCTL3              ; Clear LOCK
   MOV   #FWKEY+WRT,&FCTL1          ; Enable write
   MOV   #0123h,&0FF1Eh             ; 0123h    -> 0FF1Eh
   MOV   #FWKEY,&FCTL1              ; Done. Clear WRT
   MOV   #FWKEY+LOCK,&FCTL3         ; Set LOCK
   ...                              ; Re-enable WDT?
```

7.3.3.3 Initiating a Byte or Word Write From RAM

The flow to initiate a byte or word write from RAM is shown in Figure 7-9.

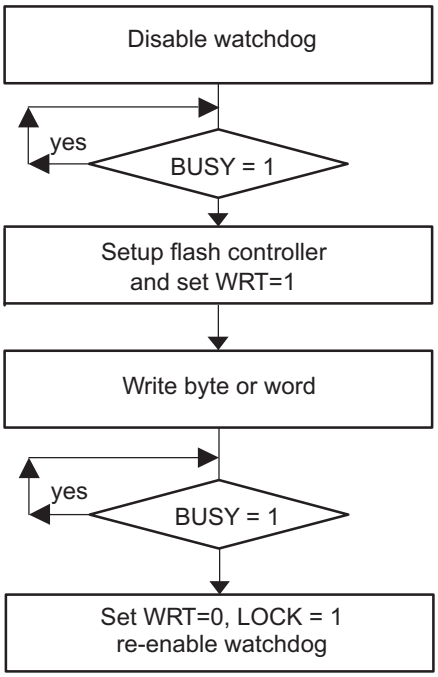


Figure 7-9. Initiating a Byte or Word Write from RAM

```
; Byte/word write from RAM. 514 kHz < SMCLK < 952 kHz
; Assumes 0FF1Eh is already erased
; Assumes ACCVIE = NMIIE = OFIE = 0.
     MOV   #WDTPW+WDTHOLD,&WDTCTL     ; Disable WDT
L1   BIT   #BUSY,&FCTL3               ; Test BUSY
     JNZ   L1                         ; Loop while busy
     MOV   #FWKEY+FSSEL1+FN0,&FCTL2   ; SMCLK/2
     MOV   #FWKEY,&FCTL3              ; Clear LOCK
     MOV   #FWKEY+WRT,&FCTL1          ; Enable write
     MOV   #0123h,&0FF1Eh             ; 0123h -> 0FF1Eh
L2   BIT   #BUSY,&FCTL3               ; Test BUSY
     JNZ   L2                         ; Loop while busy
     MOV   #FWKEY,&FCTL1              ; Clear WRT
     MOV   #FWKEY+LOCK,&FCTL3         ; Set LOCK
     ...                              ; Re-enable WDT?
```

7.3.3.4 Block Write

The block write can be used to accelerate the flash write process when many sequential bytes or words need to be programmed. The flash programming voltage remains on for the duration of writing the 64-byte block. The cumulative programming time t_{CPT} must not be exceeded for any block during a block write.

A block write cannot be initiated from within flash memory. The block write must be initiated from RAM only. The BUSY bit remains set throughout the duration of the block write. The WAIT bit must be checked between writing each byte or word in the block. When WAIT is set the next byte or word of the block can be written. When writing successive blocks, the BLKWRT bit must be cleared after the current block is complete. BLKWRT can be set initiating the next block write after the required flash recovery time given by t_{end}. BUSY is cleared following each block write completion indicating the next block can be written. Figure 7-10 shows the block write timing.

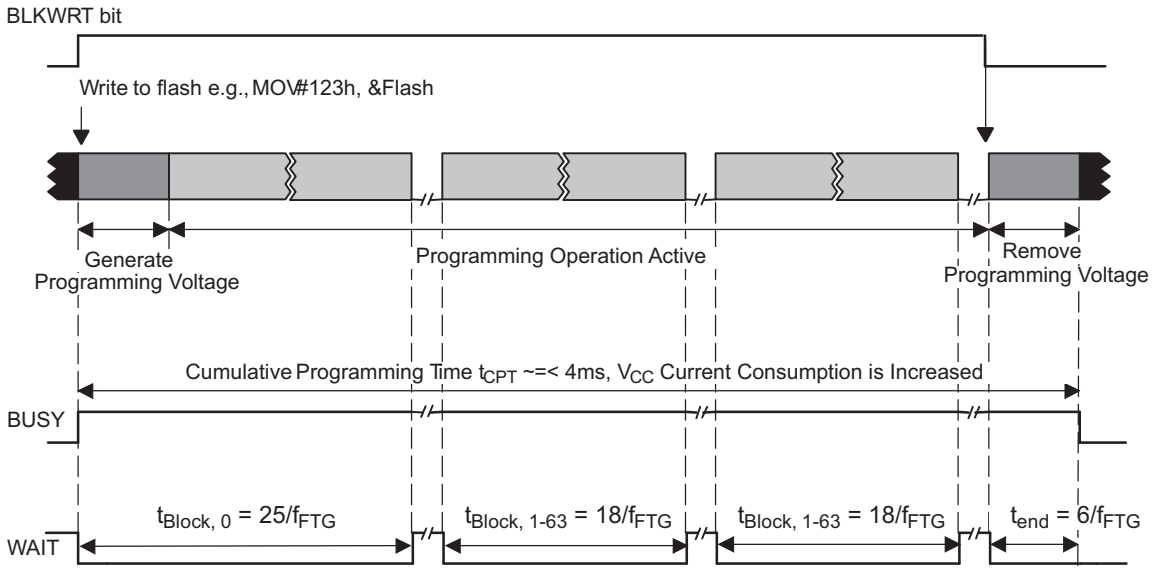


Figure 7-10. Block-Write Cycle Timing

7.3.3.5 Block Write Flow and Example

A block write flow is shown in Figure 7-11 and the following example.

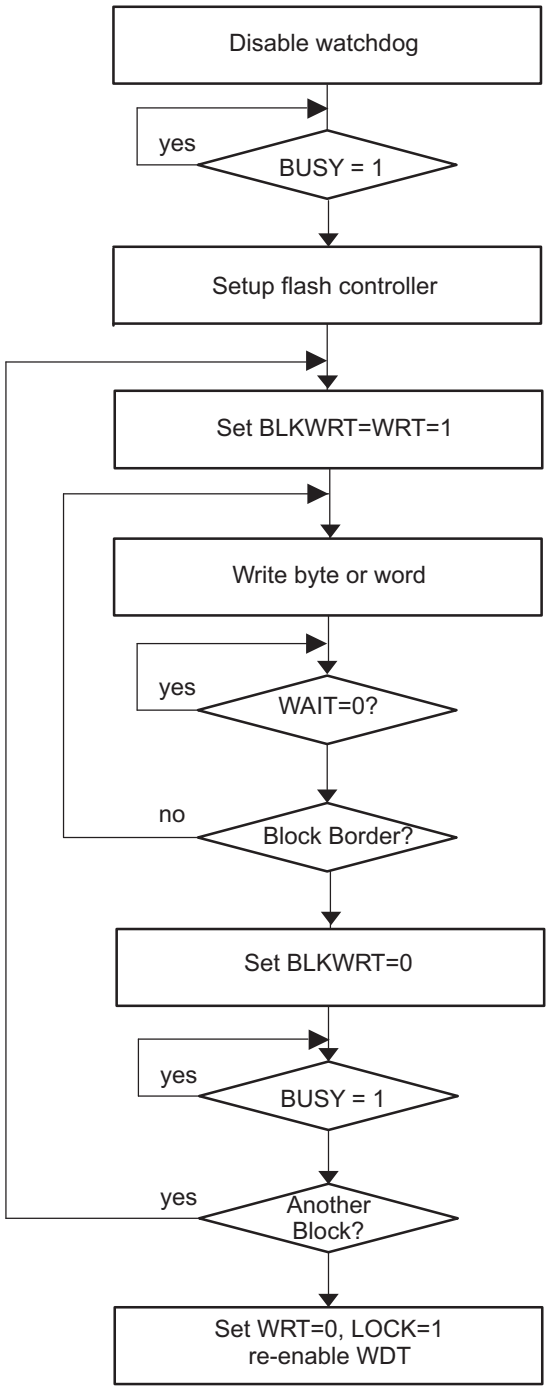


Figure 7-11. Block Write Flow

```
; Write one block starting at 0F000h.
; Must be executed from RAM, Assumes Flash is already erased.
; 514 kHz < SMCLK < 952 kHz
; Assumes ACCVIE = NMIIE = OFIE = 0.
     MOV    #32,R5                    ; Use as write counter
     MOV    #0F000h,R6                ; Write pointer
     MOV    #WDTPW+WDTHOLD,&WDTCTL    ; Disable WDT
L1   BIT    #BUSY,&FCTL3              ; Test BUSY
     JNZ    L1                        ; Loop while busy
     MOV    #FWKEY+FSSEL1+FN0,&FCTL2  ; SMCLK/2
     MOV    #FWKEY,&FCTL3             ; Clear LOCK
     MOV    #FWKEY+BLKWRT+WRT,&FCTL1  ; Enable block write
L2   MOV    Write_Value,0(R6)         ; Write location
L3   BIT    #WAIT,&FCTL3              ; Test WAIT
     JZ     L3                        ; Loop while WAIT = 0
     INCD   R6                        ; Point to next word
     DEC    R5                        ; Decrement write counter
     JNZ    L2                        ; End of block?
     MOV    #FWKEY,&FCTL1             ; Clear WRT,BLKWRT
L4   BIT    #BUSY,&FCTL3              ; Test BUSY
     JNZ    L4                        ; Loop while busy
     MOV    #FWKEY+LOCK,&FCTL3        ; Set LOCK
     ...                              ; Re-enable WDT if needed
```

7.3.4 Flash Memory Access During Write or Erase

When any write or any erase operation is initiated from RAM and while BUSY = 1, the CPU may not read or write to or from any flash location. Otherwise, an access violation occurs, ACCVIFG is set, and the result is unpredictable. Also if a write to flash is attempted with WRT = 0, the ACCVIFG interrupt flag is set, and the flash memory is unaffected.

When a byte or word write or any erase operation is initiated from within flash memory, the flash controller returns op-code 03FFFh to the CPU at the next instruction fetch. Op-code 03FFFh is the JMP PC instruction. This causes the CPU to loop until the flash operation is finished. When the operation is finished and BUSY = 0, the flash controller allows the CPU to fetch the proper op-code and program execution resumes.

The flash access conditions while BUSY = 1 are listed in Table 7-3.

Table 7-3. Flash Access While BUSY = 1

Flash Operation	Flash Access	WAIT	Result
Any erase, or byte or word write	Read	0	ACCVIFG = 0. 03FFFh is the value read.
	Write	0	ACCVIFG = 1. Write is ignored.
	Instruction fetch	0	ACCVIFG = 0. CPU fetches 03FFFh. This is the JMP PC instruction.
Block write	Any	0	ACCVIFG = 1, LOCK = 1
	Read	1	ACCVIFG = 0. 03FFFh is the value read.
	Write	1	ACCVIFG = 0. Write is written.
	Instruction fetch	1	ACCVIFG = 1, LOCK = 1

Interrupts are automatically disabled during any flash operation when EEI = 0 and EEIEX = 0 and on MSP430x20xx and MSP430G2xx devices where EEI and EEIEX are not present. After the flash operation has completed, interrupts are automatically re-enabled. Any interrupt that occurred during the operation has its associated flag set and generates an interrupt request when re-enabled.

When EEIEX = 1 and GIE = 1, an interrupt immediately aborts any flash operation and the FAIL flag is set. When EEI = 1, GIE = 1, and EEIEX = 0, a segment erase is interrupted by a pending interrupt every 32 f_{FTG} cycles. After servicing the interrupt, the segment erase is continued for at least 32 f_{FTG} cycles or until it is complete. During the servicing of the interrupt, the BUSY bit remains set but the flash memory can be accessed by the CPU without causing an access violation occurs. Nested interrupts and using the RETI instruction inside interrupt service routines are not supported.

The watchdog timer (in watchdog mode) should be disabled before a flash erase cycle. A reset aborts the erase and the results are unpredictable. After the erase cycle has completed, the watchdog may be re-enabled.

7.3.5 Stopping a Write or Erase Cycle

Any write or erase operation can be stopped before its normal completion by setting the emergency exit bit EMEX. Setting the EMEX bit stops the active operation immediately and stops the flash controller. All flash operations cease, the flash returns to read mode, and all bits in the FCTL1 register are reset. The result of the intended operation is unpredictable.

7.3.6 Marginal Read Mode

The marginal read mode can be used to verify the integrity of the flash memory contents. This feature is implemented in selected 2xx devices; see the device-specific data sheet for availability. During marginal read mode marginally programmed flash memory bit locations can be detected. Events that could produce this situation include improper f_{FTG} settings, or violation of minimum V_{CC} during erase or program operations. One method for identifying such memory locations would be to periodically perform a checksum calculation over a section of flash memory (for example, a flash segment) and repeating this procedure with the marginal read mode enabled. If they do not match, it could indicate an insufficiently programmed flash memory location. It is possible to refresh the affected Flash memory segment by disabling marginal read mode, copying to RAM, erasing the flash segment, and writing back to it from RAM.

The program checking the flash memory contents must be executed from RAM. Executing code from flash automatically disables the marginal read mode. The marginal read modes are controlled by the MRG0 and MRG1 register bits. Setting MRG1 is used to detect insufficiently programmed flash cells containing a 1 (erased bits). Setting MRG0 is used to detect insufficiently programmed flash cells containing a 0 (programmed bits). Only one of these bits should be set at a time. Therefore, a full marginal read check requires two passes of checking the flash memory content's integrity. During marginal read mode, the flash access speed (MCLK) must be limited to 1 MHz (see the device-specific data sheet).

7.3.7 Configuring and Accessing the Flash Memory Controller

The FCTLx registers are 16-bit password-protected read/write registers. Any read or write access must use word instructions and write accesses must include the write password 0A5h in the upper byte. Any write to any FCTLx register with any value other than 0A5h in the upper byte is a security key violation, sets the KEYV flag and triggers a PUC system reset. Any read of any FCTLx registers reads 096h in the upper byte.

Any write to FCTL1 during an erase or byte or word write operation is an access violation and sets ACCVIFG. Writing to FCTL1 is allowed in block write mode when WAIT = 1, but writing to FCTL1 in block write mode when WAIT = 0 is an access violation and sets ACCVIFG.

Any write to FCTL2 when the BUSY = 1 is an access violation.

Any FCTLx register may be read when BUSY = 1. A read does not cause an access violation.

7.3.8 Flash Memory Controller Interrupts

The flash controller has two interrupt sources, KEYV, and ACCVIFG. ACCVIFG is set when an access violation occurs. When the ACCVIE bit is re-enabled after a flash write or erase, a set ACCVIFG flag generates an interrupt request. ACCVIFG sources the NMI interrupt vector, so it is not necessary for GIE to be set for ACCVIFG to request an interrupt. ACCVIFG may also be checked by software to determine if an access violation occurred. ACCVIFG must be reset by software.

The key violation flag KEYV is set when any of the flash control registers are written with an incorrect password. When this occurs, a PUC is generated immediately resetting the device.

7.3.9 Programming Flash Memory Devices

There are three options for programming an MSP430 flash device. All options support in-system programming:

- Program via JTAG
- Program via the bootstrap loader
- Program via a custom solution

7.3.9.1 Programming Flash Memory via JTAG

MSP430 devices can be programmed via the JTAG port. The JTAG interface requires four signals (five signals on 20- and 28-pin devices), ground and, optionally, V_{CC} and $\overline{RST}$/NMI.

The JTAG port is protected with a fuse. Blowing the fuse completely disables the JTAG port and is not reversible. Further access to the device via JTAG is not possible. For details, see the *MSP430 Programming Via the JTAG Interface User's Guide* (SLAU320).

7.3.9.2 Programming Flash Memory via the Bootstrap Loader (BSL)

Most MSP430 flash devices contain a bootstrap loader. See the device-specific data sheet for implementation details. The BSL enables users to read or program the flash memory or RAM using a UART serial interface. Access to the MSP430 flash memory via the BSL is protected by a 256-bit user-defined password. For more details see the *MSP430 Programming Via the Bootstrap Loader User's Guide* (SLAU319).

7.3.9.3 Programming Flash Memory via a Custom Solution

The ability of the MSP430 CPU to write to its own flash memory allows for in-system and external custom programming solutions as shown in Figure 7-12. The user can choose to provide data to the MSP430 through any means available (UART, SPI, etc.). User-developed software can receive the data and program the flash memory. Since this type of solution is developed by the user, it can be completely customized to fit the application needs for programming, erasing, or updating the flash memory.

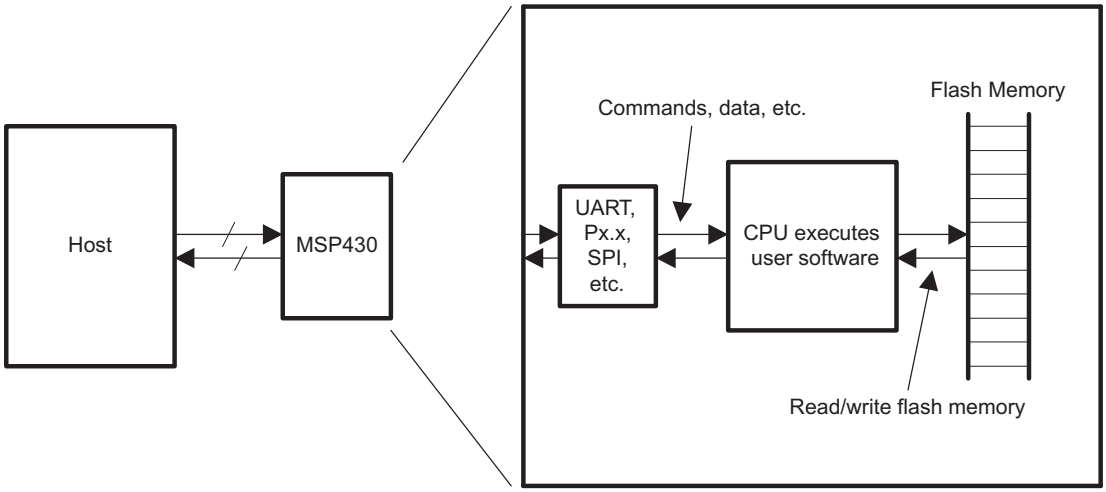


Figure 7-12. User-Developed Programming Solution

7.4 Flash Memory Registers

The flash memory registers are listed in Table 7-4.

Table 7-4. Flash Memory Registers

Register	Short Form	Register Type	Address	Initial State
Flash memory control register 1	FCTL1	Read/write	0x0128	0x9600 with PUC
Flash memory control register 2	FCTL2	Read/write	0x012A	0x9642 with PUC
Flash memory control register 3	FCTL3	Read/write	0x012C	0x9658 with PUC(1)
Flash memory control register 4(2)	FCTL4	Read/write	0x01BE	0x0000 with PUC
Interrupt Enable 1	IE1	Read/write	0x0000	Reset with PUC
Interrupt Flag 1	IFG1	Read/write	0x0002	

(1) KEYV is reset with POR.
(2) Not present in all devices. See device-specific data sheet.

7.4.1 FCTL1, Flash Memory Control Register

15	14	13	12	11	10	9	8
FRKEY, Read as 096h **FWKEY**, Must be written as 0A5h							

7	6	5	4	3	2	1	0
BLKWRT	**WRT**	**Reserved**	**EEIEX**(1)	**EEI**(1)	**MERAS**	**ERASE**	**Reserved**
rw-0	rw-0	r0	rw-0	rw-0	rw-0	rw-0	r0

FRKEY
FWKEY Bits 15-8 FCTLx password. Always reads as 096h. Must be written as 0A5h. Writing any other value generates a PUC.

BLKWRT Bit 7 Block write mode. WRT must also be set for block write mode. BLKWRT is automatically reset when EMEX is set.

0 Block-write mode is off

1 Block-write mode is on

WRT Bit 6 Write. This bit is used to select any write mode. WRT is automatically reset when EMEX is set.

0 Write mode is off

1 Write mode is on

Reserved Bit 5 Reserved. Always read as 0.

EEIEX Bit 4 Enable Emergency Interrupt Exit. Setting this bit enables an interrupt to cause an emergency exit from a flash operation when GIE = 1. EEIEX is automatically reset when EMEX is set.

0 Exit interrupt disabled.

1 Exit on interrupt enabled.

EEI Bits 3 Enable Erase Interrupts. Setting this bit allows a segment erase to be interrupted by an interrupt request. After the interrupt is serviced the erase cycle is resumed.

0 Interrupts during segment erase disabled.

1 Interrupts during segment erase enabled.

MERAS
ERASE Bit 2
Bit 1 Mass erase and erase. These bits are used together to select the erase mode. MERAS and ERASE are automatically reset when EMEX is set.

MERAS	ERASE	Erase Cycle
0	0	No erase
0	1	Erase individual segment only
1	0	Erase all main memory segments
1	1	LOCKA = 0: Erase main and information flash memory. LOCKA = 1: Erase only main flash memory.

Reserved Bit 0 Reserved. Always read as 0.

(1) Not present on MSP430x20xx and MSP430G2xx devices.

7.4.2 FCTL2, Flash Memory Control Register

15	14	13	12	11	10	9	8
FWKEYx, Read as 096h Must be written as 0A5h							

7	6	5	4	3	2	1	0
FSSELx		**FNx**					
rw-0	rw-1	rw-0	rw-0	rw-0	rw-0	rw-1	rw-0

FWKEYx Bits 15-8 FCTLx password. Always reads as 096h. Must be written as 0A5h. Writing any other value generates a PUC.

FSSELx Bits 7-6 Flash controller clock source select

00 ACLK

01 MCLK

10 SMCLK

11 SMCLK

FNx Bits 5-0 Flash controller clock divider. These six bits select the divider for the flash controller clock. The divisor value is FNx + 1. For example, when FNx = 00h, the divisor is 1. When FNx = 03Fh, the divisor is 64.

7.4.3 FCTL3, Flash Memory Control Register

15	14	13	12	11	10	9	8
FWKEYx, Read as 096h Must be written as 0A5h							

7	6	5	4	3	2	1	0
FAIL	**LOCKA**	**EMEX**	**LOCK**	**WAIT**	**ACCVIFG**	**KEYV**	**BUSY**
r(w)-0	r(w)-1	rw-0	rw-1	r-1	rw-0	rw-(0)	r(w)-0

FWKEYx Bits 15-8 FCTLx password. Always reads as 096h. Must be written as 0A5h. Writing any other value generates a PUC.

FAIL Bit 7 Operation failure. This bit is set if the fFTG clock source fails, or a flash operation is aborted from an interrupt when EEIEX = 1. FAIL must be reset with software.

0 No failure

1 Failure

LOCKA Bit 6 SegmentA and Info lock. Write a 1 to this bit to change its state. Writing 0 has no effect.

0 Segment A unlocked and all information memory is erased during a mass erase.

1 Segment A locked and all information memory is protected from erasure during a mass erase.

EMEX Bit 5 Emergency exit

0 No emergency exit

1 Emergency exit

LOCK Bit 4 Lock. This bit unlocks the flash memory for writing or erasing. The LOCK bit can be set any time during a byte or word write or erase operation, and the operation completes normally. In the block write mode if the LOCK bit is set while BLKWRT = WAIT = 1, then BLKWRT and WAIT are reset and the mode ends normally.

0 Unlocked

1 Locked

WAIT Bit 3 Wait. Indicates the flash memory is being written to.

0 The flash memory is not ready for the next byte/word write

1 The flash memory is ready for the next byte/word write

ACCVIFG Bit 2 Access violation interrupt flag

0 No interrupt pending

1 Interrupt pending

KEYV Bit 1 Flash security key violation. This bit indicates an incorrect FCTLx password was written to any flash control register and generates a PUC when set. KEYV must be reset with software.

0 FCTLx password was written correctly

1 FCTLx password was written incorrectly

BUSY Bit 0 Busy. This bit indicates the status of the flash timing generator.

0 Not Busy

1 Busy

7.4.4 FCTL4, Flash Memory Control Register

This register is not available in all devices. See the device-specific data sheet for details.

15	14	13	12	11	10	9	8
FWKEYx, Read as 096h Must be written as 0A5h							

7	6	5	4	3	2	1	0
		MRG1	**MRG0**				
r-0	r-0	rw-0	rw-0	r-0	r-0	r-0	r-0

FWKEYx	Bits 15-8	FCTLx password. Always reads as 096h. Must be written as 0A5h. Writing any other value generates a PUC.
Reserved	Bits 7-6	Reserved. Always read as 0.
MRG1	Bit 5	Marginal read 1 mode. This bit enables the marginal 1 read mode. The marginal read 1 bit is cleared if the CPU starts execution from the flash memory. If both MRG1 and MRG0 are set MRG1 is active and MRG0 is ignored. 0 Marginal 1 read mode is disabled. 1 Marginal 1 read mode is enabled.
MRG0	Bit 4	Marginal read 0 mode. This bit enables the marginal 0 read mode. The marginal mode 0 is cleared if the CPU starts execution from the flash memory. If both MRG1 and MRG0 are set MRG1 is active and MRG0 is ignored. 0 Marginal 0 read mode is disabled. 1 Marginal 0 read mode is enabled.
Reserved	Bits 3-0	Reserved. Always read as 0.

7.4.5 IE1, Interrupt Enable Register 1

7	6	5	4	3	2	1	0
		ACCVIE					
		rw-0					

	Bits 7-6	These bits may be used by other modules. See the device-specific data sheet.
ACCVIE	Bit 5	Flash memory access violation interrupt enable. This bit enables the ACCVIFG interrupt. Because other bits in IE1 may be used for other modules, it is recommended to set or clear this bit using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions. 0 Interrupt not enabled 1 Interrupt enabled
	Bits 4-0	These bits may be used by other modules. See the device-specific data sheet.

Digital I/O

This chapter describes the operation of the digital I/O ports.

Topic **Page**

8.1 Digital I/O Introduction

MSP430 devices have up to eight digital I/O ports implemented, P1 to P8. Each port has up to eight I/O pins. Every I/O pin is individually configurable for input or output direction, and each I/O line can be individually read or written to.

Ports P1 and P2 have interrupt capability. Each interrupt for the P1 and P2 I/O lines can be individually enabled and configured to provide an interrupt on a rising edge or falling edge of an input signal. All P1 I/O lines source a single interrupt vector, and all P2 I/O lines source a different, single interrupt vector.

The digital I/O features include:

- Independently programmable individual I/Os
- Any combination of input or output
- Individually configurable P1 and P2 interrupts
- Independent input and output data registers
- Individually configurable pullup or pulldown resistors
- Individually configurable pin-oscillator function (some MSP430 devices)

NOTE: **MSP430G22x0** : These devices feature digital I/O pins P1.2, P1.5, P1.6 and P1.7. The GPIOs P1.0, P1.1, P1.3, P1.4, P2.6, and P2.7 are implemented on this device but not available on the device pin-out. To avoid floating inputs, these GPIOs, these digital I/Os should be properly initialized by running a start-up code. See initialization code below:
mov.b #0x1B, P1REN; ; Terminate unavailable Port1 pins properly ; Config as Input with pull-down enabled
xor.b #0x20, BCSCTL3; ; Select VLO as low freq clock
The initialization code configures GPIOs P1.0, P1.1, P1.3, and P1.4 as inputs with pull-down resistor enabled (that is, P1REN.x = 1) and GPIOs P2.6 and P2.7 are terminated by selecting VLOCLK as ACLK – see the Basic Clock System chapter for details. The register bits of P1.0, P1.1, P1.3, and P1.4 in registers P1OUT, P1DIR, P1IFG, P1IE, P1IES, P1SEL and P1REN should not be altered after the initialization code is executed. Also, all Port2 registers are should not be altered.

8.2 Digital I/O Operation

The digital I/O is configured with user software. The setup and operation of the digital I/O is discussed in the following sections.

8.2.1 Input Register PxIN

Each bit in each PxIN register reflects the value of the input signal at the corresponding I/O pin when the pin is configured as I/O function.

Bit = 0: The input is low

Bit = 1: The input is high

NOTE: **Writing to Read-Only Registers PxIN**

Writing to these read-only registers results in increased current consumption while the write attempt is active.

8.2.2 Output Registers PxOUT

Each bit in each PxOUT register is the value to be output on the corresponding I/O pin when the pin is configured as I/O function, output direction, and the pullup/down resistor is disabled.

Bit = 0: The output is low

Bit = 1: The output is high

If the pin's pullup/pulldown resistor is enabled, the corresponding bit in the PxOUT register selects pullup or pulldown.

Bit = 0: The pin is pulled down

Bit = 1: The pin is pulled up

8.2.3 Direction Registers PxDIR

Each bit in each PxDIR register selects the direction of the corresponding I/O pin, regardless of the selected function for the pin. PxDIR bits for I/O pins that are selected for other functions must be set as required by the other function.

Bit = 0: The port pin is switched to input direction

Bit = 1: The port pin is switched to output direction

8.2.4 Pullup/Pulldown Resistor Enable Registers PxREN

Each bit in each PxREN register enables or disables the pullup/pulldown resistor of the corresponding I/O pin. The corresponding bit in the PxOUT register selects if the pin is pulled up or pulled down.

Bit = 0: Pullup/pulldown resistor disabled

Bit = 1: Pullup/pulldown resistor enabled

8.2.5 Function Select Registers PxSEL and PxSEL2

Port pins are often multiplexed with other peripheral module functions. See the device-specific data sheet to determine pin functions. Each PxSEL and PxSEL2 bit is used to select the pin function - I/O port or peripheral module function.

Table 8-1. PxSEL and PxSEL2

PxSEL2	PxSEL	Pin Function
0	0	I/O function is selected.
0	1	Primary peripheral module function is selected.
1	0	Reserved. See device-specific data sheet.
1	1	Secondary peripheral module function is selected.

Setting PxSELx = 1 does not automatically set the pin direction. Other peripheral module functions may require the PxDIRx bits to be configured according to the direction needed for the module function. See the pin schematics in the device-specific data sheet.

NOTE: Setting PxREN = 1 When PxSEL = 1

On some I/O ports on the MSP430F261x and MSP430F2416/7/8/9, enabling the pullup/pulldown resistor (PxREN = 1) while the module function is selected (PxSEL = 1) does not disable the logic output driver. This combination is not recommended and may result in unwanted current flow through the internal resistor. See the device-specific data sheet pin schematics for more information.

```
;Output ACLK on P2.0 on MSP430F21x1
  BIS.B   #01h,&P2SEL   ; Select ACLK function for pin
  BIS.B   #01h,&P2DIR   ; Set direction to output *Required*
```

NOTE: P1 and P2 Interrupts Are Disabled When PxSEL = 1

When any P1SELx or P2SELx bit is set, the corresponding pin's interrupt function is disabled. Therefore, signals on these pins will not generate P1 or P2 interrupts, regardless of the state of the corresponding P1IE or P2IE bit.

When a port pin is selected as an input to a peripheral, the input signal to the peripheral is a latched representation of the signal at the device pin. While PxSELx = 1, the internal input signal follows the signal at the pin. However, if the PxSELx = 0, the input to the peripheral maintains the value of the input signal at the device pin before the PxSELx bit was reset.

8.2.6 Pin Oscillator

Some MSP430 devices have a pin oscillator function built-in to some pins. The pin oscillator function may be used in capacitive touch sensing applications to eliminate external passive components. Additionally, the pin oscillator may be used in sensor applications.

- No external components to create the oscillation
- Capacitive sensors can be connected directly to MSP430 pin
- Robust, typical built-in hysteresis of ~0.7 V

When the pin oscillator function is enabled, other pin configurations are overwritten. The output driver is turned off while the weak pullup/pulldown is enabled and controlled by the voltage level on the pin itself. The voltage on the I/O is fed into the Schmitt trigger of the pin and then routed to a timer. The connection to the timer is device specific and, thus, defined in the device-specific data sheet. The Schmitt-trigger output is inverted and then decides if the pullup or the pulldown is enabled. Due to the inversion, the pin starts to oscillate as soon as the pin oscillator pin configuration is selected. Some of the pin-oscillator outputs are combined by a logical OR before routing to a timer clock input or timer capture channel. Therefore, only one pin oscillator should be enabled at a time. The oscillation frequency of each pin is defined by the load on the pin and by the I/O type. I/Os with analog functions typically show a lower oscillation frequency than pure digital I/Os. See the device-specific data sheet for details. Pins without external load show typical oscillation frequencies of 1 MHz to 3 MHz.

Pin oscillator in a cap touch application

A typical touch pad application using the pin oscilator is shown in Figure 8-1.

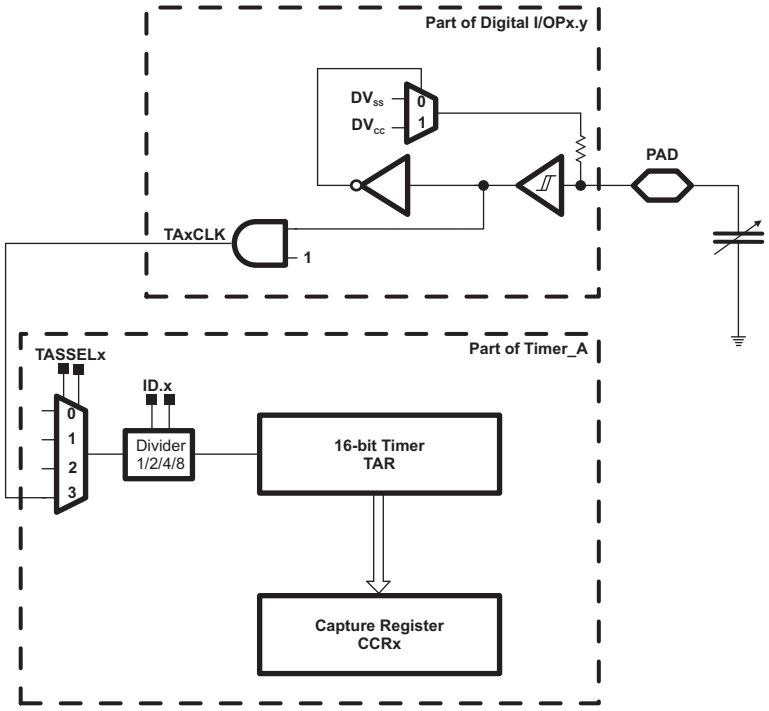


Figure 8-1. Example Circuitry and Configuration using the Pin Oscillator

A change of the capacitance of the touch pad (external capacitive load) has an effect on the pin oscillator frequency. An approaching finger tip increases the capacitance of the touch pad thus leads to a lower self-oscillation frequency due to the longer charging time. The oscillation frequency can directly be captured in a built-in Timer channel. The typical sensitivity of a pin is shown in Figure 8-2.

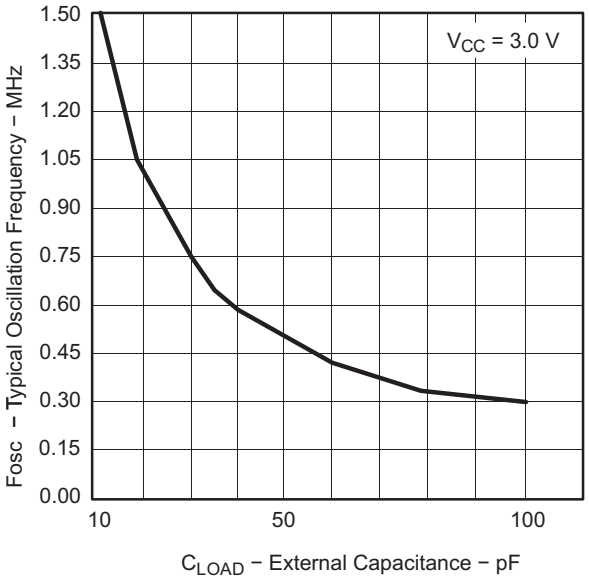


Figure 8-2. Typical Pin-Oscillation Frequency

8.2.7 P1 and P2 Interrupts

Each pin in ports P1 and P2 have interrupt capability, configured with the PxIFG, PxIE, and PxIES registers. All P1 pins source a single interrupt vector, and all P2 pins source a different single interrupt vector. The PxIFG register can be tested to determine the source of a P1 or P2 interrupt.

8.2.7.1 Interrupt Flag Registers P1IFG, P2IFG

Each PxIFGx bit is the interrupt flag for its corresponding I/O pin and is set when the selected input signal edge occurs at the pin. All PxIFGx interrupt flags request an interrupt when their corresponding PxIE bit and the GIE bit are set. Each PxIFG flag must be reset with software. Software can also set each PxIFG flag, providing a way to generate a software initiated interrupt.

Bit = 0: No interrupt is pending

Bit = 1: An interrupt is pending

Only transitions, not static levels, cause interrupts. If any PxIFGx flag becomes set during a Px interrupt service routine, or is set after the RETI instruction of a Px interrupt service routine is executed, the set PxIFGx flag generates another interrupt. This ensures that each transition is acknowledged.

NOTE: PxIFG Flags When Changing PxOUT or PxDIR

Writing to P1OUT, P1DIR, P2OUT, or P2DIR can result in setting the corresponding P1IFG or P2IFG flags.

8.2.7.2 Interrupt Edge Select Registers P1IES, P2IES

Each PxIES bit selects the interrupt edge for the corresponding I/O pin.

Bit = 0: The PxIFGx flag is set with a low-to-high transition

Bit = 1: The PxIFGx flag is set with a high-to-low transition

NOTE: Writing to PxIESx

Writing to P1IES, or P2IES can result in setting the corresponding interrupt flags.

PxIESx	PxINx	PxIFGx
0 → 1	0	May be set
0 → 1	1	Unchanged
1 → 0	0	Unchanged
1 → 0	1	May be set

8.2.7.3 Interrupt Enable P1IE, P2IE

Each PxIE bit enables the associated PxIFG interrupt flag.

Bit = 0: The interrupt is disabled.

Bit = 1: The interrupt is enabled.

8.2.8 Configuring Unused Port Pins

Unused I/O pins should be configured as I/O function, output direction, and left unconnected on the PC board, to prevent a floating input and reduce power consumption. The value of the PxOUT bit is irrelevant, since the pin is unconnected. Alternatively, the integrated pullup/pulldown resistor can be enabled by setting the PxREN bit of the unused pin to prevent the floating input. See the *System Resets, Interrupts, and Operating Modes* chapter for termination of unused pins.

8.3 Digital I/O Registers

The digital I/O registers are listed in Table 8-2.

Table 8-2. Digital I/O Registers

Port	Register	Short Form	Address	Register Type	Initial State
P1	Input	P1IN	020h	Read only	-
	Output	P1OUT	021h	Read/write	Unchanged
	Direction	P1DIR	022h	Read/write	Reset with PUC
	Interrupt Flag	P1IFG	023h	Read/write	Reset with PUC
	Interrupt Edge Select	P1IES	024h	Read/write	Unchanged
	Interrupt Enable	P1IE	025h	Read/write	Reset with PUC
	Port Select	P1SEL	026h	Read/write	Reset with PUC
	Port Select 2	P1SEL2	041h	Read/write	Reset with PUC
	Resistor Enable	P1REN	027h	Read/write	Reset with PUC
P2	Input	P2IN	028h	Read only	-
	Output	P2OUT	029h	Read/write	Unchanged
	Direction	P2DIR	02Ah	Read/write	Reset with PUC
	Interrupt Flag	P2IFG	02Bh	Read/write	Reset with PUC
	Interrupt Edge Select	P2IES	02Ch	Read/write	Unchanged
	Interrupt Enable	P2IE	02Dh	Read/write	Reset with PUC
	Port Select	P2SEL	02Eh	Read/write	0C0h with PUC
	Port Select 2	P2SEL2	042h	Read/write	Reset with PUC
	Resistor Enable	P2REN	02Fh	Read/write	Reset with PUC
P3	Input	P3IN	018h	Read only	-
	Output	P3OUT	019h	Read/write	Unchanged
	Direction	P3DIR	01Ah	Read/write	Reset with PUC
	Port Select	P3SEL	01Bh	Read/write	Reset with PUC
	Port Select 2	P3SEL2	043h	Read/write	Reset with PUC
	Resistor Enable	P3REN	010h	Read/write	Reset with PUC
P4	Input	P4IN	01Ch	Read only	-
	Output	P4OUT	01Dh	Read/write	Unchanged
	Direction	P4DIR	01Eh	Read/write	Reset with PUC
	Port Select	P4SEL	01Fh	Read/write	Reset with PUC
	Port Select 2	P4SEL2	044h	Read/write	Reset with PUC
	Resistor Enable	P4REN	011h	Read/write	Reset with PUC
P5	Input	P5IN	030h	Read only	-
	Output	P5OUT	031h	Read/write	Unchanged
	Direction	P5DIR	032h	Read/write	Reset with PUC
	Port Select	P5SEL	033h	Read/write	Reset with PUC
	Port Select 2	P5SEL2	045h	Read/write	Reset with PUC
	Resistor Enable	P5REN	012h	Read/write	Reset with PUC
P6	Input	P6IN	034h	Read only	-
	Output	P6OUT	035h	Read/write	Unchanged
	Direction	P6DIR	036h	Read/write	Reset with PUC
	Port Select	P6SEL	037h	Read/write	Reset with PUC
	Port Select 2	P6SEL2	046h	Read/write	Reset with PUC
	Resistor Enable	P6REN	013h	Read/write	Reset with PUC

Table 8-2. Digital I/O Registers (continued)

Port	Register	Short Form	Address	Register Type	Initial State
P7	Input	P7IN	038h	Read only	-
	Output	P7OUT	03Ah	Read/write	Unchanged
	Direction	P7DIR	03Ch	Read/write	Reset with PUC
	Port Select	P7SEL	03Eh	Read/write	Reset with PUC
	Port Select 2	P7SEL2	047h	Read/write	Reset with PUC
	Resistor Enable	P7REN	014h	Read/write	Reset with PUC
P8	Input	P8IN	039h	Read only	-
	Output	P8OUT	03Bh	Read/write	Unchanged
	Direction	P8DIR	03Dh	Read/write	Reset with PUC
	Port Select	P8SEL	03Fh	Read/write	Reset with PUC
	Port Select 2	P8SEL2	048h	Read/write	Reset with PUC
	Resistor Enable	P8REN	015h	Read/write	Reset with PUC

Supply Voltage Supervisor (SVS)

This chapter describes the operation of the SVS. The SVS is implemented in selected MSP430x2xx devices.

Topic **Page**

9.1 Supply Voltage Supervisor (SVS) Introduction

The SVS is used to monitor the AV_{CC} supply voltage or an external voltage. The SVS can be configured to set a flag or generate a POR reset when the supply voltage or external voltage drops below a user-selected threshold.

The SVS features include:

- AV_{CC} monitoring
- Selectable generation of POR
- Output of SVS comparator accessible by software
- Low-voltage condition latched and accessible by software
- 14 selectable threshold levels
- External channel to monitor external voltage

The SVS block diagram is shown in Figure 9-1.

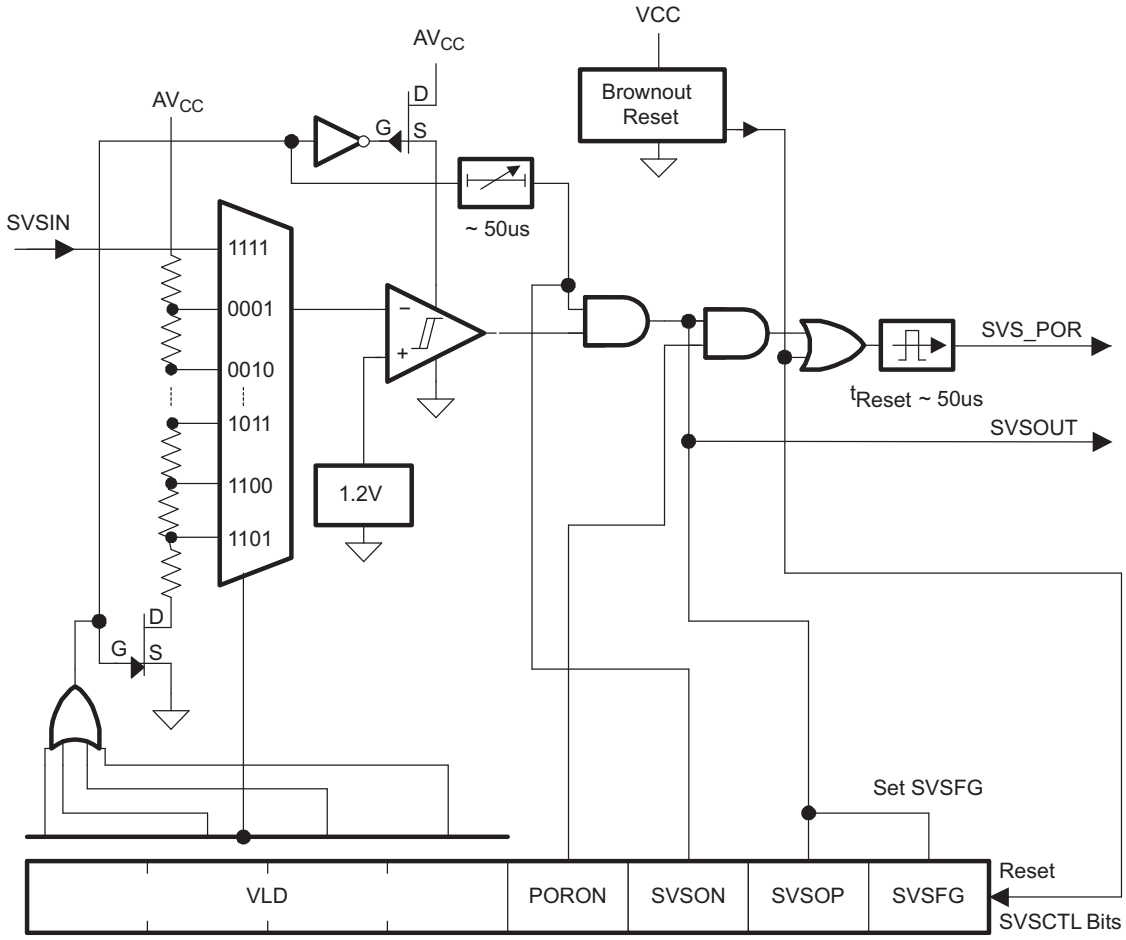


Figure 9-1. SVS Block Diagram

9.2 SVS Operation

The SVS detects if the AV_{CC} voltage drops below a selectable level. It can be configured to provide a POR or set a flag, when a low-voltage condition occurs. The SVS is disabled after a brownout reset to conserve current consumption.

9.2.1 Configuring the SVS

The VLDx bits are used to enable/disable the SVS and select one of 14 threshold levels ($V_{(SVS\_IT-)}$) for comparison with AV_{CC}. The SVS is off when VLDx = 0 and on when VLDx > 0. The SVSON bit does not turn on the SVS. Instead, it reflects the on/off state of the SVS and can be used to determine when the SVS is on.

When VLDx = 1111, the external SVSIN channel is selected. The voltage on SVSIN is compared to an internal level of approximately 1.25 V.

9.2.2 SVS Comparator Operation

A low-voltage condition exists when AV_{CC} drops below the selected threshold or when the external voltage drops below its 1.25-V threshold. Any low-voltage condition sets the SVSFG bit.

The PORON bit enables or disables the device-reset function of the SVS. If PORON = 1, a POR is generated when SVSFG is set. If PORON = 0, a low-voltage condition sets SVSFG, but does not generate a POR.

The SVSFG bit is latched. This allows user software to determine if a low-voltage condition occurred previously. The SVSFG bit must be reset by user software. If the low-voltage condition is still present when SVSFG is reset, it will be immediately set again by the SVS.

9.2.3 Changing the VLDx Bits

When the VLDx bits are changed from zero to any non-zero value there is a automatic settling delay $t_{d(SVSon)}$ implemented that allows the SVS circuitry to settle. The $t_{d(SVSon)}$ delay is approximately 50 µs. During this delay, the SVS will not flag a low-voltage condition or reset the device, and the SVSON bit is cleared. Software can test the SVSON bit to determine when the delay has elapsed and the SVS is monitoring the voltage properly. Writing to SVSCTL while SVSON = 0 will abort the SVS automatic settling delay, $t_{d(SVSon)}$, and switch the SVS to active mode immediately. In doing so, the SVS circuitry might not be settled, resulting in unpredictable behavior.

When the VLDx bits are changed from any non-zero value to any other non-zero value the circuitry requires the time t_{settle} to settle. The settling time t_{settle} is a maximum of ~12 µs. See the device-specific data sheet. There is no automatic delay implemented that prevents SVSFG to be set or to prevent a reset of the device. The recommended flow to switch between levels is shown in the following code.

```
; Enable SVS for the first time:
   MOV.B   #080h,&SVSCTL   ; Level 2.8V, do not cause POR
                           ; ...
; Change SVS level
   MOV.B   #000h,&SVSCTL   ; Temporarily disable SVS
   MOV.B   #018h,&SVSCTL   ; Level 1.9V, cause POR
                           ; ...
```

9.2.4 SVS Operating Range

Each SVS level has hysteresis to reduce sensitivity to small supply voltage changes when AV_{CC} is close to the threshold. The SVS operation and SVS/Brownout interoperation are shown in Figure 9-2.

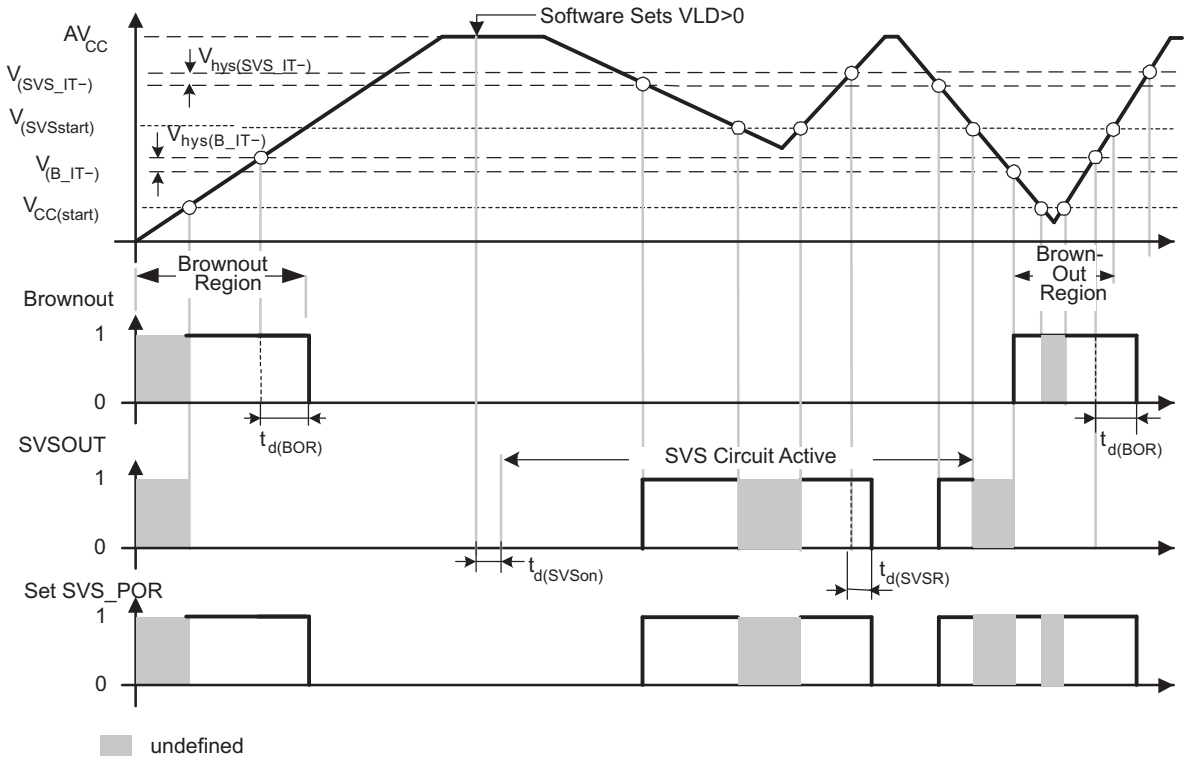


Figure 9-2. Operating Levels for SVS and Brownout/Reset Circuit

9.3 SVS Registers

The SVS registers are listed in Table 9-1.

Table 9-1. SVS Registers

Register	Short Form	Register Type	Address	Initial State
SVS Control Register	SVSCTL	Read/write	055h	Reset with BOR

9.3.1 SVSCTL, SVS Control Register

7	6	5	4	3	2	1	0
VLDx				PORON	SVSON	SVSOP	SVSFG
rw-0[1]	rw-0[1]	rw-0[1]	rw-0[1]	rw-0[1]	r[1]	r[1]	rw-0[1]

VLDx Bits 7-4 Voltage level detect. These bits turn on the SVS and select the nominal SVS threshold voltage level. See the device-specific data sheet for parameters.

- 0000 SVS is off
- 0001 1.9 V
- 0010 2.1 V
- 0011 2.2 V
- 0100 2.3 V
- 0101 2.4 V
- 0110 2.5 V
- 0111 2.65 V
- 1000 2.8 V
- 1001 2.9 V
- 1010 3.05 V
- 1011 3.2 V
- 1100 3.35 V
- 1101 3.5 V
- 1110 3.7 V
- 1111 Compares external input voltage SVSIN to 1.25 V.

PORON Bit 3 POR on. This bit enables the SVSFG flag to cause a POR device reset.

- 0 SVSFG does not cause a POR
- 1 SVSFG causes a POR

SVSON Bit 2 SVS on. This bit reflects the status of SVS operation. This bit DOES NOT turn on the SVS. The SVS is turned on by setting VLDx > 0.

- 0 SVS is Off
- 1 SVS is On

SVSOP Bit 1 SVS output. This bit reflects the output value of the SVS comparator.

- 0 SVS comparator output is low
- 1 SVS comparator output is high

SVSFG Bit 0 SVS flag. This bit indicates a low voltage condition. SVSFG remains set after a low voltage condition until reset by software.

- 0 No low voltage condition occurred
- 1 A low condition is present or has occurred

(1) Reset by a brownout reset only, not by a POR or PUC.

Watchdog Timer+ (WDT+)

The watchdog timer+ (WDT+) is a 16-bit timer that can be used as a watchdog or as an interval timer. This chapter describes the WDT+ The WDT+ is implemented in all MSP430x2xx devices.

Topic **Page**

10.1 Watchdog Timer+ (WDT+) Introduction

The primary function of the WDT+ module is to perform a controlled system restart after a software problem occurs. If the selected time interval expires, a system reset is generated. If the watchdog function is not needed in an application, the module can be configured as an interval timer and can generate interrupts at selected time intervals.

Features of the watchdog timer+ module include:

- Four software-selectable time intervals
- Watchdog mode
- Interval mode
- Access to WDT+ control register is password protected
- Control of $\overline{\text{RST}}$/NMI pin function
- Selectable clock source
- Can be stopped to conserve power
- Clock fail-safe feature

The WDT+ block diagram is shown in Figure 10-1.

NOTE: Watchdog Timer+ Powers Up Active

After a PUC, the WDT+ module is automatically configured in the watchdog mode with an initial 32768 clock cycle reset interval using the DCOCLK. The user must setup or halt the WDT+ prior to the expiration of the initial reset interval.

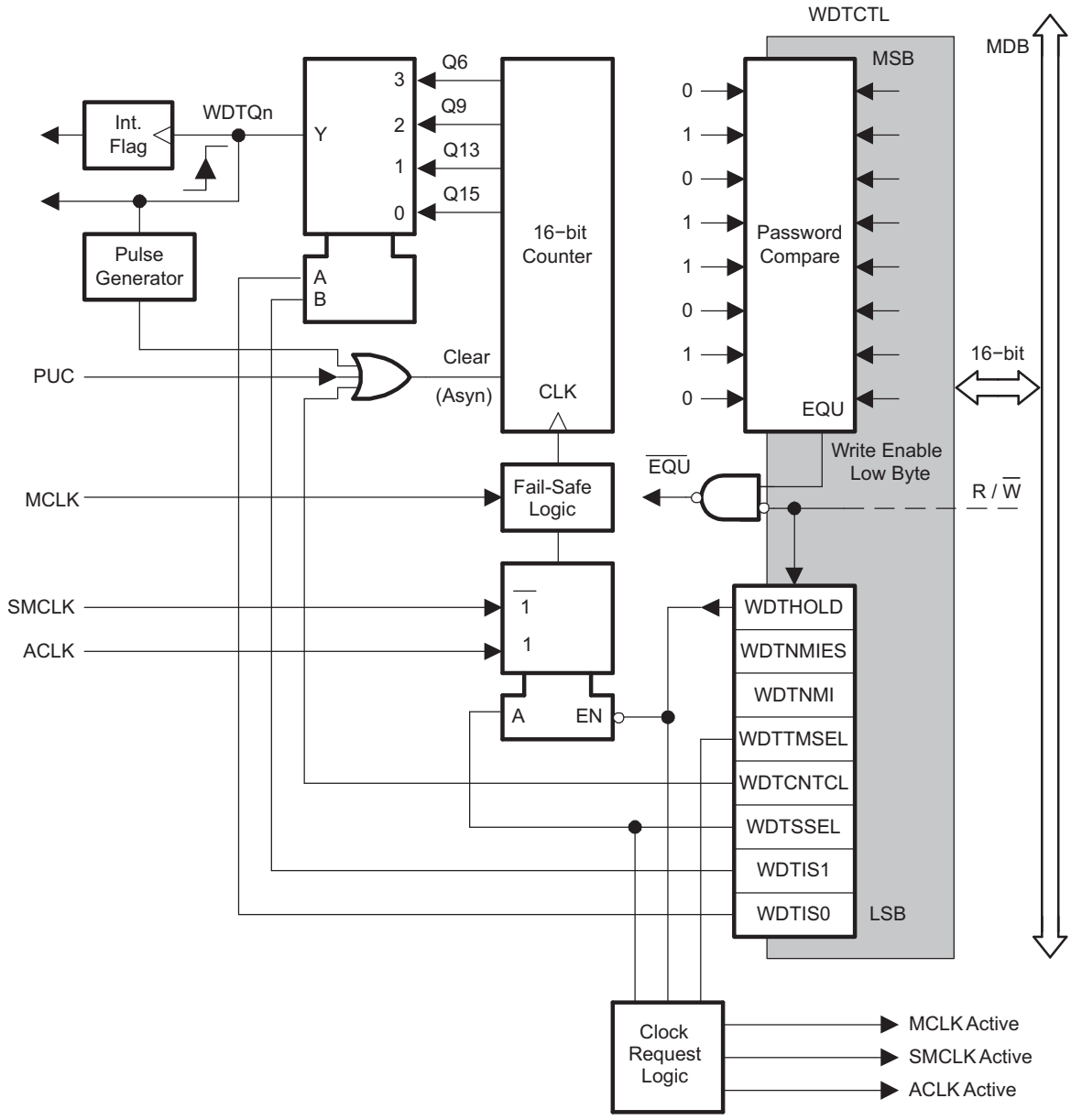


Figure 10-1. Watchdog Timer+ Block Diagram

10.2 Watchdog Timer+ Operation

The WDT+ module can be configured as either a watchdog or interval timer with the WDTCTL register. The WDTCTL register also contains control bits to configure the $\overline{RST}$/NMI pin. WDTCTL is a 16-bit, password-protected, read/write register. Any read or write access must use word instructions and write accesses must include the write password 05Ah in the upper byte. Any write to WDTCTL with any value other than 05Ah in the upper byte is a security key violation and triggers a PUC system reset regardless of timer mode. Any read of WDTCTL reads 069h in the upper byte. The WDT+ counter clock should be slower or equal than the system (MCLK) frequency.

10.2.1 Watchdog Timer+ Counter

The watchdog timer+ counter (WDTCNT) is a 16-bit up-counter that is not directly accessible by software. The WDTCNT is controlled and time intervals selected through the watchdog timer+ control register WDTCTL.

The WDTCNT can be sourced from ACLK or SMCLK. The clock source is selected with the WDTSSEL bit.

10.2.2 Watchdog Mode

After a PUC condition, the WDT+ module is configured in the watchdog mode with an initial 32768 cycle reset interval using the DCOCLK. The user must setup, halt, or clear the WDT+ prior to the expiration of the initial reset interval or another PUC will be generated. When the WDT+ is configured to operate in watchdog mode, either writing to WDTCTL with an incorrect password, or expiration of the selected time interval triggers a PUC. A PUC resets the WDT+ to its default condition and configures the $\overline{RST}$/NMI pin to reset mode.

10.2.3 Interval Timer Mode

Setting the WDTTMSEL bit to 1 selects the interval timer mode. This mode can be used to provide periodic interrupts. In interval timer mode, the WDTIFG flag is set at the expiration of the selected time interval. A PUC is not generated in interval timer mode at expiration of the selected timer interval and the WDTIFG enable bit WDTIE remains unchanged.

When the WDTIE bit and the GIE bit are set, the WDTIFG flag requests an interrupt. The WDTIFG interrupt flag is automatically reset when its interrupt request is serviced, or may be reset by software. The interrupt vector address in interval timer mode is different from that in watchdog mode.

NOTE: Modifying the Watchdog Timer+

The WDT+ interval should be changed together with WDTCNTCL = 1 in a single instruction to avoid an unexpected immediate PUC or interrupt.

The WDT+ should be halted before changing the clock source to avoid a possible incorrect interval.

10.2.4 Watchdog Timer+ Interrupts

The WDT+ uses two bits in the SFRs for interrupt control.

- The WDT+ interrupt flag, WDTIFG, located in IFG1.0
- The WDT+ interrupt enable, WDTIE, located in IE1.0

When using the WDT+ in the watchdog mode, the WDTIFG flag sources a reset vector interrupt. The WDTIFG can be used by the reset interrupt service routine to determine if the watchdog caused the device to reset. If the flag is set, then the watchdog timer+ initiated the reset condition either by timing out or by a security key violation. If WDTIFG is cleared, the reset was caused by a different source.

When using the WDT+ in interval timer mode, the WDTIFG flag is set after the selected time interval and requests a WDT+ interval timer interrupt if the WDTIE and the GIE bits are set. The interval timer interrupt vector is different from the reset vector used in watchdog mode. In interval timer mode, the WDTIFG flag is reset automatically when the interrupt is serviced, or can be reset with software.

10.2.5 Watchdog Timer+ Clock Fail-Safe Operation

The WDT+ module provides a fail-safe clocking feature assuring the clock to the WDT+ cannot be disabled while in watchdog mode. This means the low-power modes may be affected by the choice for the WDT+ clock. For example, if ACLK is the WDT+ clock source, LPM4 will not be available, because the WDT+ will prevent ACLK from being disabled. Also, if ACLK or SMCLK fail while sourcing the WDT+, the WDT+ clock source is automatically switched to MCLK. In this case, if MCLK is sourced from a crystal, and the crystal has failed, the fail-safe feature will activate the DCO and use it as the source for MCLK.

When the WDT+ module is used in interval timer mode, there is no fail-safe feature for the clock source.

10.2.6 Operation in Low-Power Modes

The MSP430 devices have several low-power modes. Different clock signals are available in different low-power modes. The requirements of the user's application and the type of clocking used determine how the WDT+ should be configured. For example, the WDT+ should not be configured in watchdog mode with SMCLK as its clock source if the user wants to use low-power mode 3 because the WDT+ will keep SMCLK enabled for its clock source, increasing the current consumption of LPM3. When the watchdog timer+ is not required, the WDTHOLD bit can be used to hold the WDTCNT, reducing power consumption.

10.2.7 Software Examples

Any write operation to WDTCTL must be a word operation with 05Ah (WDTPW) in the upper byte:

```
; Periodically clear an active watchdog
  MOV #WDTPW+WDTCNTCL,&WDTCTL
;
; Change watchdog timer+ interval
  MOV #WDTPW+WDTCNTL+WDTSSEL,&WDTCTL
;
; Stop the watchdog
  MOV #WDTPW+WDTHOLD,&WDTCTL
;
; Change WDT+ to interval timer mode, clock/8192 interval
  MOV #WDTPW+WDTCNTCL+WDTTMSEL+WDTIS0,&WDTCTL
```

10.3 Watchdog Timer+ Registers

The WDT+ registers are listed in Table 10-1.

Table 10-1. Watchdog Timer+ Registers

Register	Short Form	Register Type	Address	Initial State
Watchdog timer+ control register	WDTCTL	Read/write	0120h	06900h with PUC
SFR interrupt enable register 1	IE1	Read/write	0000h	Reset with PUC
SFR interrupt flag register 1	IFG1	Read/write	0002h	Reset with PUC (1)

(1) WDTIFG is reset with POR.

10.3.1 WDTCTL, Watchdog Timer+ Register

15	14	13	12	11	10	9	8
WDTPW, Read as 069h Must be written as 05Ah							

7	6	5	4	3	2	1	0
WDTHOLD	**WDTNMIES**	**WDTNMI**	**WDTTMSEL**	**WDTCNTCL**	**WDTSSEL**	**WDTISx**	
rw-0	rw-0	rw-0	rw-0	r0(w)	rw-0	rw-0	rw-0

WDTPW Bits 15-8 Watchdog timer+ password. Always read as 069h. Must be written as 05Ah, or a PUC is generated.

WDTHOLD Bit 7 Watchdog timer+ hold. This bit stops the watchdog timer+. Setting WDTHOLD = 1 when the WDT+ is not in use conserves power.

- 0 Watchdog timer+ is not stopped
- 1 Watchdog timer+ is stopped

WDTNMIES Bit 6 Watchdog timer+ NMI edge select. This bit selects the interrupt edge for the NMI interrupt when WDTNMI = 1. Modifying this bit can trigger an NMI. Modify this bit when WDTIE = 0 to avoid triggering an accidental NMI.

- 0 NMI on rising edge
- 1 NMI on falling edge

WDTNMI Bit 5 Watchdog timer+ NMI select. This bit selects the function for the $\overline{\text{RST}}$/NMI pin.

- 0 Reset function
- 1 NMI function

WDTTMSEL Bit 4 Watchdog timer+ mode select

- 0 Watchdog mode
- 1 Interval timer mode

WDTCNTCL Bit 3 Watchdog timer+ counter clear. Setting WDTCNTCL = 1 clears the count value to 0000h. WDTCNTCL is automatically reset.

- 0 No action
- 1 WDTCNT = 0000h

WDTSSEL Bit 2 Watchdog timer+ clock source select

- 0 SMCLK
- 1 ACLK

WDTISx Bits 1-0 Watchdog timer+ interval select. These bits select the watchdog timer+ interval to set the WDTIFG flag and/or generate a PUC.

- 00 Watchdog clock source /32768
- 01 Watchdog clock source /8192
- 10 Watchdog clock source /512
- 11 Watchdog clock source /64

10.3.2 IE1, Interrupt Enable Register 1

7	6	5	4	3	2	1	0
			NMIIE				**WDTIE**
							rw-0

	Bits 7-5	These bits may be used by other modules. See device-specific data sheet.
NMIIE	Bit 4	NMI interrupt enable. This bit enables the NMI interrupt. Because other bits in IE1 may be used for other modules, it is recommended to set or clear this bit using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions. 0 Interrupt not enabled 1 Interrupt enabled
	Bits 3-1	These bits may be used by other modules. See device-specific data sheet.
WDTIE	Bit 0	Watchdog timer+ interrupt enable. This bit enables the WDTIFG interrupt for interval timer mode. It is not necessary to set this bit for watchdog mode. Because other bits in IE1 may be used for other modules, it is recommended to set or clear this bit using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions. 0 Interrupt not enabled 1 Interrupt enabled

10.3.3 IFG1, Interrupt Flag Register 1

7	6	5	4	3	2	1	0
			NMIIFG				**WDTIFG**
			rw-0				rw-(0)

	Bits 7-5	These bits may be used by other modules. See device-specific data sheet.
NMIIFG	Bit 4	NMI interrupt flag. NMIIFG must be reset by software. Because other bits in IFG1 may be used for other modules, it is recommended to clear NMIIFG by using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions. 0 No interrupt pending 1 Interrupt pending
	Bits 3-1	These bits may be used by other modules. See device-specific data sheet.
WDTIFG	Bit 0	Watchdog timer+ interrupt flag. In watchdog mode, WDTIFG remains set until reset by software. In interval mode, WDTIFG is reset automatically by servicing the interrupt, or can be reset by software. Because other bits in IFG1 may be used for other modules, it is recommended to clear WDTIFG by using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions. 0 No interrupt pending 1 Interrupt pending

Hardware Multiplier

This chapter describes the hardware multiplier. The hardware multiplier is implemented in some MSP430x2xx devices.

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11.1 Hardware Multiplier Introduction

The hardware multiplier is a peripheral and is not part of the MSP430 CPU. This means, its activities do not interfere with the CPU activities. The multiplier registers are peripheral registers that are loaded and read with CPU instructions.

The hardware multiplier supports:

- Unsigned multiply
- Signed multiply
- Unsigned multiply accumulate
- Signed multiply accumulate
- 16x16 bits, 16x8 bits, 8x16 bits, 8x8 bits

The hardware multiplier block diagram is shown in Figure 11-1.

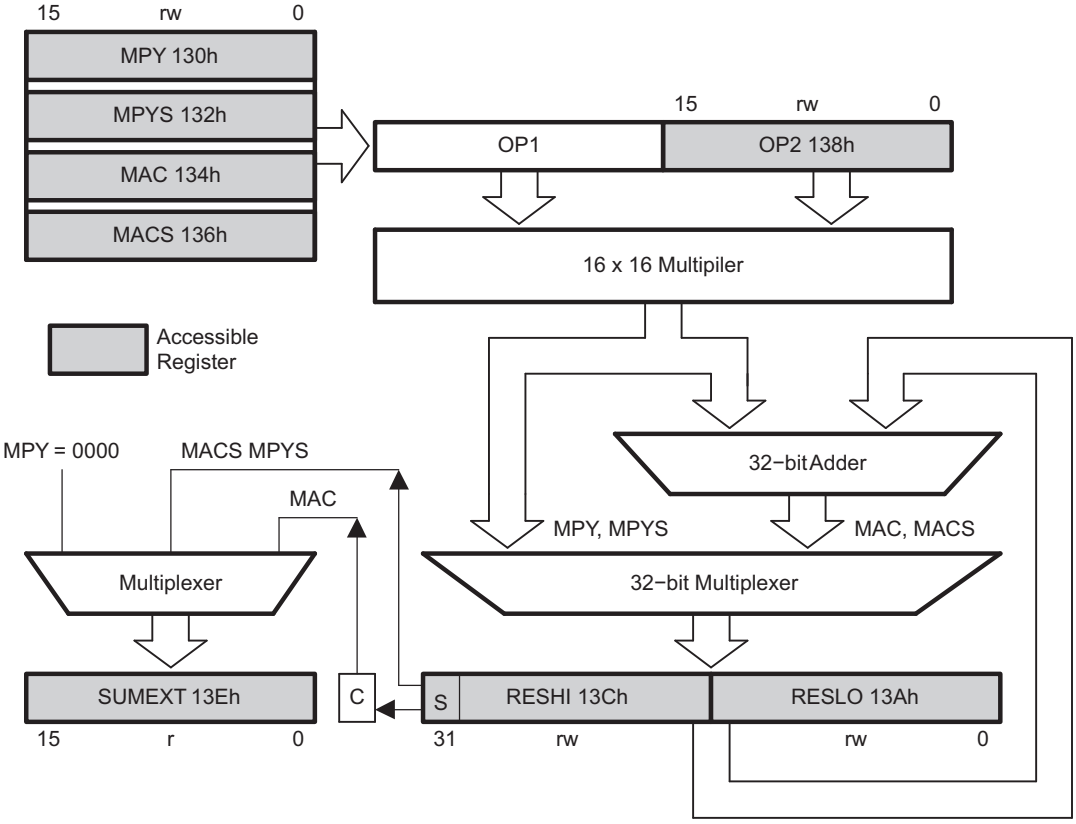


Figure 11-1. Hardware Multiplier Block Diagram

11.2 Hardware Multiplier Operation

The hardware multiplier supports unsigned multiply, signed multiply, unsigned multiply accumulate, and signed multiply accumulate operations. The type of operation is selected by the address the first operand is written to.

The hardware multiplier has two 16-bit operand registers, OP1 and OP2, and three result registers, RESLO, RESHI, and SUMEXT. RESLO stores the low word of the result, RESHI stores the high word of the result, and SUMEXT stores information about the result. The result is ready in three MCLK cycles and can be read with the next instruction after writing to OP2, except when using an indirect addressing mode to access the result. When using indirect addressing for the result, a NOP is required before the result is ready.

11.2.1 Operand Registers

The operand one register OP1 has four addresses, shown in Table 11-1, used to select the multiply mode. Writing the first operand to the desired address selects the type of multiply operation but does not start any operation. Writing the second operand to the operand two register OP2 initiates the multiply operation. Writing OP2 starts the selected operation with the values stored in OP1 and OP2. The result is written into the three result registers RESLO, RESHI, and SUMEXT.

Repeated multiply operations may be performed without reloading OP1 if the OP1 value is used for successive operations. It is not necessary to re-write the OP1 value to perform the operations.

Table 11-1. OP1 Addresses

OP1 Address	Register Name	Operation
0130h	MPY	Unsigned multiply
0132h	MPYS	Signed multiply
0134h	MAC	Unsigned multiply accumulate
0136h	MACS	Signed multiply accumulate

11.2.2 Result Registers

The result low register RESLO holds the lower 16-bits of the calculation result. The result high register RESHI contents depend on the multiply operation and are listed in Table 11-2.

Table 11-2. RESHI Contents

Mode	RESHI Contents
MPY	Upper 16-bits of the result
MPYS	The MSB is the sign of the result. The remaining bits are the upper 15-bits of the result. Two's complement notation is used for the result.
MAC	Upper 16-bits of the result
MACS	Upper 16-bits of the result. Two's complement notation is used for the result.

The sum extension registers SUMEXT contents depend on the multiply operation and are listed in Table 11-3.

Table 11-3. SUMEXT Contents

Mode	SUMEXT
MPY	SUMEXT is always 0000h
MPYS	SUMEXT contains the extended sign of the result 00000h = Result was positive or zero 0FFFFh = Result was negative
MAC	SUMEXT contains the carry of the result 0000h = No carry for result 0001h = Result has a carry
MACS	SUMEXT contains the extended sign of the result 00000h = Result was positive or zero 0FFFFh = Result was negative

11.2.2.1 MACS Underflow and Overflow

The multiplier does not automatically detect underflow or overflow in the MACS mode. The accumulator range for positive numbers is 0 to 7FFF FFFFh and for negative numbers is 0FFFF FFFFh to 8000 0000h. An underflow occurs when the sum of two negative numbers yields a result that is in the range for a positive number. An overflow occurs when the sum of two positive numbers yields a result that is in the range for a negative number. In both of these cases, the SUMEXT register contains the sign of the result, 0FFFFh for overflow and 0000h for underflow. User software must detect and handle these conditions appropriately.

11.2.3 Software Examples

Examples for all multiplier modes follow. All 8x8 modes use the absolute address for the registers because the assembler will not allow .B access to word registers when using the labels from the standard definitions file.

There is no sign extension necessary in software. Accessing the multiplier with a byte instruction during a signed operation will automatically cause a sign extension of the byte within the multiplier module.

```
; 16x16 Unsigned Multiply
   MOV     #01234h,&MPY   ; Load first operand
   MOV     #05678h,&OP2   ; Load second operand
;  ...                    ; Process results

; 8x8 Unsigned Multiply. Absolute addressing.
   MOV.B   #012h,&0130h   ; Load first operand
   MOV.B   #034h,&0138h   ; Load 2nd operand
;  ...                    ; Process results

; 16x16 Signed Multiply
   MOV     #01234h,&MPYS  ; Load first operand
   MOV     #05678h,&OP2   ; Load 2nd operand
;  ...                    ; Process results

; 8x8 Signed Multiply. Absolute addressing.
   MOV.B   #012h,&0132h   ; Load first operand
   MOV.B   #034h,&0138h   ; Load 2nd operand
;  ...                    ; Process results

; 16x16 Unsigned Multiply Accumulate
   MOV     #01234h,&MAC   ; Load first operand
   MOV     #05678h,&OP2   ; Load 2nd operand
;  ...                    ; Process results

; 8x8 Unsigned Multiply Accumulate. Absolute addressing
   MOV.B   #012h,&0134h   ; Load first operand
   MOV.B   #034h,&0138h   ; Load 2nd operand
;  ...                    ; Process results

; 16x16 Signed Multiply Accumulate
   MOV     #01234h,&MACS  ; Load first operand
   MOV     #05678h,&OP2   ; Load 2nd operand
;  ...                    ; Process results

; 8x8 Signed Multiply Accumulate. Absolute addressing
   MOV.B   #012h,&0136h   ; Load first operand
   MOV.B   #034h,R5       ; Temp. location for 2nd operand
   MOV     R5,&OP2        ; Load 2nd operand
;  ...                    ; Process results
```

11.2.4 Indirect Addressing of RESLO

When using indirect or indirect autoincrement addressing mode to access the result registers, At least one instruction is needed between loading the second operand and accessing one of the result registers:

```
; Access multiplier results with indirect addressing
   MOV   #RESLO,R5     ; RESLO address in R5 for indirect
   MOV   &OPER1,&MPY   ; Load 1st operand
   MOV   &OPER2,&OP2   ; Load 2nd operand
   NOP                 ; Need one cycle
   MOV   @R5+,&xxx     ; Move RESLO
   MOV   @R5,&xxx      ; Move RESHI
```

11.2.5 Using Interrupts

If an interrupt occurs after writing OP1, but before writing OP2, and the multiplier is used in servicing that interrupt, the original multiplier mode selection is lost and the results are unpredictable. To avoid this, disable interrupts before using the hardware multiplier or do not use the multiplier in interrupt service routines.

```
; Disable interrupts before using the hardware multiplier
   DINT               ; Disable interrupts
   NOP                ; Required for DINT
   MOV   #xxh,&MPY    ; Load 1st operand
   MOV   #xxh,&OP2    ; Load 2nd operand
   EINT               ; Interrupts may be enable before
                      ; Process results
```

11.3 Hardware Multiplier Registers

The hardware multiplier registers are listed in Table 11-4.

Table 11-4. Hardware Multiplier Registers

Register	Short Form	Register Type	Address	Initial State
Operand one - multiply	MPY	Read/write	0130h	Unchanged
Operand one - signed multiply	MPYS	Read/write	0132h	Unchanged
Operand one - multiply accumulate	MAC	Read/write	0134h	Unchanged
Operand one - signed multiply accumulate	MACS	Read/write	0136h	Unchanged
Operand two	OP2	Read/write	0138h	Unchanged
Result low word	RESLO	Read/write	013Ah	Undefined
Result high word	RESHI	Read/write	013Ch	Undefined
Sum extension register	SUMEXT	Read	013Eh	Undefined

Timer_A

Timer_A is a 16-bit timer/counter with multiple capture/compare registers. This chapter describes the operation of the Timer_A of the MSP430x2xx device family.

Topic **Page**

12.1 Timer_A Introduction

Timer_A is a 16-bit timer/counter with three capture/compare registers. Timer_A can support multiple capture/compares, PWM outputs, and interval timing. Timer_A also has extensive interrupt capabilities. Interrupts may be generated from the counter on overflow conditions and from each of the capture/compare registers.

Timer_A features include:

- Asynchronous 16-bit timer/counter with four operating modes
- Selectable and configurable clock source
- Two or three configurable capture/compare registers
- Configurable outputs with PWM capability
- Asynchronous input and output latching
- Interrupt vector register for fast decoding of all Timer_A interrupts

The block diagram of Timer_A is shown in Figure 12-1.

NOTE: Use of the Word *Count*

Count is used throughout this chapter. It means the counter must be in the process of counting for the action to take place. If a particular value is directly written to the counter, then an associated action will not take place.

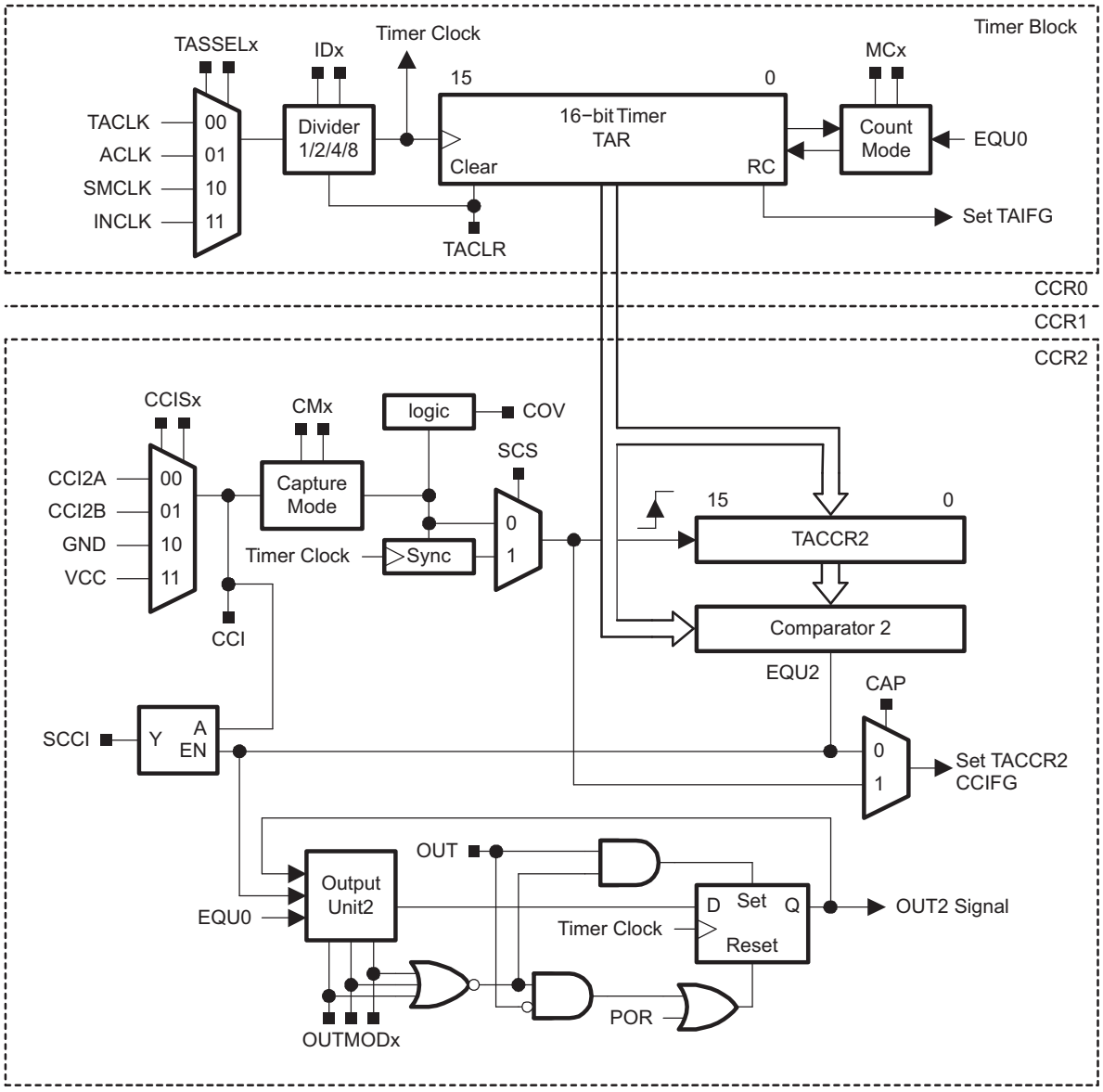


Figure 12-1. Timer_A Block Diagram

12.2 Timer_A Operation

The Timer_A module is configured with user software. The setup and operation of Timer_A is discussed in the following sections.

12.2.1 16-Bit Timer Counter

The 16-bit timer/counter register, TAR, increments or decrements (depending on mode of operation) with each rising edge of the clock signal. TAR can be read or written with software. Additionally, the timer can generate an interrupt when it overflows.

TAR may be cleared by setting the TACLR bit. Setting TACLR also clears the clock divider and count direction for up/down mode.

NOTE: Modifying Timer_A Registers

It is recommended to stop the timer before modifying its operation (with exception of the interrupt enable, and interrupt flag) to avoid errant operating conditions.

When the timer clock is asynchronous to the CPU clock, any read from TAR should occur while the timer is not operating or the results may be unpredictable. Alternatively, the timer may be read multiple times while operating, and a majority vote taken in software to determine the correct reading. Any write to TAR will take effect immediately.

12.2.1.1 Clock Source Select and Divider

The timer clock can be sourced from ACLK, SMCLK, or externally via TACLK or INCLK. The clock source is selected with the TASSELx bits. The selected clock source may be passed directly to the timer or divided by 2, 4, or 8, using the IDx bits. The timer clock divider is reset when TACLR is set.

12.2.2 Starting the Timer

The timer may be started, or restarted in the following ways:

- The timer counts when MCx > 0 and the clock source is active.
- When the timer mode is either up or up/down, the timer may be stopped by writing 0 to TACCR0. The timer may then be restarted by writing a nonzero value to TACCR0. In this scenario, the timer starts incrementing in the up direction from zero.

12.2.3 Timer Mode Control

The timer has four modes of operation as described in Table 12-1: stop, up, continuous, and up/down. The operating mode is selected with the MCx bits.

Table 12-1. Timer Modes

MCx	Mode	Description
00	Stop	The timer is halted.
01	Up	The timer repeatedly counts from zero to the value of TACCR0.
10	Continuous	The timer repeatedly counts from zero to 0FFFFh.
11	Up/down	The timer repeatedly counts from zero up to the value of TACCR0 and back down to zero.

12.2.3.1 Up Mode

The up mode is used if the timer period must be different from 0FFFFh counts. The timer repeatedly counts up to the value of compare register TACCR0, which defines the period, as shown in Figure 12-2. The number of timer counts in the period is TACCR0+1. When the timer value equals TACCR0 the timer restarts counting from zero. If up mode is selected when the timer value is greater than TACCR0, the timer immediately restarts counting from zero.

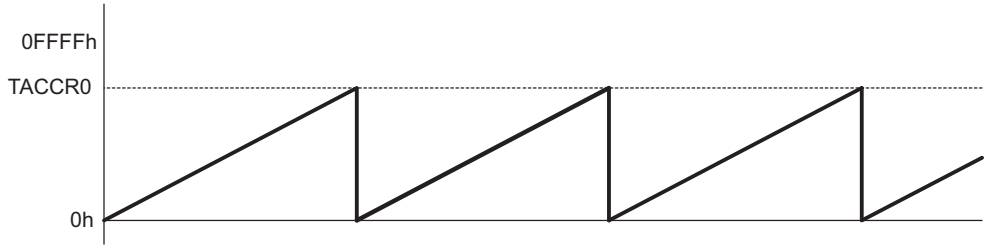


Figure 12-2. Up Mode

The TACCR0 CCIFG interrupt flag is set when the timer *counts* to the TACCR0 value. The TAIFG interrupt flag is set when the timer *counts* from TACCR0 to zero. Figure 12-3 shows the flag set cycle.

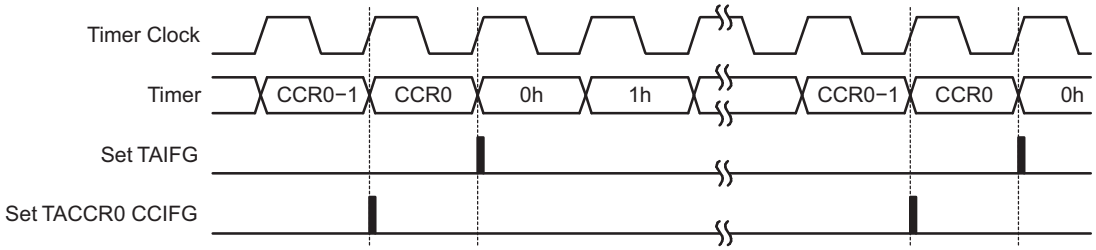


Figure 12-3. Up Mode Flag Setting

12.2.3.2 Changing the Period Register TACCR0

When changing TACCR0 while the timer is running, if the new period is greater than or equal to the old period, or greater than the current count value, the timer counts up to the new period. If the new period is less than the current count value, the timer rolls to zero. However, one additional count may occur before the counter rolls to zero.

12.2.3.3 Continuous Mode

In the continuous mode, the timer repeatedly counts up to 0FFFFh and restarts from zero as shown in Figure 12-4. The capture/compare register TACCR0 works the same way as the other capture/compare registers.

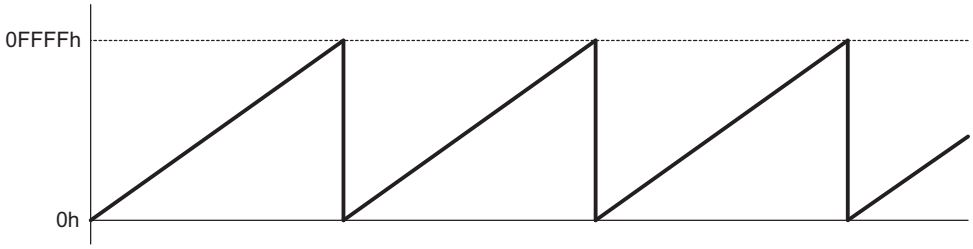


Figure 12-4. Continuous Mode

The TAIFG interrupt flag is set when the timer *counts* from 0FFFFh to zero. Figure 12-5 shows the flag set cycle.

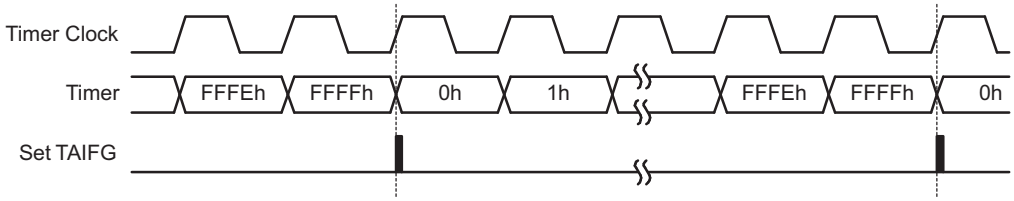


Figure 12-5. Continuous Mode Flag Setting

12.2.3.4 Use of the Continuous Mode

The continuous mode can be used to generate independent time intervals and output frequencies. Each time an interval is completed, an interrupt is generated. The next time interval is added to the TACCRx register in the interrupt service routine. Figure 12-6 shows two separate time intervals t_0 and t_1 being added to the capture/compare registers. In this usage, the time interval is controlled by hardware, not software, without impact from interrupt latency. Up to three independent time intervals or output frequencies can be generated using all three capture/compare registers.

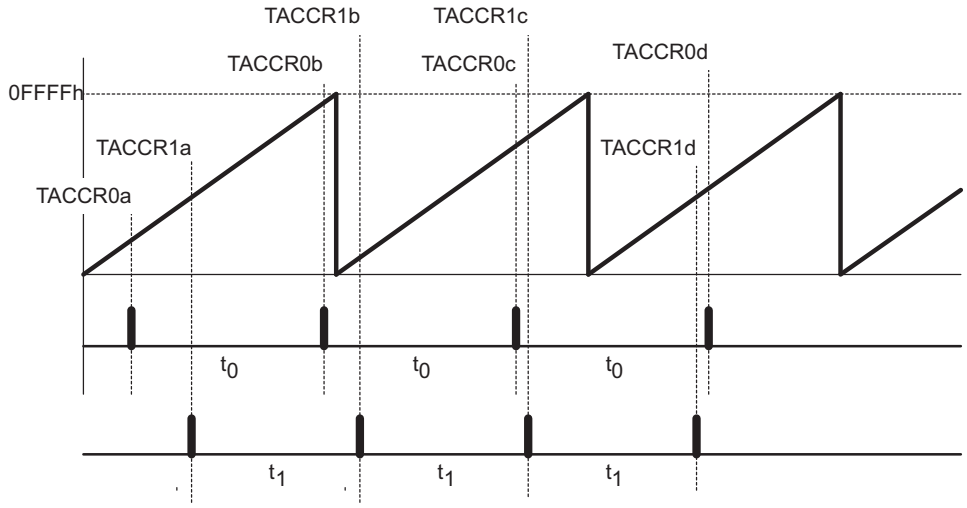


Figure 12-6. Continuous Mode Time Intervals

Time intervals can be produced with other modes as well, where TACCR0 is used as the period register. Their handling is more complex since the sum of the old TACCRx data and the new period can be higher than the TACCR0 value. When the previous TACCRx value plus t_x is greater than the TACCR0 data, TACCR0 + 1 must be subtracted to obtain the correct time interval.

12.2.3.5 Up/Down Mode

The up/down mode is used if the timer period must be different from 0FFFFh counts, and if a symmetrical pulse generation is needed. The timer repeatedly counts up to the value of compare register TACCR0 and back down to zero, as shown in Figure 12-7. The period is twice the value in TACCR0.

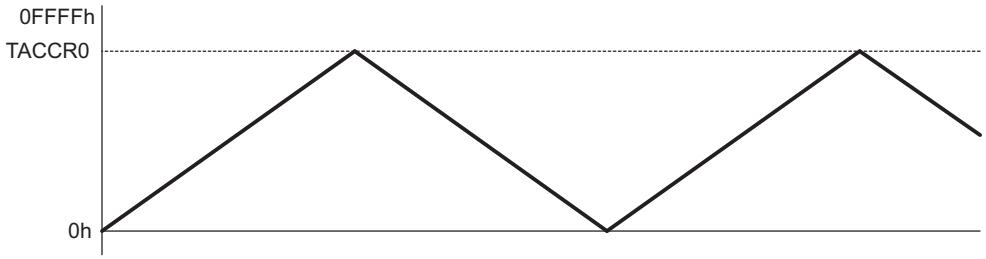


Figure 12-7. Up/Down Mode

The count direction is latched. This allows the timer to be stopped and then restarted in the same direction it was counting before it was stopped. If this is not desired, the TACLR bit must be set to clear the direction. The TACLR bit also clears the TAR value and the timer clock divider.

In up/down mode, the TACCR0 CCIFG interrupt flag and the TAIFG interrupt flag are set only once during a period, separated by 1/2 the timer period. The TACCR0 CCIFG interrupt flag is set when the timer *counts* from TACCR0 – 1 to TACCR0, and TAIFG is set when the timer completes *counting* down from 0001h to 0000h. Figure 12-8 shows the flag set cycle.

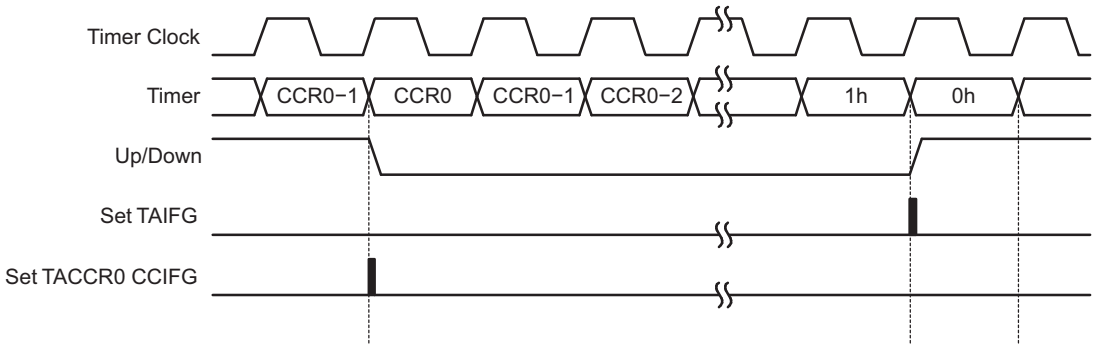


Figure 12-8. Up/Down Mode Flag Setting

12.2.3.6 Changing the Period Register TACCR0

When changing TACCR0 while the timer is running, and counting in the down direction, the timer continues its descent until it reaches zero. The value in TACCR0 is latched into TACL0 immediately, however the new period takes effect after the counter counts down to zero.

When the timer is counting in the up direction, and the new period is greater than or equal to the old period, or greater than the current count value, the timer counts up to the new period before counting down. When the timer is counting in the up direction, and the new period is less than the current count value, the timer begins counting down. However, one additional count may occur before the counter begins counting down.

12.2.3.7 Use of the Up/Down Mode

The up/down mode supports applications that require dead times between output signals (See section *Timer_A Output Unit*). For example, to avoid overload conditions, two outputs driving an H-bridge must never be in a high state simultaneously. In the example shown in Figure 12-9 the t_{dead} is:

$t_{dead} = t_{timer}$ (TACCR1 – TACCR2)

Where,

t_{dead} = Time during which both outputs need to be inactive

t_{timer} = Cycle time of the timer clock

TACCRx = Content of capture/compare register x

The TACCRx registers are not buffered. They update immediately when written to. Therefore, any required dead time will not be maintained automatically.

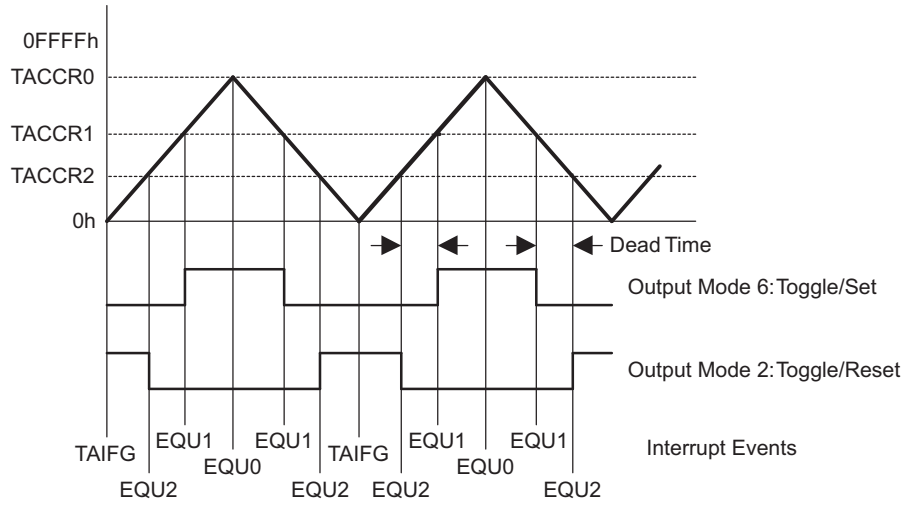


Figure 12-9. Output Unit in Up/Down Mode

12.2.4 Capture/Compare Blocks

Two or three identical capture/compare blocks, TACCRx, are present in Timer_A. Any of the blocks may be used to capture the timer data, or to generate time intervals.

Capture Mode

The capture mode is selected when CAP = 1. Capture mode is used to record time events. It can be used for speed computations or time measurements. The capture inputs CCIxA and CCIxB are connected to external pins or internal signals and are selected with the CCISx bits. The CMx bits select the capture edge of the input signal as rising, falling, or both. A capture occurs on the selected edge of the input signal. If a capture occurs:

- The timer value is copied into the TACCRx register
- The interrupt flag CCIFG is set

The input signal level can be read at any time via the CCI bit. MSP430x2xx family devices may have different signals connected to CCIxA and CCIxB. See the device-specific data sheet for the connections of these signals.

The capture signal can be asynchronous to the timer clock and cause a race condition. Setting the SCS bit will synchronize the capture with the next timer clock. Setting the SCS bit to synchronize the capture signal with the timer clock is recommended. This is illustrated in Figure 12-10.

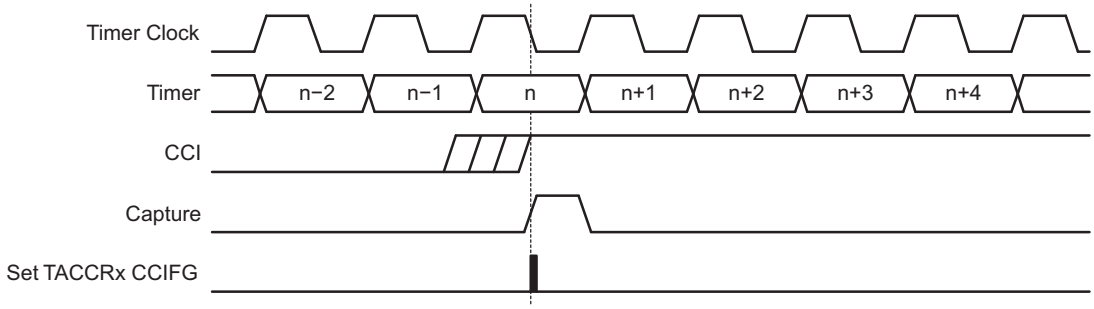


Figure 12-10. Capture Signal (SCS = 1)

Overflow logic is provided in each capture/compare register to indicate if a second capture was performed before the value from the first capture was read. Bit COV is set when this occurs as shown in Figure 12-11. COV must be reset with software.

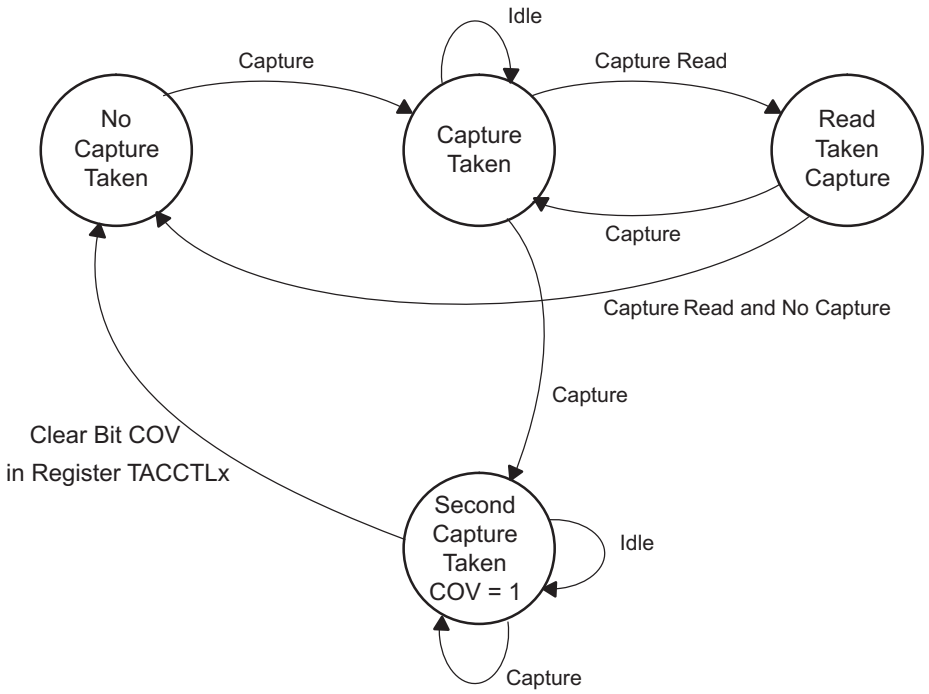


Figure 12-11. Capture Cycle

12.2.4.1 Capture Initiated by Software

Captures can be initiated by software. The CMx bits can be set for capture on both edges. Software then sets CCIS1 = 1 and toggles bit CCIS0 to switch the capture signal between V_{CC} and GND, initiating a capture each time CCIS0 changes state:

```
MOV   #CAP+SCS+CCIS1+CM_3,&TACCTLx   ; Setup TACCTLx
XOR   #CCIS0,&TACCTLx                ; TACCTLx = TAR
```

12.2.4.2 Compare Mode

The compare mode is selected when CAP = 0. The compare mode is used to generate PWM output signals or interrupts at specific time intervals. When TAR *counts* to the value in a TACCRx:

- Interrupt flag CCIFG is set
- Internal signal EQUx = 1
- EQUx affects the output according to the output mode
- The input signal CCI is latched into SCCI

12.2.5 Output Unit

Each capture/compare block contains an output unit. The output unit is used to generate output signals such as PWM signals. Each output unit has eight operating modes that generate signals based on the EQU0 and EQUx signals.

12.2.5.1 Output Modes

The output modes are defined by the OUTMODx bits and are described in Table 12-2. The OUTx signal is changed with the rising edge of the timer clock for all modes except mode 0. Output modes 2, 3, 6, and 7 are not useful for output unit 0, because EQUx = EQU0.

Table 12-2. Output Modes

OUTMODx	Mode	Description
000	Output	The output signal OUTx is defined by the OUTx bit. The OUTx signal updates immediately when OUTx is updated.
001	Set	The output is set when the timer *counts* to the TACCRx value. It remains set until a reset of the timer, or until another output mode is selected and affects the output.
010	Toggle/Reset	The output is toggled when the timer *counts* to the TACCRx value. It is reset when the timer *counts* to the TACCR0 value.
011	Set/Reset	The output is set when the timer *counts* to the TACCRx value. It is reset when the timer *counts* to the TACCR0 value.
100	Toggle	The output is toggled when the timer *counts* to the TACCRx value. The output period is double the timer period.
101	Reset	The output is reset when the timer *counts* to the TACCRx value. It remains reset until another output mode is selected and affects the output.
110	Toggle/Set	The output is toggled when the timer *counts* to the TACCRx value. It is set when the timer *counts* to the TACCR0 value.
111	Reset/Set	The output is reset when the timer *counts* to the TACCRx value. It is set when the timer *counts* to the TACCR0 value.

12.2.5.2 Output Example — Timer in Up Mode

The OUTx signal is changed when the timer *counts* up to the TACCRx value, and rolls from TACCR0 to zero, depending on the output mode. An example is shown in Figure 12-12 using TACCR0 and TACCR1.

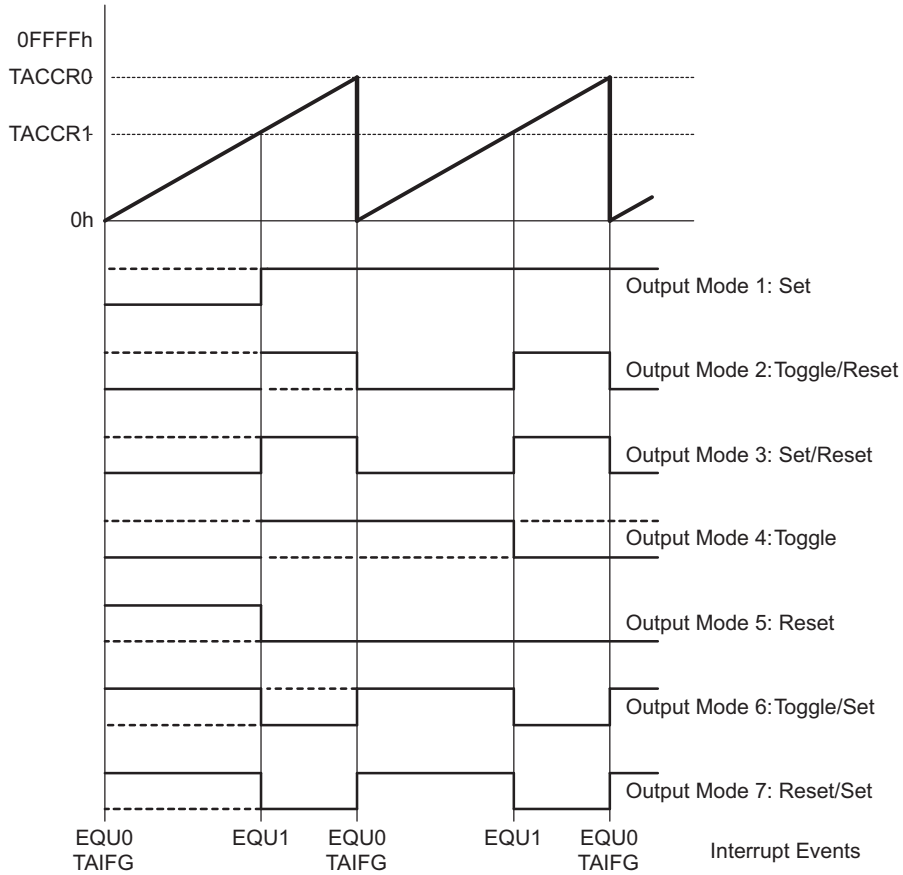


Figure 12-12. Output Example—Timer in Up Mode

12.2.5.3 Output Example — Timer in Continuous Mode

The OUTx signal is changed when the timer reaches the TACCRx and TACCR0 values, depending on the output mode. An example is shown in Figure 12-13 using TACCR0 and TACCR1.

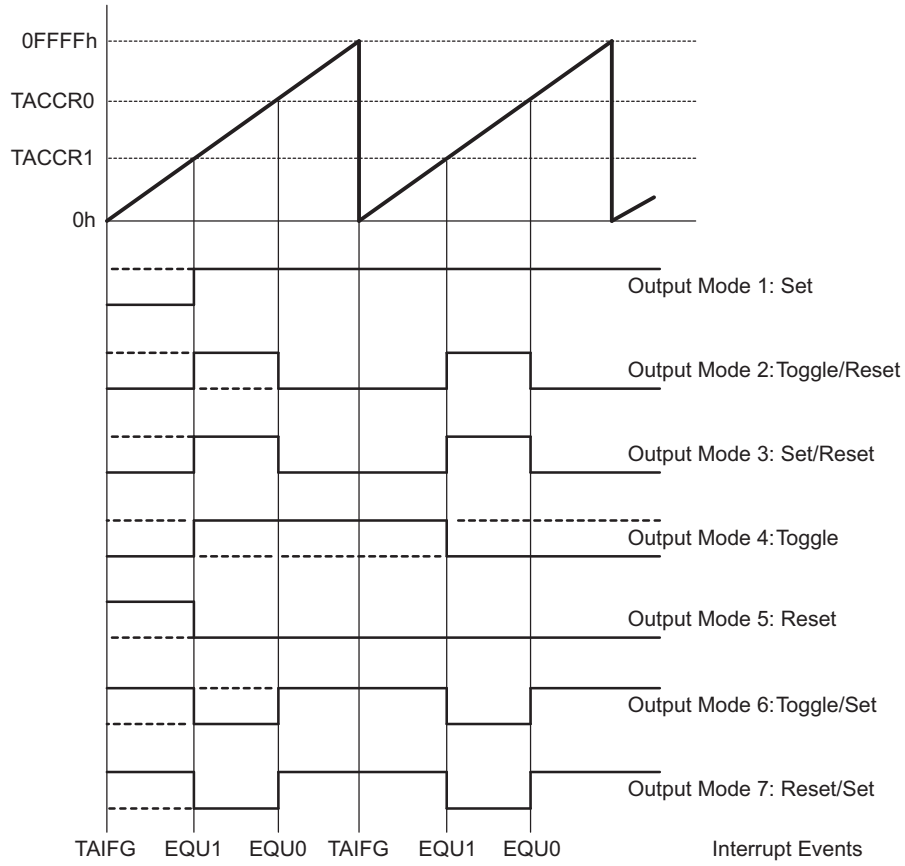


Figure 12-13. Output Example—Timer in Continuous Mode

12.2.5.4 Output Example — Timer in Up/Down Mode

The OUTx signal changes when the timer equals TACCRx in either count direction and when the timer equals TACCR0, depending on the output mode. An example is shown in Figure 12-14 using TACCR0 and TACCR2.

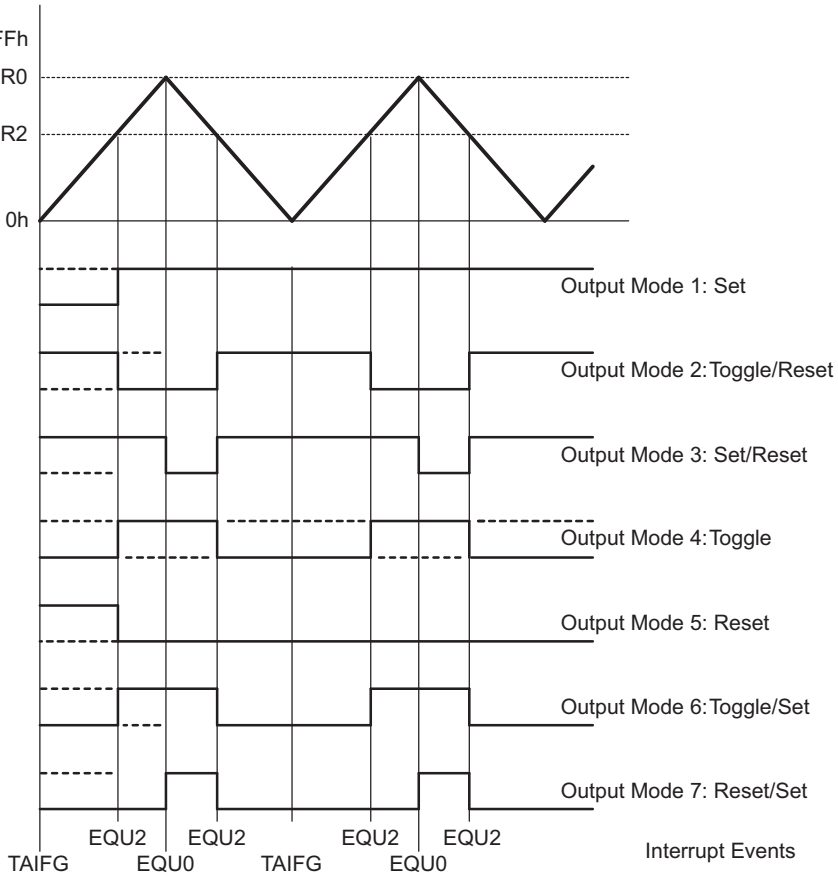


Figure 12-14. Output Example—Timer in Up/Down Mode

NOTE: Switching Between Output Modes

When switching between output modes, one of the OUTMODx bits should remain set during the transition, unless switching to mode 0. Otherwise, output glitching can occur because a NOR gate decodes output mode 0. A safe method for switching between output modes is to use output mode 7 as a transition state:

```
BIS   #OUTMOD_7,&TACCTLx   ; Set output mode=7
BIC   #OUTMODx, &TACCTLx   ; Clear unwanted bits
```

12.2.6 Timer_A Interrupts

Two interrupt vectors are associated with the 16-bit Timer_A module:

- TACCR0 interrupt vector for TACCR0 CCIFG
- TAIV interrupt vector for all other CCIFG flags and TAIFG

In capture mode any CCIFG flag is set when a timer value is captured in the associated TACCRx register. In compare mode, any CCIFG flag is set if TAR *counts* to the associated TACCRx value. Software may also set or clear any CCIFG flag. All CCIFG flags request an interrupt when their corresponding CCIE bit and the GIE bit are set.

12.2.6.1 TACCR0 Interrupt

The TACCR0 CCIFG flag has the highest Timer_A interrupt priority and has a dedicated interrupt vector as shown in Figure 12-15. The TACCR0 CCIFG flag is automatically reset when the TACCR0 interrupt request is serviced.

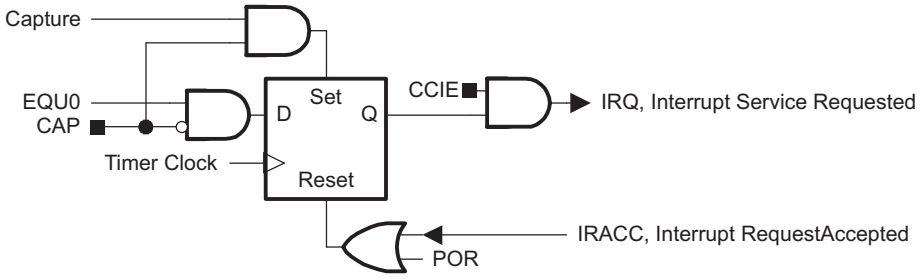


Figure 12-15. Capture/Compare TACCR0 Interrupt Flag

12.2.6.2 TAIV, Interrupt Vector Generator

The TACCR1 CCIFG, TACCR2 CCIFG, and TAIFG flags are prioritized and combined to source a single interrupt vector. The interrupt vector register TAIV is used to determine which flag requested an interrupt.

The highest priority enabled interrupt generates a number in the TAIV register (see register description). This number can be evaluated or added to the program counter to automatically enter the appropriate software routine. Disabled Timer_A interrupts do not affect the TAIV value.

Any access, read or write, of the TAIV register automatically resets the highest pending interrupt flag. If another interrupt flag is set, another interrupt is immediately generated after servicing the initial interrupt. For example, if the TACCR1 and TACCR2 CCIFG flags are set when the interrupt service routine accesses the TAIV register, TACCR1 CCIFG is reset automatically. After the RETI instruction of the interrupt service routine is executed, the TACCR2 CCIFG flag will generate another interrupt.

12.2.6.3 TAIV Software Example

The following software example shows the recommended use of TAIV and the handling overhead. The TAIV value is added to the PC to automatically jump to the appropriate routine.

The numbers at the right margin show the necessary CPU cycles for each instruction. The software overhead for different interrupt sources includes interrupt latency and return-from-interrupt cycles, but not the task handling itself. The latencies are:

- Capture/compare block TACCR0: 11 cycles
- Capture/compare blocks TACCR1, TACCR2: 16 cycles
- Timer overflow TAIFG: 14 cycles

```
; Interrupt handler for TACCR0 CCIFG                  Cycles
CCIFG_0_HND
;     ...    ; Start of handler   Interrupt latency       6
      RETI                                                5

; Interrupt handler for TAIFG, TACCR1 and TACCR2 CCIFG
TA_HND
      ...                    ; Interrupt latency          6
      ADD      &TAIV,PC      ; Add offset to Jump table   3
      RETI                   ; Vector 0: No interrupt     5
      JMP      CCIFG_1_HND   ; Vector 2: TACCR1           2
      JMP      CCIFG_2_HND   ; Vector 4: TACCR2           2
      RETI                   ; Vector 6: Reserved         5
      RETI                   ; Vector 8: Reserved         5

TAIFG_HND                    ; Vector 10: TAIFG Flag
      ...                    ; Task starts here
      RETI                                                5

CCIFG_2_HND                  ; Vector 4: TACCR2
      ...                    ; Task starts here
      RETI                   ; Back to main program       5

CCIFG_1_HND                  ; Vector 2: TACCR1
      ...                    ; Task starts here
      RETI                   ; Back to main program       5
```

12.3 Timer_A Registers

The Timer_A registers are listed in Table 12-3.

Table 12-3. Timer_A3 Registers

Register	Short Form	Register Type	Address	Initial State
Timer_A control	TACTL	Read/write	0160h	Reset with POR
Timer_A counter	TAR	Read/write	0170h	Reset with POR
Timer_A capture/compare control 0	TACCTL0	Read/write	0162h	Reset with POR
Timer_A capture/compare 0	TACCR0	Read/write	0172h	Reset with POR
Timer_A capture/compare control 1	TACCTL1	Read/write	0164h	Reset with POR
Timer_A capture/compare 1	TACCR1	Read/write	0174h	Reset with POR
Timer_A capture/compare control 2	TACCTL2(1)	Read/write	0166h	Reset with POR
Timer_A capture/compare 2	TACCR2(1)	Read/write	0176h	Reset with POR
Timer_A interrupt vector	TAIV	Read only	012Eh	Reset with POR

(1) Not present on MSP430 devices with Timer_A2 like MSP430F20xx and other devices.

12.3.1 TACTL, Timer_A Control Register

15	14	13	12	11	10	9	8
Unused						TASSELx	
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
IDx		MCx		Unused	TACLR	TAIE	TAIFG
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Unused	Bits 15-10	Unused
TASSELx	Bits 9-8	Timer_A clock source select 00 TACLK 01 ACLK 10 SMCLK 11 INCLK (INCLK is device-specific and is often assigned to the inverted TBCLK) (see the device-specific data sheet)
IDx	Bits 7-6	Input divider. These bits select the divider for the input clock. 00 /1 01 /2 10 /4 11 /8
MCx	Bits 5-4	Mode control. Setting MCx = 00h when Timer_A is not in use conserves power. 00 Stop mode: the timer is halted. 01 Up mode: the timer counts up to TACCR0. 10 Continuous mode: the timer counts up to 0FFFFh. 11 Up/down mode: the timer counts up to TACCR0 then down to 0000h.
Unused	Bit 3	Unused
TACLR	Bit 2	Timer_A clear. Setting this bit resets TAR, the clock divider, and the count direction. The TACLR bit is automatically reset and is always read as zero.
TAIE	Bit 1	Timer_A interrupt enable. This bit enables the TAIFG interrupt request. 0 Interrupt disabled 1 Interrupt enabled
TAIFG	Bit 0	Timer_A interrupt flag 0 No interrupt pending 1 Interrupt pending

12.3.2 TAR, Timer_A Register

15	14	13	12	11	10	9	8
TARx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
TARx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

TARx	Bits 15-0	Timer_A register. The TAR register is the count of Timer_A.

12.3.3 TACCRx, Timer_A Capture/Compare Register x

15	14	13	12	11	10	9	8
TACCRx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
TACCRx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

TACCRx	Bits 15-0	Timer_A capture/compare register. Compare mode: TACCRx holds the data for the comparison to the timer value in the Timer_A Register, TAR. Capture mode: The Timer_A Register, TAR, is copied into the TACCRx register when a capture is performed.

12.3.4 TACCTLx, Capture/Compare Control Register

15	14	13	12	11	10	9	8
CMx		**CCISx**		**SCS**	**SCCI**	**Unused**	**CAP**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	r	r0	rw-(0)
7	6	5	4	3	2	1	0
OUTMODx			**CCIE**	**CCI**	**OUT**	**COV**	**CCIFG**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	r	rw-(0)	rw-(0)	rw-(0)

CMx Bit 15-14 Capture mode
- 00 No capture
- 01 Capture on rising edge
- 10 Capture on falling edge
- 11 Capture on both rising and falling edges

CCISx Bit 13-12 Capture/compare input select. These bits select the TACCRx input signal. See the device-specific data sheet for specific signal connections.
- 00 CCIxA
- 01 CCIxB
- 10 GND
- 11 V_{CC}

SCS Bit 11 Synchronize capture source. This bit is used to synchronize the capture input signal with the timer clock.
- 0 Asynchronous capture
- 1 Synchronous capture

SCCI Bit 10 Synchronized capture/compare input. The selected CCI input signal is latched with the EQUx signal and can be read via this bit

Unused Bit 9 Unused. Read only. Always read as 0.

CAP Bit 8 Capture mode
- 0 Compare mode
- 1 Capture mode

OUTMODx Bits 7-5 Output mode. Modes 2, 3, 6, and 7 are not useful for TACCR0, because EQUx = EQU0.
- 000 OUT bit value
- 001 Set
- 010 Toggle/reset
- 011 Set/reset
- 100 Toggle
- 101 Reset
- 110 Toggle/set
- 111 Reset/set

CCIE Bit 4 Capture/compare interrupt enable. This bit enables the interrupt request of the corresponding CCIFG flag.
- 0 Interrupt disabled
- 1 Interrupt enabled

CCI Bit 3 Capture/compare input. The selected input signal can be read by this bit.

OUT Bit 2 Output. For output mode 0, this bit directly controls the state of the output.
- 0 Output low
- 1 Output high

COV Bit 1 Capture overflow. This bit indicates a capture overflow occurred. COV must be reset with software.
- 0 No capture overflow occurred
- 1 Capture overflow occurred

CCIFG Bit 0 Capture/compare interrupt flag
- 0 No interrupt pending
- 1 Interrupt pending

12.3.5 TAIV, Timer_A Interrupt Vector Register

15	14	13	12	11	10	9	8
0	**0**	**0**	**0**	**0**	**0**	**0**	**0**
r0	r0	r0	r0	r0	r0	r0	r0

7	6	5	4	3	2	1	0
0	**0**	**0**	**0**	**TAIVx**			**0**
r0	r0	r0	r0	r-(0)	r-(0)	r-(0)	r0

TAIVx Bits 15-0 Timer_A interrupt vector value

TAIV Contents	Interrupt Source	Interrupt Flag	Interrupt Priority
00h	No interrupt pending	-	
02h	Capture/compare 1	TACCR1 CCIFG	Highest
04h	Capture/compare 2[(1)]	TACCR2 CCIFG	
06h	Reserved	-	
08h	Reserved	-	
0Ah	Timer overflow	TAIFG	
0Ch	Reserved	-	
0Eh	Reserved	-	Lowest

(1) Not implemented in MSP430x20xx devices

Timer_B

Timer_B is a 16-bit timer/counter with multiple capture/compare registers. This chapter describes the operation of the Timer_B of the MSP430x2xx device family.

Topic **Page**

13.1 Timer_B Introduction

Timer_B is a 16-bit timer/counter with three or seven capture/compare registers. Timer_B can support multiple capture/compares, PWM outputs, and interval timing. Timer_B also has extensive interrupt capabilities. Interrupts may be generated from the counter on overflow conditions and from each of the capture/compare registers.

Timer_B features include :

- Asynchronous 16-bit timer/counter with four operating modes and four selectable lengths
- Selectable and configurable clock source
- Three or seven configurable capture/compare registers
- Configurable outputs with PWM capability
- Double-buffered compare latches with synchronized loading
- Interrupt vector register for fast decoding of all Timer_B interrupts

The block diagram of Timer_B is shown in Figure 13-1.

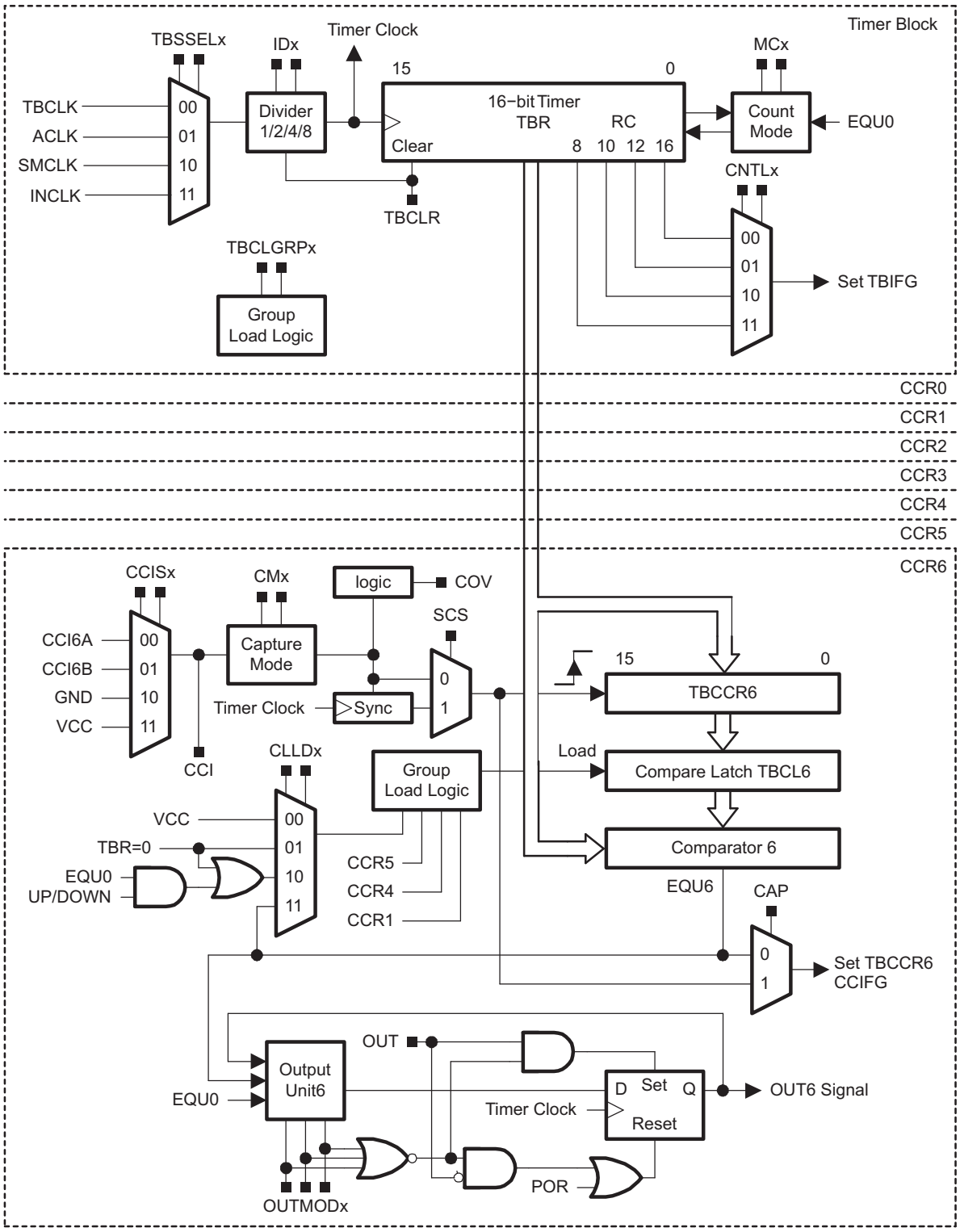
NOTE: Use of the Word *Count*

Count is used throughout this chapter. It means the counter must be in the process of counting for the action to take place. If a particular value is directly written to the counter, then an associated action does not take place.

13.1.1 Similarities and Differences From Timer_A

Timer_B is identical to Timer_A with the following exceptions:

- The length of Timer_B is programmable to be 8, 10, 12, or 16 bits.
- Timer_B TBCCRx registers are double-buffered and can be grouped.
- All Timer_B outputs can be put into a high-impedance state.
- The SCCI bit function is not implemented in Timer_B.



NOTE: INCLK is device-specific, often assigned to the inverted TBCLK, refer to device-specific data sheet.

Figure 13-1. Timer_B Block Diagram

13.2 Timer_B Operation

The Timer_B module is configured with user software. The setup and operation of Timer_B is discussed in the following sections.

13.2.1 16-Bit Timer Counter

The 16-bit timer/counter register, TBR, increments or decrements (depending on mode of operation) with each rising edge of the clock signal. TBR can be read or written with software. Additionally, the timer can generate an interrupt when it overflows.

TBR may be cleared by setting the TBCLR bit. Setting TBCLR also clears the clock divider and count direction for up/down mode.

NOTE: Modifying Timer_B Registers

It is recommended to stop the timer before modifying its operation (with exception of the interrupt enable, interrupt flag, and TBCLR) to avoid errant operating conditions.

When the timer clock is asynchronous to the CPU clock, any read from TBR should occur while the timer is not operating or the results may be unpredictable. Alternatively, the timer may be read multiple times while operating, and a majority vote taken in software to determine the correct reading. Any write to TBR will take effect immediately.

13.2.1.1 TBR Length

Timer_B is configurable to operate as an 8-, 10-, 12-, or 16-bit timer with the CNTLx bits. The maximum count value, $TBR_{(max)}$, for the selectable lengths is 0FFh, 03FFh, 0FFFh, and 0FFFFh, respectively. Data written to the TBR register in 8-, 10-, and 12-bit mode is right-justified with leading zeros.

13.2.1.2 Clock Source Select and Divider

The timer clock can be sourced from ACLK, SMCLK, or externally via TBCLK or INCLK (INCLK is device-specific, often assigned to the inverted TBCLK, refer to device-specific data sheet). The clock source is selected with the TBSSELx bits. The selected clock source may be passed directly to the timer or divided by 2,4, or 8, using the IDx bits. The clock divider is reset when TBCLR is set.

13.2.2 Starting the Timer

The timer may be started or restarted in the following ways:

- The timer counts when MCx > 0 and the clock source is active.
- When the timer mode is either up or up/down, the timer may be stopped by loading 0 to TBCL0. The timer may then be restarted by loading a nonzero value to TBCL0. In this scenario, the timer starts incrementing in the up direction from zero.

13.2.3 Timer Mode Control

The timer has four modes of operation as described in Table 13-1: stop, up, continuous, and up/down. The operating mode is selected with the MCx bits.

Table 13-1. Timer Modes

MCx	Mode	Description
00	Stop	The timer is halted.
01	Up	The timer repeatedly counts from zero to the value of compare register TBCL0.
10	Continuous	The timer repeatedly counts from zero to the value selected by the CNTLx bits.
11	Up/down	The timer repeatedly counts from zero up to the value of TBCL0 and then back down to zero.

13.2.3.1 Up Mode

The up mode is used if the timer period must be different from $TBR_{(max)}$ counts. The timer repeatedly counts up to the value of compare latch TBCL0, which defines the period, as shown in Figure 13-2. The number of timer counts in the period is TBCL0+1. When the timer value equals TBCL0 the timer restarts counting from zero. If up mode is selected when the timer value is greater than TBCL0, the timer immediately restarts counting from zero.

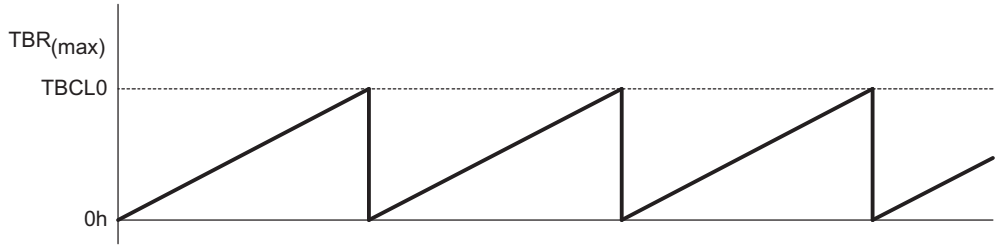


Figure 13-2. Up Mode

The TBCCR0 CCIFG interrupt flag is set when the timer *counts* to the TBCL0 value. The TBIFG interrupt flag is set when the timer *counts* from TBCL0 to zero. Figure 13-3 shows the flag set cycle.

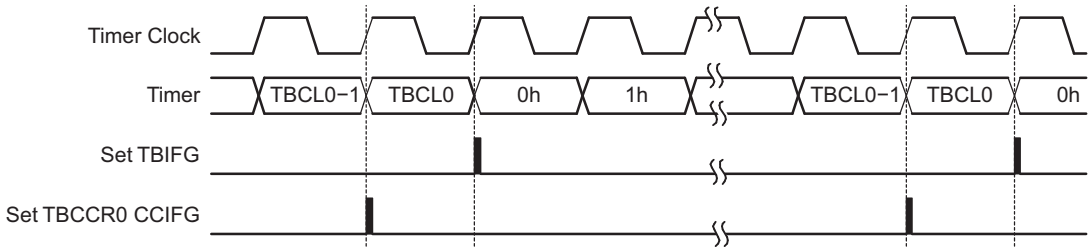


Figure 13-3. Up Mode Flag Setting

13.2.3.2 Changing the Period Register TBCL0

When changing TBCL0 while the timer is running and when the TBCL0 load event is *immediate*, CLLD0 = 00, if the new period is greater than or equal to the old period, or greater than the current count value, the timer counts up to the new period. If the new period is less than the current count value, the timer rolls to zero. However, one additional count may occur before the counter rolls to zero.

13.2.3.3 Continuous Mode

In continuous mode the timer repeatedly counts up to $TBR_{(max)}$ and restarts from zero as shown in Figure 13-4. The compare latch TBCL0 works the same way as the other capture/compare registers.

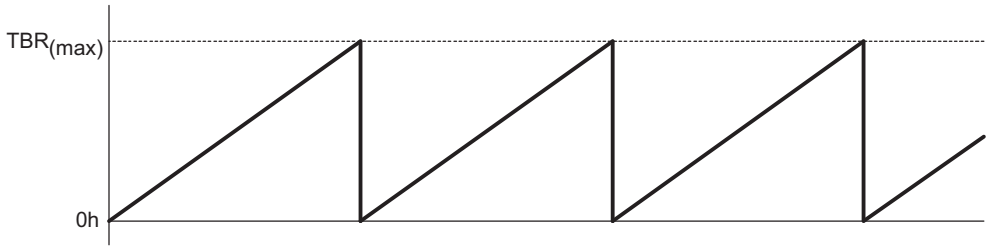


Figure 13-4. Continuous Mode

The TBIFG interrupt flag is set when the timer *counts* from $TBR_{(max)}$ to zero. Figure 13-5 shows the flag set cycle.

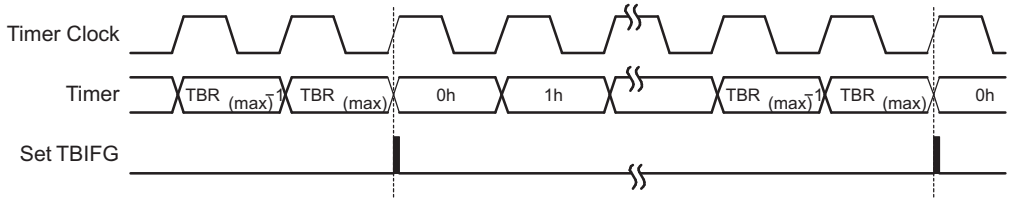


Figure 13-5. Continuous Mode Flag Setting

13.2.3.4 Use of the Continuous Mode

The continuous mode can be used to generate independent time intervals and output frequencies. Each time an interval is completed, an interrupt is generated. The next time interval is added to the TBCLx latch in the interrupt service routine. Figure 13-6 shows two separate time intervals t_0 and t_1 being added to the capture/compare registers. The time interval is controlled by hardware, not software, without impact from interrupt latency. Up to three (Timer_B3) or 7 (Timer_B7) independent time intervals or output frequencies can be generated using capture/compare registers.

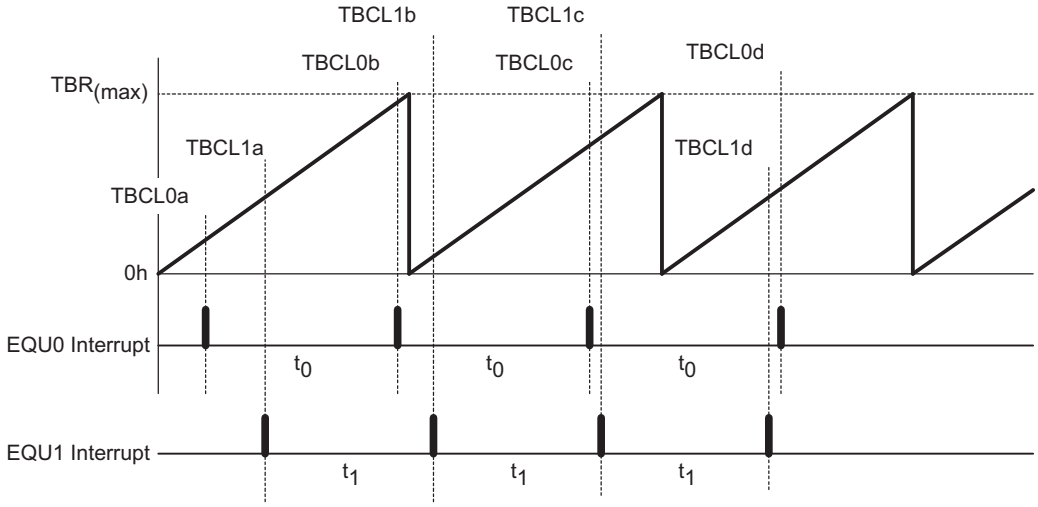


Figure 13-6. Continuous Mode Time Intervals

Time intervals can be produced with other modes as well, where TBCL0 is used as the period register. Their handling is more complex since the sum of the old TBCLx data and the new period can be higher than the TBCL0 value. When the sum of the previous TBCLx value plus t_x is greater than the TBCL0 data, TBCL0 + 1 must be subtracted to obtain the correct time interval.

13.2.3.5 Up/Down Mode

The up/down mode is used if the timer period must be different from $TBR_{(max)}$ counts, and if a symmetrical pulse generation is needed. The timer repeatedly counts up to the value of compare latch TBCL0, and back down to zero, as shown in Figure 13-7. The period is twice the value in TBCL0.

NOTE: TBCL0 > TBR(max)

If TBCL0 > $TBR_{(max)}$, the counter operates as if it were configured for continuous mode. It does not count down from $TBR_{(max)}$ to zero.

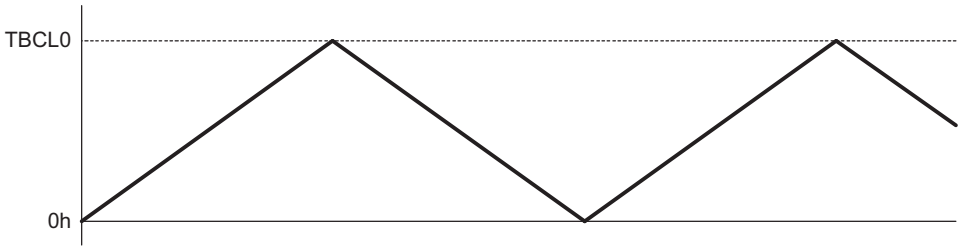


Figure 13-7. Up/Down Mode

The count direction is latched. This allows the timer to be stopped and then restarted in the same direction it was counting before it was stopped. If this is not desired, the TBCLR bit must be used to clear the direction. The TBCLR bit also clears the TBR value and the clock divider.

In up/down mode, the TBCCR0 CCIFG interrupt flag and the TBIFG interrupt flag are set only once during the period, separated by 1/2 the timer period. The TBCCR0 CCIFG interrupt flag is set when the timer *counts* from TBCL0-1 to TBCL0, and TBIFG is set when the timer completes *counting* down from 0001h to 0000h. Figure 13-8 shows the flag set cycle.

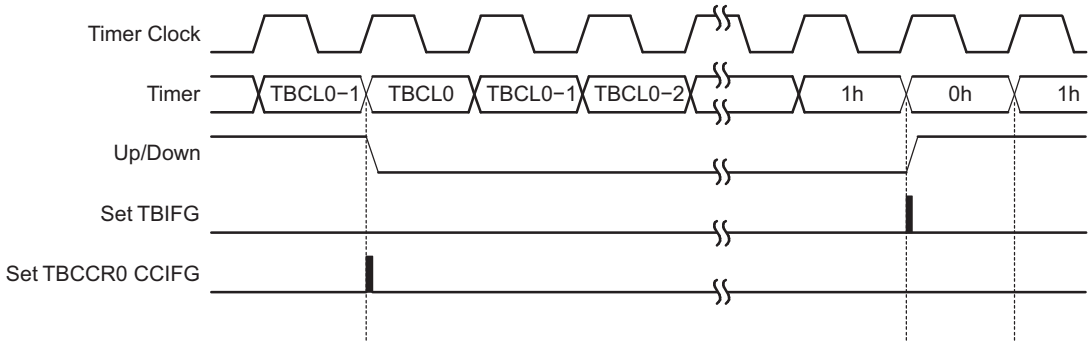


Figure 13-8. Up/Down Mode Flag Setting

13.2.3.6 Changing the Value of Period Register TBCL0

When changing TBCL0 while the timer is running, and counting in the down direction, and when the TBCL0 load event is *immediate*, the timer continues its descent until it reaches zero. The value in TBCCR0 is latched into TBCL0 immediately; however, the new period takes effect after the counter counts down to zero.

If the timer is counting in the up direction when the new period is latched into TBCL0, and the new period is greater than or equal to the old period, or greater than the current count value, the timer counts up to the new period before counting down. When the timer is counting in the up direction, and the new period is less than the current count value when TBCL0 is loaded, the timer begins counting down. However, one additional count may occur before the counter begins counting down.

13.2.3.7 Use of the Up/Down Mode

The up/down mode supports applications that require dead times between output signals (see section *Timer_B Output Unit*). For example, to avoid overload conditions, two outputs driving an H-bridge must never be in a high state simultaneously. In the example shown in Figure 13-9 the t_{dead} is:

$t_{dead} = t_{timer} \times$ (TBCL1 - TBCL3)

Where,

t_{dead} = Time during which both outputs need to be inactive

t_{timer} = Cycle time of the timer clock

TBCLx = Content of compare latch x

The ability to simultaneously load grouped compare latches assures the dead times.

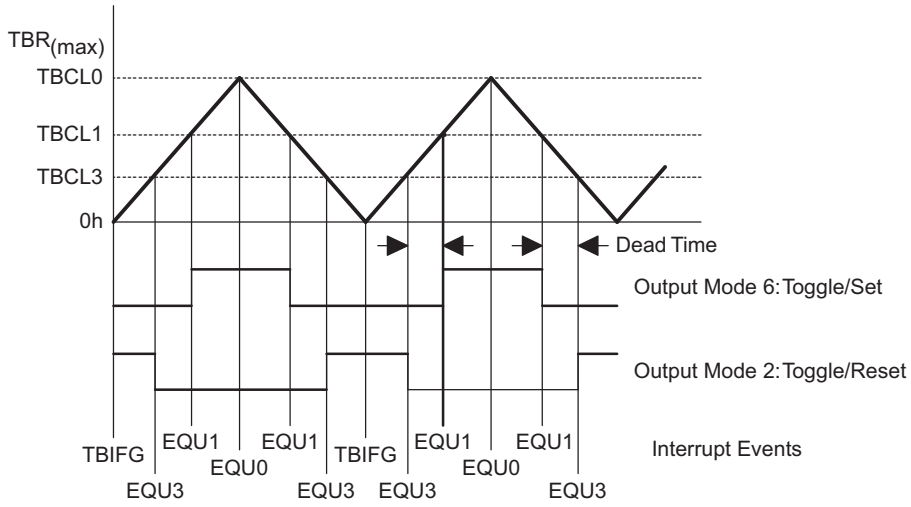


Figure 13-9. Output Unit in Up/Down Mode

13.2.4 Capture/Compare Blocks

Three or seven identical capture/compare blocks, TBCCRx, are present in Timer_B. Any of the blocks may be used to capture the timer data or to generate time intervals.

13.2.4.1 Capture Mode

The capture mode is selected when CAP = 1. Capture mode is used to record time events. It can be used for speed computations or time measurements. The capture inputs CCIxA and CCIxB are connected to external pins or internal signals and are selected with the CCISx bits. The CMx bits select the capture edge of the input signal as rising, falling, or both. A capture occurs on the selected edge of the input signal. If a capture is performed:

- The timer value is copied into the TBCCRx register
- The interrupt flag CCIFG is set

The input signal level can be read at any time via the CCI bit. MSP430x2xx family devices may have different signals connected to CCIxA and CCIxB. Refer to the device-specific data sheet for the connections of these signals.

The capture signal can be asynchronous to the timer clock and cause a race condition. Setting the SCS bit will synchronize the capture with the next timer clock. Setting the SCS bit to synchronize the capture signal with the timer clock is recommended. This is illustrated in Figure 13-10.

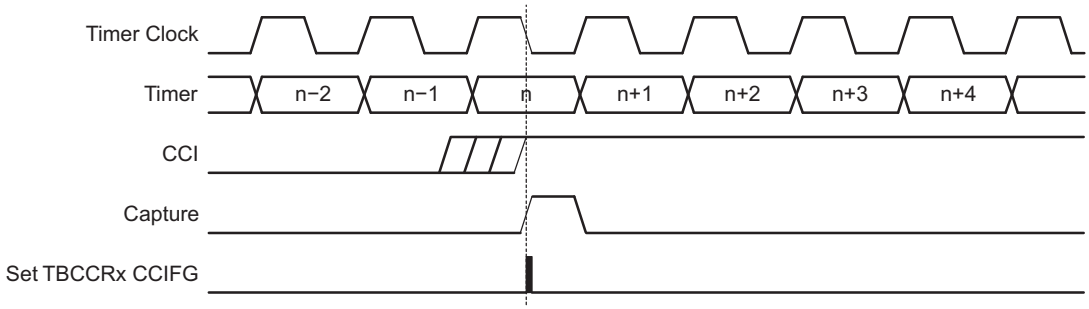


Figure 13-10. Capture Signal (SCS = 1)

Overflow logic is provided in each capture/compare register to indicate if a second capture was performed before the value from the first capture was read. Bit COV is set when this occurs as shown in Figure 13-11. COV must be reset with software.

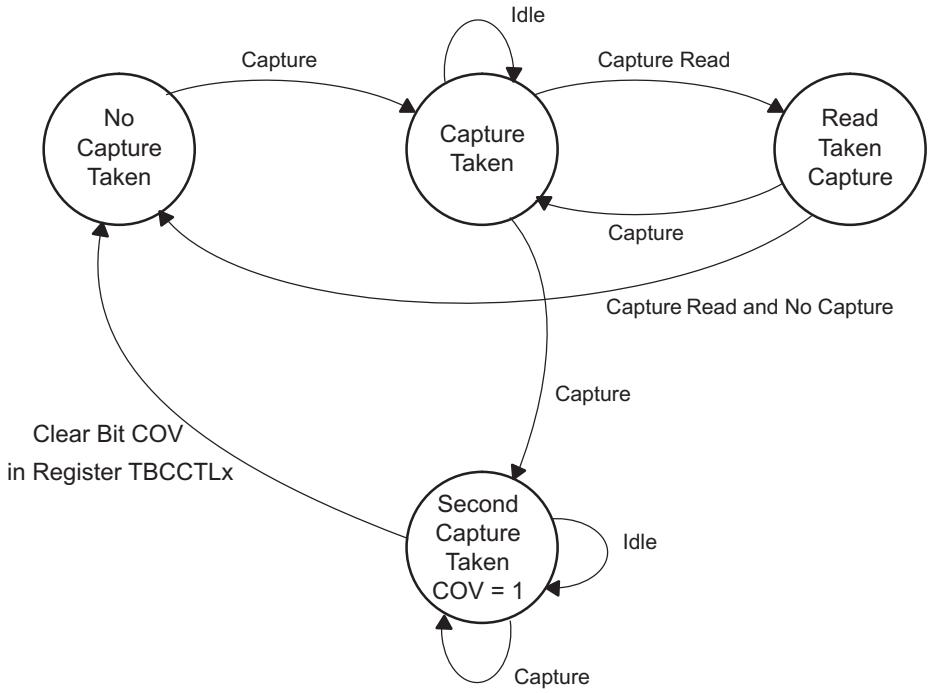


Figure 13-11. Capture Cycle

13.2.4.1.1 Capture Initiated by Software

Captures can be initiated by software. The CMx bits can be set for capture on both edges. Software then sets bit CCIS1=1 and toggles bit CCIS0 to switch the capture signal between V_{CC} and GND, initiating a capture each time CCIS0 changes state:

```
MOV   #CAP+SCS+CCIS1+CM_3,&TBCCTLx   ; Setup TBCCTLx
XOR   #CCIS0, &TBCCTLx               ; TBCCTLx = TBR
```

13.2.4.2 Compare Mode

The compare mode is selected when CAP = 0. Compare mode is used to generate PWM output signals or interrupts at specific time intervals. When TBR *counts* to the value in a TBCLx:

- Interrupt flag CCIFG is set
- Internal signal EQUx = 1
- EQUx affects the output according to the output mode

13.2.4.2.1 Compare Latch TBCLx

The TBCCRx compare latch, TBCLx, holds the data for the comparison to the timer value in compare mode. TBCLx is buffered by TBCCRx. The buffered compare latch gives the user control over when a compare period updates. The user cannot directly access TBCLx. Compare data is written to each TBCCRx and automatically transferred to TBCLx. The timing of the transfer from TBCCRx to TBCLx is user-selectable with the CLLDx bits as described in Table 13-2.

Table 13-2. TBCLx Load Events

CLLDx	Description
00	New data is transferred from TBCCRx to TBCLx immediately when TBCCRx is written to.
01	New data is transferred from TBCCRx to TBCLx when TBR *counts* to 0
10	New data is transferred from TBCCRx to TBCLx when TBR *counts* to 0 for up and continuous modes. New data is transferred to from TBCCRx to TBCLx when TBR *counts* to the old TBCL0 value or to 0 for up/down mode
11	New data is transferred from TBCCRx to TBCLx when TBR *counts* to the old TBCLx value.

13.2.4.2.2 Grouping Compare Latches

Multiple compare latches may be grouped together for simultaneous updates with the TBCLGRPx bits. When using groups, the CLLDx bits of the lowest numbered TBCCRx in the group determine the load event for each compare latch of the group, except when TBCLGRP = 3, as shown in Table 13-3. The CLLDx bits of the controlling TBCCRx must not be set to zero. When the CLLDx bits of the controlling TBCCRx are set to zero, all compare latches update immediately when their corresponding TBCCRx is written; no compare latches are grouped.

Two conditions must exist for the compare latches to be loaded when grouped. First, all TBCCRx registers of the group must be updated, even when new TBCCRx data = old TBCCRx data. Second, the load event must occur.

Table 13-3. Compare Latch Operating Modes

TBCLGRPx	Grouping	Update Control
00	None	Individual
01	TBCL1+TBCL2 TBCL3+TBCL4 TBCL5+TBCL6	TBCCR1 TBCCR3 TBCCR5
10	TBCL1+TBCL2+TBCL3 TBCL4+TBCL5+TBCL6	TBCCR1 TBCCR4
11	TBCL0+TBCL1+TBCL2+TBCL3+TBCL4+TBCL5+TBCL6	TBCCR1

13.2.5 Output Unit

Each capture/compare block contains an output unit. The output unit is used to generate output signals such as PWM signals. Each output unit has eight operating modes that generate signals based on the EQU0 and EQUx signals. The TBOUTH pin function can be used to put all Timer_B outputs into a high-impedance state. When the TBOUTH pin function is selected for the pin, and when the pin is pulled high, all Timer_B outputs are in a high-impedance state.

13.2.5.1 Output Modes

The output modes are defined by the OUTMODx bits and are described in Table 13-4. The OUTx signal is changed with the rising edge of the timer clock for all modes except mode 0. Output modes 2, 3, 6, and 7 are not useful for output unit 0 because EQUx = EQU0.

Table 13-4. Output Modes

OUTMODx	Mode	Description
000	Output	The output signal OUTx is defined by the OUTx bit. The OUTx signal updates immediately when OUTx is updated.
001	Set	The output is set when the timer *counts* to the TBCLx value. It remains set until a reset of the timer, or until another output mode is selected and affects the output.
010	Toggle/Reset	The output is toggled when the timer *counts* to the TBCLx value. It is reset when the timer *counts* to the TBCL0 value.
011	Set/Reset	The output is set when the timer *counts* to the TBCLx value. It is reset when the timer *counts* to the TBCL0 value.
100	Toggle	The output is toggled when the timer *counts* to the TBCLx value. The output period is double the timer period.
101	Reset	The output is reset when the timer *counts* to the TBCLx value. It remains reset until another output mode is selected and affects the output.
110	Toggle/Set	The output is toggled when the timer *counts* to the TBCLx value. It is set when the timer *counts* to the TBCL0 value.
111	Reset/Set	The output is reset when the timer *counts* to the TBCLx value. It is set when the timer *counts* to the TBCL0 value.

13.2.5.1.1 Output Example, Timer in Up Mode

The OUTx signal is changed when the timer *counts* up to the TBCLx value, and rolls from TBCL0 to zero, depending on the output mode. An example is shown in Figure 13-12 using TBCL0 and TBCL1.

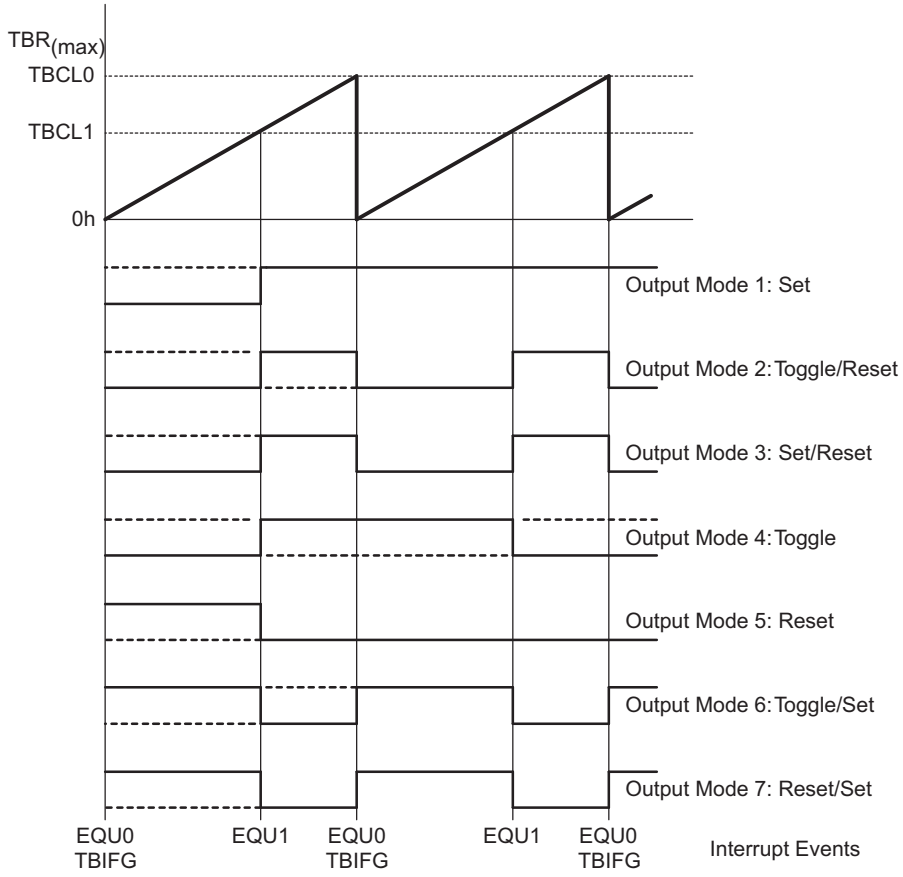


Figure 13-12. Output Example, Timer in Up Mode

13.2.5.1.2 Output Example, Timer in Continuous Mode

The OUTx signal is changed when the timer reaches the TBCLx and TBCL0 values, depending on the output mode, An example is shown in Figure 13-13 using TBCL0 and TBCL1.

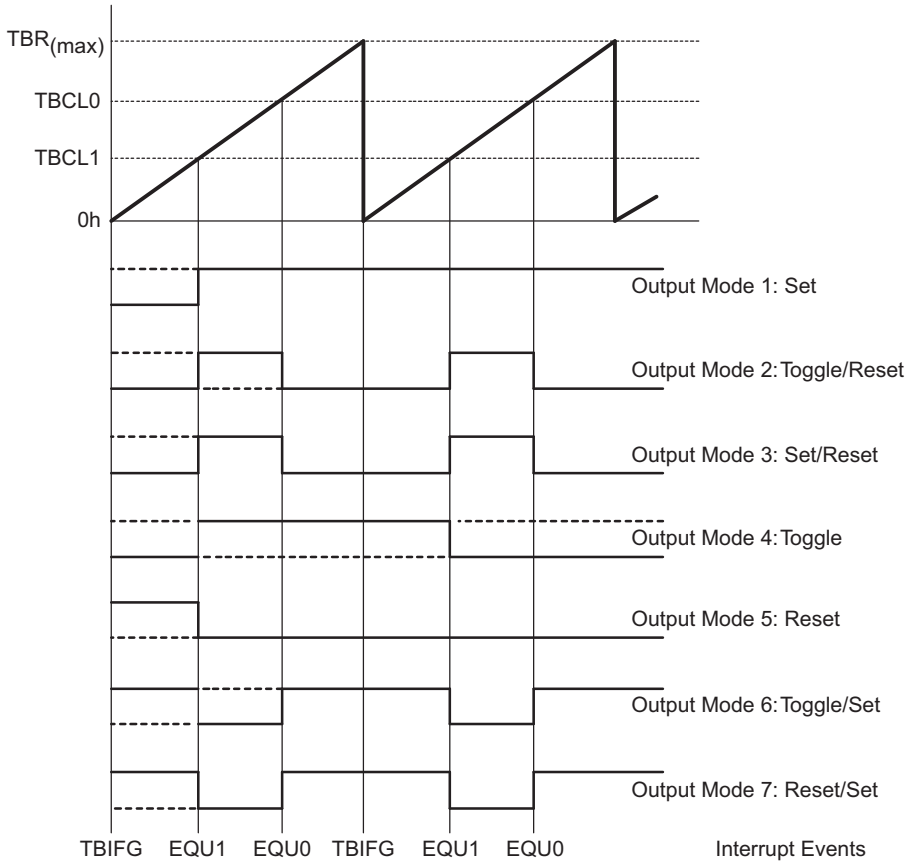


Figure 13-13. Output Example, Timer in Continuous Mode

13.2.5.1.3 Output Example, Timer in Up/Down Mode

The OUTx signal changes when the timer equals TBCLx in either count direction and when the timer equals TBCL0, depending on the output mode. An example is shown in Figure 13-14 using TBCL0 and TBCL3.

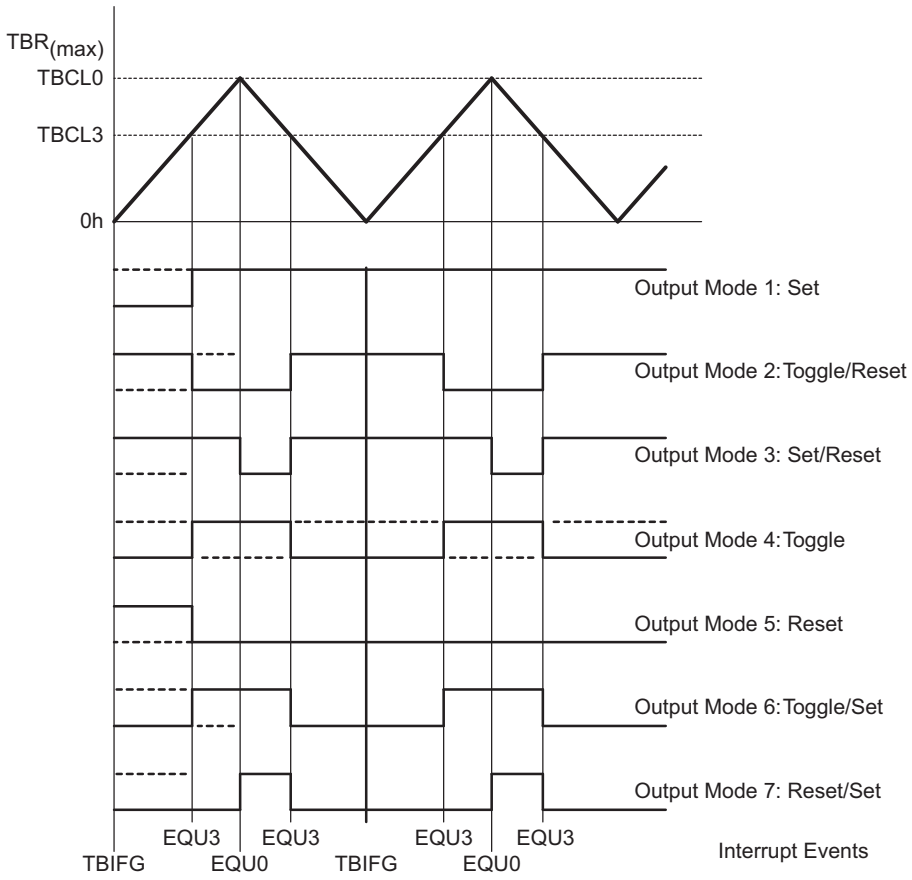


Figure 13-14. Output Example, Timer in Up/Down Mode

NOTE: Switching Between Output Modes

When switching between output modes, one of the OUTMODx bits should remain set during the transition, unless switching to mode 0. Otherwise, output glitching can occur because a NOR gate decodes output mode 0. A safe method for switching between output modes is to use output mode 7 as a transition state:

```
BIS   #OUTMOD_7,&TBCCTLx  ; Set output mode=7
BIC   #OUTMODx, &TBCCTLx  ; Clear unwanted bits
```

13.2.6 Timer_B Interrupts

Two interrupt vectors are associated with the 16-bit Timer_B module:

- TBCCR0 interrupt vector for TBCCR0 CCIFG
- TBIV interrupt vector for all other CCIFG flags and TBIFG

In capture mode, any CCIFG flag is set when a timer value is captured in the associated TBCCRx register. In compare mode, any CCIFG flag is set when TBR *counts* to the associated TBCLx value. Software may also set or clear any CCIFG flag. All CCIFG flags request an interrupt when their corresponding CCIE bit and the GIE bit are set.

13.2.6.1 TBCCR0 Interrupt Vector

The TBCCR0 CCIFG flag has the highest Timer_B interrupt priority and has a dedicated interrupt vector as shown in Figure 13-15. The TBCCR0 CCIFG flag is automatically reset when the TBCCR0 interrupt request is serviced.

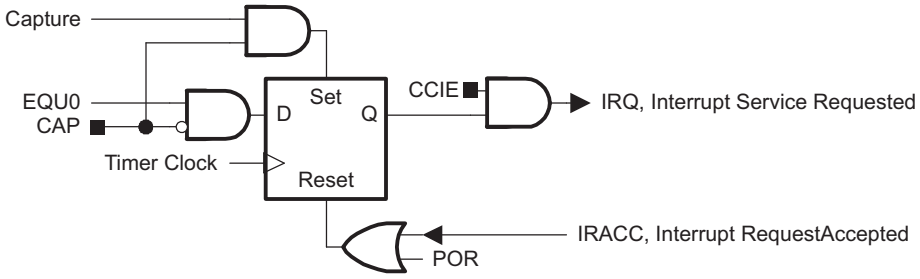


Figure 13-15. Capture/Compare TBCCR0 Interrupt Flag

13.2.6.2 TBIV, Interrupt Vector Generator

The TBIFG flag and TBCCRx CCIFG flags (excluding TBCCR0 CCIFG) are prioritized and combined to source a single interrupt vector. The interrupt vector register TBIV is used to determine which flag requested an interrupt.

The highest priority enabled interrupt (excluding TBCCR0 CCIFG) generates a number in the TBIV register (see register description). This number can be evaluated or added to the program counter to automatically enter the appropriate software routine. Disabled Timer_B interrupts do not affect the TBIV value.

Any access, read or write, of the TBIV register automatically resets the highest pending interrupt flag. If another interrupt flag is set, another interrupt is immediately generated after servicing the initial interrupt. For example, if the TBCCR1 and TBCCR2 CCIFG flags are set when the interrupt service routine accesses the TBIV register, TBCCR1 CCIFG is reset automatically. After the RETI instruction of the interrupt service routine is executed, the TBCCR2 CCIFG flag will generate another interrupt.

13.2.6.3 TBIV, Interrupt Handler Examples

The following software example shows the recommended use of TBIV and the handling overhead. The TBIV value is added to the PC to automatically jump to the appropriate routine.

The numbers at the right margin show the necessary CPU clock cycles for each instruction. The software overhead for different interrupt sources includes interrupt latency and return-from-interrupt cycles, but not the task handling itself. The latencies are:

- Capture/compare block CCR0: 11 cycles
- Capture/compare blocks CCR1 to CCR6: 16 cycles
- Timer overflow TBIFG: 14 cycles

Example 13-1 shows the recommended use of TBIV for Timer_B3.

Example 13-1. Recommended Use of TBIV

```
; Interrupt handler for TBCCR0 CCIFG.                Cycles
CCIFG_0_HND
   ...          ; Start of handler Interrupt latency      6
   RETI                                                   5

; Interrupt handler for TBIFG, TBCCR1 and TBCCR2 CCIFG.
TB_HND      ...            ; Interrupt latency            6
   ADD      &TBIV,PC       ; Add offset to Jump table     3
   RETI                    ; Vector  0: No interrupt      5
   JMP      CCIFG_1_HND    ; Vector  2: Module 1          2
   JMP      CCIFG_2_HND    ; Vector  4: Module 2          2
   RETI                    ; Vector  6
   RETI                    ; Vector  8
   RETI                    ; Vector 10
   RETI                    ; Vector 12

TBIFG_HND                  ; Vector 14: TIMOV Flag
   ...                     ; Task starts here
   RETI                                                   5

CCIFG_2_HND                ; Vector 4: Module 2
   ...                     ; Task starts here
   RETI                    ; Back to main program         5

; The Module 1 handler shows a way to look if any other
; interrupt is pending: 5 cycles have to be spent, but
; 9 cycles may be saved if another interrupt is pending
CCIFG_1_HND                ; Vector 6: Module 3
   ...                     ; Task starts here
   JMP      TB_HND         ; Look for pending ints        2
```

13.3 Timer_B Registers

The Timer_B registers are listed in Table 13-5:

Table 13-5. Timer_B Registers

Register	Short Form	Register Type	Address	Initial State
Timer_B control	TBCTL	Read/write	0180h	Reset with POR
Timer_B counter	TBR	Read/write	0190h	Reset with POR
Timer_B capture/compare control 0	TBCCTL0	Read/write	0182h	Reset with POR
Timer_B capture/compare 0	TBCCR0	Read/write	0192h	Reset with POR
Timer_B capture/compare control 1	TBCCTL1	Read/write	0184h	Reset with POR
Timer_B capture/compare 1	TBCCR1	Read/write	0194h	Reset with POR
Timer_B capture/compare control 2	TBCCTL2	Read/write	0186h	Reset with POR
Timer_B capture/compare 2	TBCCR2	Read/write	0196h	Reset with POR
Timer_B capture/compare control 3	TBCCTL3	Read/write	0188h	Reset with POR
Timer_B capture/compare 3	TBCCR3	Read/write	0198h	Reset with POR
Timer_B capture/compare control 4	TBCCTL4	Read/write	018Ah	Reset with POR
Timer_B capture/compare 4	TBCCR4	Read/write	019Ah	Reset with POR
Timer_B capture/compare control 5	TBCCTL5	Read/write	018Ch	Reset with POR
Timer_B capture/compare 5	TBCCR5	Read/write	019Ch	Reset with POR
Timer_B capture/compare control 6	TBCCTL6	Read/write	018Eh	Reset with POR
Timer_B capture/compare 6	TBCCR6	Read/write	019Eh	Reset with POR
Timer_B interrupt vector	TBIV	Read only	011Eh	Reset with POR

13.3.1 Timer_B Control Register TBCTL

15	14	13	12	11	10	9	8
Unused	**TBCLGRPx**		**CNTLx**		**Unused**	**TBSSELx**	
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
IDx		**MCx**		**Unused**	**TBCLR**	**TBIE**	**TBIFG**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	w-(0)	rw-(0)	rw-(0)

Unused	Bit 15	Unused	
TBCLGRP	Bit 14-13	TBCLx group	
		00	Each TBCLx latch loads independently
		01	TBCL1+TBCL2 (TBCCR1 CLLDx bits control the update) TBCL3+TBCL4 (TBCCR3 CLLDx bits control the update) TBCL5+TBCL6 (TBCCR5 CLLDx bits control the update) TBCL0 independent
		10	TBCL1+TBCL2+TBCL3 (TBCCR1 CLLDx bits control the update) TBCL4+TBCL5+TBCL6 (TBCCR4 CLLDx bits control the update) TBCL0 independent
		11	TBCL0+TBCL1+TBCL2+TBCL3+TBCL4+TBCL5+TBCL6 (TBCCR1 CLLDx bits control the update)
CNTLx	Bits 12-11	Counter length	
		00	16-bit, TBR(max) = 0FFFFh
		01	12-bit, TBR(max) = 0FFFh
		10	10-bit, TBR(max) = 03FFh
		11	8-bit, TBR(max) = 0FFh
Unused	Bit 10	Unused	
TBSSELx	Bits 9-8	Timer_B clock source select.	
		00	TBCLK
		01	ACLK
		10	SMCLK
		11	INCLK (INCLK is device-specific and is often assigned to the inverted TBCLK) (see the device-specific data sheet)
IDx	Bits 7-6	Input divider. These bits select the divider for the input clock.00 /101 /210 /411 /8	
MCx	Bits 5-4	Mode control. Setting MCx = 00h when Timer_B is not in use conserves power.	
		00	Stop mode: the timer is halted
		01	Up mode: the timer counts up to TBCL0
		10	Continuous mode: the timer counts up to the value set by CNTLx
		11	Up/down mode: the timer counts up to TBCL0 and down to 0000h
Unused	Bit 3	Unused	
TBCLR	Bit 2	Timer_B clear. Setting this bit resets TBR, the clock divider, and the count direction. The TBCLR bit is automatically reset and is always read as zero.	
TBIE	Bit 1	Timer_B interrupt enable. This bit enables the TBIFG interrupt request.	
		0	Interrupt disabled
		1	Interrupt enabled
TBIFG	Bit 0	Timer_B interrupt flag.	
		0	No interrupt pending
		1	Interrupt pending

13.3.2 TBR, Timer_B Register

15	14	13	12	11	10	9	8
TBRx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
TBRx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

TBRx	Bits 15-0	Timer_B register. The TBR register is the count of Timer_B.

13.3.3 TBCCRx, Timer_B Capture/Compare Register x

15	14	13	12	11	10	9	8
TBCCRx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
TBCCRx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

TBCCRx	Bits 15-0	Timer_B capture/compare register. Compare mode: Compare data is written to each TBCCRx and automatically transferred to TBCLx. TBCLx holds the data for the comparison to the timer value in the Timer_B Register, TBR. Capture mode: The Timer_B Register, TBR, is copied into the TBCCRx register when a capture is performed.

13.3.4 TBCCTLx, Capture/Compare Control Register

15	14	13	12	11	10	9	8
CMx		**CCISx**		**SCS**	**CLLDx**		**CAP**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	r-(0)	rw-(0)
7	6	5	4	3	2	1	0
OUTMODx			**CCIE**	**CCI**	**OUT**	**COV**	**CCIFG**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	r	rw-(0)	rw-(0)	rw-(0)

CMx Bit 15-14 Capture mode
- 00 No capture
- 01 Capture on rising edge
- 10 Capture on falling edge
- 11 Capture on both rising and falling edges

CCISx Bit 13-12 Capture/compare input select. These bits select the TBCCRx input signal. See the device-specific data sheet for specific signal connections.
- 00 CCIxA
- 01 CCIxB
- 10 GND
- 11 V_{CC}

SCS Bit 11 Synchronize capture source. This bit is used to synchronize the capture input signal with the timer clock.
- 0 Asynchronous capture
- 1 Synchronous capture

CLLDx Bit 10-9 Compare latch load. These bits select the compare latch load event.
- 00 TBCLx loads on write to TBCCRx
- 01 TBCLx loads when TBR *counts* to 0
- 10 TBCLx loads when TBR *counts*to 0 (up or continuous mode)
TBCLx loads when TBR *counts*to TBCL0 or to 0 (up/down mode)
- 11 TBCLx loads when TBR *counts*to TBCLx

CAP Bit 8 Capture mode
- 0 Compare mode
- 1 Capture mode

OUTMODx Bits 7-5 Output mode. Modes 2, 3, 6, and 7 are not useful for TBCL0 because EQUx = EQU0.
- 000 OUT bit value
- 001 Set
- 010 Toggle/reset
- 011 Set/reset
- 100 Toggle
- 101 Reset
- 110 Toggle/set
- 111 Reset/set

CCIE Bit 4 Capture/compare interrupt enable. This bit enables the interrupt request of the corresponding CCIFG flag.
- 0 Interrupt disabled
- 1 Interrupt enabled

CCI Bit 3 Capture/compare input. The selected input signal can be read by this bit.

OUT Bit 2 Output. For output mode 0, this bit directly controls the state of the output.
- 0 Output low
- 1 Output high

COV Bit 1 Capture overflow. This bit indicates a capture overflow occurred. COV must be reset with software.
- 0 No capture overflow occurred
- 1 Capture overflow occurred

CCIFG Bit 0 Capture/compare interrupt flag
- 0 No interrupt pending
- 1 Interrupt pending

13.3.5 TBIV, Timer_B Interrupt Vector Register

15	14	13	12	11	10	9	8
0	**0**	**0**	**0**	**0**	**0**	**0**	**0**
r0	r0	r0	r0	r0	r0	r0	r0
7	6	5	4	3	2	1	0
0	**0**	**0**	**0**	**TBIVx**			**0**
r0	r0	r0	r0	r-(0)	r-(0)	r-(0)	r0

TBIVx Bits 15-0 Timer_B interrupt vector value

TBIV Contents	Interrupt Source	Interrupt Flag	Interrupt Priority
00h	No interrupt pending	-	
02h	Capture/compare 1	TBCCR1 CCIFG	Highest
04h	Capture/compare 2	TBCCR2 CCIFG	
06h	Capture/compare 3(1)	TBCCR3 CCIFG	
08h	Capture/compare 4(1)	TBCCR4 CCIFG	
0Ah	Capture/compare 5(1)	TBCCR5 CCIFG	
0Ch	Capture/compare 6(1)	TBCCR6 CCIFG	
0Eh	Timer overflow	TBIFG	Lowest

(1) Not available on all devices

Universal Serial Interface (USI)

The Universal Serial Interface (USI) module provides SPI and I^2C serial communication with one hardware module. This chapter discusses both modes.

Topic **Page**

14.1 USI Introduction

The USI module provides the basic functionality to support synchronous serial communication. In its simplest form, it is an 8- or 16-bit shift register that can be used to output data streams, or when combined with minimal software, can implement serial communication. In addition, the USI includes built-in hardware functionality to ease the implementation of SPI and I^2C communication. The USI module also includes interrupts to further reduce the necessary software overhead for serial communication and to maintain the ultra-low-power capabilities of the MSP430.

The USI module features include:

- Three-wire SPI mode support
- I^2C mode support
- Variable data length
- Slave operation in LPM4; no internal clock required
- Selectable MSB or LSB data order
- START and STOP detection for I^2C mode with automatic SCL control
- Arbitration lost detection in master mode
- Programmable clock generation
- Selectable clock polarity and phase control

Figure 14-1 shows the USI module in SPI mode. Figure 14-2 shows the USI module in I^2C mode.

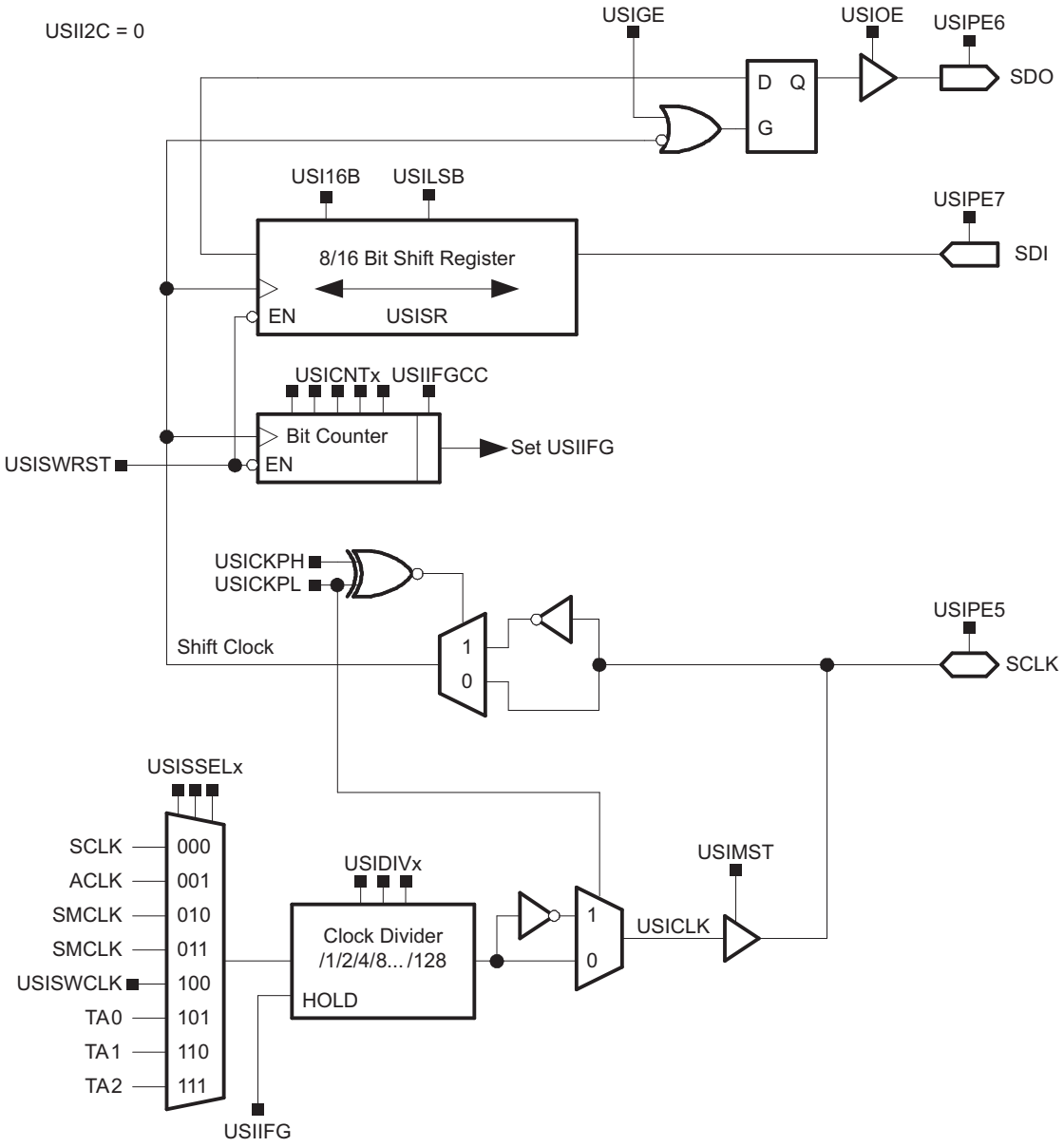


Figure 14-1. USI Block Diagram: SPI Mode

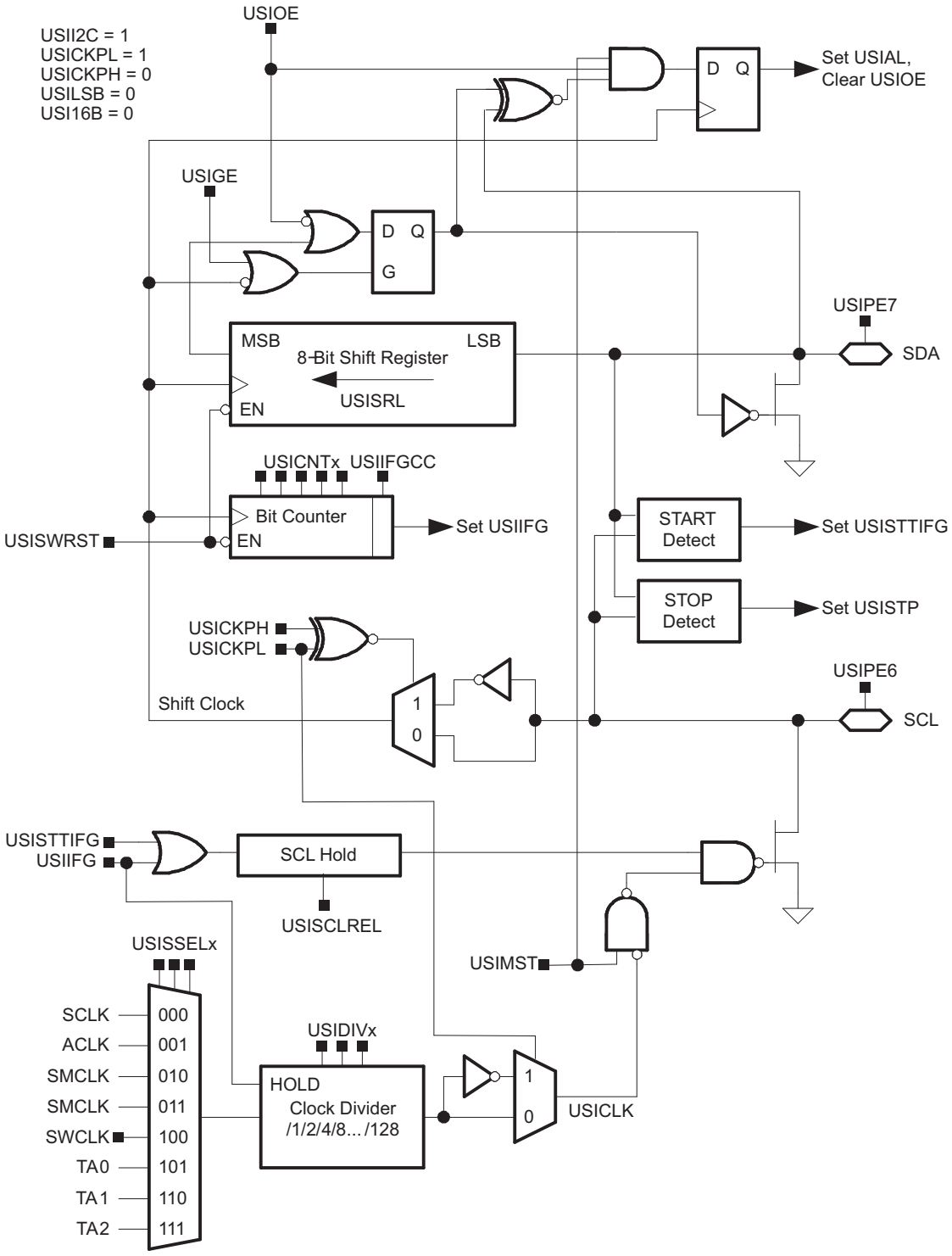


Figure 14-2. USI Block Diagram: I²C Mode

14.2 USI Operation

The USI module is a shift register and bit counter that includes logic to support SPI and I^2C communication. The USI shift register (USISR) is directly accessible by software and contains the data to be transmitted or the data that has been received.

The bit counter counts the number of sampled bits and sets the USI interrupt flag USIIFG when the USICNTx value becomes zero, either by decrementing or by directly writing zero to the USICNTx bits. Writing USICNTx with a value > 0 automatically clears USIIFG when USIIFGCC = 0, otherwise USIIFG is not affected. The USICNTx bits stop decrementing when they become 0. They will not underflow to 0FFh.

Both the counter and the shift register are driven by the same shift clock. On a rising shift clock edge, USICNTx decrements and USISR samples the next bit input. The latch connected to the shift register's output delays the change of the output to the falling edge of shift clock. It can be made transparent by setting the USIGE bit. This setting will immediately output the MSB or LSB of USISR to the SDO pin, depending on the USILSB bit.

14.2.1 USI Initialization

While the USI software reset bit, USISWRST, is set, the flags USIIFG, USISTTIFG, USISTP, and USIAL will be held in their reset state. USISR and USICNTx are not clocked and their contents are not affected. In I^2C mode, the SCL line is also released to the idle state by the USI hardware.

To activate USI port functionality the corresponding USIPEx bits in the USI control register must be set. This will select the USI function for the pin and maintains the PxIN and PxIFG functions for the pin as well. With this feature, the port input levels can be read via the PxIN register by software and the incoming data stream can generate port interrupts on data transitions. This is useful, for example, to generate a port interrupt on a START edge.

14.2.2 USI Clock Generation

The USI clock generator contains a clock selection multiplexer, a divider, and the ability to select the clock polarity as shown in the block diagrams Figure 14-1 and Figure 14-2.

The clock source can be selected from the internal clocks ACLK or SMCLK, from an external clock SCLK, as well as from the capture/compare outputs of Timer_A. In addition, it is possible to clock the module by software using the USISWCLK bit when USISSELx = 100.

The USIDIVx bits can be used to divide the selected clock by a power of 2 up to 128. The generated clock, USICLK, is stopped when USIIFG = 1 or when the module operates in slave mode.

The USICKPL bit is used to select the polarity of USICLK. When USICKPL = 0, the inactive level of USICLK is low. When USICKPL = 1 the inactive level of USICLK is high.

14.2.3 SPI Mode

The USI module is configured in SPI mode when USII2C = 0. Control bit USICKPL selects the inactive level of the SPI clock while USICKPH selects the clock edge on which SDO is updated and SDI is sampled. Figure 14-3 shows the clock/data relationship for an 8-bit, MSB-first transfer. USIPE5, USIPE6, and USIPE7 must be set to enable the SCLK, SDO, and SDI port functions.

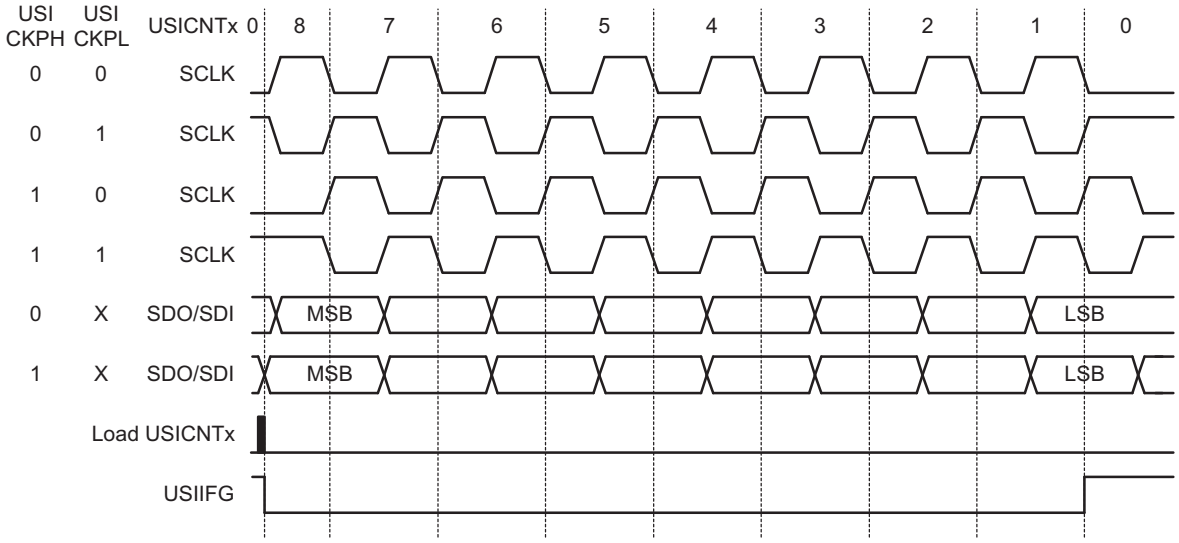


Figure 14-3. SPI Timing

14.2.3.1 SPI Master Mode

The USI module is configured as SPI master by setting the master bit USIMST and clearing the I^2C bit USII2C. Since the master provides the clock to the slave(s) an appropriate clock source needs to be selected and SCLK configured as output. When USIPE5 = 1, SCLK is automatically configured as an output.

When USIIFG = 0 and USICNTx > 0, clock generation is enabled and the master will begin clocking in/out data using USISR.

Received data must be read from the shift register before new data is written into it for transmission. In a typical application, the USI software will read received data from USISR, write new data to be transmitted to USISR, and enable the module for the next transfer by writing the number of bits to be transferred to USICNTx.

14.2.3.2 SPI Slave Mode

The USI module is configured as SPI slave by clearing the USIMST and the USII2C bits. In this mode, when USIPE5 = 1 SCLK is automatically configured as an input and the USI receives the clock externally from the master.

If the USI is to transmit data, the shift register must be loaded with the data before the master provides the first clock edge. The output must be enabled by setting USIOE. When USICKPH = 1, the MSB will be visible on SDO immediately after loading the shift register.

The SDO pin can be disabled by clearing the USIOE bit. This is useful if the slave is not addressed in an environment with multiple slaves on the bus.

Once all bits are received, the data must be read from USISR and new data loaded into USISR before the next clock edge from the master. In a typical application, after receiving data, the USI software will read the USISR register, write new data to USISR to be transmitted, and enable the USI module for the next transfer by writing the number of bits to be transferred to USICNTx.

14.2.3.3 USISR Operation

The 16-bit USISR is made up of two 8-bit registers, USISRL and USISRH. Control bit USI16B selects the number of bits of USISR that are used for data transmit and receive. When USI16B = 0, only the lower 8 bits, USISRL, are used.

To transfer < 8 bits, the data must be loaded into USISRL such that unused bits are not shifted out. The data must be MSB- or LSB-aligned depending on USILSB. Figure 14-4 shows an example of 7-bit data handling.

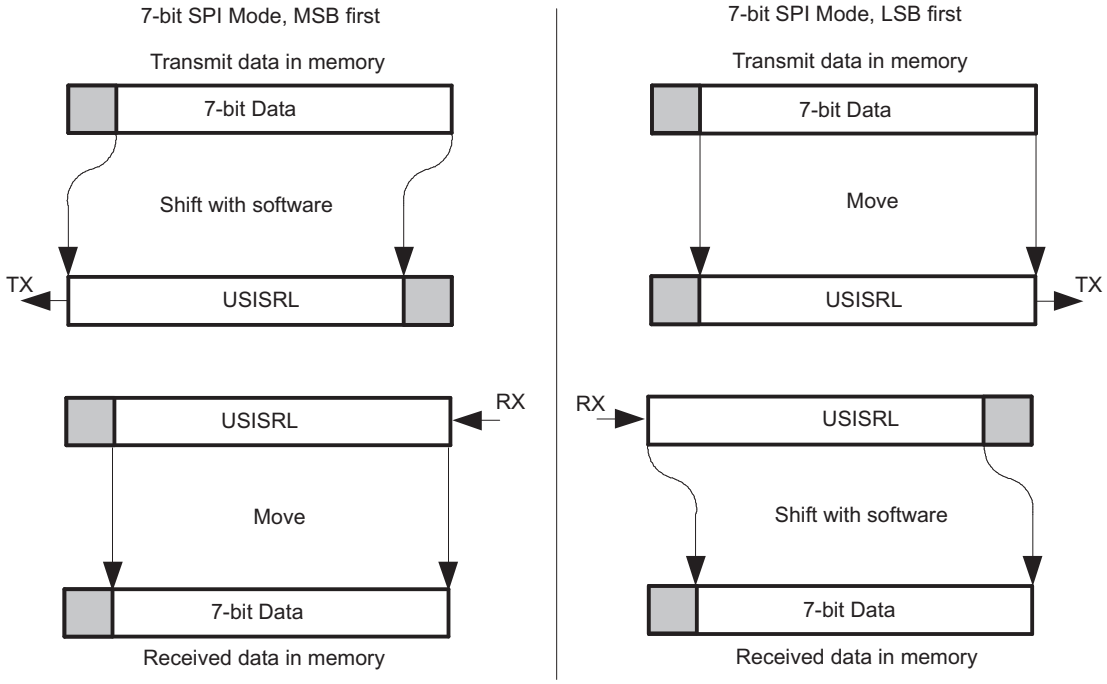


Figure 14-4. Data Adjustments for 7-Bit SPI Data

When USI16B = 1, all 16 bits are used for data handling. When using USISR to access both USISRL and USISRH, the data needs to be properly adjusted when < 16 bits are used in the same manner as shown in Figure 14-4.

14.2.3.4 SPI Interrupts

There is one interrupt vector associated with the USI module, and one interrupt flag, USIIFG, relevant for SPI operation. When USIIE and the GIE bit are set, the interrupt flag will generate an interrupt request.

USIIFG is set when USICNTx becomes zero, either by counting or by directly writing 0 to the USICNTx bits. USIIFG is cleared by writing a value > 0 to the USICNTx bits when USIIFGCC = 0, or directly by software.

14.2.4 I²C Mode

The USI module is configured in I²C mode when USII2C =1, USICKPL = 1, and USICKPH = 0. For I²C data compatibility, USILSB and USI16B must be cleared. USIPE6 and USIPE7 must be set to enable the SCL and SDA port functions.

14.2.4.1 I²C Master Mode

To configure the USI module as an I²C master the USIMST bit must be set. In master mode, clocks are generated by the USI module and output to the SCL line while USIIFG = 0. When USIIFG = 1, the SCL will stop at the idle, or high, level. Multi-master operation is supported as described in the Arbitration section.

The master supports slaves that are holding the SCL line low only when USIDIVx > 0. When USIDIVx is set to /1 clock division (USIDIVx = 0), connected slaves must not hold the SCL line low during data transmission. Otherwise the communication may fail.

14.2.4.2 I²C Slave Mode

To configure the USI module as an I²C slave the USIMST bit must be cleared. In slave mode, SCL is held low if USIIFG = 1, USISTTIFG = 1 or if USICNTx = 0. USISTTIFG must be cleared by software after the slave is setup and ready to receive the slave address from a master.

14.2.4.3 I²C Transmitter

In transmitter mode, data is first loaded into USISRL. The output is enabled by setting USIOE and the transmission is started by writing 8 into USICNTx. This clears USIIFG and SCL is generated in master mode or released from being held low in slave mode. After the transmission of all 8 bits, USIIFG is set, and the clock signal on SCL is stopped in master mode or held low at the next low phase in slave mode.

To receive the I²C acknowledgment bit, the USIOE bit is cleared with software and USICNTx is loaded with 1. This clears USIIFG and one bit is received into USISRL. When USIIFG becomes set again, the LSB of USISRL is the received acknowledge bit and can be tested in software.

```
; Receive ACK/NACK
   BIC.B  #USIOE,&USICTL0    ; SDA input
   MOV.B  #01h,&USICNT       ; USICNTx = 1
TEST_USIIFG
   BIT.B  #USIIFG,&USICTL1   ; Test USIIFG
   JZ     TEST_USIIFG
   BIT.B  #01h,&USISRL       ; Test received ACK bit
   JNZ    HANDLE_NACK        ; Handle if NACK
...Else, handle ACK
```

14.2.4.4 I²C Receiver

In I²C receiver mode the output must be disabled by clearing USIOE and the USI module is prepared for reception by writing 8 into USICNTx. This clears USIIFG and SCL is generated in master mode or released from being held low in slave mode. The USIIFG bit will be set after 8 clocks. This stops the clock signal on SCL in master mode or holds SCL low at the next low phase in slave mode.

To transmit an acknowledge or no-acknowledge bit, the MSB of the shift register is loaded with 0 or 1, the USIOE bit is set with software to enable the output, and 1 is written to the USICNTx bits. As soon as the MSB bit is shifted out, USIIFG will be become set and the module can be prepared for the reception of the next I²C data byte.

```
; Generate ACK
   BIS.B   #USIOE,&USICTL0    ; SDA output
   MOV.B   #00h,&USISRL       ; MSB = 0
   MOV.B   #01h,&USICNT       ; USICNTx = 1
TEST_USIIFG
   BIT.B   #USIIFG,&USICTL1   ; Test USIIFG
   JZ      TEST_USIIFG
...continue...

; Generate NACK
   BIS.B   #USIOE,&USICTL0    ; SDA output
   MOV.B   #0FFh,&USISRL      ; MSB = 1
   MOV.B   #01h,&USICNT       ; USICNTx = 1
TEST_USIIFG
   BIT.B   #USIIFG,&USICTL1   ; Test USIIFG
   JZ      TEST_USIIFG
...continue...
```

14.2.4.5 START Condition

A START condition is a high-to-low transition on SDA while SCL is high. The START condition can be generated by setting the MSB of the shift register to 0. Setting the USIGE and USIOE bits makes the output latch transparent and the MSB of the shift register is immediately presented to SDA and pulls the line low. Clearing USIGE resumes the clocked-latch function and holds the 0 on SDA until data is shifted out with SCL.

```
; Generate START
   MOV.B   #000h,&USISRL           ; MSB = 0
   BIS.B   #USIGE+USIOE,&USICTL0   ; Latch/SDA output enabled
   BIC.B   #USIGE,&USICTL0         ; Latch disabled
...continue...
```

14.2.4.6 STOP Condition

A STOP condition is a low-to-high transition on SDA while SCL is high. To finish the acknowledgment bit and pull SDA low to prepare the STOP condition generation requires clearing the MSB in the shift register and loading 1 into USICNTx. This will generate a low pulse on SCL and during the low phase SDA is pulled low. SCL stops in the idle, or high, state since the module is in master mode. To generate the low-to-high transition, the MSB is set in the shift register and USICNTx is loaded with 1. Setting the USIGE and USIOE bits makes the output latch transparent and the MSB of USISRL releases SDA to the idle state. Clearing USIGE stores the MSB in the output latch and the output is disabled by clearing USIOE. SDA remains high until a START condition is generated because of the external pullup.

```
; Generate STOP
   BIS.B   #USIOE,&USICTL0    ; SDA=output
   MOV.B   #000h,&USISRL      ; MSB = 0
   MOV.B   #001h,&USICNT      ; USICNT = 1 for one clock
TEST_USIIFG
   BIT.B   #USIIFG,&USICTL1   ; Test USIIFG
   JZ      test_USIIFG        ;
   MOV.B   #0FFh,&USISRL      ; USISRL = 1 to drive SDA high
   BIS.B   #USIGE,&USICTL0    ; Transparent latch enabled
   BIC.B   #USIGE+USIOE,&USICTL; Latch/SDA output disabled
...continue...
```

14.2.4.7 Releasing SCL

Setting the USISCLREL bit will release SCL if it is being held low by the USI module without requiring USIIFG to be cleared. The USISCLREL bit will be cleared automatically if a START condition is received and the SCL line will be held low on the next clock.

In slave operation this bit should be used to prevent SCL from being held low when the slave has detected that it was not addressed by the master. On the next START condition USISCLREL will be cleared and the USISTTIFG will be set.

14.2.4.8 Arbitration

The USI module can detect a lost arbitration condition in multi-master I^2C systems. The I^2C arbitration procedure uses the data presented on SDA by the competing transmitters. The first master transmitter that generates a logic high loses arbitration to the opposing master generating a logic low. The loss of arbitration is detected in the USI module by comparing the value presented to the bus and the value read from the bus. If the values are not equal arbitration is lost and the arbitration lost flag, USIAL, is set. This also clears the output enable bit USIOE and the USI module no longer drives the bus. In this case, user software must check the USIAL flag together with USIIFG and configure the USI to slave receiver when arbitration is lost. The USIAL flag must be cleared by software.

To prevent other faster masters from generating clocks during the arbitration procedure SCL is held low if another master on the bus drives SCL low and USIIFG or USISTTIFG is set, or if USICNTx = 0.

14.2.4.9 I^2C Interrupts

There is one interrupt vector associated with the USI module with two interrupt flags relevant for I^2C operation, USIIFG and USISTTIFG. Each interrupt flag has its own interrupt enable bit, USIIE and USISTTIE. When an interrupt is enabled, and the GIE bit is set, a set interrupt flag will generate an interrupt request.

USIIFG is set when USICNTx becomes zero, either by counting or by directly writing 0 to the USICNTx bits. USIIFG is cleared by writing a value > 0 to the USICNTx bits when USIIFGCC = 0, or directly by software.

USISTTIFG is set when a START condition is detected. The USISTTIFG flag must be cleared by software.

The reception of a STOP condition is indicated with the USISTP flag but there is no interrupt function associated with the USISTP flag. USISTP is cleared by writing a value > 0 to the USICNTx bits when USIIFGCC = 0 or directly by software.

14.3 USI Registers

The USI registers are listed in Table 14-1.

Table 14-1. USI Registers

Register	Short Form	Register Type	Address	Initial State
USI control register 0	USICTL0	Read/write	078h	01h with PUC
USI control register 1	USICTL1	Read/write	079h	01h with PUC
USI clock control	USICKCTL	Read/write	07Ah	Reset with PUC
USI bit counter	USICNT	Read/write	07Bh	Reset with PUC
USI low byte shift register	USISRL	Read/write	07Ch	Unchanged
USI high byte shift register	USISRH	Read/write	07Dh	Unchanged

The USI registers can be accessed with word instructions as shown in Table 14-2.

Table 14-2. Word Access to USI Registers

Register	Short Form	High-Byte Register	Low-Byte Register	Address
USI control register	USICTL	USICTL1	USICTL0	078h
USI clock and counter control register	USICCTL	USICNT	USICKCTL	07Ah
USI shift register	USISR	USISRH	USISRL	07Ch

14.3.1 USICTL0, USI Control Register 0

7	6	5	4	3	2	1	0
USIPE7	**USIPE6**	**USIPE5**	**USILSB**	**USIMST**	**USIGE**	**USIOE**	**USISWRST**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-1

USIPE7 Bit 7 USI SDI/SDA port enable. Input in SPI mode, input or open drain output in I^2C mode.
- 0 USI function disabled
- 1 USI function enabled

USIPE6 Bit 6 USI SDO/SCL port enable. Output in SPI mode, input or open drain output in I^2C mode.
- 0 USI function disabled
- 1 USI function enabled

USIPE5 Bit 5 USI SCLK port enable. Input in SPI slave mode, or I^2C mode, output in SPI master mode.
- 0 USI function disabled
- 1 USI function enabled

USILSB Bit 4 LSB first select. This bit controls the direction of the receive and transmit shift register.
- 0 MSB first
- 1 LSB first

USIMST Bit 3 Master select
- 0 Slave mode
- 1 Master mode

USIGE Bit 2 Output latch control
- 0 Output latch enable depends on shift clock
- 1 Output latch always enabled and transparent

USIOE Bit 1 Data output enable
- 0 Output disabled
- 1 Output enabled

USISWRST Bit 0 USI software reset
- 0 USI released for operation.
- 1 USI logic held in reset state.

14.3.2 USICTL1, USI Control Register 1

7	6	5	4	3	2	1	0
USICKPH	**USII2C**	**USISTTIE**	**USIIE**	**USIAL**	**USISTP**	**USISTTIFG**	**USIIFG**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-1

USICKPH Bit 7 Clock phase select
- 0 Data is changed on the first SCLK edge and captured on the following edge.
- 1 Data is captured on the first SCLK edge and changed on the following edge.

USII2C Bit 6 I^2C mode enable
- 0 I^2C mode disabled
- 1 I^2C mode enabled

USISTTIE Bit 5 START condition interrupt-enable
- 0 Interrupt on START condition disabled
- 1 Interrupt on START condition enabled

USIIE Bit 4 USI counter interrupt enable
- 0 Interrupt disabled
- 1 Interrupt enabled

USIAL Bit 3 Arbitration lost
- 0 No arbitration lost condition
- 1 Arbitration lost

USISTP Bit 2 STOP condition received. USISTP is automatically cleared if USICNTx is loaded with a value > 0 when USIIFGCC = 0.
- 0 No STOP condition received
- 1 STOP condition received

USISTTIFG Bit 1 START condition interrupt flag
- 0 No START condition received. No interrupt pending.
- 1 START condition received. Interrupt pending.

USIIFG Bit 0 USI counter interrupt flag. Set when the USICNTx = 0. Automatically cleared if USICNTx is loaded with a value > 0 when USIIFGCC = 0.
- 0 No interrupt pending
- 1 Interrupt pending

14.3.3 USICKCTL, USI Clock Control Register

7	6	5	4	3	2	1	0
USIDIVx			**USISSELx**			**USICKPL**	**USISWCLK**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

USIDIVx	Bits 7-5	Clock divider select	
		000	Divide by 1
		001	Divide by 2
		010	Divide by 4
		011	Divide by 8
		100	Divide by 16
		101	Divide by 32
		110	Divide by 64
		111	Divide by 128
USISSELx	Bits 4-2	Clock source select. Not used in slave mode.	
		000	SCLK (Not used in SPI mode)
		001	ACLK
		010	SMCLK
		011	SMCLK
		100	USISWCLK bit
		101	TACCR0
		110	TACCR1
		111	TACCR2 (Reserved on MSP430F20xx devices)
USICKPL	Bit 1	Clock polarity select	
		0	Inactive state is low
		1	Inactive state is high
USISWCLK	Bit 0	Software clock	
		0	Input clock is low
		1	Input clock is high

14.3.4 USICNT, USI Bit Counter Register

7	6	5	4	3	2	1	0
USISCLREL	**USI16B**	**USIIFGCC**	**USICNTx**				
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

USISCLREL	Bit 7	SCL release. The SCL line is released from low to idle. USISCLREL is cleared if a START condition is detected.	
		0	SCL line is held low if USIIFG is set
		1	SCL line is released
USI16B	Bit 6	16-bit shift register enable	
		0	8-bit shift register mode. Low byte register USISRL is used.
		1	16-bit shift register mode. Both high and low byte registers USISRL and USISRH are used. USISR addresses all 16 bits simultaneously.
USIIFGCC	Bit 5	USI interrupt flag clear control. When USIIFGCC = 1 the USIIFG will not be cleared automatically when USICNTx is written with a value > 0.	
		0	USIIFG automatically cleared on USICNTx update
		1	USIIFG is not cleared automatically
USICNTx	Bits 4-0	USI bit count. The USICNTx bits set the number of bits to be received or transmitted.	

14.3.5 USISRL, USI Low Byte Shift Register

7	6	5	4	3	2	1	0
USISRLx							
rw	rw	rw	rw	rw	rw	rw	rw

USISRLx	Bits 7-0	Contents of the USI low byte shift register

14.3.6 USISRH, USI High Byte Shift Register

7	6	5	4	3	2	1	0
USISRHx							
rw	rw	rw	rw	rw	rw	rw	rw

USISRHx	Bits 7-0	Contents of the USI high byte shift register. Ignored when USI16B = 0.

Universal Serial Communication Interface, UART Mode

The universal serial communication interface (USCI) supports multiple serial communication modes with one hardware module. This chapter discusses the operation of the asynchronous UART mode.

Topic **Page**

15.1 USCI Overview

The universal serial communication interface (USCI) modules support multiple serial communication modes. Different USCI modules support different modes. Each different USCI module is named with a different letter. For example, USCI_A is different from USCI_B, etc. If more than one identical USCI module is implemented on one device, those modules are named with incrementing numbers. For example, if one device has two USCI_A modules, they are named USCI_A0 and USCI_A1. See the device-specific data sheet to determine which USCI modules, if any, are implemented on which devices.

The USCI_Ax modules support:

- UART mode
- Pulse shaping for IrDA communications
- Automatic baud rate detection for LIN communications
- SPI mode

The USCI_Bx modules support:

- I^2C mode
- SPI mode

15.2 USCI Introduction: UART Mode

In asynchronous mode, the USCI_Ax modules connect the MSP430 to an external system via two external pins, UCAxRXD and UCAxTXD. UART mode is selected when the UCSYNC bit is cleared.

UART mode features include:

- 7- or 8-bit data with odd, even, or non-parity
- Independent transmit and receive shift registers
- Separate transmit and receive buffer registers
- LSB-first or MSB-first data transmit and receive
- Built-in idle-line and address-bit communication protocols for multiprocessor systems
- Receiver start-edge detection for auto-wake up from LPMx modes
- Programmable baud rate with modulation for fractional baud rate support
- Status flags for error detection and suppression
- Status flags for address detection
- Independent interrupt capability for receive and transmit

Figure 15-1 shows the USCI_Ax when configured for UART mode.

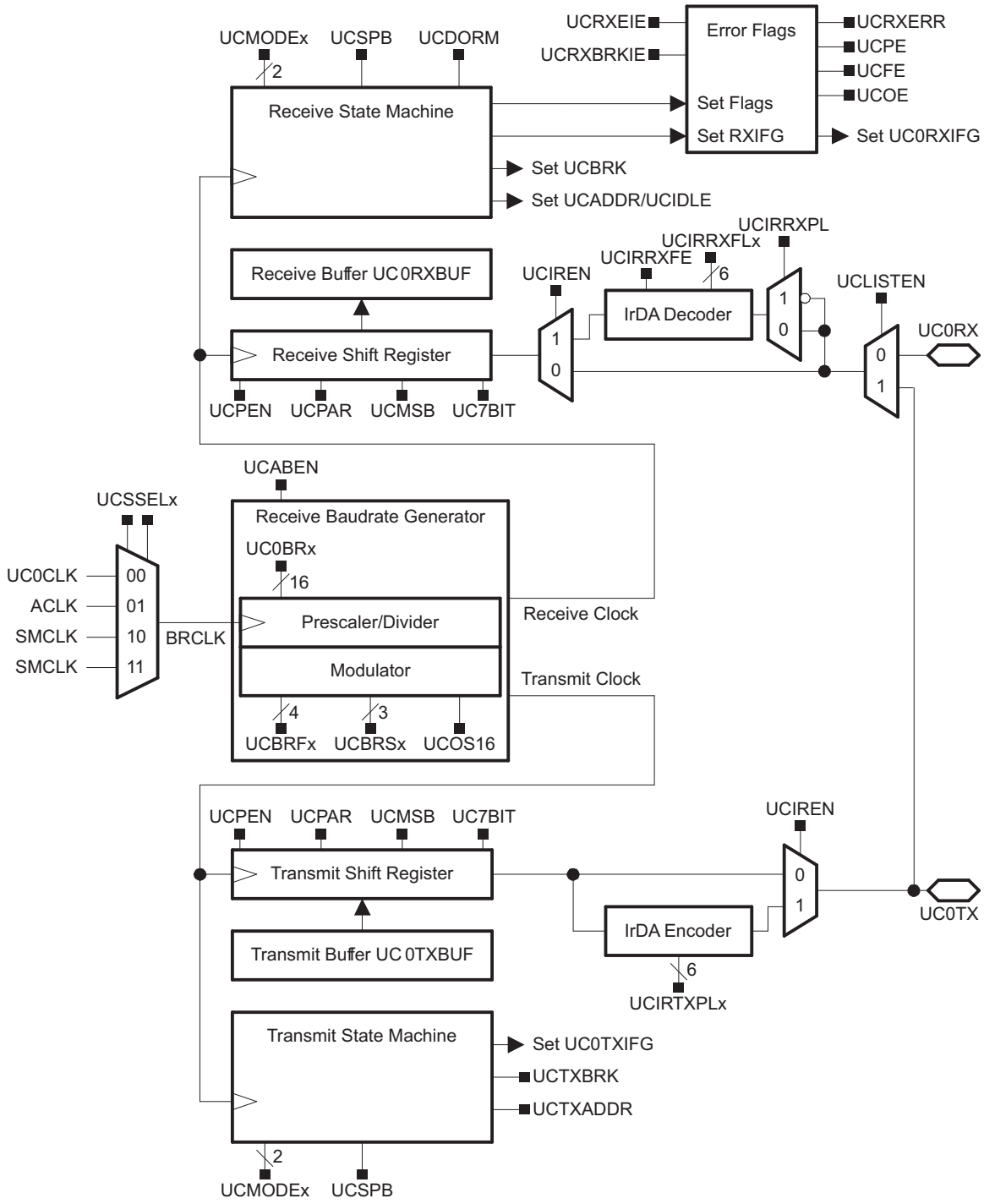


Figure 15-1. USCI_Ax Block Diagram: UART Mode (UCSYNC = 0)

15.3 USCI Operation: UART Mode

In UART mode, the USCI transmits and receives characters at a bit rate asynchronous to another device. Timing for each character is based on the selected baud rate of the USCI. The transmit and receive functions use the same baud rate frequency.

15.3.1 USCI Initialization and Reset

The USCI is reset by a PUC or by setting the UCSWRST bit. After a PUC, the UCSWRST bit is automatically set, keeping the USCI in a reset condition. When set, the UCSWRST bit resets the UCAxRXIE, UCAxTXIE, UCAxRXIFG, UCRXERR, UCBRK, UCPE, UCOE, UCFE, UCSTOE and UCBTOE bits and sets the UCAxTXIFG bit. Clearing UCSWRST releases the USCI for operation.

NOTE: Initializing or Re-Configuring the USCI Module

The recommended USCI initialization/re-configuration process is:

1. Set UCSWRST (BIS.B #UCSWRST,&UCAxCTL1)
2. Initialize all USCI registers with UCSWRST = 1 (including UCAxCTL1)
3. Configure ports.
4. Clear UCSWRST via software (BIC.B #UCSWRST,&UCAxCTL1)
5. Enable interrupts (optional) via UCAxRXIE and/or UCAxTXIE

15.3.2 Character Format

The UART character format, shown in Figure 15-2, consists of a start bit, seven or eight data bits, an even/odd/no parity bit, an address bit (address-bit mode), and one or two stop bits. The UCMSB bit controls the direction of the transfer and selects LSB or MSB first. LSB-first is typically required for UART communication.

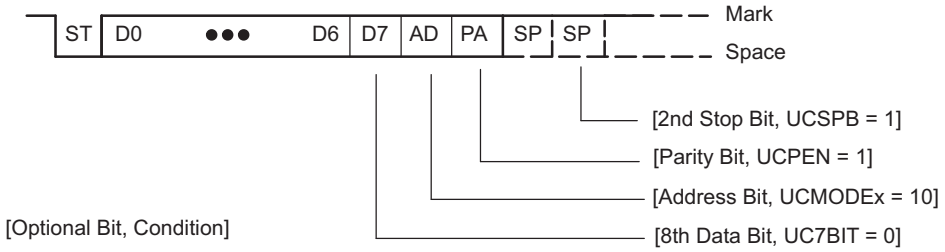


Figure 15-2. Character Format

15.3.3 Asynchronous Communication Formats

When two devices communicate asynchronously, no multiprocessor format is required for the protocol. When three or more devices communicate, the USCI supports the idle-line and address-bit multiprocessor communication formats.

15.3.3.1 Idle-Line Multiprocessor Format

When UCMODEx = 01, the idle-line multiprocessor format is selected. Blocks of data are separated by an idle time on the transmit or receive lines as shown in Figure 15-3. An idle receive line is detectedwhen 10 or more continuous ones (marks) are received after the one or two stop bits of a character. The baud rate generator is switched off after reception of an idle line until the next start edge is detected. When an idle line is detected the UCIDLE bit is set.

The first character received after an idle period is an address character. The UCIDLE bit is used as an address tag for each block of characters. In idle-line multiprocessor format, this bit is set when a received character is an address.

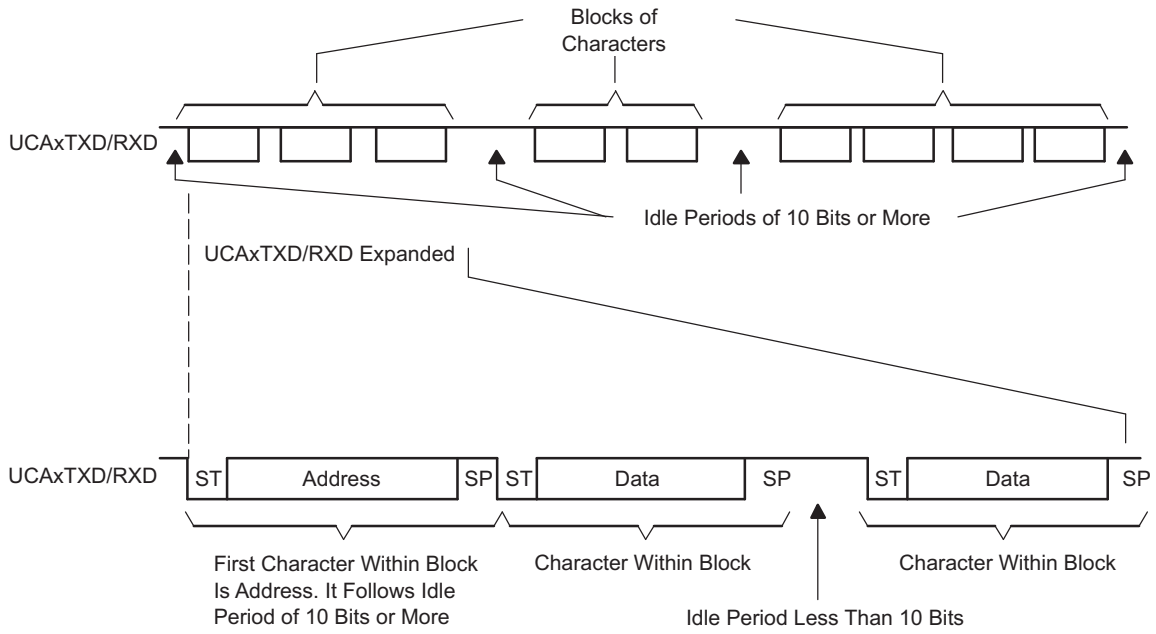


Figure 15-3. Idle-Line Format

The UCDORM bit is used to control data reception in the idle-line multiprocessor format. When UCDORM = 1, all non-address characters are assembled but not transferred into the UCAxRXBUF, and interrupts are not generated. When an address character is received, the character is transferred into UCAxRXBUF, UCAxRXIFG is set, and any applicable error flag is set when UCRXEIE = 1. When UCRXEIE = 0 and an address character is received but has a framing error or parity error, the character is not transferred into UCAxRXBUF and UCAxRXIFG is not set.

If an address is received, user software can validate the address and must reset UCDORM to continue receiving data. If UCDORM remains set, only address characters will be received. When UCDORM is cleared during the reception of a character the receive interrupt flag will be set after the reception completed. The UCDORM bit is not modified by the USCI hardware automatically.

For address transmission in idle-line multiprocessor format, a precise idle period can be generated by the USCI to generate address character identifiers on UCAxTXD. The double-buffered UCTXADDR flag indicates if the next character loaded into UCAxTXBUF is preceded by an idle line of 11 bits. UCTXADDR is automatically cleared when the start bit is generated.

15.3.3.2 Transmitting an Idle Frame

The following procedure sends out an idle frame to indicate an address character followed by associated data:

1. Set UCTXADDR, then write the address character to UCAxTXBUF. UCAxTXBUF must be ready for new data (UCAxTXIFG = 1).

   This generates an idle period of exactly 11 bits followed by the address character. UCTXADDR is reset automatically when the address character is transferred from UCAxTXBUF into the shift register.
2. Write desired data characters to UCAxTXBUF. UCAxTXBUF must be ready for new data (UCAxTXIFG = 1).

   The data written to UCAxTXBUF is transferred to the shift register and transmitted as soon as the shift register is ready for new data.

   The idle-line time must not be exceeded between address and data transmission or between data transmissions. Otherwise, the transmitted data will be misinterpreted as an address.

15.3.3.3 Address-Bit Multiprocessor Format

When UCMODEx = 10, the address-bit multiprocessor format is selected. Each processed character contains an extra bit used as an address indicator shown in Figure 15-4. The first character in a block of characters carries a set address bit which indicates that the character is an address. The USCI UCADDR bit is set when a received character has its address bit set and is transferred to UCAxRXBUF.

The UCDORM bit is used to control data reception in the address-bit multiprocessor format. When UCDORM is set, data characters with address bit = 0 are assembled by the receiver but are not transferred to UCAxRXBUF and no interrupts are generated. When a character containing a set address bit is received, the character is transferred into UCAxRXBUF, UCAxRXIFG is set, and any applicable error flag is set when UCRXEIE = 1. When UCRXEIE = 0 and a character containing a set address bit is received, but has a framing error or parity error, the character is not transferred into UCAxRXBUF and UCAxRXIFG is not set.

If an address is received, user software can validate the address and must reset UCDORM to continue receiving data. If UCDORM remains set, only address characters with address bit = 1 will be received. The UCDORM bit is not modified by the USCI hardware automatically.

When UCDORM = 0 all received characters will set the receive interrupt flag UCAxRXIFG. If UCDORM is cleared during the reception of a character the receive interrupt flag will be set after the reception is completed.

For address transmission in address-bit multiprocessor mode, the address bit of a character is controlled by the UCTXADDR bit. The value of the UCTXADDR bit is loaded into the address bit of the character transferred from UCAxTXBUF to the transmit shift register. UCTXADDR is automatically cleared when the start bit is generated.

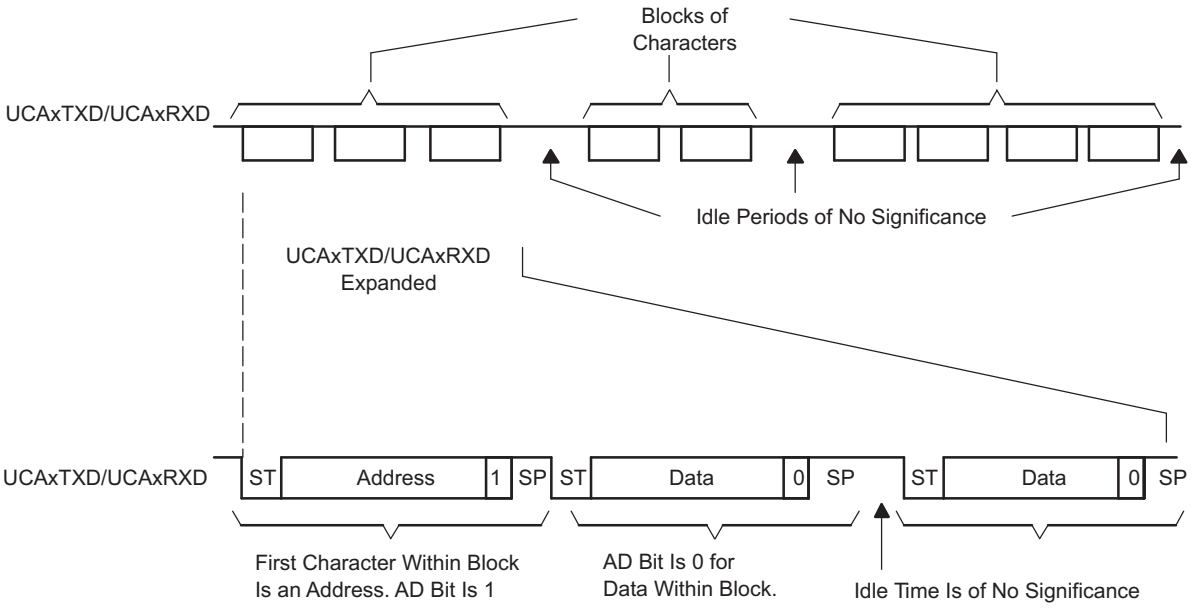


Figure 15-4. Address-Bit Multiprocessor Format

15.3.3.4 Break Reception and Generation

When UCMODEx = 00, 01, or 10 the receiver detects a break when all data, parity, and stop bits are low, regardless of the parity, address mode, or other character settings. When a break is detected, the UCBRK bit is set. If the break interrupt enable bit, UCBRKIE, is set, the receive interrupt flag UCAxRXIFG will also be set. In this case, the value in UCAxRXBUF is 0h since all data bits were zero.

To transmit a break set the UCTXBRK bit, then write 0h to UCAxTXBUF. UCAxTXBUF must be ready for new data (UCAxTXIFG = 1). This generates a break with all bits low. UCTXBRK is automatically cleared when the start bit is generated.

15.3.4 Automatic Baud Rate Detection

When UCMODEx = 11 UART mode with automatic baud rate detection is selected. For automatic baud rate detection, a data frame is preceded by a synchronization sequence that consists of a break and a synch field. A break is detected when 11 or more continuous zeros (spaces) are received. If the length of the break exceeds 22 bit times the break timeout error flag UCBTOE is set. The synch field follows the break as shown in Figure 15-5.

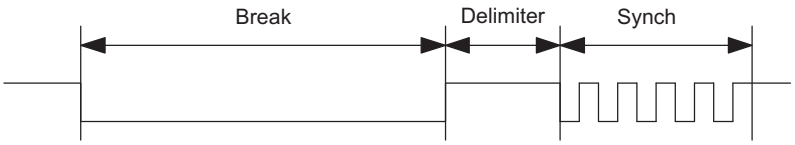


Figure 15-5. Auto Baud Rate Detection - Break/Synch Sequence

For LIN conformance the character format should be set to 8 data bits, LSB first, no parity and one stop bit. No address bit is available.

The synch field consists of the data 055h inside a byte field as shown in Figure 15-6. The synchronization is based on the time measurement between the first falling edge and the last falling edge of the pattern. The transmit baud rate generator is used for the measurement if automatic baud rate detection is enabled by setting UCABDEN. Otherwise, the pattern is received but not measured. The result of the measurement is transferred into the baud rate control registers UCAxBR0, UCAxBR1, and UCAxMCTL. If the length of the synch field exceeds the measurable time the synch timeout error flag UCSTOE is set.

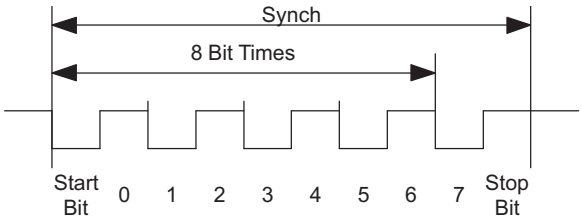


Figure 15-6. Auto Baud Rate Detection - Synch Field

The UCDORM bit is used to control data reception in this mode. When UCDORM is set, all characters are received but not transferred into the UCAxRXBUF, and interrupts are not generated. When a break/synch field is detected the UCBRK flag is set. The character following the break/synch field is transferred into UCAxRXBUF and the UCAxRXIFG interrupt flag is set. Any applicable error flag is also set. If the UCBRKIE bit is set, reception of the break/synch sets the UCAxRXIFG. The UCBRK bit is reset by user software or by reading the receive buffer UCAxRXBUF.

When a break/synch field is received, user software must reset UCDORM to continue receiving data. If UCDORM remains set, only the character after the next reception of a break/synch field will be received. The UCDORM bit is not modified by the USCI hardware automatically.

When UCDORM = 0 all received characters will set the receive interrupt flag UCAxRXIFG. If UCDORM is cleared during the reception of a character the receive interrupt flag will be set after the reception is complete.

The automatic baud rate detection mode can be used in a full-duplex communication system with some restrictions. The USCI can not transmit data while receiving the break/sync field and if a 0h byte with framing error is received any data transmitted during this time gets corrupted. The latter case can be discovered by checking the received data and the UCFE bit.

15.3.4.1 Transmitting a Break/Synch Field

The following procedure transmits a break/synch field:

- Set UCTXBRK with UMODEx = 11.
- Write 055h to UCAxTXBUF. UCAxTXBUF must be ready for new data (UCAxTXIFG = 1).

  This generates a break field of 13 bits followed by a break delimiter and the synch character. The length of the break delimiter is controlled with the UCDELIMx bits. UCTXBRK is reset automatically when the synch character is transferred from UCAxTXBUF into the shift register.
- Write desired data characters to UCAxTXBUF. UCAxTXBUF must be ready for new data (UCAxTXIFG = 1).

  The data written to UCAxTXBUF is transferred to the shift register and transmitted as soon as the shift register is ready for new data.

15.3.5 IrDA Encoding and Decoding

When UCIREN is set the IrDA encoder and decoder are enabled and provide hardware bit shaping for IrDA communication.

15.3.5.1 IrDA Encoding

The encoder sends a pulse for every zero bit in the transmit bit stream coming from the UART as shown in Figure 15-7. The pulse duration is defined by UCIRTXPLx bits specifying the number of half clock periods of the clock selected by UCIRTXCLK.

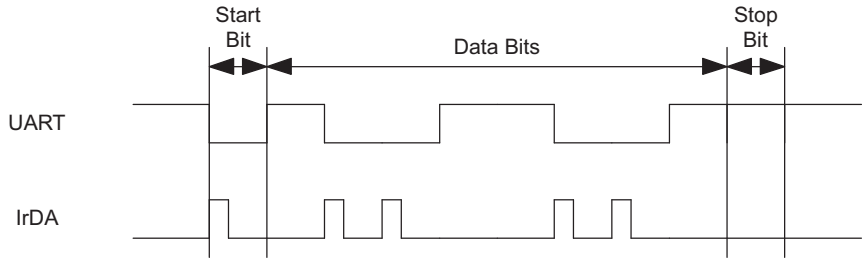


Figure 15-7. UART vs IrDA Data Format

To set the pulse time of 3/16 bit period required by the IrDA standard the BITCLK16 clock is selected with UCIRTXCLK = 1 and the pulse length is set to 6 half clock cycles with UCIRTXPLx = 6 – 1 = 5.

When UCIRTXCLK = 0, the pulse length t_{PULSE} is based on BRCLK and is calculated as follows:

$UCIRTXPLx = t_{PULSE} \times 2 \times f_{BRCLK} - 1$

When the pulse length is based on BRCLK the prescaler UCBRx must to be set to a value greater or equal to 5.

15.3.5.2 IrDA Decoding

The decoder detects high pulses when UCIRRXPL = 0. Otherwise it detects low pulses. In addition to the analog deglitch filter an additional programmable digital filter stage can be enabled by setting UCIRRXFE. When UCIRRXFE is set, only pulses longer than the programmed filter length are passed. Shorter pulses are discarded. The equation to program the filter length UCIRRXFLx is:

$UCIRRXFLx = (t_{PULSE} - t_{WAKE}) \times 2 \times f_{BRCLK} - 4$

Where,

t_{PULSE} = Minimum receive pulse width

t_{WAKE} = Wake time from any low power mode. Zero when MSP430 is in active mode.

15.3.6 Automatic Error Detection

Glitch suppression prevents the USCI from being accidentally started. Any pulse on UCAxRXD shorter than the deglitch time t_τ (approximately 150 ns) will be ignored. See the device-specific data sheet for parameters.

When a low period on UCAxRXD exceeds t_τ a majority vote is taken for the start bit. If the majority vote fails to detect a valid start bit the USCI halts character reception and waits for the next low period on UCAxRXD. The majority vote is also used for each bit in a character to prevent bit errors.

The USCI module automatically detects framing errors, parity errors, overrun errors, and break conditions when receiving characters. The bits UCFE, UCPE, UCOE, and UCBRK are set when their respective condition is detected. When the error flags UCFE, UCPE or UCOE are set, UCRXERR is also set. The error conditions are described in Table 15-1.

Table 15-1. Receive Error Conditions

Error Condition	Error Flag	Description
Framing error	UCFE	A framing error occurs when a low stop bit is detected. When two stop bits are used, both stop bits are checked for framing error. When a framing error is detected, the UCFE bit is set.
Parity error	UCPE	A parity error is a mismatch between the number of 1s in a character and the value of the parity bit. When an address bit is included in the character, it is included in the parity calculation. When a parity error is detected, the UCPE bit is set.
Receive overrun	UCOE	An overrun error occurs when a character is loaded into UCAxRXBUF before the prior character has been read. When an overrun occurs, the UCOE bit is set.
Break condition	UCBRK	When not using automatic baud rate detection, a break is detected when all data, parity, and stop bits are low. When a break condition is detected, the UCBRK bit is set. A break condition can also set the interrupt flag UCAxRXIFG if the break interrupt enable UCBRKIE bit is set.

When UCRXEIE = 0 and a framing error, or parity error is detected, no character is received into UCAxRXBUF. When UCRXEIE = 1, characters are received into UCAxRXBUF and any applicable error bit is set.

When UCFE, UCPE, UCOE, UCBRK, or UCRXERR is set, the bit remains set until user software resets it or UCAxRXBUF is read. UCOE must be reset by reading UCAxRXBUF. Otherwise it will not function properly. To detect overflows reliably, the following flow is recommended. After a character is received and UCAxRXIFG is set, first read UCAxSTAT to check the error flags including the overflow flag UCOE. Read UCAxRXBUF next. This will clear all error flags except UCOE, if UCAxRXBUF was overwritten between the read access to UCAxSTAT and to UCAxRXBUF. The UCOE flag should be checked after reading UCAxRXBUF to detect this condition. Note that, in this case, the UCRXERR flag is not set.

15.3.7 USCI Receive Enable

The USCI module is enabled by clearing the UCSWRST bit and the receiver is ready and in an idle state. The receive baud rate generator is in a ready state but is not clocked nor producing any clocks.

The falling edge of the start bit enables the baud rate generator and the UART state machine checks for a valid start bit. If no valid start bit is detected the UART state machine returns to its idle state and the baud rate generator is turned off again. If a valid start bit is detected a character will be received.

When the idle-line multiprocessor mode is selected with UCMODEx = 01 the UART state machine checks for an idle line after receiving a character. If a start bit is detected another character is received. Otherwise the UCIDLE flag is set after 10 ones are received and the UART state machine returns to its idle state and the baud rate generator is turned off.

15.3.7.1 Receive Data Glitch Suppression

Glitch suppression prevents the USCI from being accidentally started. Any glitch on UCAxRXD shorter than the deglitch time t_τ (approximately 150 ns) will be ignored by the USCI and further action will be initiated as shown in Figure 15-8. See the device-specific data sheet for parameters.

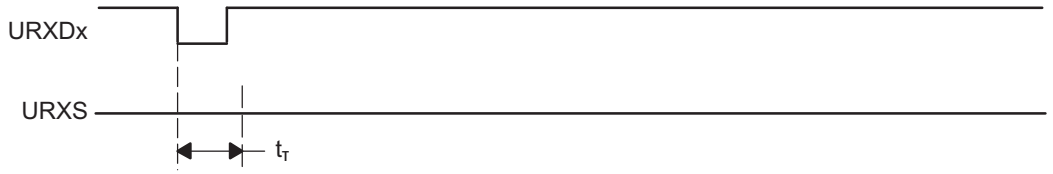


Figure 15-8. Glitch Suppression, USCI Receive Not Started

When a glitch is longer than t_τ or a valid start bit occurs on UCAxRXD, the USCI receive operation is started and a majority vote is taken as shown in Figure 15-9. If the majority vote fails to detect a start bit the USCI halts character reception.

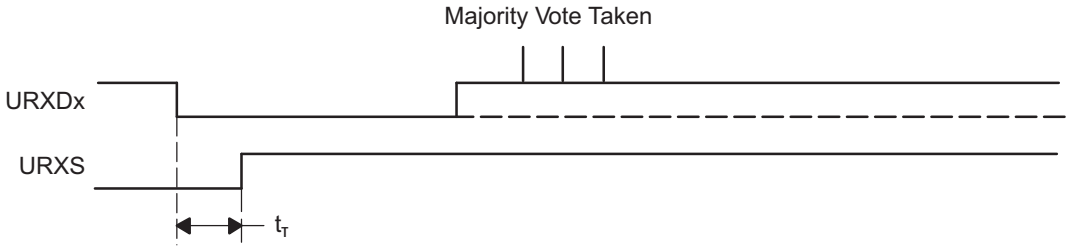


Figure 15-9. Glitch Suppression, USCI Activated

15.3.8 USCI Transmit Enable

The USCI module is enabled by clearing the UCSWRST bit and the transmitter is ready and in an idle state. The transmit baud rate generator is ready but is not clocked nor producing any clocks.

A transmission is initiated by writing data to UCAxTXBUF. When this occurs, the baud rate generator is enabled and the data in UCAxTXBUF is moved to the transmit shift register on the next BITCLK after the transmit shift register is empty. UCAxTXIFG is set when new data can be written into UCAxTXBUF.

Transmission continues as long as new data is available in UCAxTXBUF at the end of the previous byte transmission. If new data is not in UCAxTXBUF when the previous byte has transmitted, the transmitter returns to its idle state and the baud rate generator is turned off.

15.3.9 UART Baud Rate Generation

The USCI baud rate generator is capable of producing standard baud rates from non-standard source frequencies. It provides two modes of operation selected by the UCOS16 bit.

15.3.9.1 Low-Frequency Baud Rate Generation

The low-frequency mode is selected when UCOS16 = 0. This mode allows generation of baud rates from low frequency clock sources (for example, 9600 baud from a 32768-Hz crystal). By using a lower input frequency the power consumption of the module is reduced. Using this mode with higher frequencies and higher prescaler settings will cause the majority votes to be taken in an increasingly smaller window and thus decrease the benefit of the majority vote.

In low-frequency mode the baud rate generator uses one prescaler and one modulator to generate bit clock timing. This combination supports fractional divisors for baud rate generation. In this mode, the maximum USCI baud rate is one-third the UART source clock frequency BRCLK.

Timing for each bit is shown in Figure 15-10. For each bit received, a majority vote is taken to determine the bit value. These samples occur at the N/2 - 1/2, N/2, and N/2 + 1/2 BRCLK periods, where N is the number of BRCLKs per BITCLK.

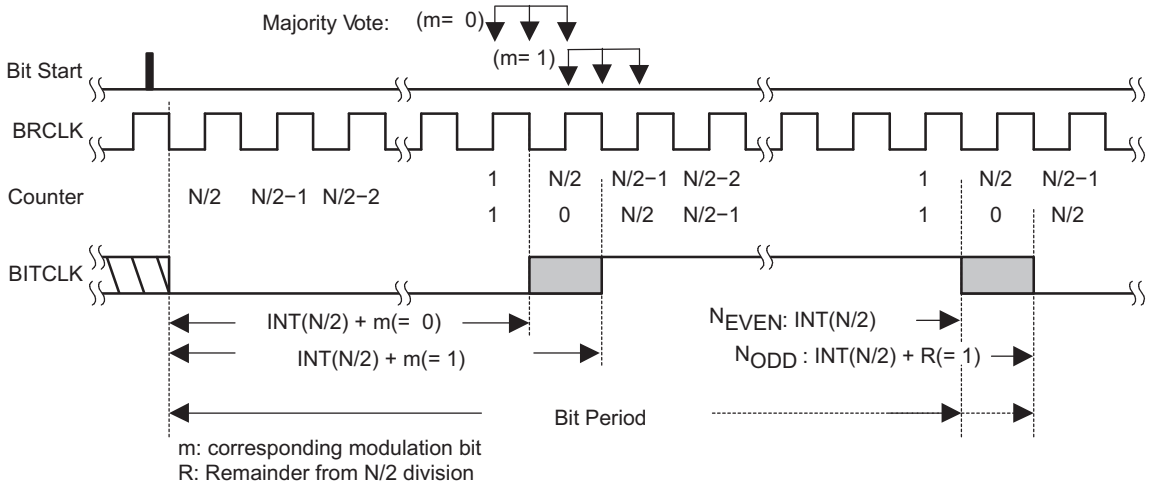


Figure 15-10. BITCLK Baud Rate Timing With UCOS16 = 0

Modulation is based on the UCBRSx setting as shown in Table 15-2. A 1 in the table indicates that m = 1 and the corresponding BITCLK period is one BRCLK period longer than a BITCLK period with m = 0. The modulation wraps around after 8 bits but restarts with each new start bit.

Table 15-2. BITCLK Modulation Pattern

UCBRSx	Bit 0 (Start Bit)	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7
0	0	0	0	0	0	0	0	0
1	0	1	0	0	0	0	0	0
2	0	1	0	0	0	1	0	0
3	0	1	0	1	0	1	0	0
4	0	1	0	1	0	1	0	1
5	0	1	1	1	0	1	0	1
6	0	1	1	1	0	1	1	1
7	0	1	1	1	1	1	1	1

15.3.9.2 Oversampling Baud Rate Generation

The oversampling mode is selected when UCOS16 = 1. This mode supports sampling a UART bit stream with higher input clock frequencies. This results in majority votes that are always 1/16 of a bit clock period apart. This mode also easily supports IrDA pulses with a 3/16 bit-time when the IrDA encoder and decoder are enabled.

This mode uses one prescaler and one modulator to generate the BITCLK16 clock that is 16 times faster than the BITCLK. An additional divider and modulator stage generates BITCLK from BITCLK16. This combination supports fractional divisions of both BITCLK16 and BITCLK for baud rate generation. In this mode, the maximum USCI baud rate is 1/16 the UART source clock frequency BRCLK. When UCBRx is set to 0 or 1 the first prescaler and modulator stage is bypassed and BRCLK is equal to BITCLK16.

Modulation for BITCLK16 is based on the UCBRFx setting as shown in Table 15-3. A 1 in the table indicates that the corresponding BITCLK16 period is one BRCLK period longer than the periods m=0. The modulation restarts with each new bit timing.

Modulation for BITCLK is based on the UCBRSx setting as shown in Table 15-2 as previously described.

Table 15-3. BITCLK16 Modulation Pattern

UCBRFx	No. of BITCLK16 Clocks After Last Falling BITCLK Edge															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
00h	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01h	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
02h	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
03h	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1
04h	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1
05h	0	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1
06h	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1
07h	0	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1
08h	0	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1
09h	0	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1
0Ah	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1
0Bh	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1
0Ch	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1
0Dh	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
0Eh	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
0Fh	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

15.3.10 Setting a Baud Rate

For a given BRCLK clock source, the baud rate used determines the required division factor N:

$$N = \frac{f_{BRCLK}}{\text{Baud rate}}$$

The division factor N is often a non-integer value thus at least one divider and one modulator stage is used to meet the factor as closely as possible.

If N is equal or greater than 16 the oversampling baud rate generation mode can be chosen by setting UCOS16.

15.3.10.1 Low-Frequency Baud Rate Mode Setting

In the low-frequency mode, the integer portion of the divisor is realized by the prescaler:

UCBRx = INT(N)

and the fractional portion is realized by the modulator with the following nominal formula:

UCBRSx = round((N – INT(N)) × 8)

Incrementing or decrementing the UCBRSx setting by one count may give a lower maximum bit error for any given bit. To determine if this is the case, a detailed error calculation must be performed for each bit for each UCBRSx setting.

15.3.10.2 Oversampling Baud Rate Mode Setting

In the oversampling mode the prescaler is set to:

$$UCBRx = INT(\frac{N}{16})$$

and the first stage modulator is set to:

$$UCBRFx = round\left(\left(\frac{N}{16} - INT(\frac{N}{16})\right) \times 16\right)$$

When greater accuracy is required, the UCBRSx modulator can also be implemented with values from 0 to 7. To find the setting that gives the lowest maximum bit error rate for any given bit, a detailed error calculation must be performed for all settings of UCBRSx from 0 to 7 with the initial UCBRFx setting and with the UCBRFx setting incremented and decremented by one.

15.3.11 Transmit Bit Timing

The timing for each character is the sum of the individual bit timings. Using the modulation features of the baud rate generator reduces the cumulative bit error. The individual bit error can be calculated using the following steps.

15.3.11.1 Low-Frequency Baud Rate Mode Bit Timing

In low-frequency mode, calculate the length of bit i $T_{bit,TX}[i]$ based on the UCBRx and UCBRSx settings:

$$T_{bit,TX}[i] = \frac{1}{f_{BRCLK}} (UCBRx + m_{UCBRSx}[i])$$

Where,

$m_{UCBRSx}[i]$ = Modulation of bit i from Table 15-2

15.3.11.2 Oversampling Baud Rate Mode Bit Timing

In oversampling baud rate mode calculate the length of bit i $T_{bit,TX}[i]$ based on the baud rate generator UCBRx, UCBRFx and UCBRSx settings:

$$T_{bit,TX}[i] = \frac{1}{f_{BRCLK}} \left((16 + m_{UCBRSx}[i]) \times UCBRx + \sum_{j=0}^{15} m_{UCBRFx}[j] \right)$$

Where,

$\sum_{j=0}^{15} m_{UCBRFx}[j]$ = Sum of ones from the corresponding row in Table 15-3

$m_{UCBRSx}[i]$ = Modulation of bit i from Table 15-2

This results in an end-of-bit time $t_{bit,TX}[i]$ equal to the sum of all previous and the current bit times:

$$t_{bit,TX}[i] = \sum_{j=0}^{i} T_{bit,TX}[j]$$

To calculate bit error, this time is compared to the ideal bit time $t_{bit,ideal,TX}[i]$:

$$t_{bit,ideal,TX}[i] = \frac{1}{\text{Baud rate}} (i + 1)$$

This results in an error normalized to one ideal bit time (1/baudrate):

$Error_{TX}[i] = (t_{bit,TX}[i] - t_{bit,ideal,TX}[i]) \times \text{Baudrate} \times 100\%$

15.3.12 Receive Bit Timing

Receive timing error consists of two error sources. The first is the bit-to-bit timing error similar to the transmit bit timing error. The second is the error between a start edge occurring and the start edge being accepted by the USCI module. Figure 15-11 shows the asynchronous timing errors between data on the UCAxRXD pin and the internal baud-rate clock. This results in an additional synchronization error. The synchronization error t_{SYNC} is between -0.5 BRCLKs and +0.5 BRCLKs independent of the selected baud rate generation mode.

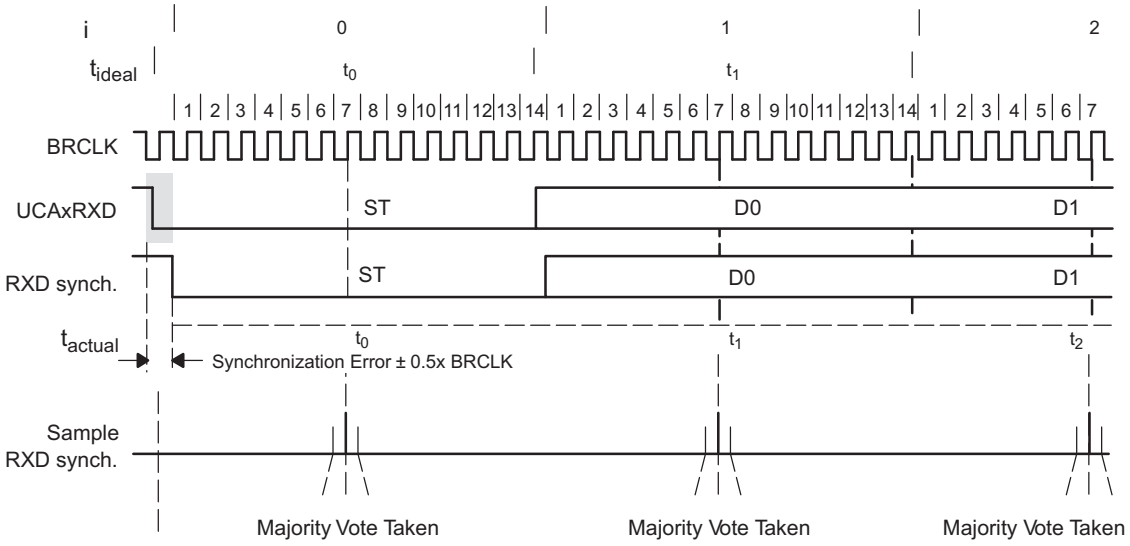


Figure 15-11. Receive Error

The ideal sampling time is in the middle of a bit period:

$$t_{bit,ideal,RX}[i] = \frac{1}{\text{Baud rate}} (i + 0.5)$$

The real sampling time is equal to the sum of all previous bits according to the formulas shown in the transmit timing section, plus one half BITCLK for the current bit i, plus the synchronization error t_{SYNC}.

This results in the following for the low-frequency baud rate mode:

$$t_{bit,RX}[i] = t_{SYNC} + \sum_{j=0}^{i-1} T_{bit,RX}[j] + \frac{1}{f_{BRCLK}} \left(\text{INT}\left(\frac{1}{2} \text{UCBRx} \right) + m_{UCBRSx}[i] \right)$$

Where,

$$T_{bit,RX}[i] = \frac{1}{f_{BRCLK}} \left(\text{UCBRx} + m_{UCBRSx}[i] \right)$$

$m_{UCBRSx}[i]$ = Modulation of bit i from Table 15-2

For the oversampling baud rate mode the sampling time of bit i is calculated by:

$$t_{bit,RX}[i] = t_{SYNC} + \sum_{j=0}^{i-1} T_{bit,RX}[j] + \frac{1}{f_{BRCLK}} \left(\left(8 + m_{UCBRSx}[i] \right) \times \text{UCBRx} + \sum_{j=0}^{7+m_{UCBRSx}[i]} m_{UCBRFx}[j] \right)$$

Where,

$$T_{bit,RX}[i] = \frac{1}{f_{BRCLK}} \left(\left(16 + m_{UCBRSx}[i] \right) \times \text{UCBRx} + \sum_{j=0}^{15} m_{UCBRFx}[j] \right)$$

$\sum_{j=0}^{7+m_{UCBRSx}[i]} m_{UCBRFx}[j]$ = Sum of ones from columns 0 - from the corresponding row in Table 15-3

$m_{UCBRSx}[i]$ = Modulation of bit i from Table 15-2

This results in an error normalized to one ideal bit time (1/baudrate) according to the following formula:

$\text{Error}_{RX}[i] = (t_{bit,RX}[i] - t_{bit,ideal,RX}[i]) \times \text{Baudrate} \times 100\%$

15.3.13 Typical Baud Rates and Errors

Standard baud rate data for UCBRx, UCBRSx and UCBRFx are listed in Table 15-4 and Table 15-5 for a 32768-Hz crystal sourcing ACLK and typical SMCLK frequencies. Ensure that the selected BRCLK frequency does not exceed the device-specific maximum USCI input frequency (see the device-specific data sheet).

The receive error is the accumulated time versus the ideal scanning time in the middle of each bit. The worst case error is given for the reception of an 8-bit character with parity and one stop bit including synchronization error.

The transmit error is the accumulated timing error versus the ideal time of the bit period. The worst case error is given for the transmission of an 8-bit character with parity and stop bit.

Table 15-4. Commonly Used Baud Rates, Settings, and Errors, UCOS16 = 0

BRCLK Frequency [Hz]	Baud Rate [Baud]	UCBRx	UCBRSx	UCBRFx	Maximum TX Error [%]		Maximum RX Error [%]	
32,768	1200	27	2	0	-2.8	1.4	-5.9	2.0
32,768	2400	13	6	0	-4.8	6.0	-9.7	8.3
32,768	4800	6	7	0	-12.1	5.7	-13.4	19.0
32,768	9600	3	3	0	-21.1	15.2	-44.3	21.3
1,048,576	9600	109	2	0	-0.2	0.7	-1.0	0.8
1,048,576	19200	54	5	0	-1.1	1.0	-1.5	2.5
1,048,576	38400	27	2	0	-2.8	1.4	-5.9	2.0
1,048,576	56000	18	6	0	-3.9	1.1	-4.6	5.7
1,048,576	115200	9	1	0	-1.1	10.7	-11.5	11.3
1,048,576	128000	8	1	0	-8.9	7.5	-13.8	14.8
1,048,576	256000	4	1	0	-2.3	25.4	-13.4	38.8
1,000,000	9600	104	1	0	-0.5	0.6	-0.9	1.2
1,000,000	19200	52	0	0	-1.8	0	-2.6	0.9
1,000,000	38400	26	0	0	-1.8	0	-3.6	1.8
1,000,000	56000	17	7	0	-4.8	0.8	-8.0	3.2
1,000,000	115200	8	6	0	-7.8	6.4	-9.7	16.1
1,000,000	128000	7	7	0	-10.4	6.4	-18.0	11.6
1,000,000	256000	3	7	0	-29.6	0	-43.6	5.2
4,000,000	9600	416	6	0	-0.2	0.2	-0.2	0.4
4,000,000	19200	208	3	0	-0.2	0.5	-0.3	0.8
4,000,000	38400	104	1	0	-0.5	0.6	-0.9	1.2
4,000,000	56000	71	4	0	-0.6	1.0	-1.7	1.3
4,000,000	115200	34	6	0	-2.1	0.6	-2.5	3.1
4,000,000	128000	31	2	0	-0.8	1.6	-3.6	2.0
4,000,000	256000	15	5	0	-4.0	3.2	-8.4	5.2
8,000,000	9600	833	2	0	-0.1	0	-0.2	0.1
8,000,000	19200	416	6	0	-0.2	0.2	-0.2	0.4
8,000,000	38400	208	3	0	-0.2	0.5	-0.3	0.8
8,000,000	56000	142	7	0	-0.6	0.1	-0.7	0.8
8,000,000	115200	69	4	0	-0.6	0.8	-1.8	1.1
8,000,000	128000	62	4	0	-0.8	0	-1.2	1.2
8,000,000	256000	31	2	0	-0.8	1.6	-3.6	2.0
12,000,000	9600	1250	0	0	0	0	-0.05	0.05
12,000,000	19200	625	0	0	0	0	-0.2	0
12,000,000	38400	312	4	0	-0.2	0	-0.2	0.2
12,000,000	56000	214	2	0	-0.3	0.2	-0.4	0.5

Table 15-4. Commonly Used Baud Rates, Settings, and Errors, UCOS16 = 0 (continued)

BRCLK Frequency [Hz]	Baud Rate [Baud]	UCBRx	UCBRSx	UCBRFx	Maximum TX Error [%]		Maximum RX Error [%]	
12,000,000	115200	104	1	0	-0.5	0.6	-0.9	1.2
12,000,000	128000	93	6	0	-0.8	0	-1.5	0.4
12,000,000	256000	46	7	0	-1.9	0	-2.0	2.0
16,000,000	9600	1666	6	0	-0.05	0.05	-0.05	0.1
16,000,000	19200	833	2	0	-0.1	0.05	-0.2	0.1
16,000,000	38400	416	6	0	-0.2	0.2	-0.2	0.4
16,000,000	56000	285	6	0	-0.3	0.1	-0.5	0.2
16,000,000	115200	138	7	0	-0.7	0	-0.8	0.6
16,000,000	128000	125	0	0	0	0	-0.8	0
16,000,000	256000	62	4	0	-0.8	0	-1.2	1.2

Table 15-5. Commonly Used Baud Rates, Settings, and Errors, UCOS16 = 1

BRCLK Frequency [Hz]	Baud Rate [Baud]	UCBRx	UCBRSx	UCBRFx	Maximum TX Error [%]		Maximum RX Error [%]	
1,048,576	9600	6	0	13	-2.3	0	-2.2	0.8
1,048,576	19200	3	1	6	-4.6	3.2	-5.0	4.7
1,000,000	9600	6	0	8	-1.8	0	-2.2	0.4
1,000,000	19200	3	0	4	-1.8	0	-2.6	0.9
1,000,000	57600	1	7	0	-34.4	0	-33.4	0
4,000,000	9600	26	0	1	0	0.9	0	1.1
4,000,000	19200	13	0	0	-1.8	0	-1.9	0.2
4,000,000	38400	6	0	8	-1.8	0	-2.2	0.4
4,000,000	57600	4	5	3	-3.5	3.2	-1.8	6.4
4,000,000	115200	2	3	2	-2.1	4.8	-2.5	7.3
4,000,000	230400	1	7	0	-34.4	0	-33.4	0
8,000,000	9600	52	0	1	-0.4	0	-0.4	0.1
8,000,000	19200	26	0	1	0	0.9	0	1.1
8,000,000	38400	13	0	0	-1.8	0	-1.9	0.2
8,000,000	57600	8	0	11	0	0.88	0	1.6
8,000,000	115200	4	5	3	-3.5	3.2	-1.8	6.4
8,000,000	230400	2	3	2	-2.1	4.8	-2.5	7.3
8,000,000	460800	1	7	0	-34.4	0	-33.4	0
12,000,000	9600	78	0	2	0	0	-0.05	0.05
12,000,000	19200	39	0	1	0	0	0	0.2
12,000,000	38400	19	0	8	-1.8	0	-1.8	0.1
12,000,000	57600	13	0	0	-1.8	0	-1.9	0.2
12,000,000	115200	6	0	8	-1.8	0	-2.2	0.4
12,000,000	230400	3	0	4	-1.8	0	-2.6	0.9
16,000,000	9600	104	0	3	0	0.2	0	0.3
16,000,000	19200	52	0	1	-0.4	0	-0.4	0.1
16,000,000	38400	26	0	1	0	0.9	0	1.1
16,000,000	57600	17	0	6	0	0.9	-0.1	1.0
16,000,000	115200	8	0	11	0	0.9	0	1.6
16,000,000	230400	4	5	3	-3.5	3.2	-1.8	6.4
16,000,000	460800	2	3	2	-2.1	4.8	-2.5	7.3

15.3.14 Using the USCI Module in UART Mode with Low Power Modes

The USCI module provides automatic clock activation for SMCLK for use with low-power modes. When SMCLK is the USCI clock source, and is inactive because the device is in a low-power mode, the USCI module automatically activates it when needed, regardless of the control-bit settings for the clock source. The clock remains active until the USCI module returns to its idle condition. After the USCI module returns to the idle condition, control of the clock source reverts to the settings of its control bits. Automatic clock activation is not provided for ACLK.

When the USCI module activates an inactive clock source, the clock source becomes active for the whole device and any peripheral configured to use the clock source may be affected. For example, a timer using SMCLK will increment while the USCI module forces SMCLK active.

15.3.15 USCI Interrupts

The USCI has one interrupt vector for transmission and one interrupt vector for reception.

15.3.15.1 USCI Transmit Interrupt Operation

The UCAxTXIFG interrupt flag is set by the transmitter to indicate that UCAxTXBUF is ready to accept another character. An interrupt request is generated if UCAxTXIE and GIE are also set. UCAxTXIFG is automatically reset if a character is written to UCAxTXBUF.

UCAxTXIFG is set after a PUC or when UCSWRST = 1. UCAxTXIE is reset after a PUC or when UCSWRST = 1.

15.3.15.2 USCI Receive Interrupt Operation

The UCAxRXIFG interrupt flag is set each time a character is received and loaded into UCAxRXBUF. An interrupt request is generated if UCAxRXIE and GIE are also set. UCAxRXIFG and UCAxRXIE are reset by a system reset PUC signal or when UCSWRST = 1. UCAxRXIFG is automatically reset when UCAxRXBUF is read.

Additional interrupt control features include:

- When UCAxRXEIE = 0 erroneous characters will not set UCAxRXIFG.
- When UCDORM = 1, non-address characters will not set UCAxRXIFG in multiprocessor modes. In plain UART mode, no characters will set UCAxRXIFG.
- When UCBRKIE = 1 a break condition will set the UCBRK bit and the UCAxRXIFG flag.

15.3.15.3 USCI Interrupt Usage

USCI_Ax and USCI_Bx share the same interrupt vectors. The receive interrupt flags UCAxRXIFG and UCBxRXIFG are routed to one interrupt vector, the transmit interrupt flags UCAxTXIFG and UCBxTXIFG share another interrupt vector.

Example 15-1 shows an extract of an interrupt service routine to handle data receive interrupts from USCI_A0 in either UART or SPI mode and USCI_B0 in SPI mode.

Example 15-1. Shared Interrupt Vectors Software Example, Data Receive

```
USCIA0_RX_USCIB0_RX_ISR
   BIT.B #UCA0RXIFG, &IFG2 ; USCI_A0 Receive Interrupt?
   JNZ USCIA0_RX_ISR
USCIB0_RX_ISR?
   ; Read UCB0RXBUF (clears UCB0RXIFG)
   ...
   RETI
USCIA0_RX_ISR
   ; Read UCA0RXBUF (clears UCA0RXIFG)
   ...
   RETI
```

Example 15-2 shows an extract of an interrupt service routine to handle data transmit interrupts from USCI_A0 in either UART or SPI mode and USCI_B0 in SPI mode.

Example 15-2. Shared Interrupt Vectors Software Example, Data Transmit

```
USCIA0_TX_USCIB0_TX_ISR
BIT.B #UCA0TXIFG, &IFG2 ; USCI_A0 Transmit Interrupt?
JNZ USCIA0_TX_ISR
USCIB0_TX_ISR
; Write UCB0TXBUF (clears UCB0TXIFG)
...
RETI
USCIA0_TX_ISR
; Write UCA0TXBUF (clears UCA0TXIFG)
...
RETI
```

15.4 USCI Registers: UART Mode

The USCI registers applicable in UART mode are listed in Table 15-6 and Table 15-7.

Table 15-6. USCI_A0 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USCI_A0 control register 0	UCA0CTL0	Read/write	060h	Reset with PUC
USCI_A0 control register 1	UCA0CTL1	Read/write	061h	001h with PUC
USCI_A0 Baud rate control register 0	UCA0BR0	Read/write	062h	Reset with PUC
USCI_A0 baud rate control register 1	UCA0BR1	Read/write	063h	Reset with PUC
USCI_A0 modulation control register	UCA0MCTL	Read/write	064h	Reset with PUC
USCI_A0 status register	UCA0STAT	Read/write	065h	Reset with PUC
USCI_A0 receive buffer register	UCA0RXBUF	Read	066h	Reset with PUC
USCI_A0 transmit buffer register	UCA0TXBUF	Read/write	067h	Reset with PUC
USCI_A0 Auto baud control register	UCA0ABCTL	Read/write	05Dh	Reset with PUC
USCI_A0 IrDA transmit control register	UCA0IRTCTL	Read/write	05Eh	Reset with PUC
USCI_A0 IrDA receive control register	UCA0IRRCTL	Read/write	05Fh	Reset with PUC
SFR interrupt enable register 2	IE2	Read/write	001h	Reset with PUC
SFR interrupt flag register 2	IFG2	Read/write	003h	00Ah with PUC

NOTE: Modifying SFR bits

To avoid modifying control bits of other modules, it is recommended to set or clear the IEx and IFGx bits using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions.

Table 15-7. USCI_A1 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USCI_A1 control register 0	UCA1CTL0	Read/write	0D0h	Reset with PUC
USCI_A1 control register 1	UCA1CTL1	Read/write	0D1h	001h with PUC
USCI_A1 baud rate control register 0	UCA1BR0	Read/write	0D2h	Reset with PUC
USCI_A1 baud rate control register 1	UCA1BR1	Read/write	0D3h	Reset with PUC
USCI_A1 modulation control register	UCA1MCTL	Read/write	0D4h	Reset with PUC
USCI_A1 status register	UCA1STAT	Read/write	0D5h	Reset with PUC
USCI_A1 receive buffer register	UCA1RXBUF	Read	0D6h	Reset with PUC
USCI_A1 transmit buffer register	UCA1TXBUF	Read/write	0D7h	Reset with PUC
USCI_A1 auto baud control register	UCA1ABCTL	Read/write	0CDh	Reset with PUC
USCI_A1 IrDA transmit control register	UCA1IRTCTL	Read/write	0CEh	Reset with PUC
USCI_A1 IrDA receive control register	UCA1IRRCTL	Read/write	0CFh	Reset with PUC
USCI_A1/B1 interrupt enable register	UC1IE	Read/write	006h	Reset with PUC
USCI_A1/B1 interrupt flag register	UC1IFG	Read/write	007h	00Ah with PUC

15.4.1 UCAxCTL0, USCI_Ax Control Register 0

7	6	5	4	3	2	1	0
UCPEN	**UCPAR**	**UCMSB**	**UC7BIT**	**UCSPB**	**UCMODEx**		**UCSYNC**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

UCPEN	Bit 7	Parity enable	
		0	Parity disabled.
		1	Parity enabled. Parity bit is generated (UCAxTXD) and expected (UCAxRXD). In address-bit multiprocessor mode, the address bit is included in the parity calculation.
UCPAR	Bit 6	Parity select. UCPAR is not used when parity is disabled.	
		0	Odd parity
		1	Even parity
UCMSB	Bit 5	MSB first select. Controls the direction of the receive and transmit shift register.	
		0	LSB first
		1	MSB first
UC7BIT	Bit 4	Character length. Selects 7-bit or 8-bit character length.	
		0	8-bit data
		1	7-bit data
UCSPB	Bit 3	Stop bit select. Number of stop bits.	
		0	One stop bit
		1	Two stop bits
UCMODEx	Bits 2-1	USCI mode. The UCMODEx bits select the asynchronous mode when UCSYNC = 0.	
		00	UART mode
		01	Idle-line multiprocessor mode
		10	Address-bit multiprocessor mode
		11	UART mode with automatic baud rate detection
UCSYNC	Bit 0	Synchronous mode enable	
		0	Asynchronous mode
		1	Synchronous mode

15.4.2 UCAxCTL1, USCI_Ax Control Register 1

7	6	5	4	3	2	1	0
UCSSELx		**UCRXEIE**	**UCBRKIE**	**UCDORM**	**UCTXADDR**	**UCTXBRK**	**UCSWRST**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-1

UCSSELx	Bits 7-6	USCI clock source select. These bits select the BRCLK source clock. 00 UCLK 01 ACLK 10 SMCLK 11 SMCLK
UCRXEIE	Bit 5	Receive erroneous-character interrupt-enable 0 Erroneous characters rejected and UCAxRXIFG is not set 1 Erroneous characters received will set UCAxRXIFG
UCBRKIE	Bit 4	Receive break character interrupt-enable 0 Received break characters do not set UCAxRXIFG. 1 Received break characters set UCAxRXIFG.
UCDORM	Bit 3	Dormant. Puts USCI into sleep mode. 0 Not dormant. All received characters will set UCAxRXIFG. 1 Dormant. Only characters that are preceded by an idle-line or with address bit set will set UCAxRXIFG. In UART mode with automatic baud rate detection only the combination of a break and synch field will set UCAxRXIFG.
UCTXADDR	Bit 2	Transmit address. Next frame to be transmitted will be marked as address depending on the selected multiprocessor mode. 0 Next frame transmitted is data 1 Next frame transmitted is an address
UCTXBRK	Bit 1	Transmit break. Transmits a break with the next write to the transmit buffer. In UART mode with automatic baud rate detection 055h must be written into UCAxTXBUF to generate the required break/synch fields. Otherwise 0h must be written into the transmit buffer. 0 Next frame transmitted is not a break 1 Next frame transmitted is a break or a break/synch
UCSWRST	Bit 0	Software reset enable 0 Disabled. USCI reset released for operation. 1 Enabled. USCI logic held in reset state.

15.4.3 UCAxBR0, USCI_Ax Baud Rate Control Register 0

7	6	5	4	3	2	1	0
UCBRx							
rw	rw	rw	rw	rw	rw	rw	rw

15.4.4 UCAxBR1, USCI_Ax Baud Rate Control Register 1

7	6	5	4	3	2	1	0
UCBRx							
rw	rw	rw	rw	rw	rw	rw	rw

UCBRx	7-0	Clock prescaler setting of the Baud rate generator. The 16-bit value of (UCAxBR0 + UCAxBR1 × 256) forms the prescaler value.

15.4.5 UCAxMCTL, USCI_Ax Modulation Control Register

7	6	5	4	3	2	1	0
UCBRFx				UCBRSx			UCOS16
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

UCBRFx	Bits 7-4	First modulation stage select. These bits determine the modulation pattern for BITCLK16 when UCOS16 = 1. Ignored with UCOS16 = 0. Table 15-3 shows the modulation pattern.
UCBRSx	Bits 3-1	Second modulation stage select. These bits determine the modulation pattern for BITCLK. Table 15-2 shows the modulation pattern.
UCOS16	Bit 0	Oversampling mode enabled
		0 Disabled
		1 Enabled

15.4.6 UCAxSTAT, USCI_Ax Status Register

7	6	5	4	3	2	1	0
UCLISTEN	UCFE	UCOE	UCPE	UCBRK	UCRXERR	UCADDR UCIDLE	UCBUSY
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	r-0

UCLISTEN	Bit 7	Listen enable. The UCLISTEN bit selects loopback mode.
		0 Disabled
		1 Enabled. UCAxTXD is internally fed back to the receiver.
UCFE	Bit 6	Framing error flag
		0 No error
		1 Character received with low stop bit
UCOE	Bit 5	Overrun error flag. This bit is set when a character is transferred into UCAxRXBUF before the previous character was read. UCOE is cleared automatically when UCxRXBUF is read, and must not be cleared by software. Otherwise, it will not function correctly.
		0 No error
		1 Overrun error occurred
UCPE	Bit 4	Parity error flag. When UCPEN = 0, UCPE is read as 0.
		0 No error
		1 Character received with parity error
UCBRK	Bit 3	Break detect flag
		0 No break condition
		1 Break condition occurred
UCRXERR	Bit 2	Receive error flag. This bit indicates a character was received with error(s). When UCRXERR = 1, on or more error flags (UCFE, UCPE, UCOE) is also set. UCRXERR is cleared when UCAxRXBUF is read.
		0 No receive errors detected
		1 Receive error detected
UCADDR	Bit 1	Address received in address-bit multiprocessor mode.
		0 Received character is data
		1 Received character is an address
UCIDLE		Idle line detected in idle-line multiprocessor mode.
		0 No idle line detected
		1 Idle line detected
UCBUSY	Bit 0	USCI busy. This bit indicates if a transmit or receive operation is in progress.
		0 USCI inactive
		1 USCI transmitting or receiving

15.4.7 UCAxRXBUF, USCI_Ax Receive Buffer Register

7	6	5	4	3	2	1	0
UCRXBUFx							
rw	rw	rw	rw	rw	rw	rw	rw

UCRXBUFx	Bits 7-0	The receive-data buffer is user accessible and contains the last received character from the receive shift register. Reading UCAxRXBUF resets the receive-error bits, the UCADDR or UCIDLE bit, and UCAxRXIFG. In 7-bit data mode, UCAxRXBUF is LSB justified and the MSB is always reset.

15.4.8 UCAxTXBUF, USCI_Ax Transmit Buffer Register

7	6	5	4	3	2	1	0
UCTXBUFx							
rw	rw	rw	rw	rw	rw	rw	rw

UCTXBUFx	Bits 7-0	The transmit data buffer is user accessible and holds the data waiting to be moved into the transmit shift register and transmitted on UCAxTXD. Writing to the transmit data buffer clears UCAxTXIFG. The MSB of UCAxTXBUF is not used for 7-bit data and is reset.

15.4.9 UCAxIRTCTL, USCI_Ax IrDA Transmit Control Register

7	6	5	4	3	2	1	0
UCIRTXPLx						UCIRTXCLK	UCIREN
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

UCIRTXPLx	Bits 7-2	Transmit pulse length. Pulse length t_{PULSE} = (UCIRTXPLx + 1) / (2 × $f_{IRTXCLK}$)
UCIRTXCLK	Bit 1	IrDA transmit pulse clock select
		0 BRCLK
		1 BITCLK16 when UCOS16 = 1. Otherwise, BRCLK
UCIREN	Bit 0	IrDA encoder/decoder enable.
		0 IrDA encoder/decoder disabled
		1 IrDA encoder/decoder enabled

15.4.10 UCAxIRRCTL, USCI_Ax IrDA Receive Control Register

7	6	5	4	3	2	1	0
UCIRRXFLx						UCIRRXPL	UCIRRXFE
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

UCIRRXFLx	Bits 7-2	Receive filter length. The minimum pulse length for receive is given by: t_{MIN} = (UCIRRXFLx + 4) / (2 × $f_{IRTXCLK}$)
UCIRRXPL	Bit 1	IrDA receive input UCAxRXD polarity
		0 IrDA transceiver delivers a high pulse when a light pulse is seen
		1 IrDA transceiver delivers a low pulse when a light pulse is seen
UCIRRXFE	Bit 0	IrDA receive filter enabled
		0 Receive filter disabled
		1 Receive filter enabled

15.4.11 UCAxABCTL, USCI_Ax Auto Baud Rate Control Register

7	6	5	4	3	2	1	0
Reserved		**UCDELIMx**		**UCSTOE**	**UCBTOE**	**Reserved**	**UCABDEN**
r-0	r-0	rw-0	rw-0	rw-0	rw-0	r-0	rw-0

Reserved	Bits 7-6	Reserved	
UCDELIMx	Bits 5-4	Break/synch delimiter length	
		00	1 bit time
		01	2 bit times
		10	3 bit times
		11	4 bit times
UCSTOE	Bit 3	Synch field time out error	
		0	No error
		1	Length of synch field exceeded measurable time.
UCBTOE	Bit 2	Break time out error	
		0	No error
		1	Length of break field exceeded 22 bit times.
Reserved	Bit 1	Reserved	
UCABDEN	Bit 0	Automatic baud rate detect enable	
		0	Baud rate detection disabled. Length of break and synch field is not measured.
		1	Baud rate detection enabled. Length of break and synch field is measured and baud rate settings are changed accordingly.

15.4.12 IE2, Interrupt Enable Register 2

7	6	5	4	3	2	1	0
						UCA0TXIE	**UCA0RXIE**
						rw-0	rw-0

	Bits 7-2	These bits may be used by other modules (see the device-specific data sheet).	
UCA0TXIE	Bit 1	USCI_A0 transmit interrupt enable	
		0	Interrupt disabled
		1	Interrupt enabled
UCA0RXIE	Bit 0	USCI_A0 receive interrupt enable	
		0	Interrupt disabled
		1	Interrupt enabled

15.4.13 IFG2, Interrupt Flag Register 2

7	6	5	4	3	2	1	0
						UCA0TXIFG	**UCA0RXIFG**
						rw-1	rw-0

	Bits 7-2	These bits may be used by other modules (see the device-specific data sheet).	
UCA0TXIFG	Bit 1	USCI_A0 transmit interrupt flag. UCA0TXIFG is set when UCA0TXBUF is empty.	
		0	No interrupt pending
		1	Interrupt pending
UCA0RXIFG	Bit 0	USCI_A0 receive interrupt flag. UCA0RXIFG is set when UCA0RXBUF has received a complete character.	
		0	No interrupt pending
		1	Interrupt pending

15.4.14 UC1IE, USCI_A1 Interrupt Enable Register

7	6	5	4	3	2	1	0
Unused						UCA1TXIE	UCA1RXIE
rw-0	rw-0	rw-0	rw-0			rw-0	rw-0

Unused	Bits 7-4	Unused
	Bits 3-2	These bits may be used by other USCI modules (see the device-specific data sheet).
UCA1TXIE	Bit 1	USCI_A1 transmit interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCA1RXIE	Bit 0	USCI_A1 receive interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled

15.4.15 UC1IFG, USCI_A1 Interrupt Flag Register

7	6	5	4	3	2	1	0
Unused						UCA1TXIFG	UCA1RXIFG
rw-0	rw-0	rw-0	rw-0			rw-1	rw-0

Unused	Bits 7-4	Unused
	Bits 3-2	These bits may be used by other USCI modules (see the device-specific data sheet).
UCA1TXIFG	Bit 1	USCI_A1 transmit interrupt flag. UCA1TXIFG is set when UCA1TXBUF is empty.
		0 No interrupt pending
		1 Interrupt pending
UCA1RXIFG	Bit 0	USCI_A1 receive interrupt flag. UCA1RXIFG is set when UCA1RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending

Universal Serial Communication Interface, SPI Mode

The universal serial communication interface (USCI) supports multiple serial communication modes with one hardware module. This chapter discusses the operation of the synchronous peripheral interface or SPI mode.

Topic **Page**

16.1 USCI Overview

The universal serial communication interface (USCI) modules support multiple serial communication modes. Different USCI modules support different modes. Each different USCI module is named with a different letter (for example, USCI_A is different from USCI_B). If more than one identical USCI module is implemented on one device, those modules are named with incrementing numbers. For example, if one device has two USCI_A modules, they are named USCI_A0 and USCI_A1. See the device-specific data sheet to determine which USCI modules, if any, are implemented on each device.

The USCI_Ax modules support:

- UART mode
- Pulse shaping for IrDA communications
- Automatic baud rate detection for LIN communications
- SPI mode

The USCI_Bx modules support:

- I^2C mode
- SPI mode

16.2 USCI Introduction: SPI Mode

In synchronous mode, the USCI connects the MSP430 to an external system via three or four pins: UCxSIMO, UCxSOMI, UCxCLK, and UCxSTE. SPI mode is selected when the UCSYNC bit is set and SPI mode (3-pin or 4-pin) is selected with the UCMODEx bits.

SPI mode features include:

- 7- or 8-bit data length
- LSB-first or MSB-first data transmit and receive
- 3-pin and 4-pin SPI operation
- Master or slave modes
- Independent transmit and receive shift registers
- Separate transmit and receive buffer registers
- Continuous transmit and receive operation
- Selectable clock polarity and phase control
- Programmable clock frequency in master mode
- Independent interrupt capability for receive and transmit
- Slave operation in LPM4

Figure 16-1 shows the USCI when configured for SPI mode.

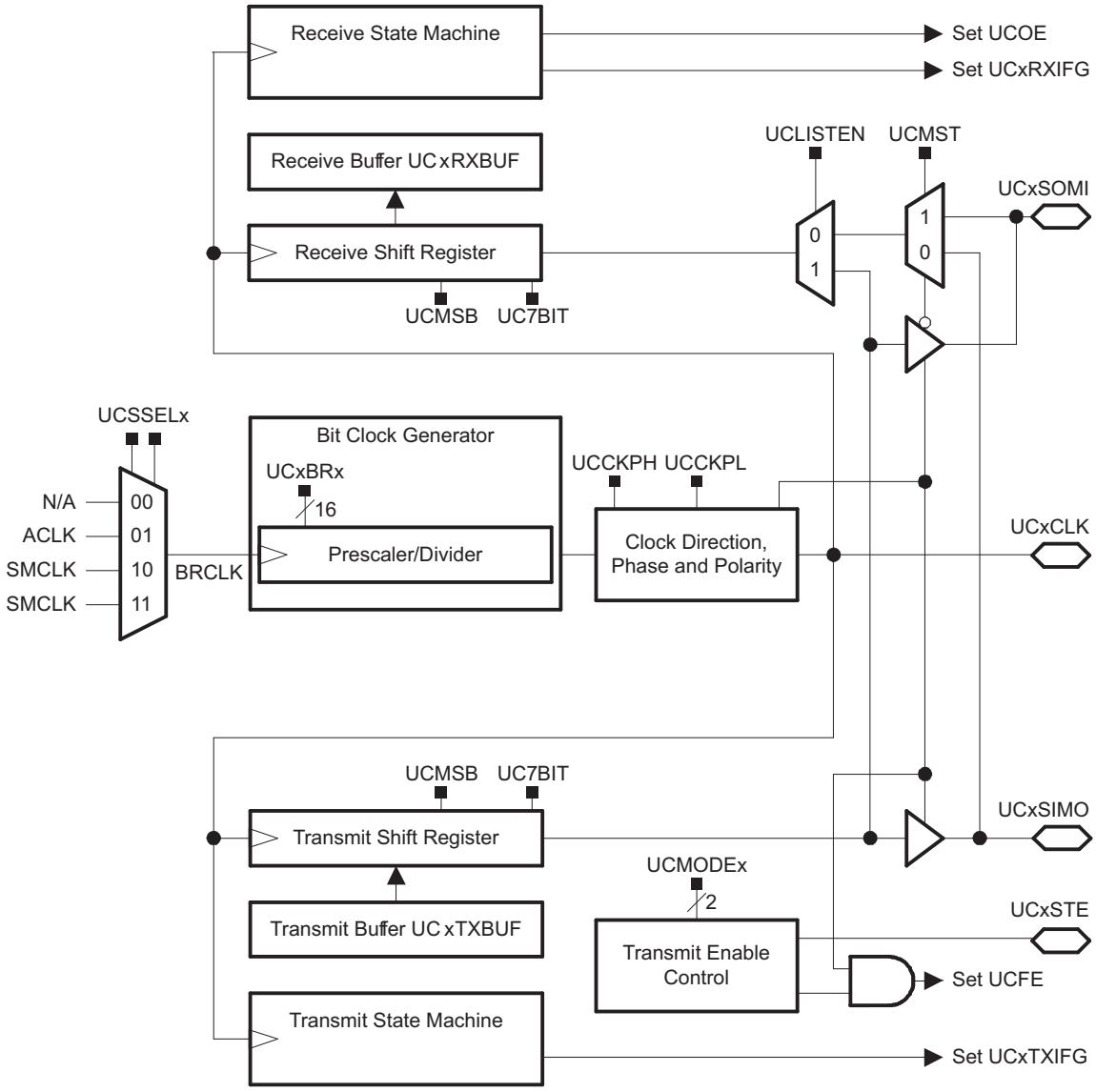


Figure 16-1. USCI Block Diagram: SPI Mode

16.3 USCI Operation: SPI Mode

In SPI mode, serial data is transmitted and received by multiple devices using a shared clock provided by the master. An additional pin, UCxSTE, is provided to enable a device to receive and transmit data and is controlled by the master.

Three or four signals are used for SPI data exchange:

- UCxSIMO: Slave in, master out
  - Master mode: UCxSIMO is the data output line.
  - Slave mode: UCxSIMO is the data input line.
- UCxSOMI: Slave out, master in
  - Master mode: UCxSOMI is the data input line.
  - Slave mode: UCxSOMI is the data output line.
- UCxCLK: USCI SPI clock
  - Master mode: UCxCLK is an output.
  - Slave mode: UCxCLK is an input.
- UCxSTE: Slave transmit enable
  Used in 4-pin mode to allow multiple masters on a single bus. Not used in 3-pin mode. Table 16-1 describes the UCxSTE operation.

Table 16-1. UCxSTE Operation

UCMODEx	UCxSTE Active State	UCxSTE	Slave	Master
01	High	0	Inactive	Active
		1	Active	Inactive
10	Low	0	Active	Inactive
		1	Inactive	Active

16.3.1 USCI Initialization and Reset

The USCI is reset by a PUC or by the UCSWRST bit. After a PUC, the UCSWRST bit is automatically set, keeping the USCI in a reset condition. When set, the UCSWRST bit resets the UCxRXIE, UCxTXIE, UCxRXIFG, UCOE, and UCFE bits and sets the UCxTXIFG flag. Clearing UCSWRST releases the USCI for operation.

NOTE: Initializing or Re-Configuring the USCI Module

The recommended USCI initialization/re-configuration process is:

1. Set UCSWRST (BIS.B #UCSWRST,&UCxCTL1)
2. Initialize all USCI registers with UCSWRST=1 (including UCxCTL1)
3. Configure ports
4. Clear UCSWRST via software (BIC.B #UCSWRST,&UCxCTL1)
5. Enable interrupts (optional) via UCxRXIE and/or UCxTXIE

16.3.2 Character Format

The USCI module in SPI mode supports 7-bit and 8-bit character lengths selected by the UC7BIT bit. In 7-bit data mode, UCxRXBUF is LSB justified and the MSB is always reset. The UCMSB bit controls the direction of the transfer and selects LSB or MSB first.

NOTE: Default Character Format

The default SPI character transmission is LSB first. For communication with other SPI interfaces it MSB-first mode may be required.

NOTE: Character Format for Figures

Figures throughout this chapter use MSB first format.

16.3.3 Master Mode

Figure 16-2 shows the USCI as a master in both 3-pin and 4-pin configurations. The USCI initiates data transfer when data is moved to the transmit data buffer UCxTXBUF. The UCxTXBUF data is moved to the TX shift register when the TX shift register is empty, initiating data transfer on UCxSIMO starting with either the most-significant or least-significant bit depending on the UCMSB setting. Data on UCxSOMI is shifted into the receive shift register on the opposite clock edge. When the character is received, the receive data is moved from the RX shift register to the received data buffer UCxRXBUF and the receive interrupt flag, UCxRXIFG, is set, indicating the RX/TX operation is complete.

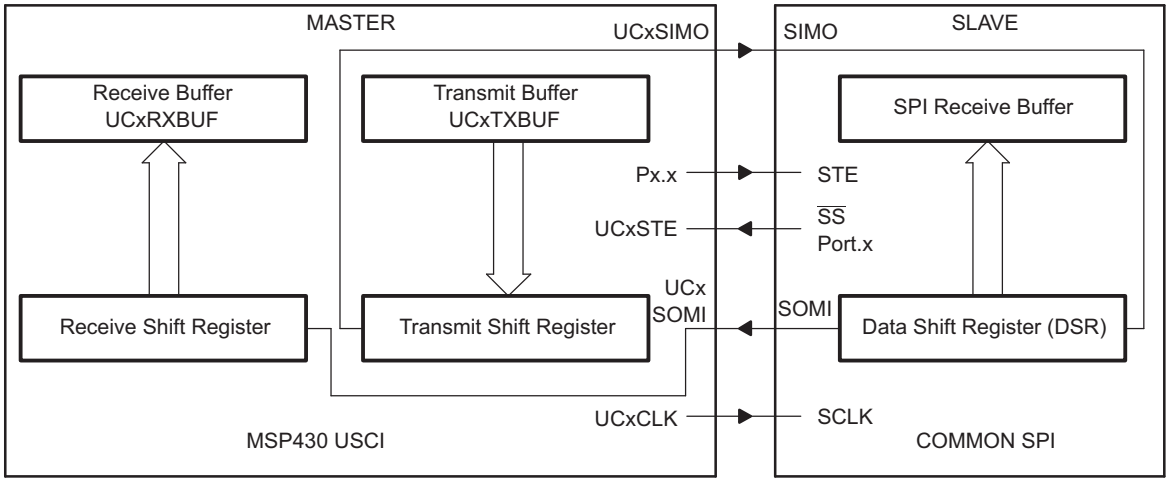


Figure 16-2. USCI Master and External Slave

A set transmit interrupt flag, UCxTXIFG, indicates that data has moved from UCxTXBUF to the TX shift register and UCxTXBUF is ready for new data. It does not indicate RX/TX completion.

To receive data into the USCI in master mode, data must be written to UCxTXBUF because receive and transmit operations operate concurrently.

16.3.3.1 Four-Pin SPI Master Mode

In 4-pin master mode, UCxSTE is used to prevent conflicts with another master and controls the master as described in Table 16-1. When UCxSTE is in the master-inactive state:

- UCxSIMO and UCxCLK are set to inputs and no longer drive the bus
- The error bit UCFE is set indicating a communication integrity violation to be handled by the user.
- The internal state machines are reset and the shift operation is aborted.

If data is written into UCxTXBUF while the master is held inactive by UCxSTE, it will be transmitted as soon as UCxSTE transitions to the master-active state. If an active transfer is aborted by UCxSTE transitioning to the master-inactive state, the data must be re-written into UCxTXBUF to be transferred when UCxSTE transitions back to the master-active state. The UCxSTE input signal is not used in 3-pin master mode.

16.3.4 Slave Mode

Figure 16-3 shows the USCI as a slave in both 3-pin and 4-pin configurations. UCxCLK is used as the input for the SPI clock and must be supplied by the external master. The data-transfer rate is determined by this clock and not by the internal bit clock generator. Data written to UCxTXBUF and moved to the TX shift register before the start of UCxCLK is transmitted on UCxSOMI. Data on UCxSIMO is shifted into the receive shift register on the opposite edge of UCxCLK and moved to UCxRXBUF when the set number of bits are received. When data is moved from the RX shift register to UCxRXBUF, the UCxRXIFG interrupt flag is set, indicating that data has been received. The overrun error bit, UCOE, is set when the previously received data is not read from UCxRXBUF before new data is moved to UCxRXBUF.

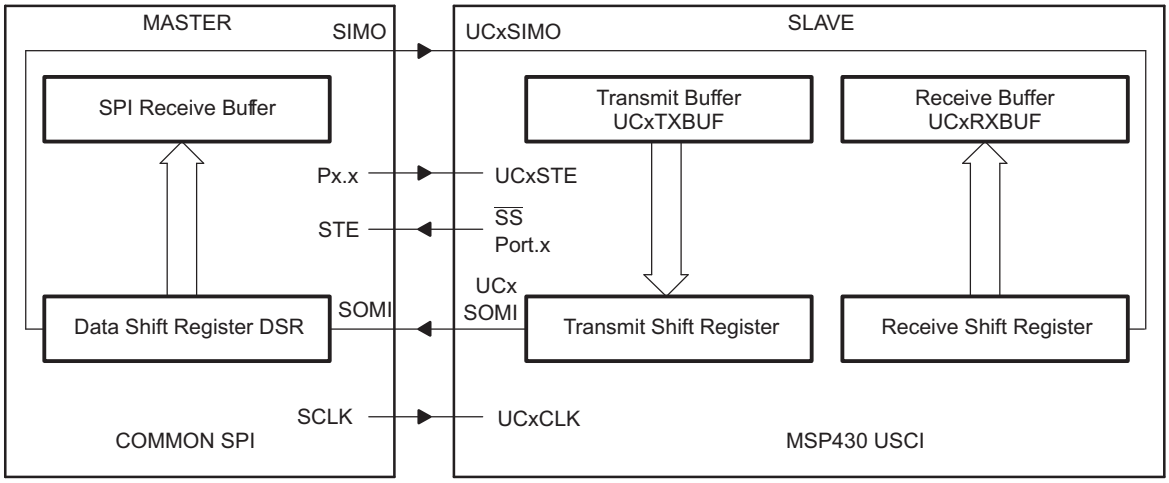


Figure 16-3. USCI Slave and External Master

16.3.4.1 Four-Pin SPI Slave Mode

In 4-pin slave mode, UCxSTE is used by the slave to enable the transmit and receive operations and is provided by the SPI master. When UCxSTE is in the slave-active state, the slave operates normally. When UCxSTE is in the slave- inactive state:

- Any receive operation in progress on UCxSIMO is halted
- UCxSOMI is set to the input direction
- The shift operation is halted until the UCxSTE line transitions into the slave transmit active state.

The UCxSTE input signal is not used in 3-pin slave mode.

16.3.5 SPI Enable

When the USCI module is enabled by clearing the UCSWRST bit it is ready to receive and transmit. In master mode the bit clock generator is ready, but is not clocked nor producing any clocks. In slave mode the bit clock generator is disabled and the clock is provided by the master.

A transmit or receive operation is indicated by UCBUSY = 1.

A PUC or set UCSWRST bit disables the USCI immediately and any active transfer is terminated.

16.3.5.1 Transmit Enable

In master mode, writing to UCxTXBUF activates the bit clock generator and the data will begin to transmit.

In slave mode, transmission begins when a master provides a clock and, in 4-pin mode, when the UCxSTE is in the slave-active state.

16.3.5.2 Receive Enable

The SPI receives data when a transmission is active. Receive and transmit operations operate concurrently.

16.3.6 Serial Clock Control

UCxCLK is provided by the master on the SPI bus. When UCMST = 1, the bit clock is provided by the USCI bit clock generator on the UCxCLK pin. The clock used to generate the bit clock is selected with the UCSSELx bits. When UCMST = 0, the USCI clock is provided on the UCxCLK pin by the master, the bit clock generator is not used, and the UCSSELx bits are don't care. The SPI receiver and transmitter operate in parallel and use the same clock source for data transfer.

The 16-bit value of UCBRx in the bit rate control registers UCxxBR1 and UCxxBR0 is the division factor of the USCI clock source, BRCLK. The maximum bit clock that can be generated in master mode is BRCLK. Modulation is not used in SPI mode and UCAxMCTL should be cleared when using SPI mode for USCI_A. The UCAxCLK/UCBxCLK frequency is given by:

$$f_{BitClock} = \frac{f_{BRCLK}}{UCBRx}$$

16.3.6.1 Serial Clock Polarity and Phase

The polarity and phase of UCxCLK are independently configured via the UCCKPL and UCCKPH control bits of the USCI. Timing for each case is shown in Figure 16-4.

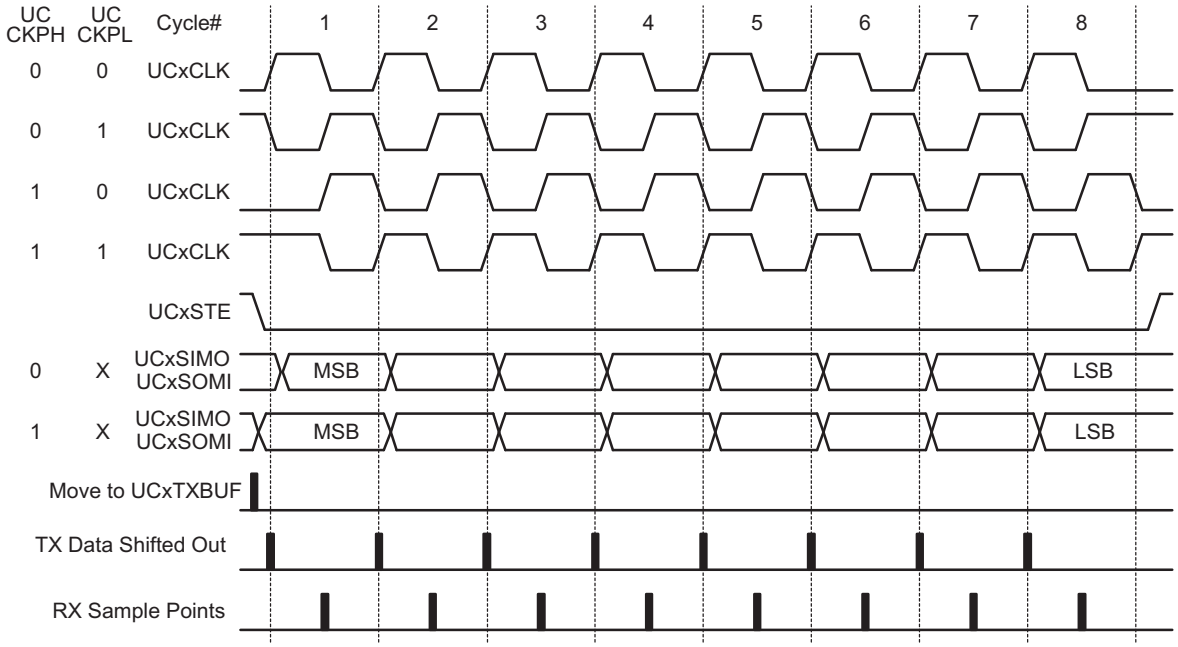


Figure 16-4. USCI SPI Timing with UCMSB = 1

16.3.7 Using the SPI Mode With Low-Power Modes

The USCI module provides automatic clock activation for SMCLK for use with low-power modes. When SMCLK is the USCI clock source, and is inactive because the device is in a low-power mode, the USCI module automatically activates it when needed, regardless of the control-bit settings for the clock source. The clock remains active until the USCI module returns to its idle condition. After the USCI module returns to the idle condition, control of the clock source reverts to the settings of its control bits. Automatic clock activation is not provided for ACLK.

When the USCI module activates an inactive clock source, the clock source becomes active for the whole device and any peripheral configured to use the clock source may be affected. For example, a timer using SMCLK increments while the USCI module forces SMCLK active.

In SPI slave mode, no internal clock source is required because the clock is provided by the external master. It is possible to operate the USCI in SPI slave mode while the device is in LPM4 and all clock sources are disabled. The receive or transmit interrupt can wake up the CPU from any low power mode.

16.3.8 SPI Interrupts

The USCI has one interrupt vector for transmission and one interrupt vector for reception.

16.3.8.1 SPI Transmit Interrupt Operation

The UCxTXIFG interrupt flag is set by the transmitter to indicate that UCxTXBUF is ready to accept another character. An interrupt request is generated if UCxTXIE and GIE are also set. UCxTXIFG is automatically reset if a character is written to UCxTXBUF. UCxTXIFG is set after a PUC or when UCSWRST = 1. UCxTXIE is reset after a PUC or when UCSWRST = 1.

NOTE: Writing to UCxTXBUF in SPI Mode

Data written to UCxTXBUF when UCxTXIFG = 0 may result in erroneous data transmission.

16.3.8.2 SPI Receive Interrupt Operation

The UCxRXIFG interrupt flag is set each time a character is received and loaded into UCxRXBUF. An interrupt request is generated if UCxRXIE and GIE are also set. UCxRXIFG and UCxRXIE are reset by a system reset PUC signal or when UCSWRST = 1. UCxRXIFG is automatically reset when UCxRXBUF is read.

16.3.8.3 USCI Interrupt Usage

USCI_Ax and USCI_Bx share the same interrupt vectors. The receive interrupt flags UCAxRXIFG and UCBxRXIFG are routed to one interrupt vector, the transmit interrupt flags UCAxTXIFG and UCBxTXIFG share another interrupt vector.

Example 16-1 shows an extract of an interrupt service routine to handle data receive interrupts from USCI_A0 in either UART or SPI mode and USCI_B0 in SPI mode.

Example 16-1. Shared Receive Interrupt Vectors Software Example

```
USCIA0_RX_USCIB0_RX_ISR
   BIT.B   #UCA0RXIFG, &IFG2   ; USCI_A0 Receive Interrupt?
   JNZ     USCIA0_RX_ISR
USCIB0_RX_ISR?
   ; Read UCB0RXBUF (clears UCB0RXIFG)
   ...
   RETI
USCIA0_RX_ISR
   ; Read UCA0RXBUF (clears UCA0RXIFG)
   ...
   RETI
```

Example 16-2 shows an extract of an interrupt service routine to handle data transmit interrupts from USCI_A0 in either UART or SPI mode and USCI_B0 in SPI mode.

Example 16-2. Shared Transmit Interrupt Vectors Software Example

```
USCIA0_TX_USCIB0_TX_ISR
   BIT.B   #UCA0TXIFG, &IFG2   ; USCI_A0 Transmit Interrupt?
   JNZ     USCIA0_TX_ISR
USCIB0_TX_ISR
   ; Write UCB0TXBUF (clears UCB0TXIFG)
   ...
   RETI
USCIA0_TX_ISR
   ; Write UCA0TXBUF  (clears UCA0TXIFG)
   ...
   RETI
```

16.4 USCI Registers: SPI Mode

The USCI registers applicable in SPI mode for USCI_A0 and USCI_B0 are listed in Table 16-2. Registers applicable in SPI mode for USCI_A1 and USCI_B1 are listed in Table 16-3.

Table 16-2. USCI_A0 and USCI_B0 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USCI_A0 control register 0	UCA0CTL0	Read/write	060h	Reset with PUC
USCI_A0 control register 1	UCA0CTL1	Read/write	061h	001h with PUC
USCI_A0 baud rate control register 0	UCA0BR0	Read/write	062h	Reset with PUC
USCI_A0 baud rate control register 1	UCA0BR1	Read/write	063h	Reset with PUC
USCI_A0 modulation control register	UCA0MCTL	Read/write	064h	Reset with PUC
USCI_A0 status register	UCA0STAT	Read/write	065h	Reset with PUC
USCI_A0 receive buffer register	UCA0RXBUF	Read	066h	Reset with PUC
USCI_A0 transmit buffer register	UCA0TXBUF	Read/write	067h	Reset with PUC
USCI_B0 control register 0	UCB0CTL0	Read/write	068h	001h with PUC
USCI_B0 control register 1	UCB0CTL1	Read/write	069h	001h with PUC
USCI_B0 bit rate control register 0	UCB0BR0	Read/write	06Ah	Reset with PUC
USCI_B0 bit rate control register 1	UCB0BR1	Read/write	06Bh	Reset with PUC
USCI_B0 status register	UCB0STAT	Read/write	06Dh	Reset with PUC
USCI_B0 receive buffer register	UCB0RXBUF	Read	06Eh	Reset with PUC
USCI_B0 transmit buffer register	UCB0TXBUF	Read/write	06Fh	Reset with PUC
SFR interrupt enable register 2	IE2	Read/write	001h	Reset with PUC
SFR interrupt flag register 2	IFG2	Read/write	003h	00Ah with PUC

NOTE: Modifying SFR bits

To avoid modifying control bits of other modules, it is recommended to set or clear the IEx and IFGx bits using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions.

Table 16-3. USCI_A1 and USCI_B1 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USCI_A1 control register 0	UCA1CTL0	Read/write	0D0h	Reset with PUC
USCI_A1 control register 1	UCA1CTL1	Read/write	0D1h	001h with PUC
USCI_A1 baud rate control register 0	UCA1BR0	Read/write	0D2h	Reset with PUC
USCI_A1 baud rate control register 1	UCA1BR1	Read/write	0D3h	Reset with PUC
USCI_A1 modulation control register	UCA10MCTL	Read/write	0D4h	Reset with PUC
USCI_A1 status register	UCA1STAT	Read/write	0D5h	Reset with PUC
USCI_A1 receive buffer register	UCA1RXBUF	Read	0D6h	Reset with PUC
USCI_A1 transmit buffer register	UCA1TXBUF	Read/write	0D7h	Reset with PUC
USCI_B1 control register 0	UCB1CTL0	Read/write	0D8h	001h with PUC
USCI_B1 control register 1	UCB1CTL1	Read/write	0D9h	001h with PUC
USCI_B1 bit rate control register 0	UCB1BR0	Read/write	0DAh	Reset with PUC
USCI_B1 bit rate control register 1	UCB1BR1	Read/write	0DBh	Reset with PUC
USCI_B1 status register	UCB1STAT	Read/write	0DDh	Reset with PUC
USCI_B1 receive buffer register	UCB1RXBUF	Read	0DEh	Reset with PUC
USCI_B1 transmit buffer register	UCB1TXBUF	Read/write	0DFh	Reset with PUC
USCI_A1/B1 interrupt enable register	UC1IE	Read/write	006h	Reset with PUC
USCI_A1/B1 interrupt flag register	UC1IFG	Read/write	007h	00Ah with PUC

16.4.1 UCAxCTL0, USCI_Ax Control Register 0, UCBxCTL0, USCI_Bx Control Register 0

7	6	5	4	3	2	1	0
UCCKPH	**UCCKPL**	**UCMSB**	**UC7BIT**	**UCMST**	**UCMODEx**		**UCSYNC=1**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	

UCCKPH	Bit 7	Clock phase select.
		0 Data is changed on the first UCLK edge and captured on the following edge.
		1 Data is captured on the first UCLK edge and changed on the following edge.
UCCKPL	Bit 6	Clock polarity select.
		0 The inactive state is low.
		1 The inactive state is high.
UCMSB	Bit 5	MSB first select. Controls the direction of the receive and transmit shift register.
		0 LSB first
		1 MSB first
UC7BIT	Bit 4	Character length. Selects 7-bit or 8-bit character length.
		0 8-bit data
		1 7-bit data
UCMST	Bit 3	Master mode select
		0 Slave mode
		1 Master mode
UCMODEx	Bits 2-1	USCI mode. The UCMODEx bits select the synchronous mode when UCSYNC = 1.
		00 3-pin SPI
		01 4-pin SPI with UCxSTE active high: slave enabled when UCxSTE = 1
		10 4-pin SPI with UCxSTE active low: slave enabled when UCxSTE = 0
		11 I^2C mode
UCSYNC	Bit 0	Synchronous mode enable
		0 Asynchronous mode
		1 Synchronous mode

16.4.2 UCAxCTL1, USCI_Ax Control Register 1, UCBxCTL1, USCI_Bx Control Register 1

7	6	5	4	3	2	1	0
UCSSELx		**Unused**					**UCSWRST**
rw-0	rw-0	rw-0[1] r0[2]	rw-0	rw-0	rw-0	rw-0	rw-1

UCSSELx	Bits 7-6	USCI clock source select. These bits select the BRCLK source clock in master mode. UCxCLK is always used in slave mode.
		00 NA
		01 ACLK
		10 SMCLK
		11 SMCLK
Unused	Bits 5-1	Unused
UCSWRST	Bit 0	Software reset enable
		0 Disabled. USCI reset released for operation.
		1 Enabled. USCI logic held in reset state.

(1) UCAxCTL1 (USCI_Ax)
(2) UCBxCTL1 (USCI_Bx)

16.4.3 UCAxBR0, USCI_Ax Bit Rate Control Register 0, UCBxBR0, USCI_Bx Bit Rate Control Register 0

7	6	5	4	3	2	1	0
UCBRx - low byte							
rw	rw	rw	rw	rw	rw	rw	rw

16.4.4 UCAxBR1, USCI_Ax Bit Rate Control Register 1, UCBxBR1, USCI_Bx Bit Rate Control Register 1

7	6	5	4	3	2	1	0
UCBRx - high byte							
rw	rw	rw	rw	rw	rw	rw	rw

UCBRx		Bit clock prescaler setting. The 16-bit value of (UCxxBR0 + UCxxBR1 × 256) forms the prescaler value.

16.4.5 UCAxSTAT, USCI_Ax Status Register, UCBxSTAT, USCI_Bx Status Register

7	6	5	4	3	2	1	0
UCLISTEN	**UCFE**	**UCOE**	**Unused**				**UCBUSY**
rw-0	rw-0	rw-0	rw-0[1] r0[2]	rw-0	rw-0	rw-0	r-0

UCLISTEN	Bit 7	Listen enable. The UCLISTEN bit selects loopback mode. 0 Disabled 1 Enabled. The transmitter output is internally fed back to the receiver.
UCFE	Bit 6	Framing error flag. This bit indicates a bus conflict in 4-wire master mode. UCFE is not used in 3-wire master or any slave mode. 0 No error 1 Bus conflict occurred
UCOE	Bit 5	Overrun error flag. This bit is set when a character is transferred into UCxRXBUF before the previous character was read. UCOE is cleared automatically when UCxRXBUF is read, and must not be cleared by software. Otherwise, it will not function correctly. 0 No error 1 Overrun error occurred
Unused	Bits 4-1	Unused
UCBUSY	Bit 0	USCI busy. This bit indicates if a transmit or receive operation is in progress. 0 USCI inactive 1 USCI transmitting or receiving

(1) UCAxSTAT (USCI_Ax)
(2) UCBxSTAT (USCI_Bx)

16.4.6 UCAxRXBUF, USCI_Ax Receive Buffer Register, UCBxRXBUF, USCI_Bx Receive Buffer Register

7	6	5	4	3	2	1	0
UCRXBUFx							
r	r	r	r	r	r	r	r

UCRXBUFx	Bits 7-0	The receive-data buffer is user accessible and contains the last received character from the receive shift register. Reading UCxRXBUF resets the receive-error bits, and UCxRXIFG. In 7-bit data mode, UCxRXBUF is LSB justified and the MSB is always reset.

16.4.7 UCAxTXBUF, USCI_Ax Transmit Buffer Register, UCBxTXBUF, USCI_Bx Transmit Buffer Register

7	6	5	4	3	2	1	0
UCTXBUFx							
rw	rw	rw	rw	rw	rw	rw	rw

UCTXBUFx	Bits 7-0	The transmit data buffer is user accessible and holds the data waiting to be moved into the transmit shift register and transmitted. Writing to the transmit data buffer clears UCxTXIFG. The MSB of UCxTXBUF is not used for 7-bit data and is reset.

16.4.8 IE2, Interrupt Enable Register 2

7	6	5	4	3	2	1	0
				UCB0TXIE	UCB0RXIE	UCA0TXIE	UCA0RXIE
				rw-0	rw-0	rw-0	rw-0

	Bits 7-4	These bits may be used by other modules (see the device-specific data sheet).
UCB0TXIE	Bit 3	USCI_B0 transmit interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCB0RXIE	Bit 2	USCI_B0 receive interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCA0TXIE	Bit 1	USCI_A0 transmit interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCA0RXIE	Bit 0	USCI_A0 receive interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled

16.4.9 IFG2, Interrupt Flag Register 2

7	6	5	4	3	2	1	0
				UCB0TXIFG	UCB0RXIFG	UCA0TXIFG	UCA0RXIFG
				rw-1	rw-0	rw-1	rw-0

	Bits 7-4	These bits may be used by other modules (see the device-specific data sheet).
UCB0TXIFG	Bit 3	USCI_B0 transmit interrupt flag. UCB0TXIFG is set when UCB0TXBUF is empty.
		0 No interrupt pending
		1 Interrupt pending
UCB0RXIFG	Bit 2	USCI_B0 receive interrupt flag. UCB0RXIFG is set when UCB0RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending
UCA0TXIFG	Bit 1	USCI_A0 transmit interrupt flag. UCA0TXIFG is set when UCA0TXBUF empty.
		0 No interrupt pending
		1 Interrupt pending
UCA0RXIFG	Bit 0	USCI_A0 receive interrupt flag. UCA0RXIFG is set when UCA0RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending

16.4.10 UC1IE, USCI_A1/USCI_B1 Interrupt Enable Register

7	6	5	4	3	2	1	0
Unused				UCB1TXIE	UCB1RXIE	UCA1TXIE	UCA1RXIE
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

Unused	Bits 7-4	Unused
UCB1TXIE	Bit 3	USCI_B1 transmit interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCB1RXIE	Bit 2	USCI_B1 receive interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCA1TXIE	Bit 1	USCI_A1 transmit interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCA1RXIE	Bit 0	USCI_A1 receive interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled

16.4.11 UC1IFG, USCI_A1/USCI_B1 Interrupt Flag Register

7	6	5	4	3	2	1	0
Unused				UCB1TXIFG	UCB1RXIFG	UCA1TXIFG	UCA1RXIFG
rw-0	rw-0	rw-0	rw-0	rw-1	rw-0	rw-1	rw-0

Unused	Bits 7-4	Unused
UCB1TXIFG	Bit 3	USCI_B1 transmit interrupt flag. UCB1TXIFG is set when UCB1TXBUF is empty.
		0 No interrupt pending
		1 Interrupt pending
UCB1RXIFG	Bit 2	USCI_B1 receive interrupt flag. UCB1RXIFG is set when UCB1RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending
UCA1TXIFG	Bit 1	USCI_A1 transmit interrupt flag. UCA1TXIFG is set when UCA1TXBUF empty.
		0 No interrupt pending
		1 Interrupt pending
UCA1RXIFG	Bit 0	USCI_A1 receive interrupt flag. UCA1RXIFG is set when UCA1RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending

Universal Serial Communication Interface, I²C Mode

The universal serial communication interface (USCI) supports multiple serial communication modes with one hardware module. This chapter discusses the operation of the I²C mode.

Topic **Page**

17.1 USCI Overview

The universal serial communication interface (USCI) modules support multiple serial communication modes. Different USCI modules support different modes. Each different USCI module is named with a different letter. For example, USCI_A is different from USCI_B, etc. If more than one identical USCI module is implemented on one device, those modules are named with incrementing numbers. For example, if one device has two USCI_A modules, they are named USCI_A0 and USCI_A1. See the device-specific data sheet to determine which USCI modules, if any, are implemented on which devices.

The USCI_Ax modules support:

- UART mode
- Pulse shaping for IrDA communications
- Automatic baud rate detection for LIN communications
- SPI mode

The USCI_Bx modules support:

- I^2C mode
- SPI mode

17.2 USCI Introduction: I^2C Mode

In I^2C mode, the USCI module provides an interface between the MSP430 and I^2C-compatible devices connected by way of the two-wire I^2C serial bus. External components attached to the I^2C bus serially transmit and/or receive serial data to/from the USCI module through the 2-wire I^2C interface.

The I^2C mode features include:

- Compliance to the Philips Semiconductor I^2C specification v2.1
  - 7-bit and 10-bit device addressing modes
  - General call
  - START/RESTART/STOP
  - Multi-master transmitter/receiver mode
  - Slave receiver/transmitter mode
  - Standard mode up to 100 kbps and fast mode up to 400 kbps support
- Programmable UCxCLK frequency in master mode
- Designed for low power
- Slave receiver START detection for auto-wake up from LPMx modes
- Slave operation in LPM4

Figure 17-1 shows the USCI when configured in I^2C mode.

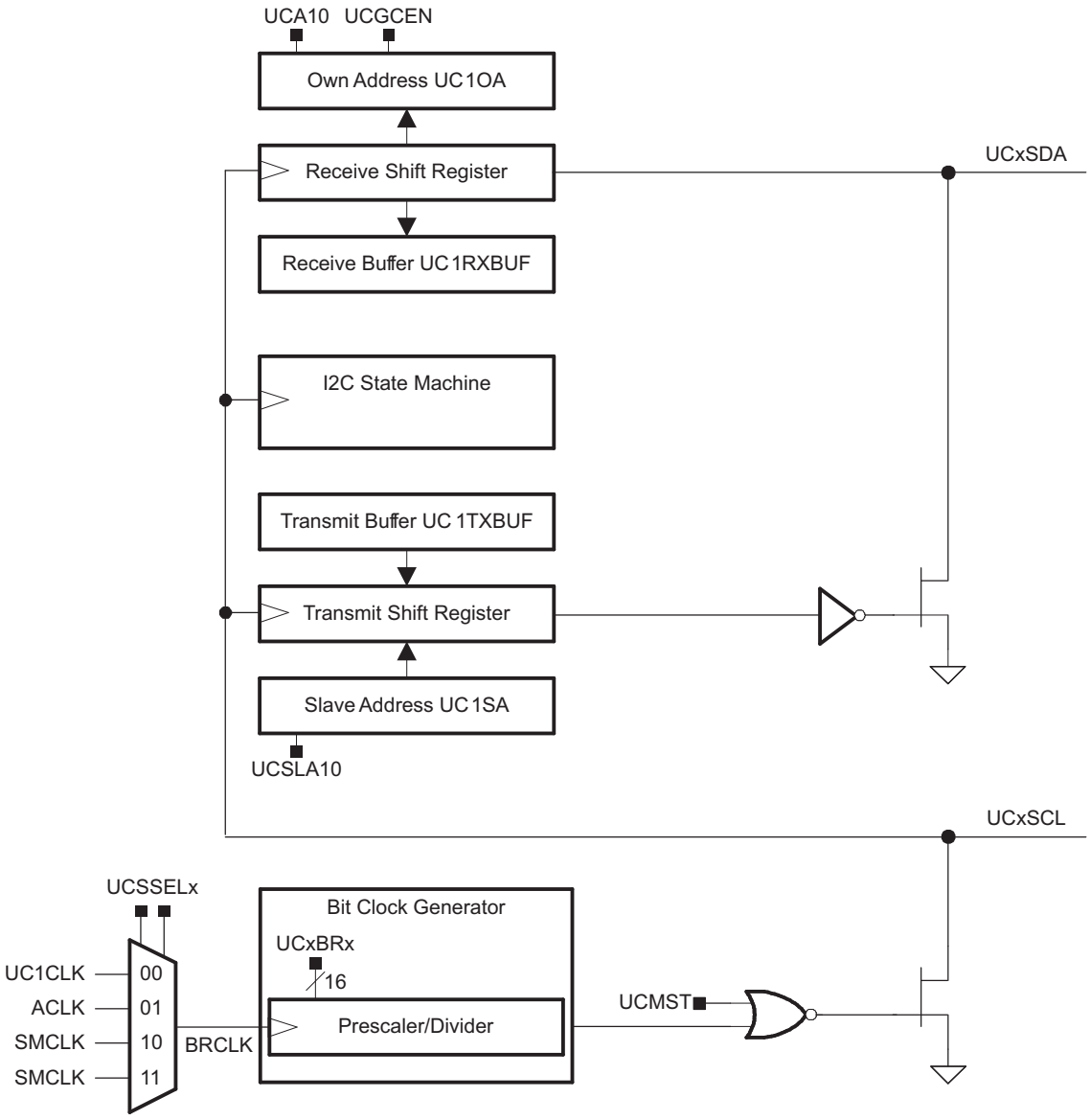


Figure 17-1. USCI Block Diagram: I²C Mode

17.3 USCI Operation: I²C Mode

The I²C mode supports any slave or master I²C-compatible device. Figure 17-2 shows an example of an I²C bus. Each I²C device is recognized by a unique address and can operate as either a transmitter or a receiver. A device connected to the I²C bus can be considered as the master or the slave when performing data transfers. A master initiates a data transfer and generates the clock signal SCL. Any device addressed by a master is considered a slave.

I²C data is communicated using the serial data pin (SDA) and the serial clock pin (SCL). Both SDA and SCL are bidirectional, and must be connected to a positive supply voltage using a pullup resistor.

NOTE: SDA and SCL Levels

The MSP430 SDA and SCL pins must not be pulled up above the MSP430 V_{CC} level.

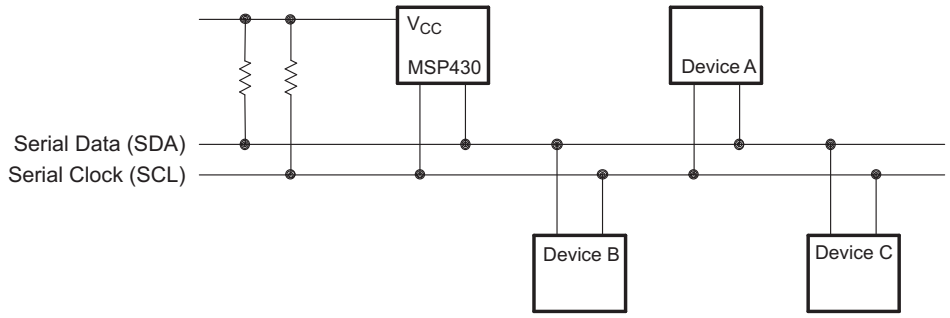


Figure 17-2. I²C Bus Connection Diagram

17.3.1 USCI Initialization and Reset

The USCI is reset by a PUC or by setting the UCSWRST bit. After a PUC, the UCSWRST bit is automatically set, keeping the USCI in a reset condition. To select I²C operation the UCMODEx bits must be set to 11. After module initialization, it is ready for transmit or receive operation. Clearing UCSWRST releases the USCI for operation.

Configuring and reconfiguring the USCI module should be done when UCSWRST is set to avoid unpredictable behavior. Setting UCSWRST in I²C mode has the following effects:

- I²C communication stops
- SDA and SCL are high impedance
- UCBxI2CSTAT, bits 6-0 are cleared
- UCBxTXIE and UCBxRXIE are cleared
- UCBxTXIFG and UCBxRXIFG are cleared
- All other bits and registers remain unchanged.

NOTE: Initializing or Reconfiguring the USCI Module

The recommended USCI initialization or reconfiguration process is:

1. Set UCSWRST (BIS.B #UCSWRST,&UCxCTL1)
2. Initialize all USCI registers with UCSWRST=1 (including UCxCTL1)
3. Configure ports.
4. Clear UCSWRST via software (BIC.B #UCSWRST,&UCxCTL1)
5. Enable interrupts (optional) via UCxRXIE and/or UCxTXIE

17.3.2 I²C Serial Data

One clock pulse is generated by the master device for each data bit transferred. The I²C mode operates with byte data. Data is transferred most significant bit first as shown in Figure 17-3.

The first byte after a START condition consists of a 7-bit slave address and the R/W bit. When R/W = 0, the master transmits data to a slave. When R/W = 1, the master receives data from a slave. The ACK bit is sent from the receiver after each byte on the 9th SCL clock.

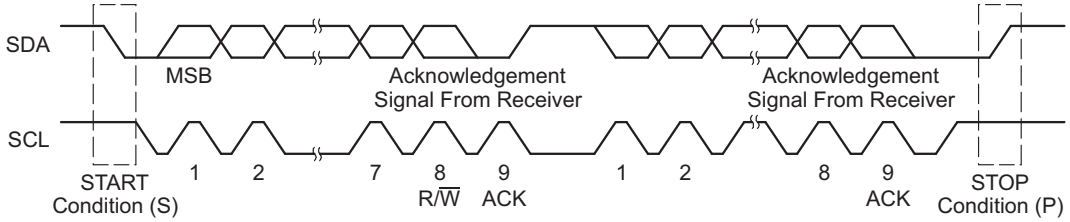


Figure 17-3. I²C Module Data Transfer

START and STOP conditions are generated by the master and are shown in Figure 17-3. A START condition is a high-to-low transition on the SDA line while SCL is high. A STOP condition is a low-to-high transition on the SDA line while SCL is high. The bus busy bit, UCBBUSY, is set after a START and cleared after a STOP.

Data on SDA must be stable during the high period of SCL as shown in Figure 17-4. The high and low state of SDA can only change when SCL is low, otherwise START or STOP conditions will be generated.

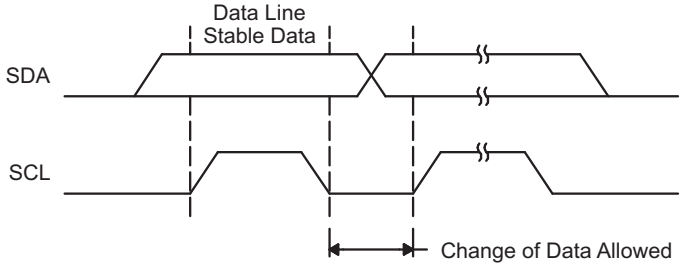


Figure 17-4. Bit Transfer on the I²C Bus

17.3.3 I²C Addressing Modes

The I²C mode supports 7-bit and 10-bit addressing modes.

17.3.3.1 7-Bit Addressing

In the 7-bit addressing format, shown in Figure 17-5, the first byte is the 7-bit slave address and the R/W bit. The ACK bit is sent from the receiver after each byte.

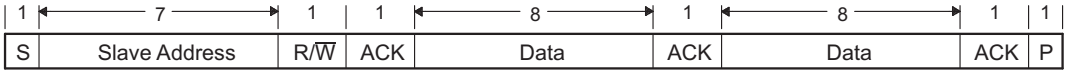


Figure 17-5. I²C Module 7-Bit Addressing Format

17.3.3.2 10-Bit Addressing

In the 10-bit addressing format, shown in Figure 17-6, the first byte is made up of 11110b plus the two MSBs of the 10-bit slave address and the R/W bit. The ACK bit is sent from the receiver after each byte. The next byte is the remaining 8 bits of the 10-bit slave address, followed by the ACK bit and the 8-bit data.

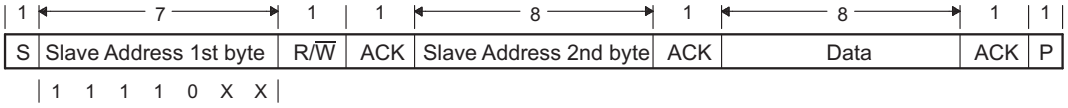


Figure 17-6. I²C Module 10-Bit Addressing Format

17.3.3.3 Repeated Start Conditions

The direction of data flow on SDA can be changed by the master, without first stopping a transfer, by issuing a repeated START condition. This is called a RESTART. After a RESTART is issued, the slave address is again sent out with the new data direction specified by the R/W bit. The RESTART condition is shown in Figure 17-7.

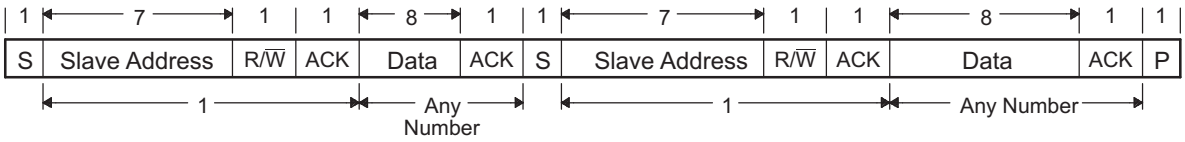


Figure 17-7. I²C Module Addressing Format with Repeated START Condition

17.3.4 I²C Module Operating Modes

In I²C mode the USCI module can operate in master transmitter, master receiver, slave transmitter, or slave receiver mode. The modes are discussed in the following sections. Time lines are used to illustrate the modes.

Figure 17-8 shows how to interpret the time line figures. Data transmitted by the master is represented by grey rectangles, data transmitted by the slave by white rectangles. Data transmitted by the USCI module, either as master or slave, is shown by rectangles that are taller than the others.

Actions taken by the USCI module are shown in grey rectangles with an arrow indicating where in the data stream the action occurs. Actions that must be handled with software are indicated with white rectangles with an arrow pointing to where in the data stream the action must take place.

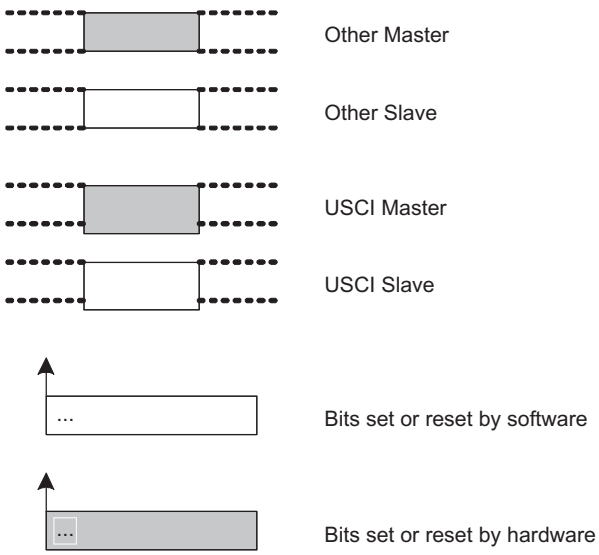


Figure 17-8. I²C Time Line Legend

17.3.4.1 Slave Mode

The USCI module is configured as an I²C slave by selecting the I²C mode with UCMODEx = 11 and UCSYNC = 1 and clearing the UCMST bit.

Initially the USCI module must to be configured in receiver mode by clearing the UCTR bit to receive the I²C address. Afterwards, transmit and receive operations are controlled automatically depending on the R/W bit received together with the slave address.

The USCI slave address is programmed with the UCBxI2COA register. When UCA10 = 0, 7-bit addressing is selected. When UCA10 = 1, 10-bit addressing is selected. The UCGCEN bit selects if the slave responds to a general call.

When a START condition is detected on the bus, the USCI module will receive the transmitted address and compare it against its own address stored in UCBxI2COA. The UCSTTIFG flag is set when address received matches the USCI slave address.

17.3.4.1.1 I²C Slave Transmitter Mode

Slave transmitter mode is entered when the slave address transmitted by the master is identical to its own address with a set R/W bit. The slave transmitter shifts the serial data out on SDA with the clock pulses that are generated by the master device. The slave device does not generate the clock, but it will hold SCL low while intervention of the CPU is required after a byte has been transmitted.

If the master requests data from the slave the USCI module is automatically configured as a transmitter and UCTR and UCBxTXIFG become set. The SCL line is held low until the first data to be sent is written into the transmit buffer UCBxTXBUF. Then the address is acknowledged, the UCSTTIFG flag is cleared, and the data is transmitted. As soon as the data is transferred into the shift register the UCBxTXIFG is set again. After the data is acknowledged by the master the next data byte written into UCBxTXBUF is transmitted or if the buffer is empty the bus is stalled during the acknowledge cycle by holding SCL low until new data is written into UCBxTXBUF. If the master sends a NACK succeeded by a STOP condition the UCSTPIFG flag is set. If the NACK is succeeded by a repeated START condition the USCI I²C state machine returns to its address-reception state.

Figure 17-9 shows the slave transmitter operation.

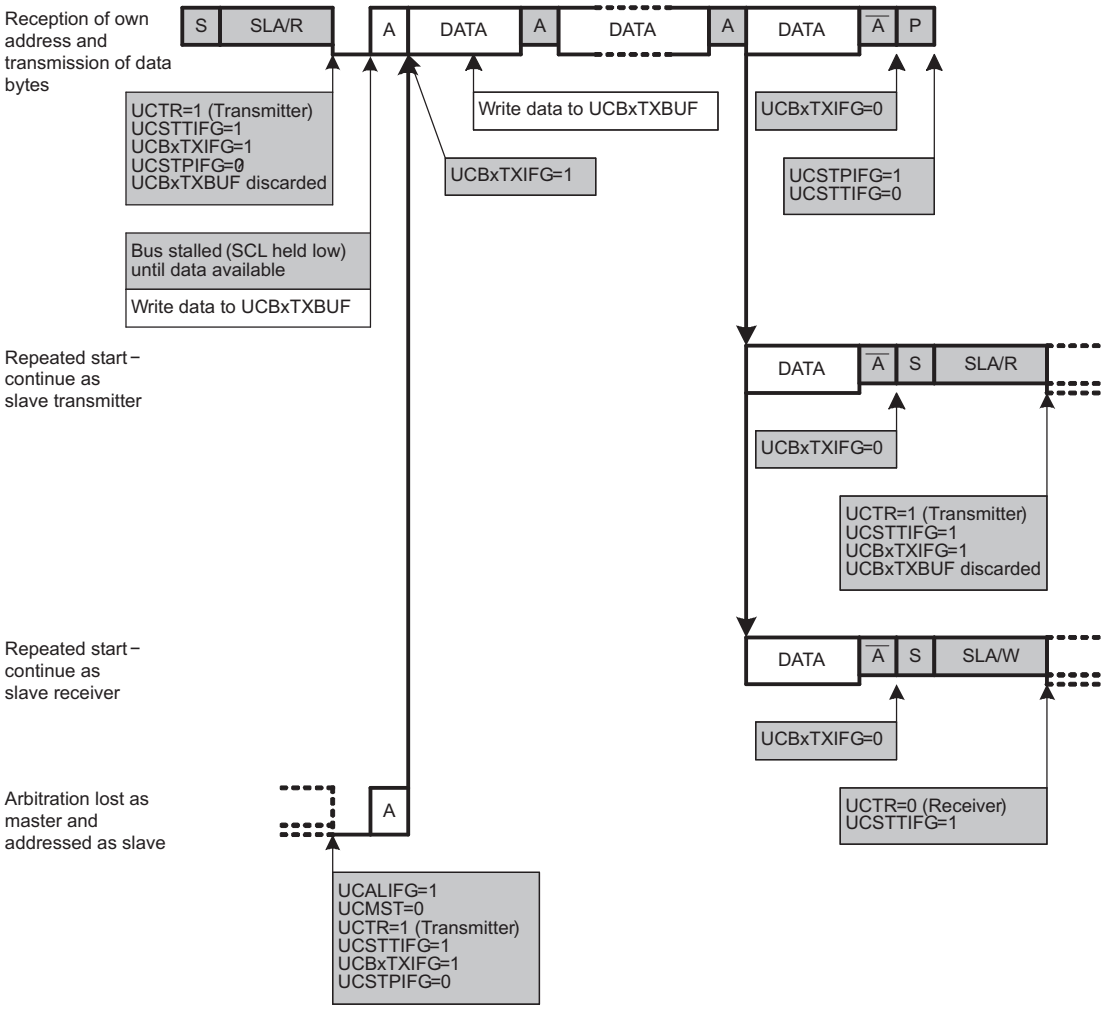


Figure 17-9. I²C Slave Transmitter Mode

17.3.4.1.2 I²C Slave Receiver Mode

Slave receiver mode is entered when the slave address transmitted by the master is identical to its own address and a cleared R/W bit is received. In slave receiver mode, serial data bits received on SDA are shifted in with the clock pulses that are generated by the master device. The slave device does not generate the clock, but it can hold SCL low if intervention of the CPU is required after a byte has been received.

If the slave should receive data from the master the USCI module is automatically configured as a receiver and UCTR is cleared. After the first data byte is received the receive interrupt flag UCBxRXIFG is set. The USCI module automatically acknowledges the received data and can receive the next data byte.

If the previous data was not read from the receive buffer UCBxRXBUF at the end of a reception, the bus is stalled by holding SCL low. As soon as UCBxRXBUF is read the new data is transferred into UCBxRXBUF, an acknowledge is sent to the master, and the next data can be received.

Setting the UCTXNACK bit causes a NACK to be transmitted to the master during the next acknowledgment cycle. A NACK is sent even if UCBxRXBUF is not ready to receive the latest data. If the UCTXNACK bit is set while SCL is held low the bus will be released, a NACK is transmitted immediately, and UCBxRXBUF is loaded with the last received data. Since the previous data was not read that data will be lost. To avoid loss of data the UCBxRXBUF needs to be read before UCTXNACK is set**.**

When the master generates a STOP condition the UCSTPIFG flag is set.

If the master generates a repeated START condition the USCI I²C state machine returns to its address reception state.

Figure 17-10 shows the I²C slave receiver operation.

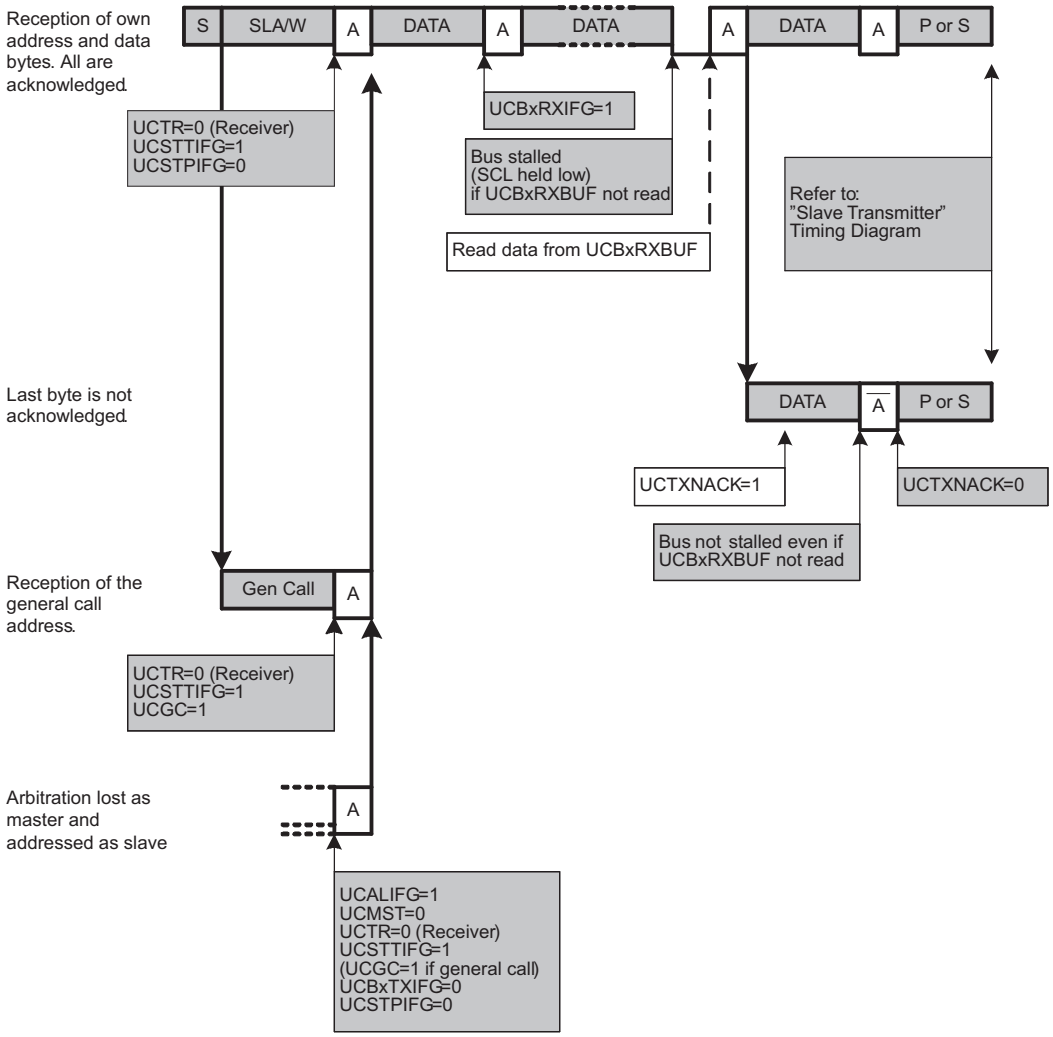


Figure 17-10. I²C Slave Receiver Mode

17.3.4.1.3 I²C Slave 10-bit Addressing Mode

The 10-bit addressing mode is selected when UCA10 = 1 and is as shown in Figure 17-11. In 10-bit addressing mode, the slave is in receive mode after the full address is received. The USCI module indicates this by setting the UCSTTIFG flag while the UCTR bit is cleared. To switch the slave into transmitter mode the master sends a repeated START condition together with the first byte of the address but with the R/W bit set. This will set the UCSTTIFG flag if it was previously cleared by software and the USCI modules switches to transmitter mode with UCTR = 1.

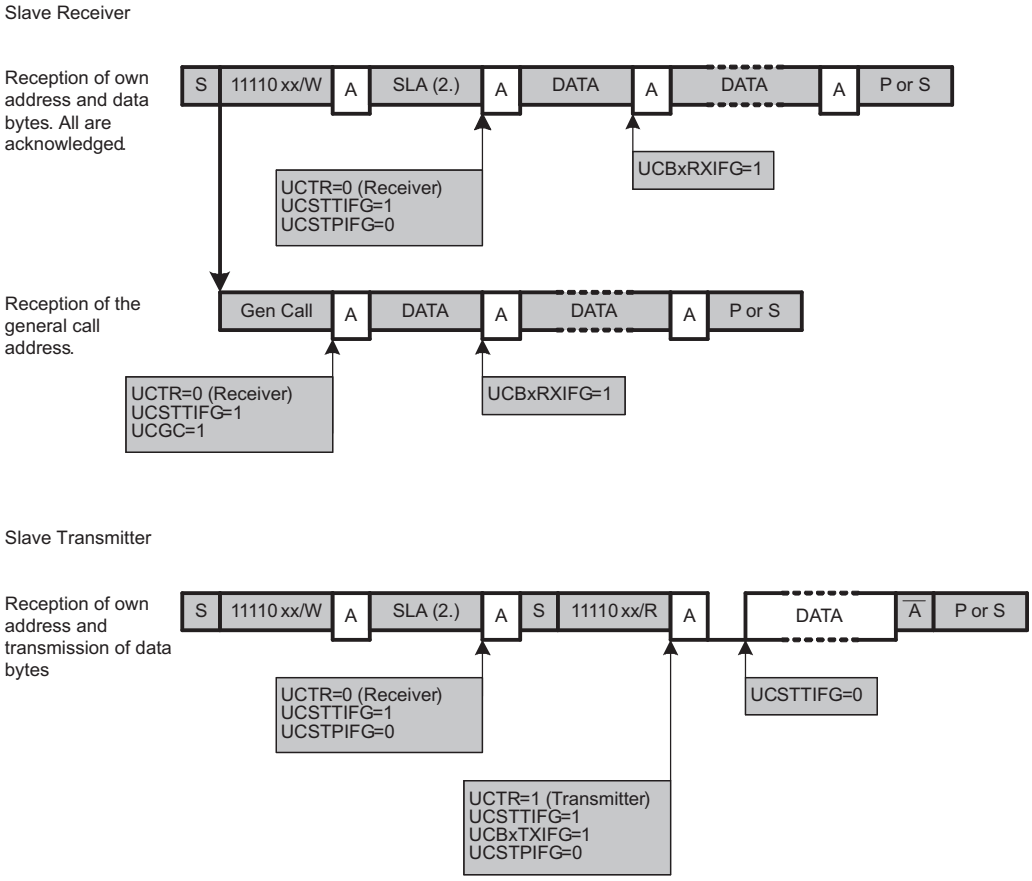


Figure 17-11. I²C Slave 10-bit Addressing Mode

17.3.4.2 Master Mode

The USCI module is configured as an I²C master by selecting the I²C mode with UCMODEx = 11 and UCSYNC = 1 and setting the UCMST bit. When the master is part of a multi-master system, UCMM must be set and its own address must be programmed into the UCBxI2COA register. When UCA10 = 0, 7-bit addressing is selected. When UCA10 = 1, 10-bit addressing is selected. The UCGCEN bit selects if the USCI module responds to a general call.

17.3.4.2.1 I²C Master Transmitter Mode

After initialization, master transmitter mode is initiated by writing the desired slave address to the UCBxI2CSA register, selecting the size of the slave address with the UCSLA10 bit, setting UCTR for transmitter mode, and setting UCTXSTT to generate a START condition.

The USCI module checks if the bus is available, generates the START condition, and transmits the slave address. The UCBxTXIFG bit is set when the START condition is generated and the first data to be transmitted can be written into UCBxTXBUF. As soon as the slave acknowledges the address the UCTXSTT bit is cleared.

The data written into UCBxTXBUF is transmitted if arbitration is not lost during transmission of the slave address. UCBxTXIFG is set again as soon as the data is transferred from the buffer into the shift register. If there is no data loaded to UCBxTXBUF before the acknowledge cycle, the bus is held during the acknowledge cycle with SCL low until data is written into UCBxTXBUF. Data is transmitted or the bus is held as long as the UCTXSTP bit or UCTXSTT bit is not set.

Setting UCTXSTP will generate a STOP condition after the next acknowledge from the slave. If UCTXSTP is set during the transmission of the slave's address or while the USCI module waits for data to be written into UCBxTXBUF, a STOP condition is generated even if no data was transmitted to the slave. When transmitting a single byte of data, the UCTXSTP bit must be set while the byte is being transmitted, or anytime after transmission begins, without writing new data into UCBxTXBUF. Otherwise, only the address will be transmitted. When the data is transferred from the buffer to the shift register, UCBxTXIFG will become set indicating data transmission has begun and the UCTXSTP bit may be set.

Setting UCTXSTT will generate a repeated START condition. In this case, UCTR may be set or cleared to configure transmitter or receiver, and a different slave address may be written into UCBxI2CSA if desired.

If the slave does not acknowledge the transmitted data the not-acknowledge interrupt flag UCNACKIFG is set. The master must react with either a STOP condition or a repeated START condition. If data was already written into UCBxTXBUF it will be discarded. If this data should be transmitted after a repeated START it must be written into UCBxTXBUF again. Any set UCTXSTT is discarded, too. To trigger a repeated start UCTXSTT needs to be set again.

Figure 17-12 shows the I²C master transmitter operation.

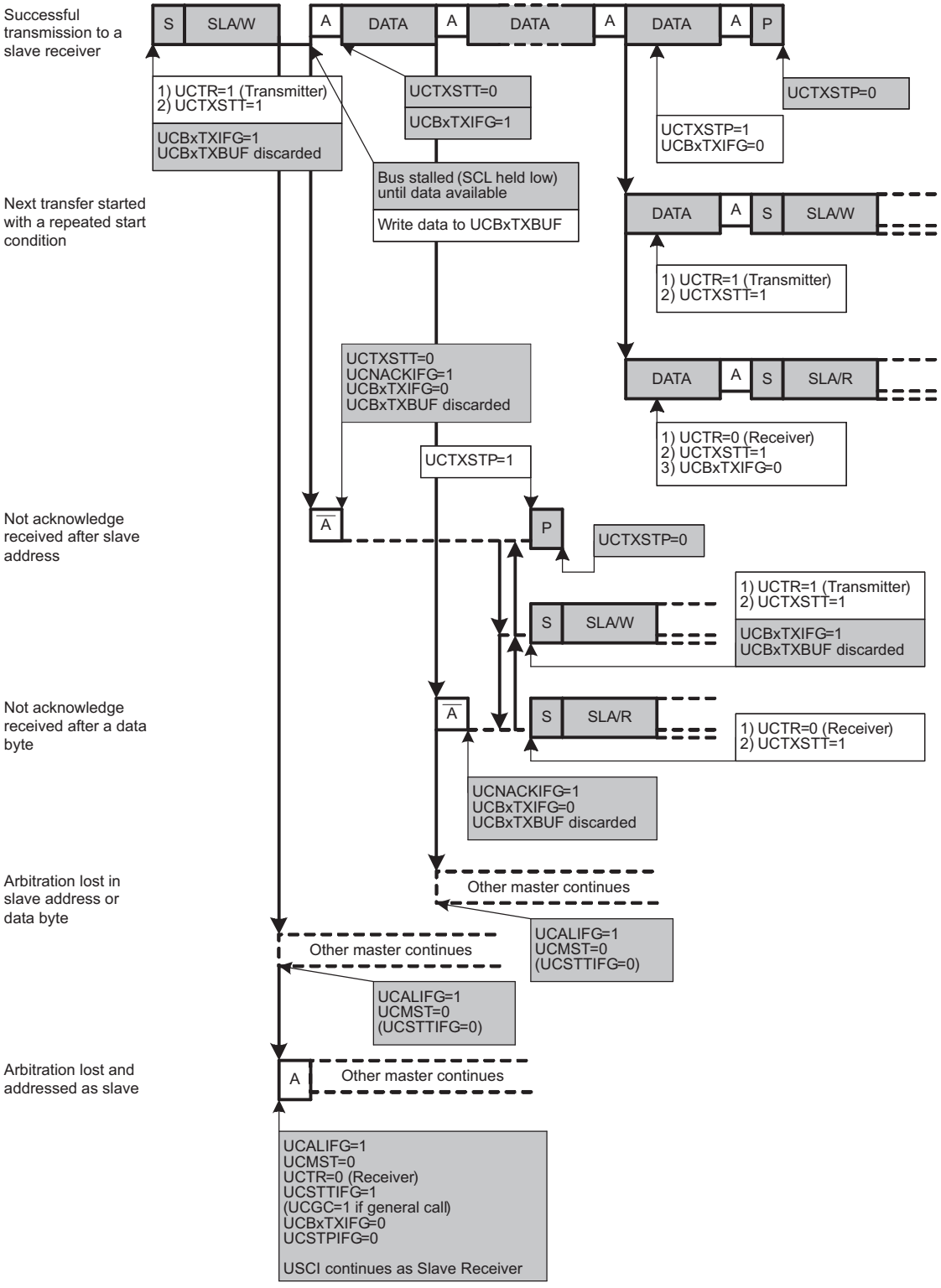


Figure 17-12. I²C Master Transmitter Mode

17.3.4.2.2 I²C Master Receiver Mode

After initialization, master receiver mode is initiated by writing the desired slave address to the UCBxI2CSA register, selecting the size of the slave address with the UCSLA10 bit, clearing UCTR for receiver mode, and setting UCTXSTT to generate a START condition.

The USCI module checks if the bus is available, generates the START condition, and transmits the slave address. As soon as the slave acknowledges the address the UCTXSTT bit is cleared.

After the acknowledge of the address from the slave the first data byte from the slave is received and acknowledged and the UCBxRXIFG flag is set. Data is received from the slave ss long as UCTXSTP or UCTXSTT is not set. If UCBxRXBUF is not read the master holds the bus during reception of the last data bit and until the UCBxRXBUF is read.

If the slave does not acknowledge the transmitted address the not-acknowledge interrupt flag UCNACKIFG is set. The master must react with either a STOP condition or a repeated START condition.

Setting the UCTXSTP bit will generate a STOP condition. After setting UCTXSTP, a NACK followed by a STOP condition is generated after reception of the data from the slave, or immediately if the USCI module is currently waiting for UCBxRXBUF to be read.

If a master wants to receive a single byte only, the UCTXSTP bit must be set while the byte is being received. For this case, the UCTXSTT may be polled to determine when it is cleared:

```
          BIS.B   #UCTXSTT,&UCB0CTL1   ;Transmit START cond.
POLL_STT  BIT.B   #UCTXSTT,&UCB0CTL1   ;Poll UCTXSTT bit
          JC      POLL_STT             ;When cleared,
          BIS.B   #UCTXSTP,&UCB0CTL1   ;transmit STOP cond.
```

Setting UCTXSTT will generate a repeated START condition. In this case, UCTR may be set or cleared to configure transmitter or receiver, and a different slave address may be written into UCBxI2CSA if desired.

Figure 17-13 shows the I²C master receiver operation.

NOTE: Consecutive Master Transactions Without Repeated Start

When performing multiple consecutive I²C master transactions without the repeated start feature, the current transaction must be completed before the next one is initiated. This can be done by ensuring that the transmit stop condition flag UCTXSTP is cleared before the next I²C transaction is initiated with setting UCTXSTT = 1. Otherwise, the current transaction might be affected.

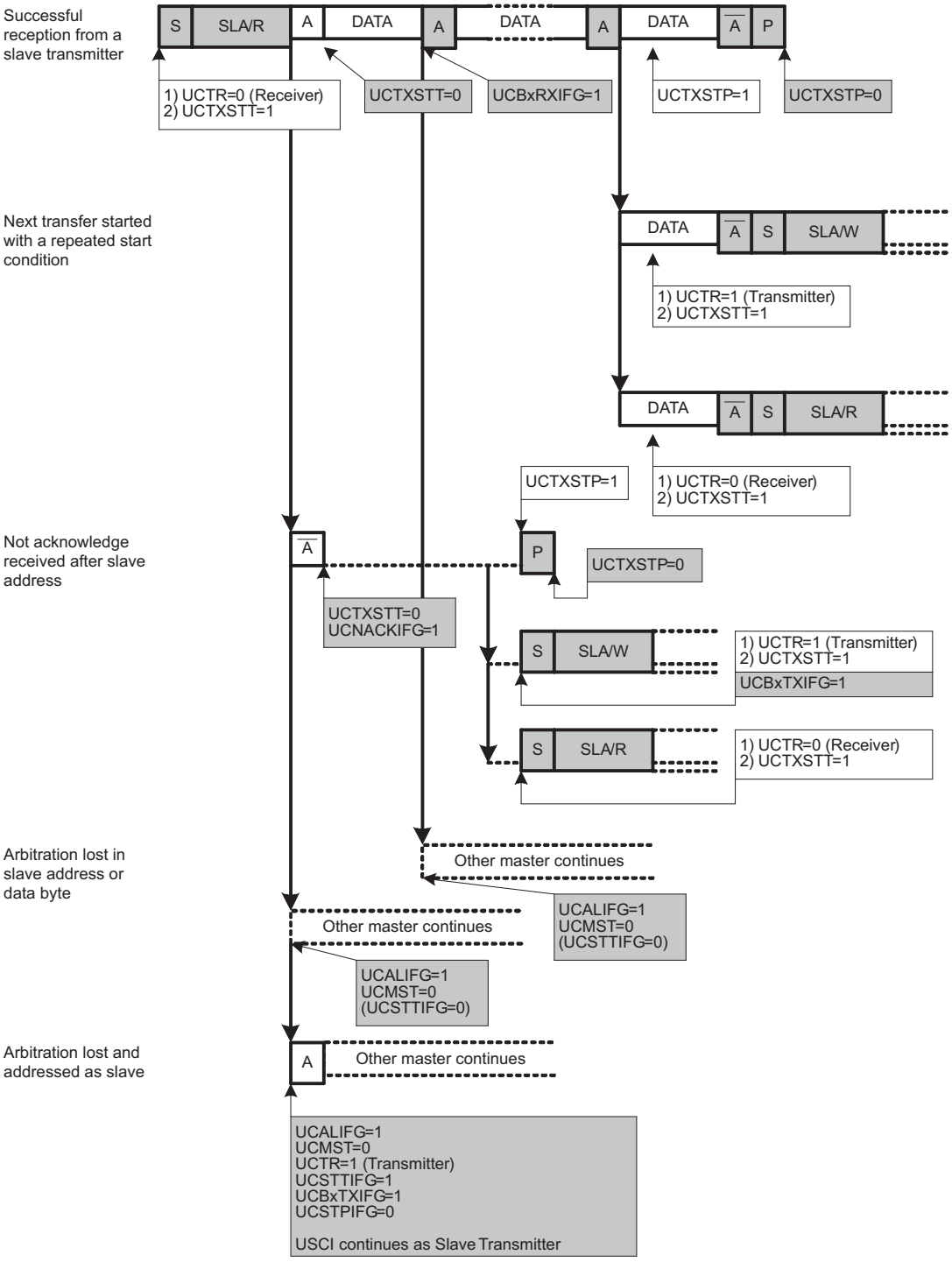


Figure 17-13. I²C Master Receiver Mode

17.3.4.2.3 I²C Master 10-Bit Addressing Mode

The 10-bit addressing mode is selected when UCSLA10 = 1 and is shown in Figure 17-14.

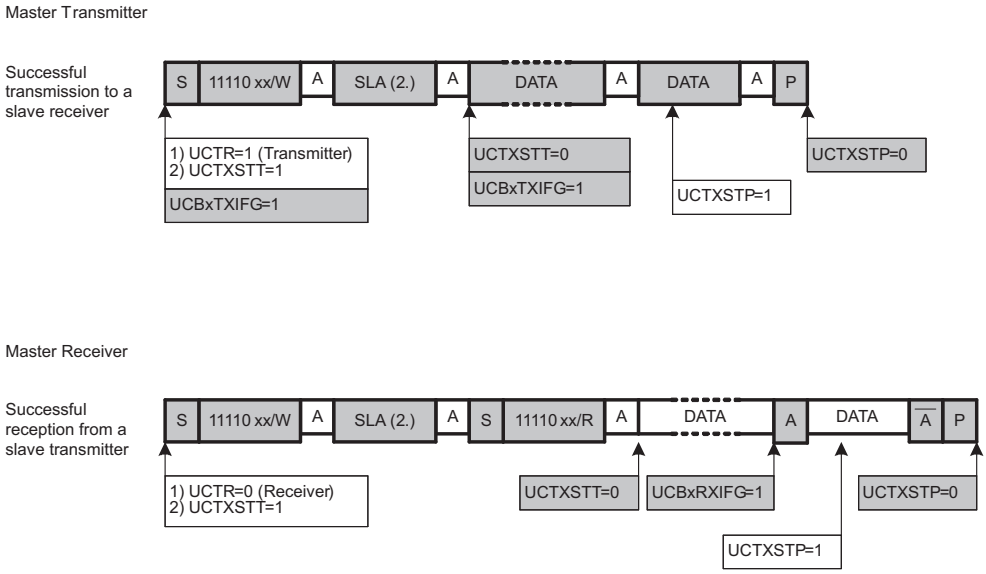


Figure 17-14. I²C Master 10-bit Addressing Mode

17.3.4.2.4 Arbitration

If two or more master transmitters simultaneously start a transmission on the bus, an arbitration procedure is invoked. Figure 17-15 shows the arbitration procedure between two devices. The arbitration procedure uses the data presented on SDA by the competing transmitters. The first master transmitter that generates a logic high is overruled by the opposing master generating a logic low. The arbitration procedure gives priority to the device that transmits the serial data stream with the lowest binary value. The master transmitter that lost arbitration switches to the slave receiver mode, and sets the arbitration lost flag UCALIFG. If two or more devices send identical first bytes, arbitration continues on the subsequent bytes.

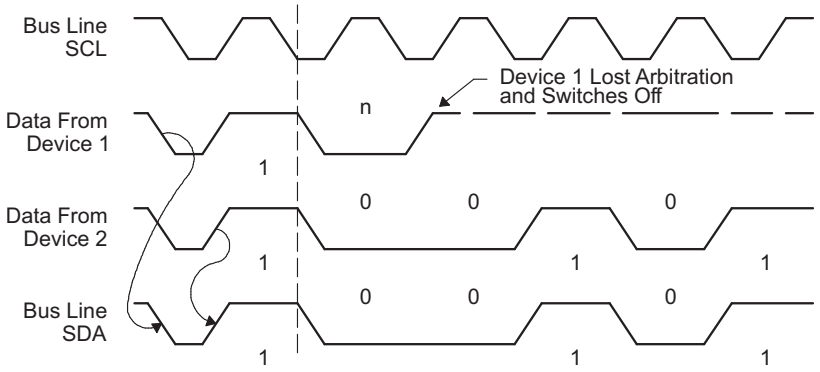


Figure 17-15. Arbitration Procedure Between Two Master Transmitters

If the arbitration procedure is in progress when a repeated START condition or STOP condition is transmitted on SDA, the master transmitters involved in arbitration must send the repeated START condition or STOP condition at the same position in the format frame. Arbitration is not allowed between:

- A repeated START condition and a data bit
- A STOP condition and a data bit
- A repeated START condition and a STOP condition

17.3.5 I²C Clock Generation and Synchronization

The I²C clock SCL is provided by the master on the I²C bus. When the USCI is in master mode, BITCLK is provided by the USCI bit clock generator and the clock source is selected with the UCSSELx bits. In slave mode the bit clock generator is not used and the UCSSELx bits are don't care.

The 16-bit value of UCBRx in registers UCBxBR1 and UCBxBR0 is the division factor of the USCI clock source, BRCLK. The maximum bit clock that can be used in single master mode is $f_{BRCLK}/4$. In multi-master mode the maximum bit clock is $f_{BRCLK}/8$. The BITCLK frequency is given by:

$$f_{BitClock} = \frac{f_{BRCLK}}{UCBRx}$$

The minimum high and low periods of the generated SCL are

$$t_{LOW,MIN} = t_{HIGH,MIN} = \frac{UCBRx / 2}{f_{BRCLK}}$$ when UCBRx is even and

$$t_{LOW,MIN} = t_{HIGH,MIN} = \frac{(UCBRx - 1) / 2}{f_{BRCLK}}$$ when UCBRx is odd.

The USCI clock source frequency and the prescaler setting UCBRx must to be chosen such that the minimum low and high period times of the I²C specification are met.

During the arbitration procedure the clocks from the different masters must be synchronized. A device that first generates a low period on SCL overrules the other devices forcing them to start their own low periods. SCL is then held low by the device with the longest low period. The other devices must wait for SCL to be released before starting their high periods. Figure 17-16 shows the clock synchronization. This allows a slow slave to slow down a fast master.

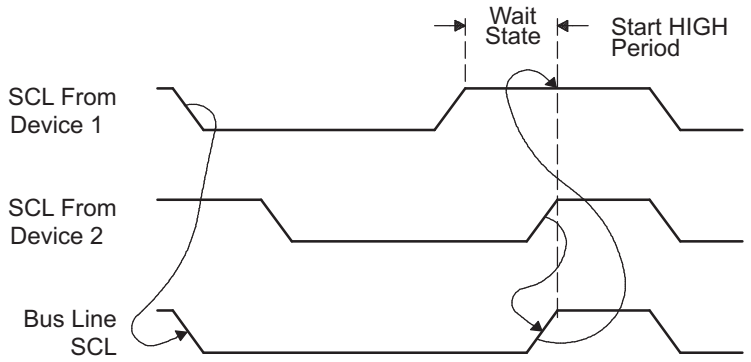


Figure 17-16. Synchronization of Two I²C Clock Generators During Arbitration

17.3.5.1 Clock Stretching

The USCI module supports clock stretching and also makes use of this feature as described in the operation mode sections.

The UCSCLLOW bit can be used to observe if another device pulls SCL low while the USCI module already released SCL due to the following conditions:

- USCI is acting as master and a connected slave drives SCL low.
- USCI is acting as master and another master drives SCL low during arbitration.

The UCSCLLOW bit is also active if the USCI holds SCL low because it is waiting as transmitter for data being written into UCBxTXBUF or as receiver for the data being read from UCBxRXBUF.

The UCSCLLOW bit might get set for a short time with each rising SCL edge because the logic observes the external SCL and compares it to the internally generated SCL.

17.3.6 Using the USCI Module in I²C Mode with Low-Power Modes

The USCI module provides automatic clock activation for SMCLK for use with low-power modes. When SMCLK is the USCI clock source, and is inactive because the device is in a low-power mode, the USCI module automatically activates it when needed, regardless of the control-bit settings for the clock source. The clock remains active until the USCI module returns to its idle condition. After the USCI module returns to the idle condition, control of the clock source reverts to the settings of its control bits. Automatic clock activation is not provided for ACLK.

When the USCI module activates an inactive clock source, the clock source becomes active for the whole device and any peripheral configured to use the clock source may be affected. For example, a timer using SMCLK will increment while the USCI module forces SMCLK active.

In I²C slave mode no internal clock source is required because the clock is provided by the external master. It is possible to operate the USCI in I²C slave mode while the device is in LPM4 and all internal clock sources are disabled. The receive or transmit interrupts can wake up the CPU from any low power mode.

17.3.7 USCI Interrupts in I²C Mode

There are two interrupt vectors for the USCI module in I²C mode. One interrupt vector is associated with the transmit and receive interrupt flags. The other interrupt vector is associated with the four state change interrupt flags. Each interrupt flag has its own interrupt enable bit. When an interrupt is enabled, and the GIE bit is set, the interrupt flag will generate an interrupt request. DMA transfers are controlled by the UCBxTXIFG and UCBxRXIFG flags on devices with a DMA controller.

17.3.7.1 I²C Transmit Interrupt Operation

The UCBxTXIFG interrupt flag is set by the transmitter to indicate that UCBxTXBUF is ready to accept another character. An interrupt request is generated if UCBxTXIE and GIE are also set. UCBxTXIFG is automatically reset if a character is written to UCBxTXBUF or if a NACK is received. UCBxTXIFG is set when UCSWRST = 1 and the I²C mode is selected. UCBxTXIE is reset after a PUC or when UCSWRST = 1.

17.3.7.2 I²C Receive Interrupt Operation

The UCBxRXIFG interrupt flag is set when a character is received and loaded into UCBxRXBUF. An interrupt request is generated if UCBxRXIE and GIE are also set. UCBxRXIFG and UCBxRXIE are reset after a PUC signal or when UCSWRST = 1. UCxRXIFG is automatically reset when UCxRXBUF is read.

17.3.7.3 I²C State Change Interrupt Operation

Table 17-1 describes the I²C state change interrupt flags.

Table 17-1. State Change Interrupt Flags

Interrupt Flag	Interrupt Condition
UCALIFG	Arbitration-lost. Arbitration can be lost when two or more transmitters start a transmission simultaneously, or when the USCI operates as master but is addressed as a slave by another master in the system. The UCALIFG flag is set when arbitration is lost. When UCALIFG is set the UCMST bit is cleared and the I²C controller becomes a slave.
UCNACKIFG	Not-acknowledge interrupt. This flag is set when an acknowledge is expected but is not received. UCNACKIFG is automatically cleared when a START condition is received.
UCSTTIFG	Start condition detected interrupt. This flag is set when the I²C module detects a START condition together with its own address while in slave mode. UCSTTIFG is used in slave mode only and is automatically cleared when a STOP condition is received.
UCSTPIFG	Stop condition detected interrupt. This flag is set when the I²C module detects a STOP condition while in slave mode. UCSTPIFG is used in slave mode only and is automatically cleared when a START condition is received.

17.3.7.4 Interrupt Vector Assignment

USCI_Ax and USCI_Bx share the same interrupt vectors. In I²C mode the state change interrupt flags UCSTTIFG, UCSTPIFG, UCNACKIFG, UCALIFG from USCI_Bx and UCAxRXIFG from USCI_Ax are routed to one interrupt vector. The I²C transmit and receive interrupt flags UCBxTXIFG and UCBxRXIFG from USCI_Bx and UCAxTXIFG from USCI_Ax share another interrupt vector.

Example 17-1 shows an extract of the interrupt service routine to handle data receive interrupts from USCI_A0 in either UART or SPI mode and state change interrupts from USCI_B0 in I²C mode.

Example 17-1. Shared Receive Interrupt Vectors Software Example

```
USCIA0_RX_USCIB0_I2C_STATE_ISR
   BIT.B   #UCA0RXIFG, &IFG2  ; USCI_A0 Receive Interrupt?
   JNZ     USCIA0_RX_ISR
USCIB0_I2C_STATE_ISR
   ; Decode I2C state changes ...
   ; Decode I2C state changes ...
   ...
   RETI
USCIA0_RX_ISR
   ; Read UCA0RXBUF ... - clears UCA0RXIFG
   ...
   RETI
```

Example 17-2 shows an extract of the interrupt service routine that handles data transmit interrupts from USCI_A0 in either UART or SPI mode and the data transfer interrupts from USCI_B0 in I²C mode.

Example 17-2. Shared Transmit Interrupt Vectors Software Example

```
USCIA0_TX_USCIB0_I2C_DATA_ISR
   BIT.B   #UCA0TXIFG, &IFG2  ; USCI_A0 Transmit Interrupt?
   JNZ     USCIA0_TX_ISR
USCIB0_I2C_DATA_ISR
   BIT.B   #UCB0RXIFG, &IFG2
   JNZ     USCIB0_I2C_RX
USCIB0_I2C_TX
   ; Write UCB0TXBUF... - clears UCB0TXIFG
   ...
   RETI
USCIB0_I2C_RX
   ; Read UCB0RXBUF... - clears UCB0RXIFG
   ...
   RETI
USCIA0_TX_ISR
   ; Write UCA0TXBUF ... - clears UCA0TXIFG
   ...
   RETI
```

17.4 USCI Registers: I²C Mode

The USCI registers applicable in I²C mode for USCI_B0 are listed in Table 17-2, and for USCI_B1 in Table 17-3.

Table 17-2. USCI_B0 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USCI_B0 control register 0	UCB0CTL0	Read/write	068h	001h with PUC
USCI_B0 control register 1	UCB0CTL1	Read/write	069h	001h with PUC
USCI_B0 bit rate control register 0	UCB0BR0	Read/write	06Ah	Reset with PUC
USCI_B0 bit rate control register 1	UCB0BR1	Read/write	06Bh	Reset with PUC
USCI_B0 I²C interrupt enable register	UCB0I2CIE	Read/write	06Ch	Reset with PUC
USCI_B0 status register	UCB0STAT	Read/write	06Dh	Reset with PUC
USCI_B0 receive buffer register	UCB0RXBUF	Read	06Eh	Reset with PUC
USCI_B0 transmit buffer register	UCB0TXBUF	Read/write	06Fh	Reset with PUC
USCI_B0 I²C own address register	UCB0I2COA	Read/write	0118h	Reset with PUC
USCI_B0 I²C slave address register	UCB0I2CSA	Read/write	011Ah	Reset with PUC
SFR interrupt enable register 2	IE2	Read/write	001h	Reset with PUC
SFR interrupt flag register 2	IFG2	Read/write	003h	00Ah with PUC

NOTE: Modifying SFR bits

To avoid modifying control bits of other modules, it is recommended to set or clear the IEx and IFGx bits using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions.

Table 17-3. USCI_B1 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USCI_B1 control register 0	UCB1CTL0	Read/write	0D8h	Reset with PUC
USCI_B1 control register 1	UCB1CTL1	Read/write	0D9h	001h with PUC
USCI_B1 baud rate control register 0	UCB1BR0	Read/write	0DAh	Reset with PUC
USCI_B1 baud rate control register 1	UCB1BR1	Read/write	0DBh	Reset with PUC
USCI_B1 I²C interrupt enable register	UCB1I2CIE	Read/write	0DCh	Reset with PUC
USCI_B1 status register	UCB1STAT	Read/write	0DDh	Reset with PUC
USCI_B1 receive buffer register	UCB1RXBUF	Read	0DEh	Reset with PUC
USCI_B1 transmit buffer register	UCB1TXBUF	Read/write	0DFh	Reset with PUC
USCI_B1 I²C own address register	UCB1I2COA	Read/write	017Ch	Reset with PUC
USCI_B1 I²C slave address register	UCB1I2CSA	Read/write	017Eh	Reset with PUC
USCI_A1/B1 interrupt enable register	UC1IE	Read/write	006h	Reset with PUC
USCI_A1/B1 interrupt flag register	UC1IFG	Read/write	007h	00Ah with PUC

17.4.1 UCBxCTL0, USCI_Bx Control Register 0

7	6	5	4	3	2	1	0
UCA10	**UCSLA10**	**UCMM**	**Unused**	**UCMST**	**UCMODEx=11**		**UCSYNC=1**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	r-1

UCA10	Bit 7	Own addressing mode select	
		0	Own address is a 7-bit address
		1	Own address is a 10-bit address
UCSLA10	Bit 6	Slave addressing mode select	
		0	Address slave with 7-bit address
		1	Address slave with 10-bit address
UCMM	Bit 5	Multi-master environment select	
		0	Single master environment. There is no other master in the system. The address compare unit is disabled.
		1	Multi-master environment
Unused	Bit 4	Unused	
UCMST	Bit 3	Master mode select. When a master loses arbitration in a multi-master environment (UCMM = 1) the UCMST bit is automatically cleared and the module acts as slave.	
		0	Slave mode
		1	Master mode
UCMODEx	Bits 2-1	USCI Mode. The UCMODEx bits select the synchronous mode when UCSYNC = 1.	
		00	3-pin SPI
		01	4-pin SPI (master/slave enabled if STE = 1)
		10	4-pin SPI (master/slave enabled if STE = 0)
		11	I²C mode
UCSYNC	Bit 0	Synchronous mode enable	
		0	Asynchronous mode
		1	Synchronous mode

17.4.2 UCBxCTL1, USCI_Bx Control Register 1

7	6	5	4	3	2	1	0
UCSSELx		**Unused**	**UCTR**	**UCTXNACK**	**UCTXSTP**	**UCTXSTT**	**UCSWRST**
rw-0	rw-0	r0	rw-0	rw-0	rw-0	rw-0	rw-1

UCSSELx	Bits 7-6	USCI clock source select. These bits select the BRCLK source clock.	
		00	UCLKI
		01	ACLK
		10	SMCLK
		11	SMCLK
Unused	Bit 5	Unused	
UCTR	Bit 4	Transmitter/receiver	
		0	Receiver
		1	Transmitter
UCTXNACK	Bit 3	Transmit a NACK. UCTXNACK is automatically cleared after a NACK is transmitted.	
		0	Acknowledge normally
		1	Generate NACK
UCTXSTP	Bit 2	Transmit STOP condition in master mode. Ignored in slave mode. In master receiver mode the STOP condition is preceded by a NACK. UCTXSTP is automatically cleared after STOP is generated.	
		0	No STOP generated
		1	Generate STOP
UCTXSTT	Bit 1	Transmit START condition in master mode. Ignored in slave mode. In master receiver mode a repeated START condition is preceded by a NACK. UCTXSTT is automatically cleared after START condition and address information is transmitted. Ignored in slave mode.	
		0	Do not generate START condition
		1	Generate START condition
UCSWRST	Bit 0	Software reset enable	
		0	Disabled. USCI reset released for operation.
		1	Enabled. USCI logic held in reset state.

17.4.3 UCBxBR0, USCI_Bx Baud Rate Control Register 0

7	6	5	4	3	2	1	0
UCBRx - low byte							
rw	rw	rw	rw	rw	rw	rw	rw

17.4.4 UCBxBR1, USCI_Bx Baud Rate Control Register 1

7	6	5	4	3	2	1	0
UCBRx - high byte							
rw	rw	rw	rw	rw	rw	rw	rw

UCBRx	Bit clock prescaler setting. The 16-bit value of (UCBxBR0 + UCBxBR1 × 256) forms the prescaler value.

17.4.5 UCBxSTAT, USCI_Bx Status Register

7	6	5	4	3	2	1	0
Unused	**UCSCLLOW**	**UCGC**	**UCBBUSY**	**UCNACKIFG**	**UCSTPIFG**	**UCSTTIFG**	**UCALIFG**
rw-0	r-0	rw-0	r-0	rw-0	rw-0	rw-0	rw-0

Unused Bit 7 Unused.

UCSCLLOW Bit 6 SCL low
- 0 SCL is not held low
- 1 SCL is held low

UCGC Bit 5 General call address received. UCGC is automatically cleared when a START condition is received.
- 0 No general call address received
- 1 General call address received

UCBBUSY Bit 4 Bus busy
- 0 Bus inactive
- 1 Bus busy

UCNACKIFG Bit 3 Not-acknowledge received interrupt flag. UCNACKIFG is automatically cleared when a START condition is received.
- 0 No interrupt pending
- 1 Interrupt pending

UCSTPIFG Bit 2 Stop condition interrupt flag. UCSTPIFG is automatically cleared when a START condition is received.
- 0 No interrupt pending
- 1 Interrupt pending

UCSTTIFG Bit 1 Start condition interrupt flag. UCSTTIFG is automatically cleared if a STOP condition is received.
- 0 No interrupt pending
- 1 Interrupt pending

UCALIFG Bit 0 Arbitration lost interrupt flag
- 0 No interrupt pending
- 1 Interrupt pending

17.4.6 UCBxRXBUF, USCI_Bx Receive Buffer Register

7	6	5	4	3	2	1	0
UCRXBUFx							
r	r	r	r	r	r	r	r

UCRXBUFx Bits 7-0 The receive-data buffer is user accessible and contains the last received character from the receive shift register. Reading UCBxRXBUF resets UCBxRXIFG.

17.4.7 UCBxTXBUF, USCI_Bx Transmit Buffer Register

7	6	5	4	3	2	1	0
UCTXBUFx							
rw	rw	rw	rw	rw	rw	rw	rw

UCTXBUFx Bits 7-0 The transmit data buffer is user accessible and holds the data waiting to be moved into the transmit shift register and transmitted. Writing to the transmit data buffer clears UCBxTXIFG.

17.4.8 UCBxI2COA, USCIBx I²C Own Address Register

15	14	13	12	11	10	9	8
UCGCEN	**0**	**0**	**0**	**0**	**0**	**I2COAx**	
rw-0	r0	r0	r0	r0	r0	rw-0	rw-0
7	6	5	4	3	2	1	0
I2COAx							
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

UCGCEN	Bit 15	General call response enable 0 Do not respond to a general call 1 Respond to a general call
I2COAx	Bits 9-0	I²C own address. The I2COAx bits contain the local address of the USCI_Bx I²C controller. The address is right-justified. In 7-bit addressing mode, bit 6 is the MSB, and bits 9-7 are ignored. In 10-bit addressing mode, bit 9 is the MSB.

17.4.9 UCBxI2CSA, USCI_Bx I²C Slave Address Register

15	14	13	12	11	10	9	8
0	**0**	**0**	**0**	**0**	**0**	**I2CSAx**	
r0	r0	r0	r0	r0	r0	rw-0	rw-0
7	6	5	4	3	2	1	0
I2CSAx							
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

I2CSAx	Bits 9-0	I²C slave address. The I2CSAx bits contain the slave address of the external device to be addressed by the USCI_Bx module. It is only used in master mode. The address is right-justified. In 7-bit slave addressing mode, bit 6 is the MSB, and bits 9-7 are ignored. In 10-bit slave addressing mode, bit 9 is the MSB.

17.4.10 UCBxI2CIE, USCI_Bx I²C Interrupt Enable Register

7	6	5	4	3	2	1	0
Reserved				**UCNACKIE**	**UCSTPIE**	**UCSTTIE**	**UCALIE**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

Reserved	Bits 7-4	Reserved
UCNACKIE	Bit 3	Not-acknowledge interrupt enable 0 Interrupt disabled 1 Interrupt enabled
UCSTPIE	Bit 2	Stop condition interrupt enable 0 Interrupt disabled 1 Interrupt enabled
UCSTTIE	Bit 1	Start condition interrupt enable 0 Interrupt disabled 1 Interrupt enabled
UCALIE	Bit 0	Arbitration lost interrupt enable 0 Interrupt disabled 1 Interrupt enabled

17.4.11 IE2, Interrupt Enable Register 2

7	6	5	4	3	2	1	0
				UCB0TXIE	**UCB0RXIE**		
				rw-0	rw-0		

	Bits 7-4	These bits may be used by other modules (see the device-specific data sheet).
UCB0TXIE	Bit 3	USCI_B0 transmit interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCB0RXIE	Bit 2	USCI_B0 receive interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
	Bits 1-0	These bits may be used by other modules (see the device-specific data sheet).

17.4.12 IFG2, Interrupt Flag Register 2

7	6	5	4	3	2	1	0
				UCB0TXIFG	**UCB0RXIFG**		
				rw-1	rw-0		

	Bits 7-4	These bits may be used by other modules (see the device-specific data sheet).
UCB0TXIFG	Bit 3	USCI_B0 transmit interrupt flag. UCB0TXIFG is set when UCB0TXBUF is empty.
		0 No interrupt pending
		1 Interrupt pending
UCB0RXIFG	Bit 2	USCI_B0 receive interrupt flag. UCB0RXIFG is set when UCB0RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending
	Bits 1-0	These bits may be used by other modules (see the device-specific data sheet).

17.4.13 UC1IE, USCI_B1 Interrupt Enable Register

7	6	5	4	3	2	1	0
Unused				**UCB1TXIE**	**UCB1RXIE**		
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0		

Unused	Bits 7-4	Unused
UCB1TXIE	Bit 3	USCI_B1 transmit interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
UCB1RXIE	Bit 2	USCI_B1 receive interrupt enable
		0 Interrupt disabled
		1 Interrupt enabled
	Bits 1-0	These bits may be used by other USCI modules (see the device-specific data sheet).

17.4.14 UC1IFG, USCI_B1 Interrupt Flag Register

7	6	5	4	3	2	1	0
Unused				UCB1TXIFG	UCB1RXIFG		
rw-0	rw-0	rw-0	rw-0	rw-1	rw-0		

Unused	Bits 7-4	Unused.
UCB1TXIFG	Bit 3	USCI_B1 transmit interrupt flag. UCB1TXIFG is set when UCB1TXBUF is empty.
		0 No interrupt pending
		1 Interrupt pending
UCB1RXIFG	Bit 2	USCI_B1 receive interrupt flag. UCB1RXIFG is set when UCB1RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending
	Bits 1-0	These bits may be used by other modules (see the device-specific data sheet).

USART Peripheral Interface, UART Mode

The universal synchronous/asynchronous receive/transmit (USART) peripheral interface supports two serial modes with one hardware module. This chapter discusses the operation of the asynchronous UART mode. USART0 is implemented on the MSP430AFE2xx devices.

Topic **Page**

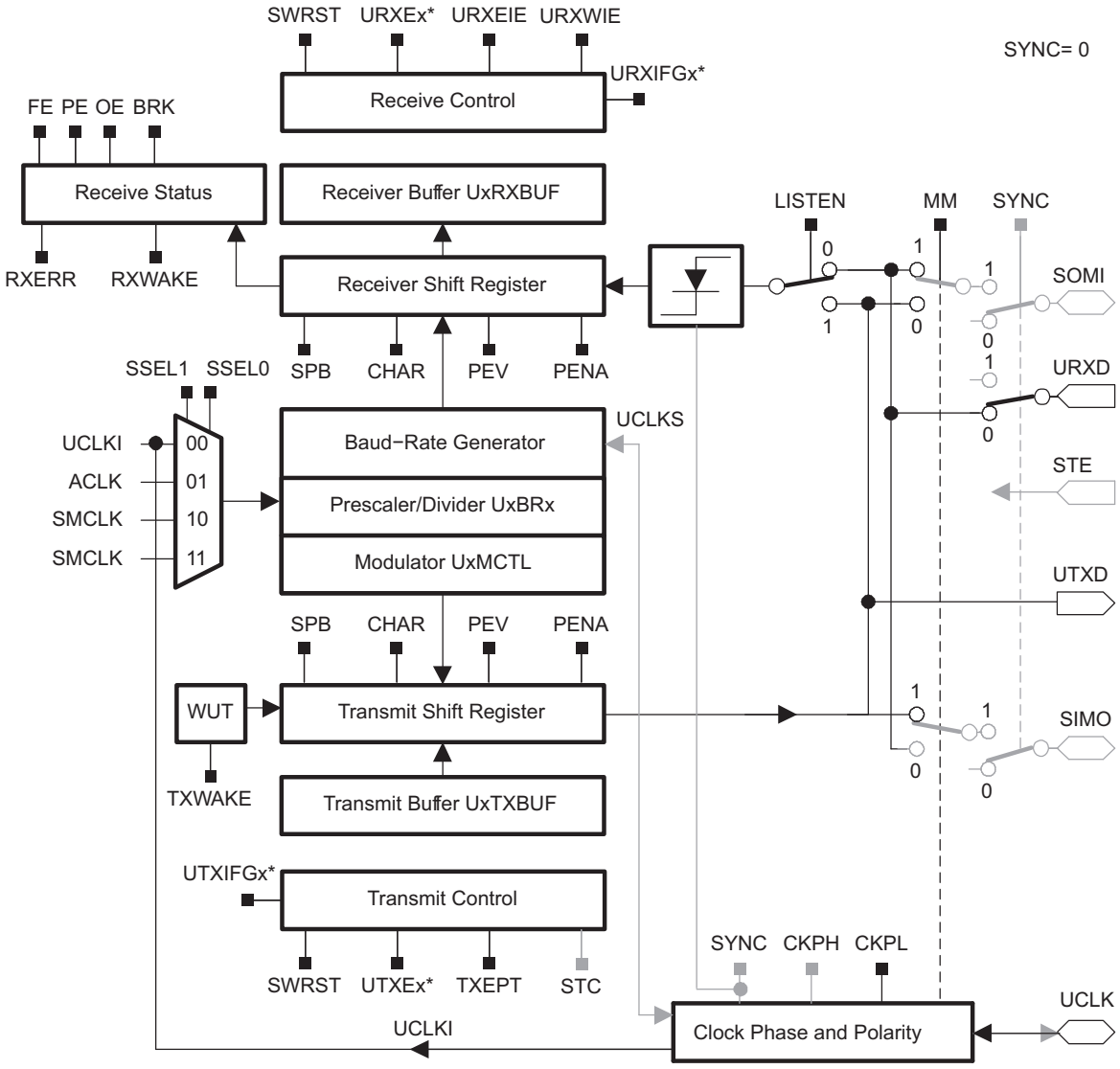
18.1 USART Introduction: UART Mode

In asynchronous mode, the USART connects the MSP430 to an external system via two external pins, URXD and UTXD. UART mode is selected when the SYNC bit is cleared.

UART mode features include:

- 7- or 8-bit data with odd parity, even parity, or non-parity
- Independent transmit and receive shift registers
- Separate transmit and receive buffer registers
- LSB-first data transmit and receive
- Built-in idle-line and address-bit communication protocols for multiprocessor systems
- Receiver start-edge detection for auto-wake up from LPMx modes
- Programmable baud rate with modulation for fractional baud rate support
- Status flags for error detection and suppression and address detection
- Independent interrupt capability for receive and transmit

Figure 18-1 shows the USART when configured for UART mode.



* See the device-specific data sheet for SFR locations.

Figure 18-1. USART Block Diagram: UART Mode

18.2 USART Operation: UART Mode

In UART mode, the USART transmits and receives characters at a bit rate asynchronous to another device. Timing for each character is based on the selected baud rate of the USART. The transmit and receive functions use the same baud rate frequency.

18.2.1 USART Initialization and Reset

The USART is reset by a PUC or by setting the SWRST bit. After a PUC, the SWRST bit is automatically set, keeping the USART in a reset condition. When set, the SWRST bit resets the URXIEx, UTXIEx, URXIFGx, RXWAKE, TXWAKE, RXERR, BRK, PE, OE, and FE bits and sets the UTXIFGx and TXEPT bits. The receive and transmit enable flags, URXEx and UTXEx, are not altered by SWRST. Clearing SWRST releases the USART for operation. See also chapter *USART Module, I²C mode* for USART0 when reconfiguring from I²C mode to UART mode.

NOTE: Initializing or Reconfiguring the USART Module

The required USART initialization/reconfiguration process is:

1. Set SWRST (BIS.B #SWRST,&UxCTL)
2. Initialize all USART registers with SWRST = 1 (including UxCTL)
3. Enable USART module via the MEx SFRs (URXEx and/or UTXEx)
4. Clear SWRST via software (BIC.B #SWRST,&UxCTL)
5. Enable interrupts (optional) via the IEx SFRs (URXIEx and/or UTXIEx)

Failure to follow this process may result in unpredictable USART behavior.

18.2.2 Character Format

The UART character format, shown in Figure 18-2, consists of a start bit, seven or eight data bits, an even/odd/no parity bit, an address bit (address-bit mode), and one or two stop bits. The bit period is defined by the selected clock source and setup of the baud rate registers.

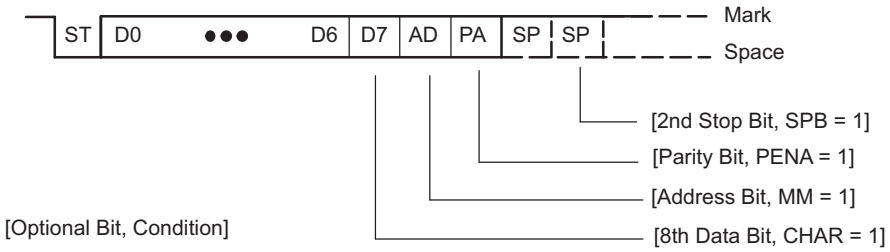


Figure 18-2. Character Format

18.2.3 Asynchronous Communication Formats

When two devices communicate asynchronously, the idle-line format is used for the protocol. When three or more devices communicate, the USART supports the idle-line and address-bit multiprocessor communication formats.

18.2.3.1 Idle-Line Multiprocessor Format

When MM = 0, the idle-line multiprocessor format is selected. Blocks of data are separated by an idle time on the transmit or receive lines as shown in Figure 18-3. An idle receive line is detectedwhen 10 or more continuous ones (marks) are received after the first stop bit of a character. When two stop bits are used for the idle line the second stop bit is counted as the first mark bit of the idle period.

The first character received after an idle period is an address character. The RXWAKE bit is used as an address tag for each block of characters. In the idle-line multiprocessor format, this bit is set when a received character is an address and is transferred to UxRXBUF.

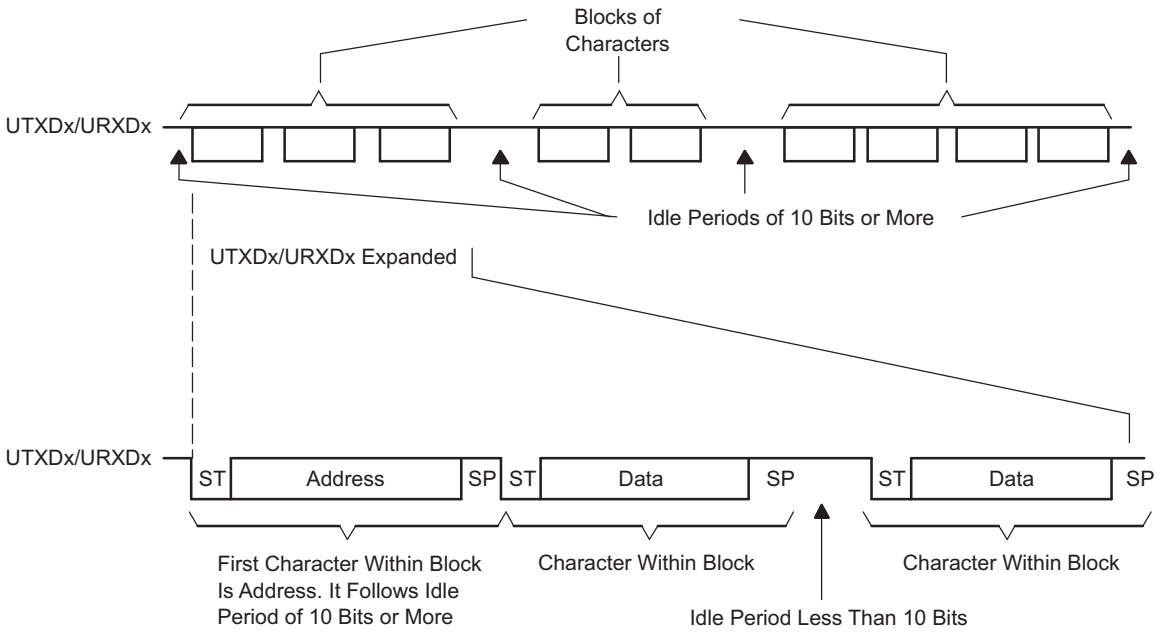


Figure 18-3. Idle-Line Format

The URXWIE bit is used to control data reception in the idle-line multiprocessor format. When the URXWIE bit is set, all non-address characters are assembled but not transferred into the UxRXBUF, and interrupts are not generated. When an address character is received, the receiver is temporarily activated to transfer the character to UxRXBUF and sets the URXIFGx interrupt flag. Any applicable error flag is also set. The user can then validate the received address.

If an address is received, user software can validate the address and must reset URXWIE to continue receiving data. If URXWIE remains set, only address characters are received. The URXWIE bit is not modified by the USART hardware automatically.

For address transmission in idle-line multiprocessor format, a precise idle period can be generated by the USART to generate address character identifiers on UTXDx. The wake-up temporary (WUT) flag is an internal flag double-buffered with the user-accessible TXWAKE bit. When the transmitter is loaded from UxTXBUF, WUT is also loaded from TXWAKE resetting the TXWAKE bit.

The following procedure sends out an idle frame to indicate an address character follows:

1. Set TXWAKE, then write any character to UxTXBUF. UxTXBUF must be ready for new data (UTXIFGx = 1).

   The TXWAKE value is shifted to WUT and the contents of UxTXBUF are shifted to the transmit shift register when the shift register is ready for new data. This sets WUT, which suppresses the start, data, and parity bits of a normal transmission, then transmits an idle period of exactly 11 bits. When two stop bits are used for the idle line, the second stop bit is counted as the first mark bit of the idle period. TXWAKE is reset automatically.
2. Write desired address character to UxTXBUF. UxTXBUF must be ready for new data (UTXIFGx = 1).

   The new character representing the specified address is shifted out following the address-identifying idle period on UTXDx. Writing the first "don't care" character to UxTXBUF is necessary in order to shift the TXWAKE bit to WUT and generate an idle-line condition. This data is discarded and does not appear on UTXDx.

18.2.3.2 Address-Bit Multiprocessor Format

When MM = 1, the address-bit multiprocessor format is selected. Each processed character contains an extra bit used as an address indicator shown in Figure 18-4. The first character in a block of characters carries a set address bit which indicates that the character is an address. The USART RXWAKE bit is set when a received character is a valid address character and is transferred to UxRXBUF.

The URXWIE bit is used to control data reception in the address-bit multiprocessor format. If URXWIE is set, data characters (address bit = 0) are assembled by the receiver but are not transferred to UxRXBUF and no interrupts are generated. When a character containing a set address bit is received, the receiver is temporarily activated to transfer the character to UxRXBUF and set URXIFGx. All applicable error status flags are also set.

If an address is received, user software must reset URXWIE to continue receiving data. If URXWIE remains set, only address characters (address bit = 1) are received. The URXWIE bit is not modified by the USART hardware automatically.

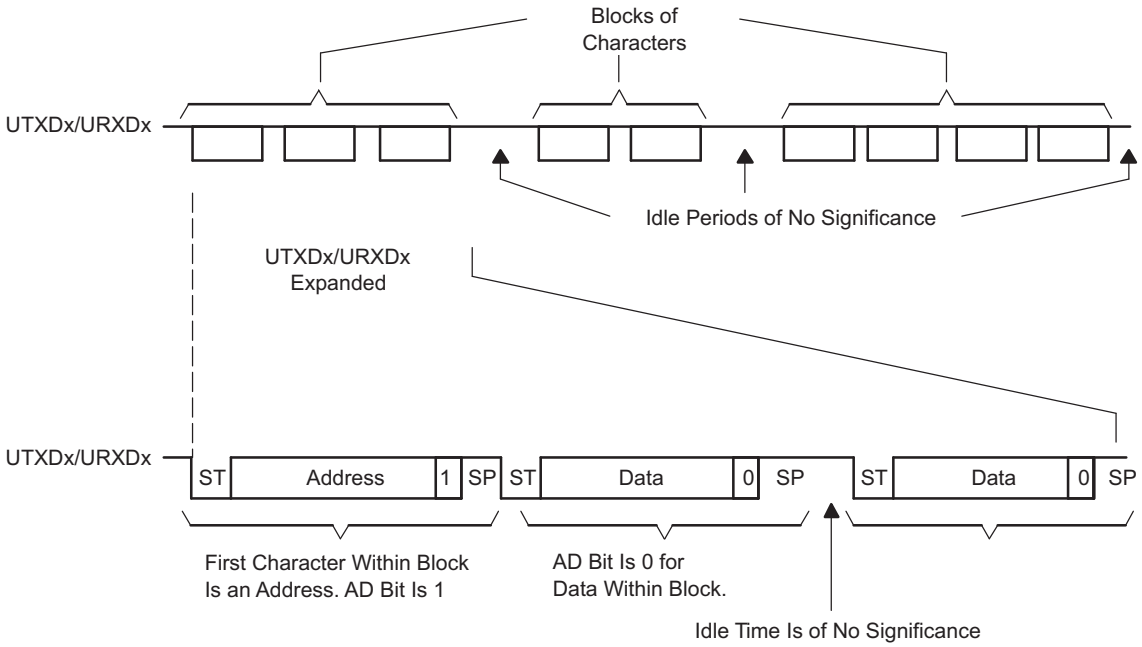


Figure 18-4. Address-Bit Multiprocessor Format

For address transmission in address-bit multiprocessor mode, the address bit of a character can be controlled by writing to the TXWAKE bit. The value of the TXWAKE bit is loaded into the address bit of the character transferred from UxTXBUF to the transmit shift register, automatically clearing the TXWAKE bit. TXWAKE must not be cleared by software. It is cleared by USART hardware after it is transferred to WUT or by setting SWRST.

18.2.3.3 Automatic Error Detection

Glitch suppression prevents the USART from being accidentally started. Any low-level on URXDx shorter than the deglitch time t_τ (approximately 300 ns) is ignored. See the device-specific data sheet for parameters.

When a low period on URXDx exceeds t_τ a majority vote is taken for the start bit. If the majority vote fails to detect a valid start bit the USART halts character reception and waits for the next low period on URXDx. The majority vote is also used for each bit in a character to prevent bit errors.

The USART module automatically detects framing errors, parity errors, overrun errors, and break conditions when receiving characters. The bits FE, PE, OE, and BRK are set when their respective condition is detected. When any of these error flags are set, RXERR is also set. The error conditions are described in Table 18-1.

Table 18-1. Receive Error Conditions

Error Condition	Description
Framing error	A framing error occurs when a low stop bit is detected. When two stop bits are used, only the first stop bit is checked for framing error. When a framing error is detected, the FE bit is set.
Parity error	A parity error is a mismatch between the number of 1s in a character and the value of the parity bit. When an address bit is included in the character, it is included in the parity calculation. When a parity error is detected, the PE bit is set.
Receive overrun error	An overrun error occurs when a character is loaded into UxRXBUF before the prior character has been read. When an overrun occurs, the OE bit is set.
Break condition	A break condition is a period of 10 or more low bits received on URXDx after a missing stop bit. When a break condition is detected, the BRK bit is set. A break condition can also set the interrupt flag URXIFGx when URXEIE = 0.

When URXEIE = 0 and a framing error, parity error, or break condition is detected, no character is received into UxRXBUF. When URXEIE = 1, characters are received into UxRXBUF and any applicable error bit is set.

When any of the FE, PE, OE, BRK, or RXERR bits are set, the bit remains set until user software resets it or UxRXBUF is read.

18.2.4 USART Receive Enable

The receive enable bit, URXEx, enables or disables data reception on URXDx as shown in Figure 18-5. Disabling the USART receiver stops the receive operation following completion of any character currently being received or immediately if no receive operation is active. The receive-data buffer, UxRXBUF, contains the character moved from the RX shift register after the character is received.

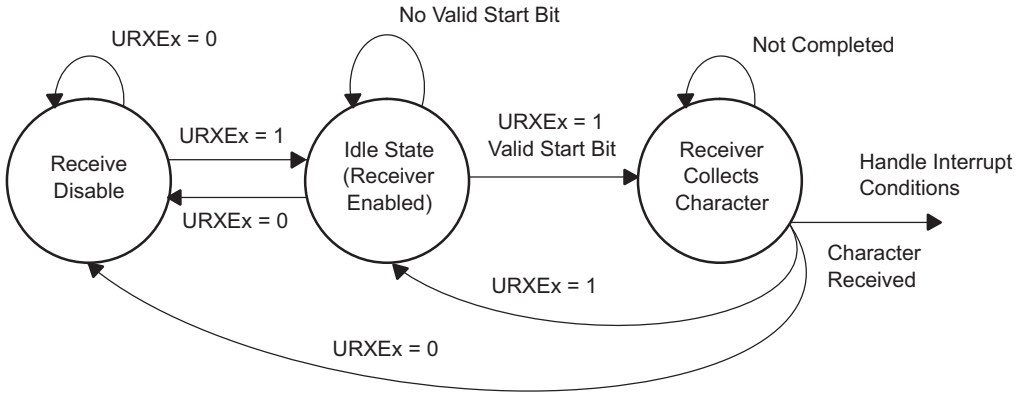


Figure 18-5. State Diagram of Receiver Enable

NOTE: Re-Enabling the Receiver (Setting URXEx): UART Mode

When the receiver is disabled (URXEx = 0), re-enabling the receiver (URXEx = 1) is asynchronous to any data stream that may be present on URXDx at the time. Synchronization can be performed by testing for an idle line condition before receiving a valid character (see URXWIE).

18.2.5 USART Transmit Enable

When UTXEx is set, the UART transmitter is enabled. Transmission is initiated by writing data to UxTXBUF. The data is then moved to the transmit shift register on the next BITCLK after the TX shift register is empty, and transmission begins. This process is shown in Figure 18-6.

When the UTXEx bit is reset the transmitter is stopped. Any data moved to UxTXBUF and any active transmission of data currently in the transmit shift register prior to clearing UTXEx continue until all data transmission is completed.

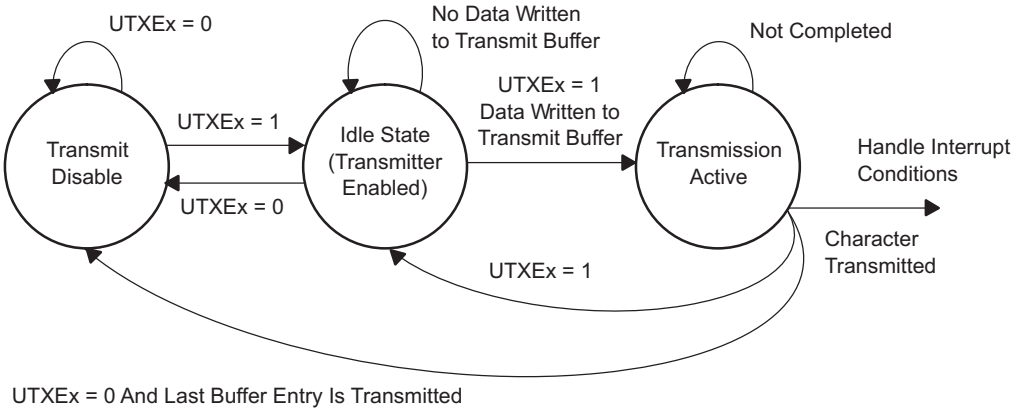


Figure 18-6. State Diagram of Transmitter Enable

When the transmitter is enabled (UTXEx = 1), data should not be written to UxTXBUF unless it is ready for new data indicated by UTXIFGx = 1. Violation can result in an erroneous transmission if data in UxTXBUF is modified as it is being moved into the TX shift register.

It is recommended that the transmitter be disabled (UTXEx = 0) only after any active transmission is complete. This is indicated by a set transmitter empty bit (TXEPT = 1). Any data written to UxTXBUF while the transmitter is disabled are held in the buffer but are not moved to the transmit shift register or transmitted. Once UTXEx is set, the data in the transmit buffer is immediately loaded into the transmit shift register and character transmission resumes.

18.2.6 USART Baud Rate Generation

The USART baud rate generator is capable of producing standard baud rates from non-standard source frequencies. The baud rate generator uses one prescaler/divider and a modulator as shown in Figure 18-7. This combination supports fractional divisors for baud rate generation. The maximum USART baud rate is one-third the UART source clock frequency BRCLK.

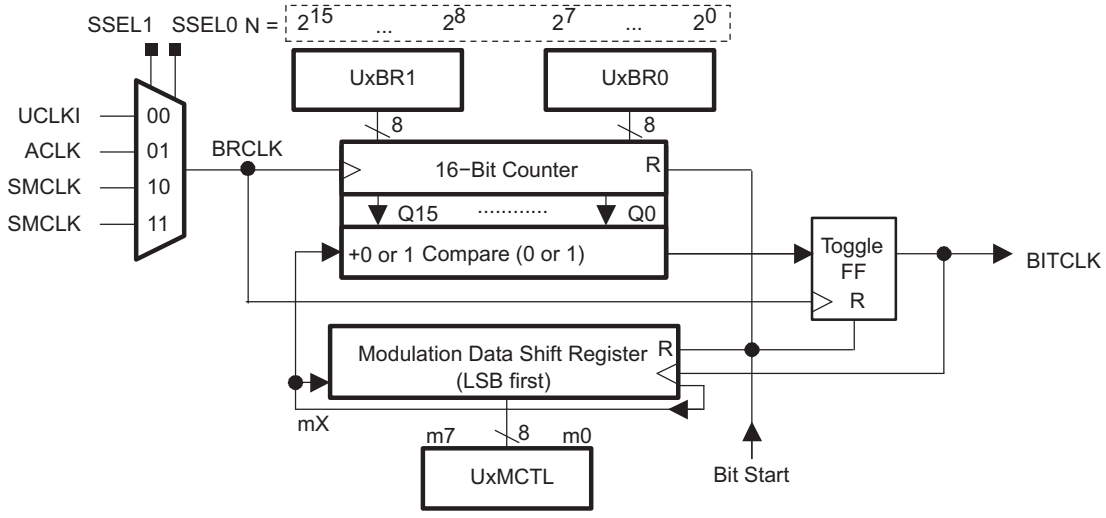


Figure 18-7. MSP430 Baud Rate Generator

Timing for each bit is shown in Figure 18-8. For each bit received, a majority vote is taken to determine the bit value. These samples occur at the N/2-1, N/2, and N/2+1 BRCLK periods, where N is the number of BRCLKs per BITCLK.

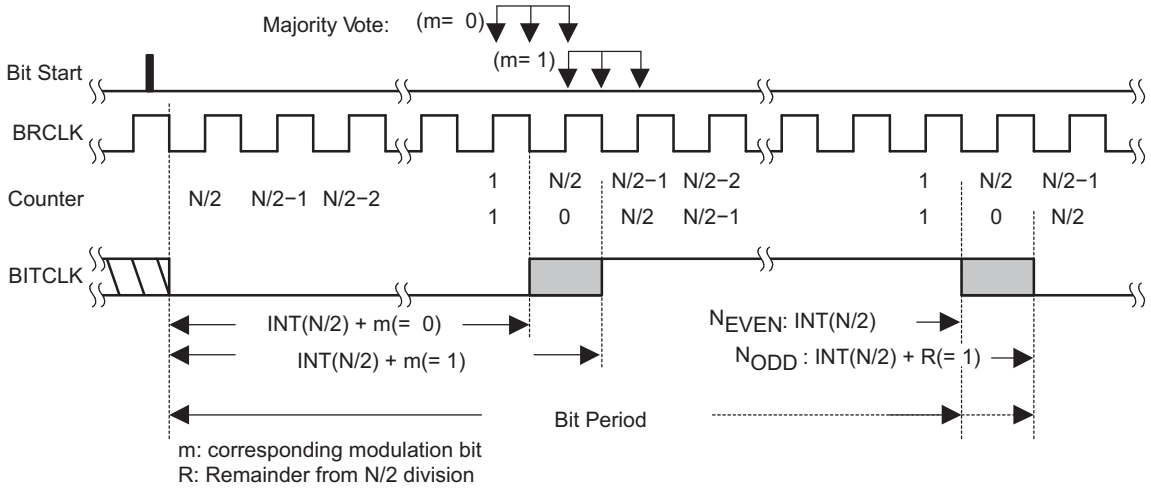


Figure 18-8. BITCLK Baud Rate Timing

18.2.6.1 Baud Rate Bit Timing

The first stage of the baud rate generator is the 16-bit counter and comparator. At the beginning of each bit transmitted or received, the counter is loaded with INT(N/2) where N is the value stored in the combination of UxBR0 and UxBR1. The counter reloads INT(N/2) for each bit period half-cycle, giving a total bit period of N BRCLKs. For a given BRCLK clock source, the baud rate used determines the required division factor N:

$$N = \frac{BRCLK}{Baud\ Rate}$$

The division factor N is often a non-integer value of which the integer portion can be realized by the prescaler/divider. The second stage of the baud rate generator, the modulator, is used to meet the fractional part as closely as possible. The factor *N* is then defined as:

$$N = UxBR + \frac{1}{n}\sum_{i=0}^{n-1} m_i$$

Where,

N = Target division factor

UxBR = 16-bit representation of registers UxBR0 and UxBR1

i = Bit position in the character

n = Total number of bits in the character

m_i = Data of each corresponding modulation bit (1 or 0)

$$Baud\ rate = \frac{BRCLK}{N} + \frac{BRCLK}{UxBR + \frac{1}{n}\sum_{i=0}^{n-1} m_i}$$

The BITCLK can be adjusted from bit to bit with the modulator to meet timing requirements when a non-integer divisor is needed. Timing of each bit is expanded by one BRCLK clock cycle if the modulator bit m_i is set. Each time a bit is received or transmitted, the next bit in the modulation control register determines the timing for that bit. A set modulation bit increases the division factor by one while a cleared modulation bit maintains the division factor given by UxBR.

The timing for the start bit is determined by UxBR plus m0, the next bit is determined by UxBR plus m1, and so on. The modulation sequence begins with the LSB. When the character is greater than 8 bits, the modulation sequence restarts with m0 and continues until all bits are processed.

18.2.6.2 Determining the Modulation Value

Determining the modulation value is an interactive process. Using the timing error formula provided, beginning with the start bit , the individual bit errors are calculated with the corresponding modulator bit set and cleared. The modulation bit setting with the lower error is selected and the next bit error is calculated. This process is continued until all bit errors are minimized. When a character contains more than 8 bits, the modulation bits repeat. For example, the ninth bit of a character uses modulation bit 0.

18.2.6.3 Transmit Bit Timing

The timing for each character is the sum of the individual bit timings. By modulating each bit, the cumulative bit error is reduced. The individual bit error can be calculated by:

$$\text{Error [\%]} = \left\{ \frac{\text{baud rate}}{\text{BRCLK}} \times \left[(j + 1) \times \text{UxBR} + \sum_{i=0}^{j} m_i \right] - (j + 1) \right\} \times 100\%$$

Where,

baud rate = Desired baud rate

BRCLK = Input frequency - UCLKI, ACLK, or SMCLK

j = Bit position - 0 for the start bit, 1 for data bit D0, and so on

UxBR = Division factor in registers UxBR1 and UxBR0

For example, the transmit errors for the following conditions are calculated:

Baud rate = 2400

BRCLK = 32 768 Hz (ACLK)

UxBR = 13, since the ideal division factor is 13.65

UxMCTL = 6Bh: m7 = 0, m6 = 1, m5 = 1, m4 = 0, m3 = 1, m2 = 0, m1 = 1, and m0 = 1. The LSB of UxMCTL is used first.

Start bit Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((0+1) \cdot \text{UxBR}+1) - 1\right) \cdot 100\% = 2.54\%$

Data bit D0 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((1+1) \cdot \text{UxBR}+2) - 2\right) \cdot 100\% = 5.08\%$

Data bit D1 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((2+1) \cdot \text{UxBR}+2) - 3\right) \cdot 100\% = 0.29\%$

Data bit D2 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((3+1) \cdot \text{UxBR}+3) - 4\right) \cdot 100\% = 2.83\%$

Data bit D3 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((4+1) \cdot \text{UxBR}+3) - 5\right) \cdot 100\% = -1.95\%$

Data bit D4 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((5+1) \cdot \text{UxBR}+4) - 6\right) \cdot 100\% = 0.59\%$

Data bit D5 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((6+1) \cdot \text{UxBR}+5) - 7\right) \cdot 100\% = 3.13\%$

Data bit D6 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((7+1) \cdot \text{UxBR}+5) - 8\right) \cdot 100\% = -1.66\%$

Data bit D7 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((8+1) \cdot \text{UxBR}+6) - 9\right) \cdot 100\% = 0.88\%$

Parity bit Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((9+1) \cdot \text{UxBR}+7) - 10\right) \cdot 100\% = 3.42\%$

Stop bit 1 Error [%]= $\left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot ((10+1) \cdot \text{UxBR}+7) - 11\right) \cdot 100\% = -1.37\%$

The results show the maximum per-bit error to be 5.08% of a BITCLK period.

18.2.6.4 Receive Bit Timing

Receive timing is subject to two error sources. The first is the bit-to-bit timing error. The second is the error between a start edge occurring and the start edge being accepted by the USART. Figure 18-9 shows the asynchronous timing errors between data on the URXDx pin and the internal baud-rate clock.

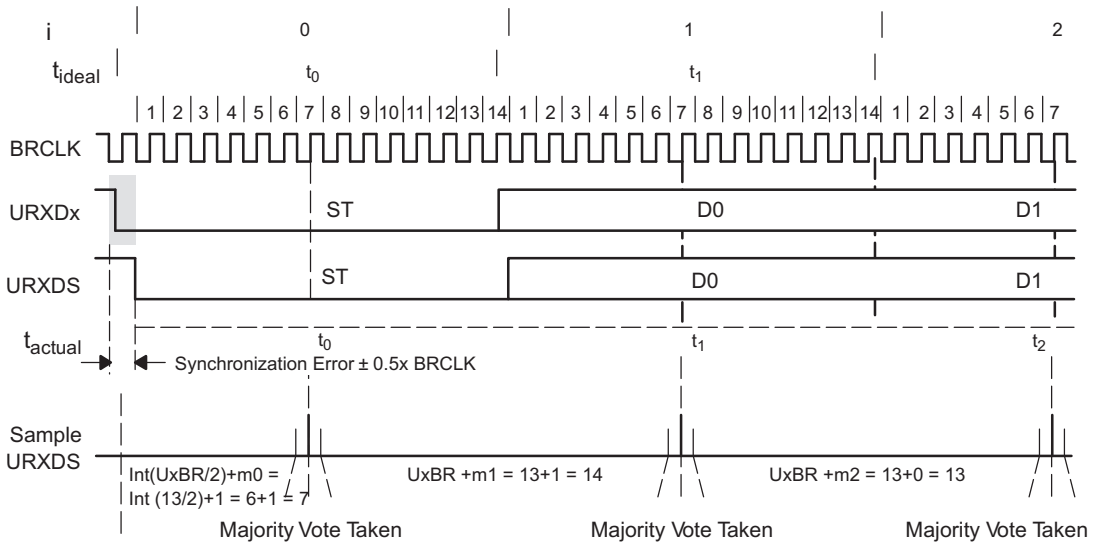


Figure 18-9. Receive Error

The ideal start bit timing $t_{ideal(0)}$ is half the baud-rate timing $t_{baudrate}$, because the bit is tested in the middle of its period. The ideal baud-rate timing $t_{ideal(i)}$ for the remaining character bits is the baud rate timing $t_{baudrate}$. The individual bit errors can be calculated by:

$$\text{Error [\%]} = \left\{ \frac{\text{baud rate}}{\text{BRCLK}} \times \left(2 \times \left[m0 + \text{int}\left(\frac{\text{UxBR}}{2} \right) \right] + \left[i \times \text{UxBR} + \sum_{i=1}^{j} m_i \right] \right) - 1 - j \right\} \times 100\%$$

Where,

baud rate = the required baud rate

BRCLK = the input frequency; selected for UCLK, ACLK, or SMCLK

j = 0 for the start bit, 1 for data bit D0, and so on

UxBR = the division factor in registers UxBR1 and UxBR0

For example, the receive errors for the following conditions are calculated:

Baud rate = 2400

BRCLK = 32 768 Hz (ACLK)

UxBR = 13, since the ideal division factor is 13.65

UxMCTL = 6B: m7 = 0, m6 = 1, m5 = 1, m4 = 0, m3 = 1, m2 = 0, m1 = 1 and m0 = 1. The LSB of UxMCTL is used first.

$$\text{Data bit D1 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+2 \cdot \text{UxBR}+1]-1-2\right) \cdot 100\% = 0.29\%$$

$$\text{Data bit D2 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+3 \cdot \text{UxBR}+2]-1-3\right) \cdot 100\% = 2.83\%$$

$$\text{Data bit D3 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+4 \cdot \text{UxBR}+2]-1-4\right) \cdot 100\% = -1.95\%$$

$$\text{Data bit D4 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+5 \cdot \text{UxBR}+3]-1-5\right) \cdot 100\% = 0.59\%$$

$$\text{Data bit D5 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+6 \cdot \text{UxBR}+4]-1-6\right) \cdot 100\% = 3.13\%$$

$$\text{Data bit D6 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+7 \cdot \text{UxBR}+4]-1-7\right) \cdot 100\% = -1.66\%$$

$$\text{Data bit D7 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+8 \cdot \text{UxBR}+5]-1-8\right) \cdot 100\% = 0.88\%$$

$$\text{Parity bit Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+9 \cdot \text{UxBR}+6]-1-9\right) \cdot 100\% = 3.42\%$$

$$\text{Stop bit 1 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+10 \cdot \text{UxBR}+6]-1-10\right) \cdot 100\% = -1.37\%$$

$$\text{Start bit Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+0 \cdot \text{UxBR}+0]-1-0\right) \cdot 100\% = 2.54\%$$

$$\text{Data bit D0 Error [\%]} = \left(\frac{\text{baud rate}}{\text{BRCLK}} \cdot [2x(1+6)+1 \cdot \text{UxBR}+1]-1-1\right) \cdot 100\% = 5.08\%$$

The results show the maximum per-bit error to be 5.08% of a BITCLK period.

18.2.6.5 Typical Baud Rates and Errors

Standard baud rate frequency data for UxBRx and UxMCTL are listed in Table 18-2 for a 32 768-Hz watch crystal (ACLK) and a typical 1 048 576-Hz SMCLK.

The receive error is the accumulated time versus the ideal scanning time in the middle of each bit. The transmit error is the accumulated timing error versus the ideal time of the bit period.

Table 18-2. Commonly Used Baud Rates, Baud Rate Data, and Errors

Baud Rate	Divide by		A: BRCLK = 32 768 Hz						B: BRCLK = 1 048 576 Hz				
	A:	B:	UxBR1	UxBR0	UxMCTL	Max TX Error %	Max RX Error %	Synch RX Error %	UxBR1	UxBR0	UxMCTL	Max TX Error %	Max RX Error %
1200	27.31	873.81	0	1B	03	-4/3	-4/3	±2	03	69	FF	0/0.3	±2
2400	13.65	436.91	0	0D	6B	-6/3	-6/3	±4	01	B4	FF	0/0.3	±2
4800	6.83	218.45	0	06	6F	-9/11	-9/11	±7	0	DA	55	0/0.4	±2
9600	3.41	109.23	0	03	4A	-21/12	-21/12	±15	0	6D	03	-0.4/1	±2
19 200		54.61							0	36	6B	-0.2/2	±2
38 400		27.31							0	1B	03	-4/3	±2
76 800		13.65							0	0D	6B	-6/3	±4
115 200		9.1							0	09	08	-5/7	±7

18.2.7 USART Interrupts

The USART has one interrupt vector for transmission and one interrupt vector for reception.

18.2.7.1 USART Transmit Interrupt Operation

The UTXIFGx interrupt flag is set by the transmitter to indicate that UxTXBUF is ready to accept another character. An interrupt request is generated if UTXIEx and GIE are also set. UTXIFGx is automatically reset if the interrupt request is serviced or if a character is written to UxTXBUF.

UTXIFGx is set after a PUC or when SWRST = 1. UTXIEx is reset after a PUC or when SWRST = 1. The operation is shown is Figure 18-10.

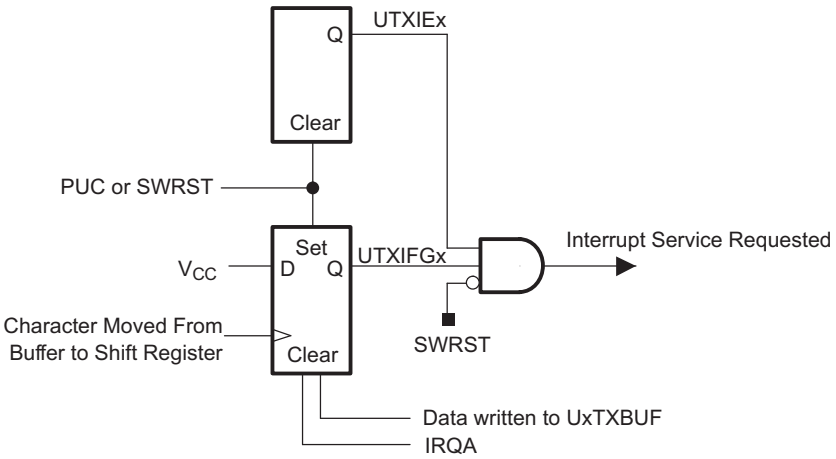


Figure 18-10. Transmit Interrupt Operation

18.2.7.2 USART Receive Interrupt Operation

The URXIFGx interrupt flag is set each time a character is received and loaded into UxRXBUF. An interrupt request is generated if URXIEx and GIE are also set. URXIFGx and URXIEx are reset by a system reset PUC signal or when SWRST = 1. URXIFGx is automatically reset if the pending interrupt is served (when URXSE = 0) or when UxRXBUF is read. The operation is shown in Figure 18-11.

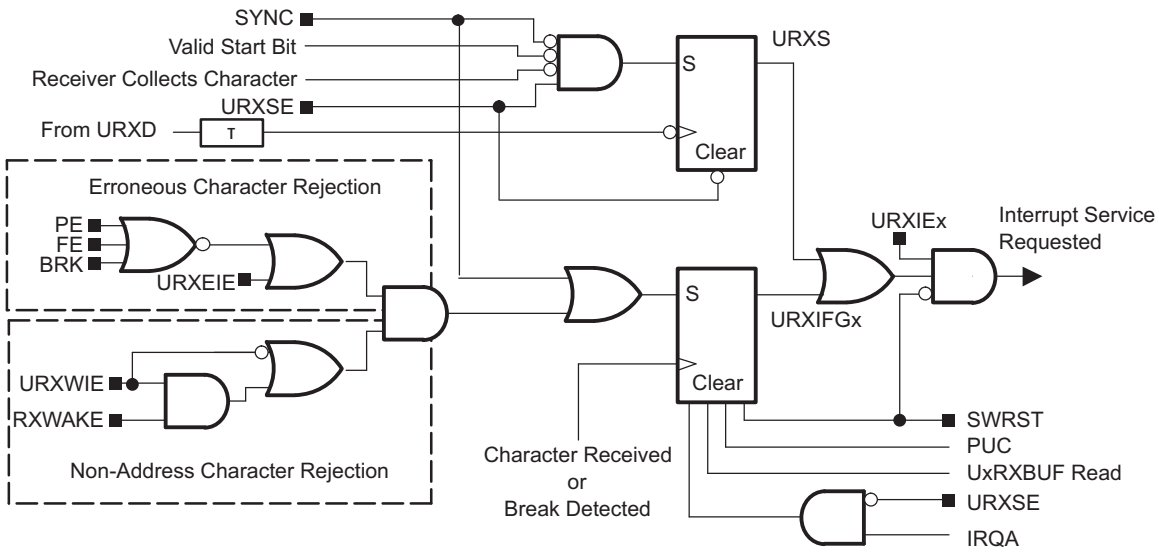


Figure 18-11. Receive Interrupt Operation

URXEIE is used to enable or disable erroneous characters from setting URXIFGx. When using multiprocessor addressing modes, URXWIE is used to auto-detect valid address characters and reject unwanted data characters.

Two types of characters do not set URXIFGx:

- Erroneous characters when URXEIE = 0
- Non-address characters when URXWIE = 1

When URXEIE = 1 a break condition sets the BRK bit and the URXIFGx flag.

18.2.7.3 Receive-Start Edge Detect Operation

The URXSE bit enables the receive start-edge detection feature. The recommended usage of the receive-start edge feature is when BRCLK is sourced by the DCO and when the DCO is off because of low-power mode operation. The ultra-fast turn-on of the DCO allows character reception after the start edge detection.

When URXSE, URXIEx and GIE are set and a start edge occurs on URXDx, the internal signal URXS is set. When URXS is set, a receive interrupt request is generated but URXIFGx is not set. User software in the receive interrupt service routine can test URXIFGx to determine the source of the interrupt. When URXIFGx = 0 a start edge was detected, and when URXIFGx = 1 a valid character (or break) was received.

When the ISR determines the interrupt request was from a start edge, user software toggles URXSE, and must enable the BRCLK source by returning from the ISR to active mode or to a low-power mode where the source is active. If the ISR returns to a low-power mode where the BRCLK source is inactive, the character is not received. Toggling URXSE clears the URXS signal and re-enables the start edge detect feature for future characters. See chapter *System Resets, Interrupts, and Operating Modes* for information on entering and exiting low-power modes.

The now active BRCLK allows the USART to receive the balance of the character. After the full character is received and moved to UxRXBUF, URXIFGx is set and an interrupt service is again requested. Upon ISR entry, URXIFGx = 1 indicating a character was received. The URXIFGx flag is cleared when user software reads UxRXBUF.

```
; Interrupt handler for start condition and
; Character receive. BRCLK = DCO.

U0RX_Int  BIT.B  #URXIFG0,&IFG1    ; Test URXIFGx to determine
          JZ     ST_COND           ; If start or character
          MOV.B  &UxRXBUF,dst      ; Read buffer
          ...                      ;
          RETI                     ;

ST_COND   BIC.B  #URXSE,&U0TCTL    ; Clear URXS signal
          BIS.B  #URXSE,&U0TCTL    ; Re-enable edge detect
          BIC    #SCG0+SCG1,0(SP)  ; Enable BRCLK = DCO
          RETI                     ;
```

NOTE: Break Detect With Halted UART Clock

When using the receive start-edge detect feature, a break condition cannot be detected when the BRCLK source is off.

18.2.7.4 Receive-Start Edge Detect Conditions

When URXSE = 1, glitch suppression prevents the USART from being accidentally started. Any low-level on URXDx shorter than the deglitch time t_τ (approximately 300 ns) is ignored by the USART and no interrupt request is generated (see Figure 18-12). See the device-specific data sheet for parameters.

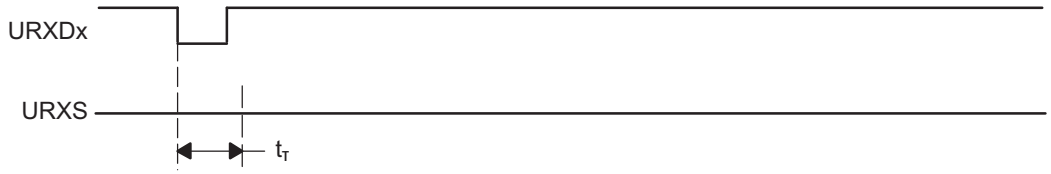


Figure 18-12. Glitch Suppression, USART Receive Not Started

When a glitch is longer than t_τ or a valid start bit occurs on URXDx, the USART receive operation is started and a majority vote is taken as shown in Figure 18-13. If the majority vote fails to detect a start bit, the USART halts character reception.

If character reception is halted, an active BRCLK is not necessary. A time-out period longer than the character receive duration can be used by software to indicate that a character was not received in the expected time, and the software can disable BRCLK.

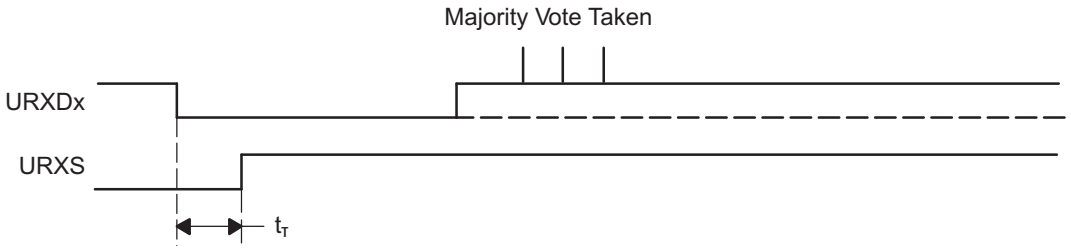


Figure 18-13. Glitch Suppression, USART Activated

18.3 USART Registers: UART Mode

Table 18-3 lists the registers for all devices implementing a USART module. Table 18-4 applies only to devices with a second USART module, USART1.

Table 18-3. USART0 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USART control register	U0CTL	Read/write	070h	001h with PUC
Transmit control register	U0TCTL	Read/write	071h	001h with PUC
Receive control register	U0RCTL	Read/write	072h	000h with PUC
Modulation control register	U0MCTL	Read/write	073h	Unchanged
Baud rate control register 0	U0BR0	Read/write	074h	Unchanged
Baud rate control register 1	U0BR1	Read/write	075h	Unchanged
Receive buffer register	U0RXBUF	Read	076h	Unchanged
Transmit buffer register	U0TXBUF	Read/write	077h	Unchanged
SFR interrupt enable register 1	IE1	Read/write	000h	000h with PUC
SFR interrupt flag register 1	IFG1	Read/write	002h	082h with PUC

Table 18-4. USART1 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USART control register	U1CTL	Read/write	078h	001h with PUC
Transmit control register	U1TCTL	Read/write	079h	001h with PUC
Receive control register	U1RCTL	Read/write	07Ah	000h with PUC
Modulation control register	U1MCTL	Read/write	07Bh	Unchanged
Baud rate control register 0	U1BR0	Read/write	07Ch	Unchanged
Baud rate control register 1	U1BR1	Read/write	07Dh	Unchanged
Receive buffer register	U1RXBUF	Read	07Eh	Unchanged
Transmit buffer register	U1TXBUF	Read/write	07Fh	Unchanged
SFR interrupt enable register 2	IE2	Read/write	001h	000h with PUC
SFR interrupt flag register 2	IFG2	Read/write	003h	020h with PUC

NOTE: Modifying SFR bits

To avoid modifying control bits of other modules, it is recommended to set or clear the IEx and IFGx bits using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions.

18.3.1 UxCTL, USART Control Register

7	6	5	4	3	2	1	0
PENA	**PEV**	**SPB**	**CHAR**	**LISTEN**	**SYNC**	**MM**	**SWRST**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-1

PENA Bit 7 Parity enable
- 0 Parity disabled
- 1 Parity enabled. Parity bit is generated (UTXDx) and expected (URXDx). In address-bit multiprocessor mode, the address bit is included in the parity calculation.

PEV Bit 6 Parity select. PEV is not used when parity is disabled.
- 0 Odd parity
- 1 Even parity

SPB Bit 5 Stop bit select. Number of stop bits transmitted. The receiver always checks for one stop bit.
- 0 One stop bit
- 1 Two stop bits

CHAR Bit 4 Character length. Selects 7-bit or 8-bit character length.
- 0 7-bit data
- 1 8-bit data

LISTEN Bit 3 Listen enable. The LISTEN bit selects loopback mode.
- 0 Disabled
- 1 Enabled. UTXDx is internally fed back to the receiver.

SYNC Bit 2 Synchronous mode enable
- 0 UART mode
- 1 SPI mode

MM Bit 1 Multiprocessor mode select
- 0 Idle-line multiprocessor protocol
- 1 Address-bit multiprocessor protocol

SWRST Bit 0 Software reset enable
- 0 Disabled. USART reset released for operation
- 1 Enabled. USART logic held in reset state

18.3.2 UxTCTL, USART Transmit Control Register

7	6	5	4	3	2	1	0
Unused	**CKPL**	**SSELx**		**URXSE**	**TXWAKE**	**Unused**	**TXEPT**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-1

Unused	Bit 7	Unused	
CKPL	Bit 6	Clock polarity select	
		0	UCLKI = UCLK
		1	UCLKI = inverted UCLK
SSELx	Bits 5-4	Source select. These bits select the BRCLK source clock.	
		00	UCLKI
		01	ACLK
		10	SMCLK
		11	SMCLK
URXSE	Bit 3	UART receive start-edge. The bit enables the UART receive start-edge feature.	
		0	Disabled
		1	Enabled
TXWAKE	Bit 2	Transmitter wake	
		0	Next frame transmitted is data
		1	Next frame transmitted is an address
Unused	Bit 1	Unused	
TXEPT	Bit 0	Transmitter empty flag	
		0	UART is transmitting data and/or data is waiting in UxTXBUF
		1	Transmitter shift register and UxTXBUF are empty or SWRST = 1

18.3.3 UxRCTL, USART Receive Control Register

7	6	5	4	3	2	1	0
FE	**PE**	**OE**	**BRK**	**URXEIE**	**URXWIE**	**RXWAKE**	**RXERR**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

FE	Bit 7	Framing error flag
		0 No error
		1 Character received with low stop bit
PE	Bit 6	Parity error flag. When PENA = 0, PE is read as 0.
		0 No error
		1 Character received with parity error
OE	Bit 5	Overrun error flag. This bit is set when a character is transferred into UxRXBUF before the previous character was read.
		0 No error
		1 Overrun error occurred
BRK	Bit 4	Break detect flag
		0 No break condition
		1 Break condition occurred
URXEIE	Bit 3	Receive erroneous-character interrupt-enable
		0 Erroneous characters rejected and URXIFGx is not set
		1 Erroneous characters received set URXIFGx
URXWIE	Bit 2	Receive wake-up interrupt-enable. This bit enables URXIFGx to be set when an address character is received. When URXEIE = 0, an address character does not set URXIFGx if it is received with errors.
		0 All received characters set URXIFGx
		1 Only received address characters set URXIFGx
RXWAKE	Bit 1	Receive wake-up flag
		0 Received character is data
		1 Received character is an address
RXERR	Bit 0	Receive error flag. This bit indicates a character was received with error(s). When RXERR = 1, on or more error flags (FE, PE, OE, BRK) is also set. RXERR is cleared when UxRXBUF is read.
		0 No receive errors detected
		1 Receive error detected

18.3.4 UxBR0, USART Baud Rate Control Register 0

7	6	5	4	3	2	1	0
2^7	**2^6**	**2^5**	**2^4**	**2^3**	**2^2**	**2^1**	**2^0**
rw	rw	rw	rw	rw	rw	rw	rw

18.3.5 UxBR1, USART Baud Rate Control Register 1

7	6	5	4	3	2	1	0
2^{15}	**2^{14}**	**2^{13}**	**2^{12}**	**2^{11}**	**2^{10}**	**2^9**	**2^8**
rw	rw	rw	rw	rw	rw	rw	rw

UxBRx	The valid baud-rate control range is 3 ≤ UxBR ≤ 0FFFFh, where UxBR = (UxBR1 + UxBR0). Unpredictable receive and transmit timing occurs if UxBR < 3.

18.3.6 UxMCTL, USART Modulation Control Register

7	6	5	4	3	2	1	0
m7	**m6**	**m5**	**m4**	**m3**	**m2**	**m1**	**m0**
rw	rw	rw	rw	rw	rw	rw	rw

UxMCTLx		Modulation bits. These bits select the modulation for BRCLK.

18.3.7 UxRXBUF, USART Receive Buffer Register

7	6	5	4	3	2	1	0
2^7	**2^6**	**2^5**	**2^4**	**2^3**	**2^2**	**2^1**	**2^0**
r	r	r	r	r	r	r	r

UxRXBUFx	Bits 7-0	The receive-data buffer is user accessible and contains the last received character from the receive shift register. Reading UxRXBUF resets the receive-error bits, the RXWAKE bit, and URXIFGx. In 7-bit data mode, UxRXBUF is LSB justified and the MSB is always reset.

18.3.8 UxTXBUF, USART Transmit Buffer Register

7	6	5	4	3	2	1	0
2^7	**2^6**	**2^5**	**2^4**	**2^3**	**2^2**	**2^1**	**2^0**
rw	rw	rw	rw	rw	rw	rw	rw

UxTXBUFx	Bits 7-0	The transmit data buffer is user accessible and holds the data waiting to be moved into the transmit shift register and transmitted on UTXDx. Writing to the transmit data buffer clears UTXIFGx. The MSB of UxTXBUF is not used for 7-bit data and is reset.

18.3.9 IE1, Interrupt Enable Register 1

7	6	5	4	3	2	1	0
UTXIE0	**URXIE0**						
rw-0	rw-0						

UTXIE0	Bit 7	USART0 transmit interrupt enable. This bit enables the UTXIFG0 interrupt. 0 Interrupt not enabled 1 Interrupt enabled
URXIE0	Bit 6	USART0 receive interrupt enable. This bit enables the URXIFG0 interrupt. 0 Interrupt not enabled 1 Interrupt enabled
	Bits 5-0	These bits may be used by other modules. See device-specific data sheet.

18.3.10 IE2, Interrupt Enable Register 2

7	6	5	4	3	2	1	0
		UTXIE1	**URXIE1**				
		rw-0	rw-0				

	Bits 7-6	These bits may be used by other modules. See device-specific data sheet.
UTXIE1	Bit 5	USART1 transmit interrupt enable. This bit enables the UTXIFG1 interrupt. 0 Interrupt not enabled 1 Interrupt enabled
URXIE1	Bit 4	USART1 receive interrupt enable. This bit enables the URXIFG1 interrupt. 0 Interrupt not enabled 1 Interrupt enabled
	Bits 3-0	These bits may be used by other modules. See device-specific data sheet.

18.3.11 IFG1, Interrupt Flag Register 1

7	6	5	4	3	2	1	0
UTXIFG0	**URXIFG0**						
rw-1	rw-0						

UTXIFG0	Bit 7	USART0 transmit interrupt flag. UTXIFG0 is set when U0TXBUF is empty. 0 No interrupt pending 1 Interrupt pending
URXIFG0	Bit 6	USART0 receive interrupt flag. URXIFG0 is set when U0RXBUF has received a complete character. 0 No interrupt pending 1 Interrupt pending
	Bits 5-0	These bits may be used by other modules. See device-specific data sheet.

18.3.12 IFG2, Interrupt Flag Register 2

7	6	5	4	3	2	1	0
		UTXIFG1	**URXIFG1**				
		rw-1	rw-0				

	Bits 7-6	These bits may be used by other modules. See device-specific data sheet.
UTXIFG1	Bit 5	USART1 transmit interrupt flag. UTXIFG1 is set when U1TXBUF empty.
		0 No interrupt pending
		1 Interrupt pending
URXIFG1	Bit 4	USART1 receive interrupt flag. URXIFG1 is set when U1RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending
	Bits 3-0	These bits may be used by other modules. See device-specific data sheet.

USART Peripheral Interface, SPI Mode

The universal synchronous/asynchronous receive/transmit (USART) peripheral interface supports two serial modes with one hardware module. This chapter discusses the operation of the synchronous peripheral interface or SPI mode. USART0 is implemented on the MSP430AFE2xx devices.

Topic **Page**

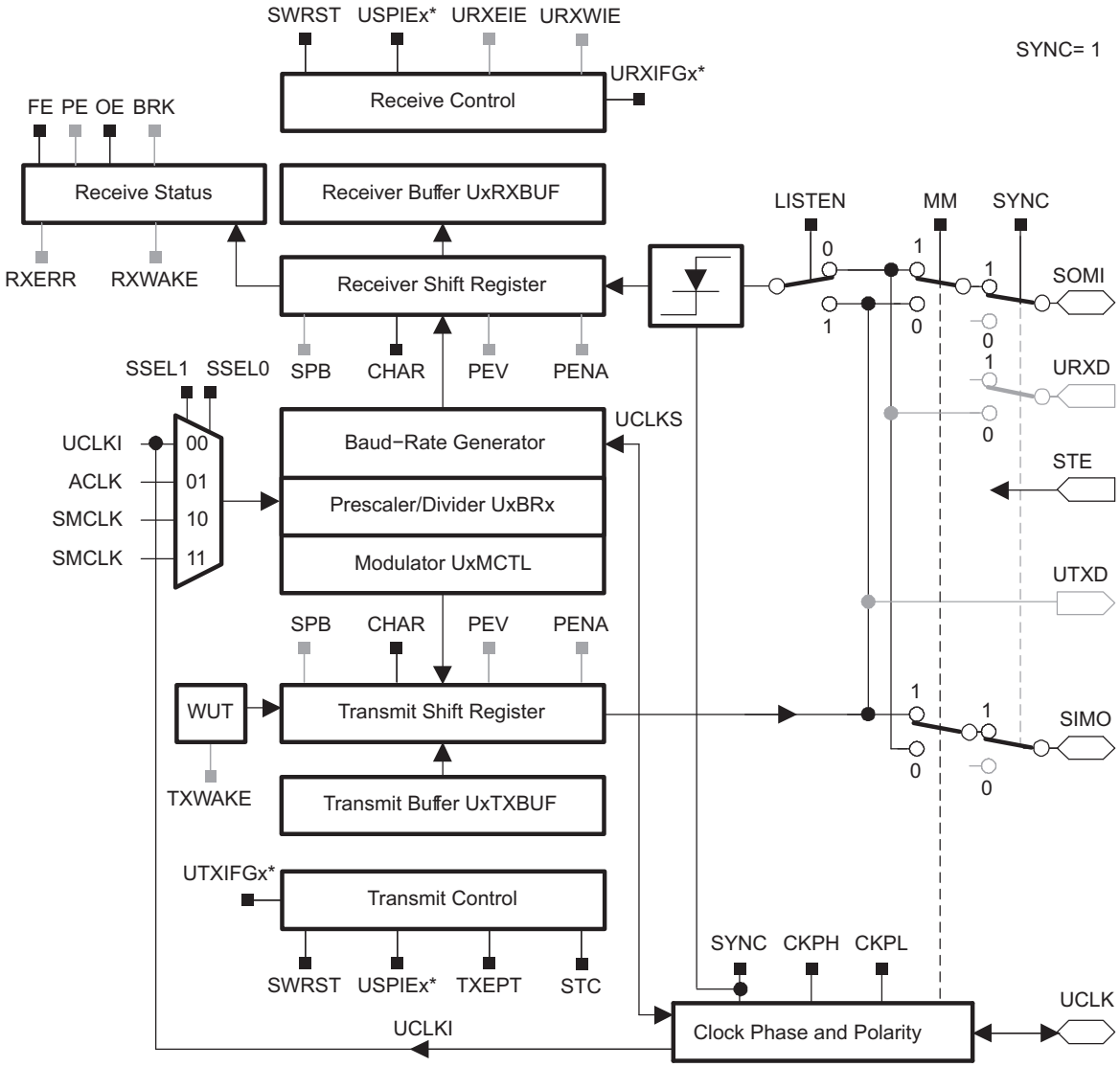
19.1 USART Introduction: SPI Mode

In synchronous mode, the USART connects the MSP430 to an external system via three or four pins: SIMO, SOMI, UCLK, and STE. SPI mode is selected when the SYNC bit is set and the I2C bit is cleared.

SPI mode features include:

- 7-bit or 8-bit data length
- 3-pin and 4-pin SPI operation
- Master or slave modes
- Independent transmit and receive shift registers
- Separate transmit and receive buffer registers
- Selectable UCLK polarity and phase control
- Programmable UCLK frequency in master mode
- Independent interrupt capability for receive and transmit

Figure 19-1 shows the USART when configured for SPI mode.



* See the device-specific data sheet for SFR locations.

Figure 19-1. USART Block Diagram: SPI Mode

19.2 USART Operation: SPI Mode

In SPI mode, serial data is transmitted and received by multiple devices using a shared clock provided by the master. An additional pin, STE, is provided as to enable a device to receive and transmit data and is controlled by the master.

Three or four signals are used for SPI data exchange:

- SIMO: Slave in, master out
  - Master mode: SIMO is the data output line.
  - Slave mode: SIMO is the data input line.
- SOMI: Slave out, master in
  - Master mode: SOMI is the data input line.
  - Slave mode: SOMI is the data output line.
- UCLK: USART SPI clock
  - Master mode: UCLK is an output.
  - Slave mode: UCLK is an input.
- STE: Slave transmit enable. Used in 4-pin mode to allow multiple masters on a single bus. Not used in 3-pin mode.
  - 4-pin master mode:
    - When STE is high, SIMO and UCLK operate normally.
    - When STE is low, SIMO and UCLK are set to the input direction.
  - 4-pin slave mode:
    - When STE is high, RX/TX operation of the slave is disabled and SOMI is forced to the input direction.
    - When STE is low, RX/TX operation of the slave is enabled and SOMI operates normally.

19.2.1 USART Initialization and Reset

The USART is reset by a PUC or by the SWRST bit. After a PUC, the SWRST bit is automatically set, keeping the USART in a reset condition. When set, the SWRST bit resets the URXIEx, UTXIEx, URXIFGx, OE, and FE bits and sets the UTXIFGx flag. The USPIEx bit is not altered by SWRST. Clearing SWRST releases the USART for operation.

NOTE: Initializing or Reconfiguring the USART Module

The required USART initialization/reconfiguration process is:

1. Set SWRST (BIS.B #SWRST,&UxCTL)
2. Initialize all USART registers with SWRST=1 (including UxCTL)
3. Enable USART module via the MEx SFRs (USPIEx)
4. Clear SWRST via software (BIC.B #SWRST,&UxCTL)
5. Enable interrupts (optional) via the IEx SFRs (URXIEx and/or UTXIEx)

Failure to follow this process may result in unpredictable USART behavior.

19.2.2 Master Mode

Figure 19-2 shows the USART as a master in both 3-pin and 4-pin configurations. The USART initiates a data transfer when data is moved to the transmit data buffer UxTXBUF. The UxTXBUF data is moved to the TX shift register when the TX shift register is empty, initiating data transfer on SIMO starting with the most significant bit. Data on SOMI is shifted into the receive shift register on the opposite clock edge, starting with the most significant bit. When the character is received, the receive data is moved from the RX shift register to the received data buffer UxRXBUF and the receive interrupt flag, URXIFGx, is set, indicating the RX/TX operation is complete.

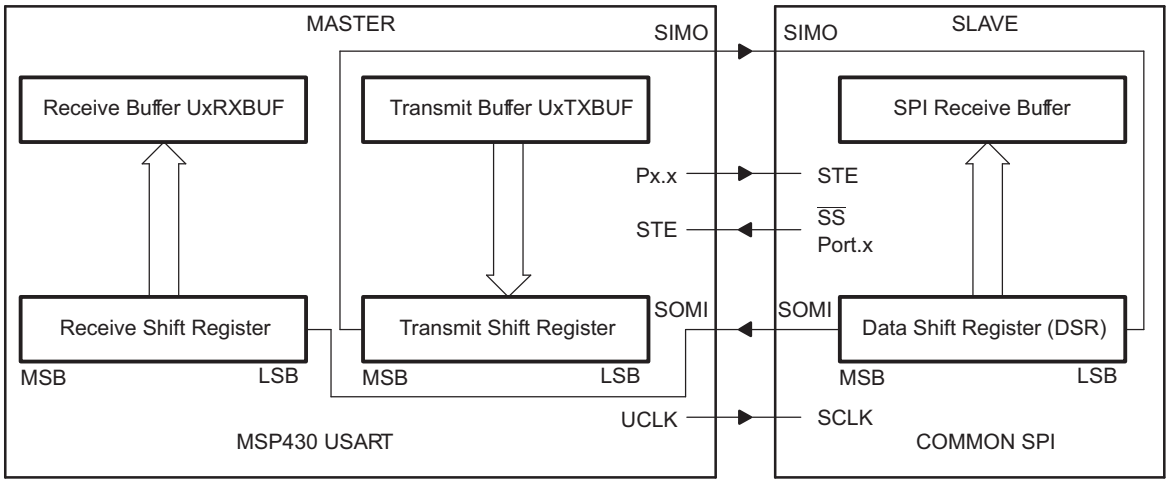


Figure 19-2. USART Master and External Slave

A set transmit interrupt flag, UTXIFGx, indicates that data has moved from UxTXBUF to the TX shift register and UxTXBUF is ready for new data. It does not indicate RX/TX completion. In master mode, the completion of an active transmission is indicated by a set transmitter empty bit TXEPT = 1.

To receive data into the USART in master mode, data must be written to UxTXBUF because receive and transmit operations operate concurrently.

19.2.2.1 Four-Pin SPI Master Mode

In 4-pin master mode, STE is used to prevent conflicts with another master. The master operates normally when STE is high. When STE is low:

- SIMO and UCLK are set to inputs and no longer drive the bus
- The error bit FE is set indicating a communication integrity violation to be handled by the user

A low STE signal does not reset the USART module. The STE input signal is not used in 3-pin master mode.

19.2.3 Slave Mode

Figure 19-3 shows the USART as a slave in both 3-pin and 4-pin configurations. UCLK is used as the input for the SPI clock and must be supplied by the external master. The data transfer rate is determined by this clock and not by the internal baud rate generator. Data written to UxTXBUF and moved to the TX shift register before the start of UCLK is transmitted on SOMI. Data on SIMO is shifted into the receive shift register on the opposite edge of UCLK and moved to UxRXBUF when the set number of bits are received. When data is moved from the RX shift register to UxRXBUF, the URXIFGx interrupt flag is set, indicating that data has been received. The overrun error bit, OE, is set when the previously received data is not read from UxRXBUF before new data is moved to UxRXBUF.

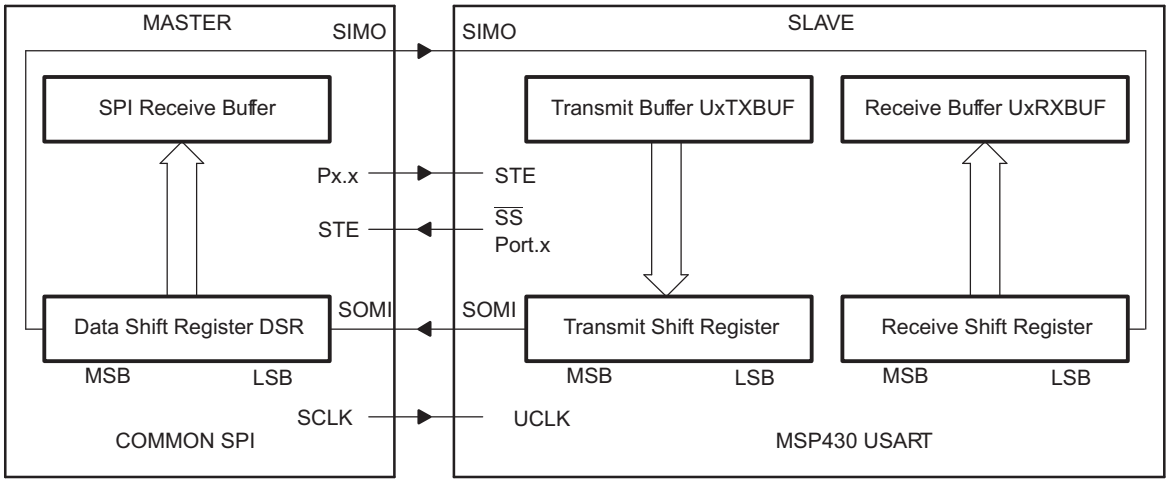


Figure 19-3. USART Slave and External Master

19.2.3.1 Four-Pin SPI Slave Mode

In 4-pin slave mode, STE is used by the slave to enable the transmit and receive operations and is provided by the SPI master. When STE is low, the slave operates normally. When STE is high:

- Any receive operation in progress on SIMO is halted
- SOMI is set to the input direction

A high STE signal does not reset the USART module. The STE input signal is not used in 3-pin slave mode.

19.2.4 SPI Enable

The SPI transmit/receive enable bit USPIEx enables or disables the USART in SPI mode. When USPIEx = 0, the USART stops operation after the current transfer completes, or immediately if no operation is active. A PUC or set SWRST bit disables the USART immediately and any active transfer is terminated.

19.2.4.1 Transmit Enable

When USPIEx = 0, any further write to UxTXBUF does not transmit. Data written to UxTXBUF begin to transmit when USPIEx = 1 and the BRCLK source is active. Figure 19-4 and Figure 19-5 show the transmit enable state diagrams.

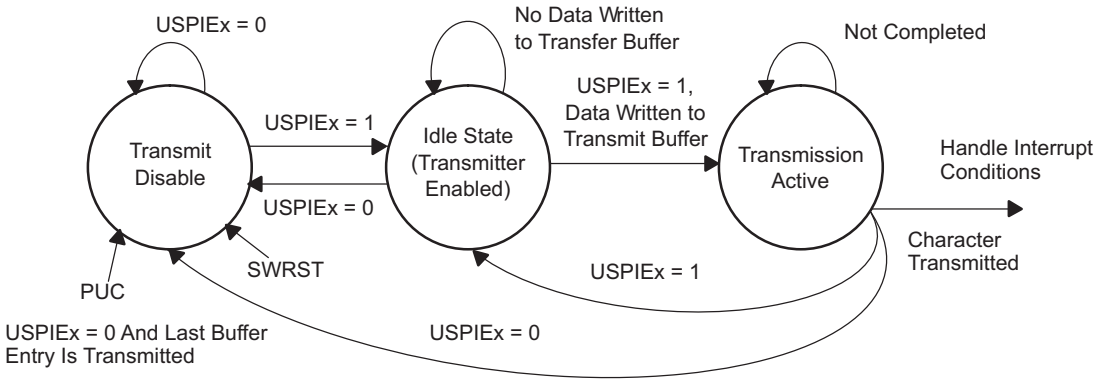


Figure 19-4. Master Transmit Enable State Diagram

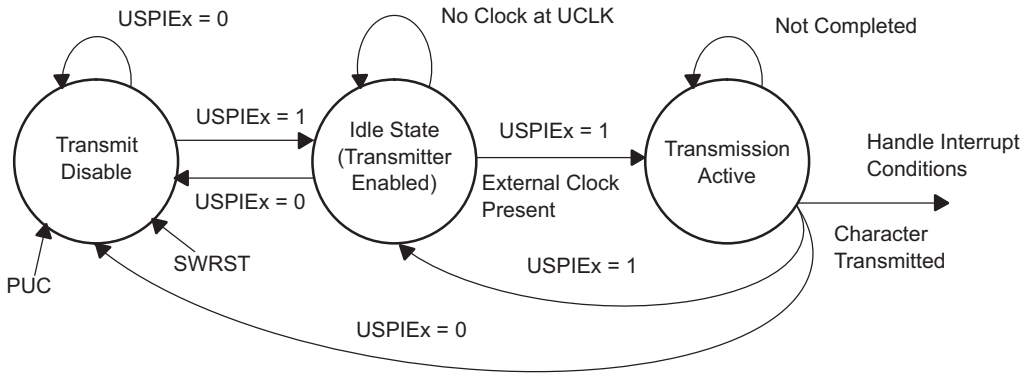


Figure 19-5. Slave Transmit Enable State Diagram

19.2.4.2 Receive Enable

The SPI receive enable state diagrams are shown in Figure 19-6 and Figure 19-7. When USPIEx = 0, UCLK is disabled from shifting data into the RX shift register.

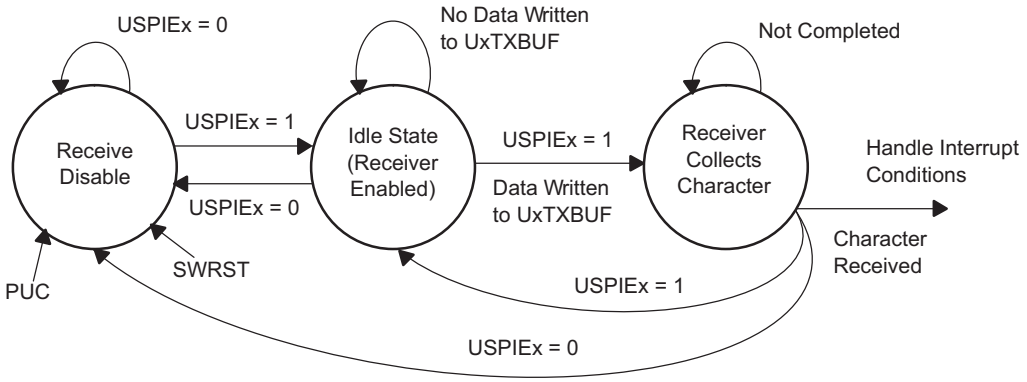


Figure 19-6. SPI Master Receive-Enable State Diagram

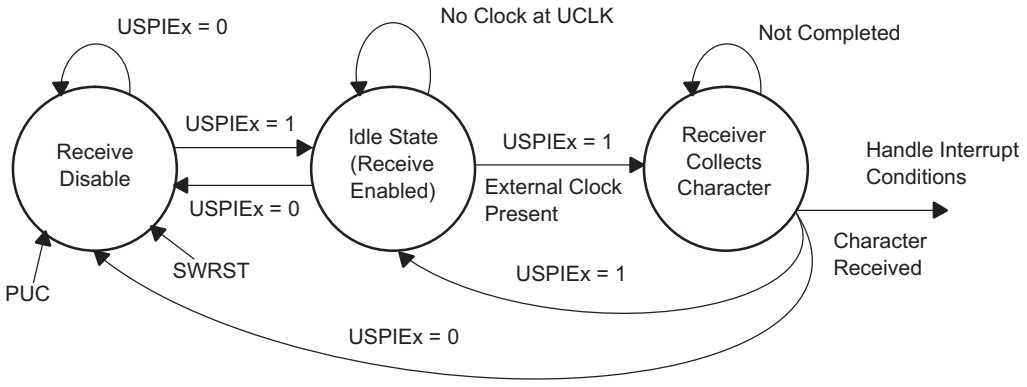


Figure 19-7. SPI Slave Receive-Enable State Diagram

19.2.5 Serial Clock Control

UCLK is provided by the master on the SPI bus. When MM = 1, BITCLK is provided by the USART baud rate generator on the UCLK pin as shown in Figure 19-8. When MM = 0, the USART clock is provided on the UCLK pin by the master and, the baud rate generator is not used and the SSELx bits are “don’t care”. The SPI receiver and transmitter operate in parallel and use the same clock source for data transfer.

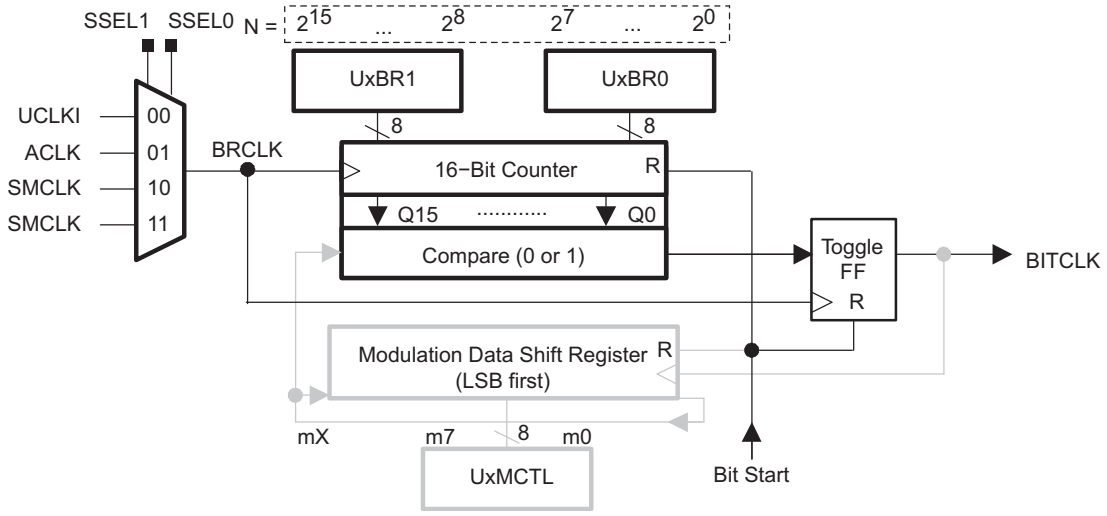


Figure 19-8. SPI Baud Rate Generator

The 16-bit value of UxBR0+UxBR1 is the division factor of the USART clock source, BRCLK. The maximum baud rate that can be generated in master mode is BRCLK/2. The maximum baud rate that can be generated in slave mode is BRCLK The modulator in the USART baud rate generator is not used for SPI mode and is recommended to be set to 000h. The UCLK frequency is given by:

$$\text{Baud rate} = \frac{\text{BRCLK}}{\text{UxBR}} \text{ with UxBR= [UxBR1, UxBR0]}$$

19.2.5.1 Serial Clock Polarity and Phase

The polarity and phase of UCLK are independently configured via the CKPL and CKPH control bits of the USART. Timing for each case is shown in Figure 19-9.

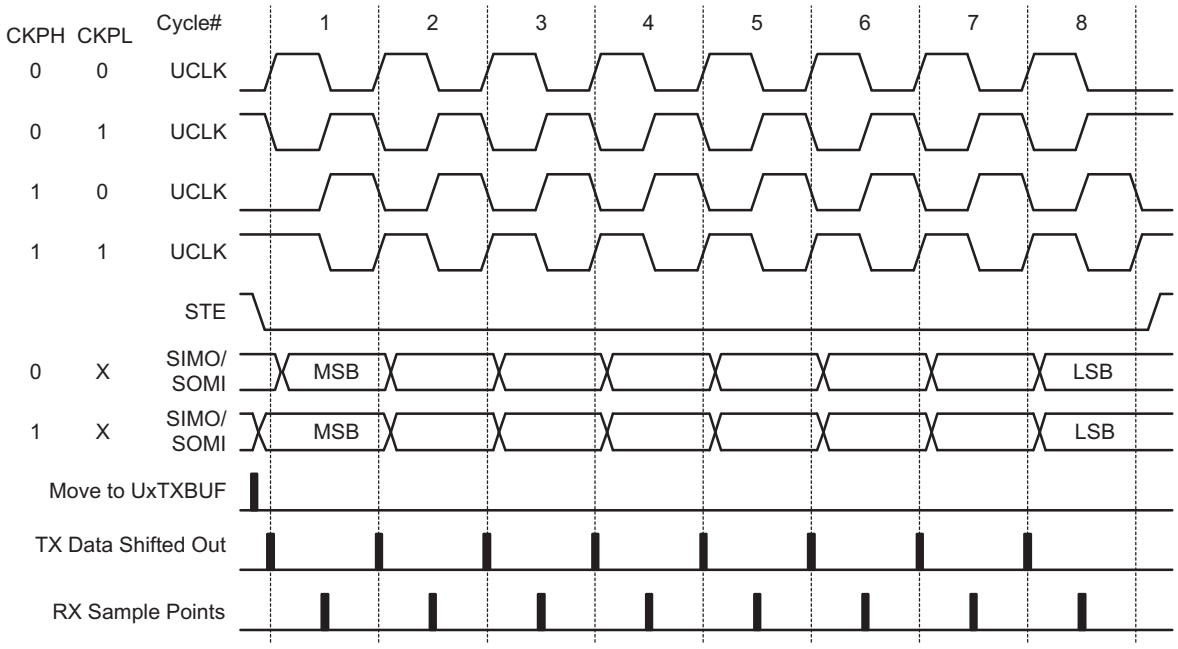


Figure 19-9. USART SPI Timing

19.2.6 SPI Interrupts

The USART has one interrupt vector for transmission and one interrupt vector for reception.

19.2.6.1 SPI Transmit Interrupt Operation

The UTXIFGx interrupt flag is set by the transmitter to indicate that UxTXBUF is ready to accept another character. An interrupt request is generated if UTXIEx and GIE are also set. UTXIFGx is automatically reset if the interrupt request is serviced or if a character is written to UxTXBUF.

UTXIFGx is set after a PUC or when SWRST = 1. UTXIEx is reset after a PUC or when SWRST = 1. The operation is shown is Figure 19-10.

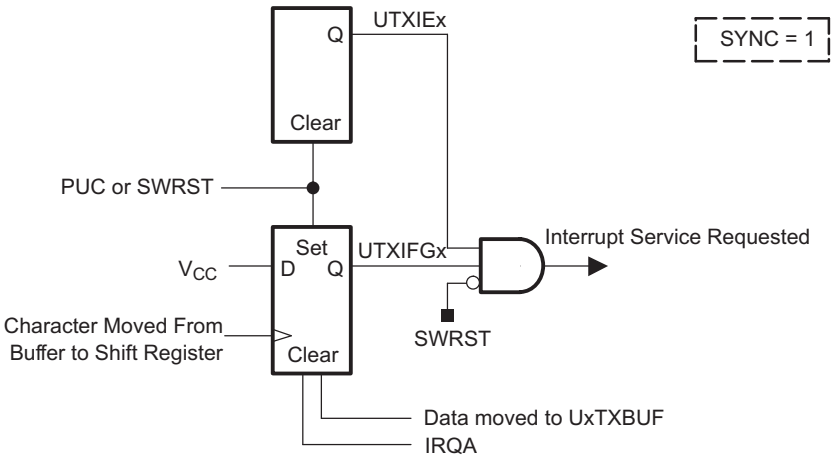


Figure 19-10. Transmit Interrupt Operation

NOTE: Writing to UxTXBUF in SPI Mode

Data written to UxTXBUF when UTXIFGx = 0 and USPIEx = 1 may result in erroneous data transmission.

19.2.6.2 SPI Receive Interrupt Operation

The URXIFGx interrupt flag is set each time a character is received and loaded into UxRXBUF as shown in Figure 19-11 and Figure 19-12. An interrupt request is generated if URXIEx and GIE are also set. URXIFGx and URXIEx are reset by a system reset PUC signal or when SWRST = 1. URXIFGx is automatically reset if the pending interrupt is served or when UxRXBUF is read.

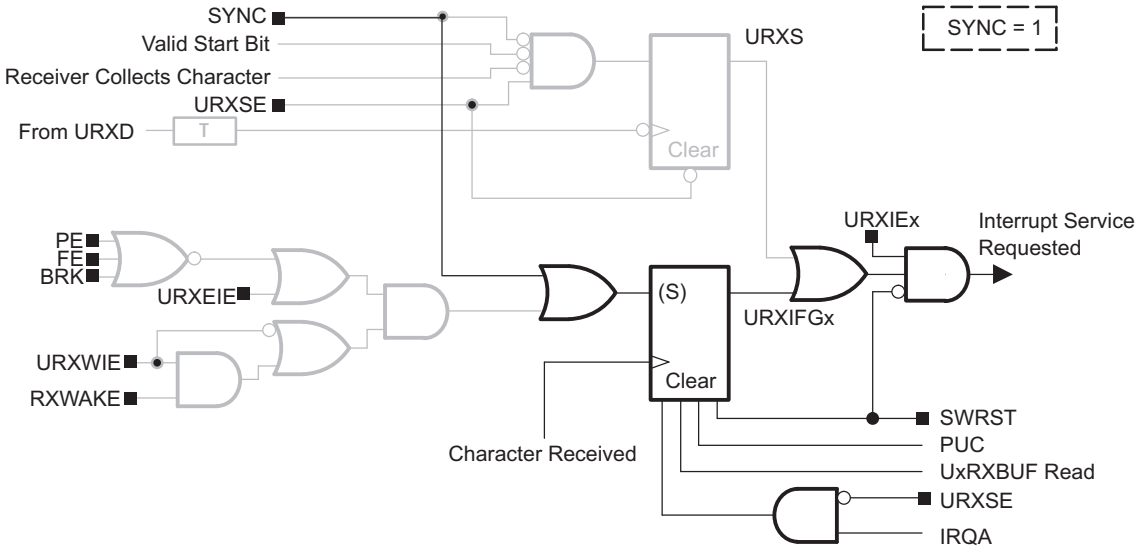


Figure 19-11. Receive Interrupt Operation

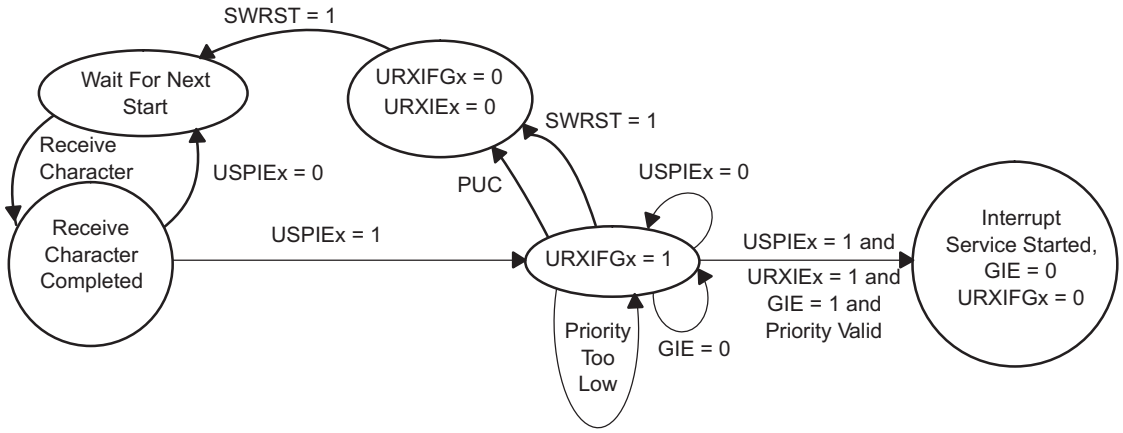


Figure 19-12. Receive Interrupt State Diagram

19.3 USART Registers: SPI Mode

Table 19-1 lists the registers for all devices implementing a USART module. Table 19-2 applies only to devices with a second USART module, USART1.

Table 19-1. USART0 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USART control register	U0CTL	Read/write	070h	001h with PUC
Transmit control register	U0TCTL	Read/write	071h	001h with PUC
Receive control register	U0RCTL	Read/write	072h	000h with PUC
Modulation control register	U0MCTL	Read/write	073h	Unchanged
Baud rate control register 0	U0BR0	Read/write	074h	Unchanged
Baud rate control register 1	U0BR1	Read/write	075h	Unchanged
Receive buffer register	U0RXBUF	Read	076h	Unchanged
Transmit buffer register	U0TXBUF	Read/write	077h	Unchanged
SFR module enable register 1	ME1	Read/write	004h	000h with PUC
SFR interrupt enable register 1	IE1	Read/write	000h	000h with PUC
SFR interrupt flag register 1	IFG1	Read/write	002h	082h with PUC

Table 19-2. USART1 Control and Status Registers

Register	Short Form	Register Type	Address	Initial State
USART control register	U1CTL	Read/write	078h	001h with PUC
Transmit control register	U1TCTL	Read/write	079h	001h with PUC
Receive control register	U1RCTL	Read/write	07Ah	000h with PUC
Modulation control register	U1MCTL	Read/write	07Bh	Unchanged
Baud rate control register 0	U1BR0	Read/write	07Ch	Unchanged
Baud rate control register 1	U1BR1	Read/write	07Dh	Unchanged
Receive buffer register	U1RXBUF	Read	07Eh	Unchanged
Transmit buffer register	U1TXBUF	Read/write	07Fh	Unchanged
SFR module enable register 2	ME2	Read/write	005h	000h with PUC
SFR interrupt enable register 2	IE2	Read/write	001h	000h with PUC
SFR interrupt flag register 2	IFG2	Read/write	003h	020h with PUC

NOTE: Modifying the SFR bits

To avoid modifying control bits for other modules, it is recommended to set or clear the IEx and IFGx bits using BIS.B or BIC.B instructions, rather than MOV.B or CLR.B instructions.

19.3.1 UxCTL, USART Control Register

7	6	5	4	3	2	1	0
Unused		I2C	CHAR	LISTEN	SYNC	MM	SWRST
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-1

Unused Bits 7-6 Unused

I2C Bit 5 I^2C mode enable. This bit selects I^2C or SPI operation when SYNC = 1.
- 0 SPI mode
- 1 I^2C mode

CHAR Bit 4 Character length
- 0 7-bit data
- 1 8-bit data

LISTEN Bit 3 Listen enable. The LISTEN bit selects the loopback mode
- 0 Disabled
- 1 Enabled. The transmit signal is internally fed back to the receiver.

SYNC Bit 2 Synchronous mode enable
- 0 UART mode
- 1 SPI mode

MM Bit 1 Master mode
- 0 USART is slave
- 1 USART is master

SWRST Bit 0 Software reset enable
- 0 Disabled. USART reset released for operation.
- 1 Enabled. USART logic held in reset state.

19.3.2 UxTCTL, USART Transmit Control Register

7	6	5	4	3	2	1	0
CKPH	CKPL	SSELx		Unused		STC	TXEPT
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-1

CKPH Bit 7 Clock phase select.
- 0 Data is changed on the first UCLK edge and captured on the following edge.
- 1 Data is captured on the first UCLK edge and changed on the following edge.

CKPL Bit 6 Clock polarity select
- 0 The inactive state is low.
- 1 The inactive state is high.

SSELx Bits 5-4 Source select. These bits select the BRCLK source clock.
- 00 External UCLK (valid for slave mode only)
- 01 ACLK (valid for master mode only)
- 10 SMCLK (valid for master mode only)
- 11 SMCLK (valid for master mode only)

Unused Bits 3-2 Unused

STC Bit 1 Slave transmit control.
- 0 4-pin SPI mode: STE enabled.
- 1 3-pin SPI mode: STE disabled.

TXEPT Bit 0 Transmitter empty flag. The TXEPT flag is not used in slave mode.
- 0 Transmission active and/or data waiting in UxTXBUF
- 1 UxTXBUF and TX shift register are empty

19.3.3 UxRCTL, USART Receive Control Register

7	6	5	4	3	2	1	0
FE	**Unused**	**OE**	**Unused**				
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

FE	Bit 7	Framing error flag. This bit indicates a bus conflict when MM = 1 and STC = 0. FE is unused in slave mode. 0 No conflict detected 1 A negative edge occurred on STE, indicating bus conflict
Unused	Bit 6	Unused
OE	Bit 5	Overrun error flag. This bit is set when a character is transferred into UxRXBUF before the previous character was read. OE is automatically reset when UxRXBUF is read, when SWRST = 1, or can be reset by software. 0 No error 1 Overrun error occurred
Unused	Bits 4-0	Unused

19.3.4 UxBR0, USART Baud Rate Control Register 0

7	6	5	4	3	2	1	0
2^7	**2^6**	**2^5**	**2^4**	**2^3**	**2^2**	**2^1**	**2^0**
rw	rw	rw	rw	rw	rw	rw	rw

19.3.5 UxBR1, USART Baud Rate Control Register 1

7	6	5	4	3	2	1	0
2^{15}	**2^{14}**	**2^{13}**	**2^{12}**	**2^{11}**	**2^{10}**	**2^9**	**2^8**
rw	rw	rw	rw	rw	rw	rw	rw

UxBRx	The baud-rate generator uses the content of {UxBR1+UxBR0} to set the baud rate. Unpredictable SPI operation occurs if UxBR < 2.

19.3.6 UxMCTL, USART Modulation Control Register

7	6	5	4	3	2	1	0
m7	**m6**	**m5**	**m4**	**m3**	**m2**	**m1**	**m0**
rw	rw	rw	rw	rw	rw	rw	rw

UxMCTLx	Bits 7-0	The modulation control register is not used for SPI mode and should be set to 000h.

19.3.7 UxRXBUF, USART Receive Buffer Register

7	6	5	4	3	2	1	0
2^7	**2^6**	**2^5**	**2^4**	**2^3**	**2^2**	**2^1**	**2^0**
r	r	r	r	r	r	r	r

UxRXBUFx	Bits 7-0	The receive-data buffer is user accessible and contains the last received character from the receive shift register. Reading UxRXBUF resets the OE bit and URXIFGx flag. In 7-bit data mode, UxRXBUF is LSB justified and the MSB is always reset.

19.3.8 UxTXBUF, USART Transmit Buffer Register

7	6	5	4	3	2	1	0
2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
rw	rw	rw	rw	rw	rw	rw	rw

UxTXBUFx	Bits 7-0	The transmit data buffer is user accessible and contains current data to be transmitted. When seven-bit character-length is used, the data should be MSB justified before being moved into UxTXBUF. Data is transmitted MSB first. Writing to UxTXBUF clears UTXIFGx.

19.3.9 ME1, Module Enable Register 1

7	6	5	4	3	2	1	0
	USPIE0						
	rw-0						

	Bit 7	This bit may be used by other modules. See device-specific data sheet.
USPIE0	Bit 6	USART0 SPI enable. This bit enables the SPI mode for USART0. 0 Module not enabled 1 Module enabled
	Bits 5-0	These bits may be used by other modules. See device-specific data sheet.

19.3.10 ME2, Module Enable Register 2

7	6	5	4	3	2	1	0
			USPIE1				
			rw-0				

	Bits 7-5	These bits may be used by other modules. See device-specific data sheet.
USPIE1	Bit 4	USART1 SPI enable. This bit enables the SPI mode for USART1. 0 Module not enabled 1 Module enabled
	Bits 3-0	These bits may be used by other modules. See device-specific data sheet.

19.3.11 IE1, Interrupt Enable Register 1

7	6	5	4	3	2	1	0
UTXIE0	**URXIE0**						
rw-0	rw-0						

UTXIE0	Bit 7	USART0 transmit interrupt enable. This bit enables the UTXIFG0 interrupt. 0 Interrupt not enabled 1 Interrupt enabled
URXIE0	Bit 6	USART0 receive interrupt enable. This bit enables the URXIFG0 interrupt. 0 Interrupt not enabled 1 Interrupt enabled
	Bits 5-0	These bits may be used by other modules. See device-specific data sheet.

19.3.12 IE2, Interrupt Enable Register 2

7	6	5	4	3	2	1	0
		UTXIE1	**URXIE1**				
		rw-0	rw-0				

	Bits 7-6	These bits may be used by other modules. See device-specific data sheet.
UTXIE1	Bit 5	USART1 transmit interrupt enable. This bit enables the UTXIFG1 interrupt.
		0 Interrupt not enabled
		1 Interrupt enabled
URXIE1	Bit 4	USART1 receive interrupt enable. This bit enables the URXIFG1 interrupt.
		0 Interrupt not enabled
		1 Interrupt enabled
	Bits 3-0	These bits may be used by other modules. See device-specific data sheet.

19.3.13 IFG1, Interrupt Flag Register 1

7	6	5	4	3	2	1	0
UTXIFG0	**URXIFG0**						
rw-1	rw-0						

UTXIFG0	Bit 7	USART0 transmit interrupt flag. UTXIFG0 is set when U0TXBUF is empty.
		0 No interrupt pending
		1 Interrupt pending
URXIFG0	Bit 6	USART0 receive interrupt flag. URXIFG0 is set when U0RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending
	Bits 5-0	These bits may be used by other modules. See device-specific data sheet.

19.3.14 IFG2, Interrupt Flag Register 2

7	6	5	4	3	2	1	0
		UTXIFG1	**URXIFG1**				
		rw-1	rw-0				

	Bits 7-6	These bits may be used by other modules. See device-specific data sheet.
UTXIFG1	Bit 5	USART1 transmit interrupt flag. UTXIFG1 is set when U1TXBUF empty.
		0 No interrupt pending
		1 Interrupt pending
URXIFG1	Bit 4	USART1 receive interrupt flag. URXIFG1 is set when U1RXBUF has received a complete character.
		0 No interrupt pending
		1 Interrupt pending
	Bits 3-0	These bits may be used by other modules. See device-specific data sheet.

OA

The OA is a general purpose operational amplifier. This chapter describes the OA. Two OA modules are implemented in the MSP430x22x4 devices.

Topic **Page**

20.1 OA Introduction

The OA operational amplifiers support front-end analog signal conditioning prior to analog-to-digital conversion.

Features of the OA include:

- Single supply, low-current operation
- Rail-to-rail output
- Programmable settling time vs. power consumption
- Software selectable configurations
- Software selectable feedback resistor ladder for PGA implementations

NOTE: Multiple OA Modules

Some devices may integrate more than one OA module. If more than one OA is present on a device, the multiple OA modules operate identically.

Throughout this chapter, nomenclature appears such as OAxCTL0 to describe register names. When this occurs, the x is used to indicate which OA module is being discussed. In cases where operation is identical, the register is simply referred to as OAxCTL0.

The block diagram of the OA module is shown in Figure 20-1.

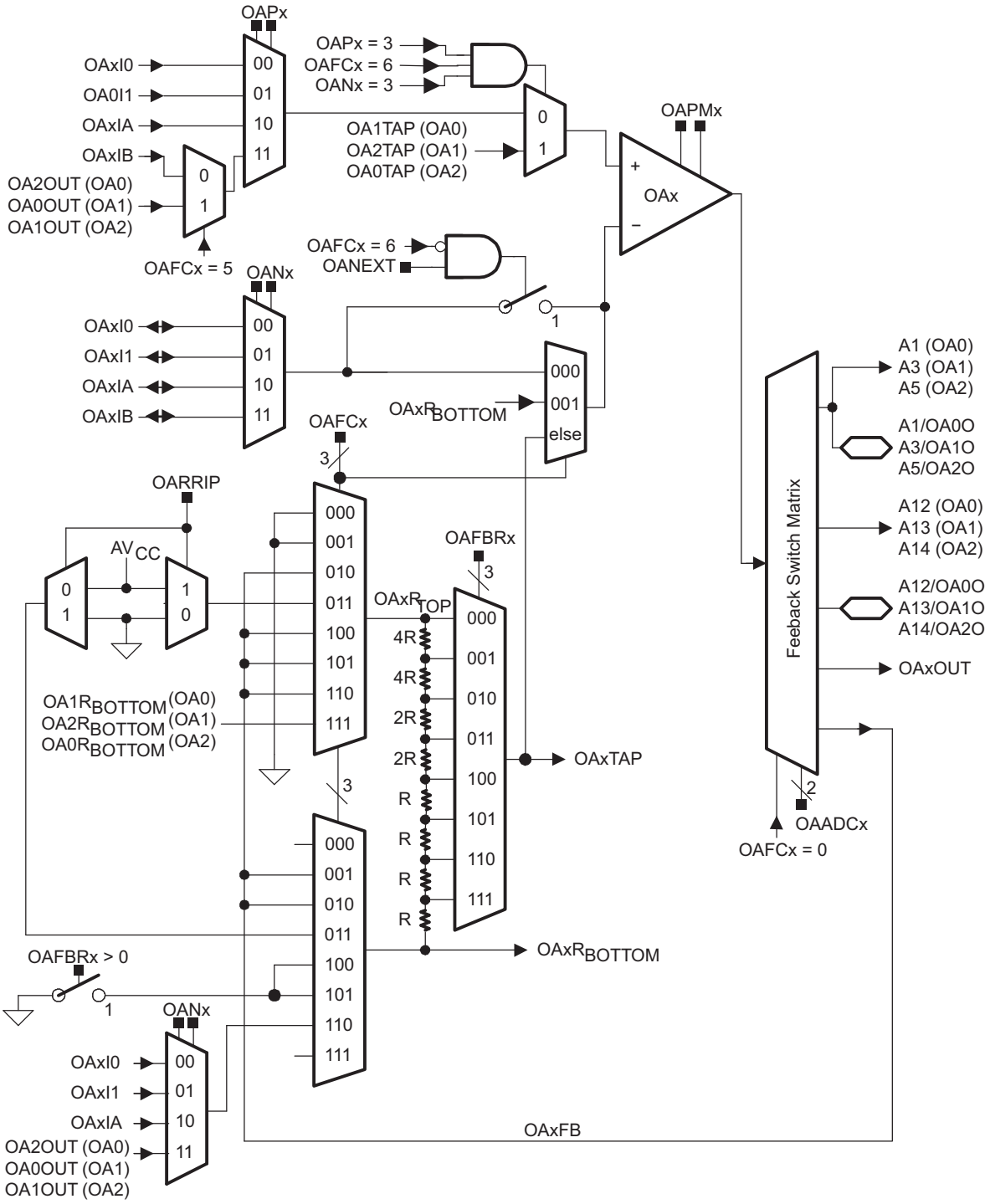


Figure 20-1. OA Block Diagram

20.2 OA Operation

The OA module is configured with user software. The setup and operation of the OA is discussed in the following sections.

20.2.1 OA Amplifier

The OA is a configurable, low-current, rail-to-rail output operational amplifier. It can be configured as an inverting amplifier, or a non-inverting amplifier, or can be combined with other OA modules to form differential amplifiers. The output slew rate of the OA can be configured for optimized settling time vs power consumption with the OAPMx bits. When OAPMx = 00 the OA is off and the output is high-impedance. When OAPMx > 0, the OA is on. See the device-specific data sheet for parameters.

20.2.2 OA Input

The OA has configurable input selection. The signals for the + and - inputs are individually selected with the OANx and OAPx bits and can be selected as external signals or internal signals. OAxI0 and OAxI1 are external signals provided for each OA module. OA0I1 provides a non-inverting input that is tied together internally for all OA modules. OAxIA and OAxIB provide device-dependent inputs. See the device data sheet for signal connections.

When the external inverting input is not needed for a mode, setting the OANEXT bit makes the internal inverting input externally available.

20.2.3 OA Output and Feedback Routing

The OA has configurable output selection controlled by the OAADCx bits and the OAFCx bits. The OA output signals can be routed to ADC inputs A12 (OA0), A13 (OA1), or A14 (OA2) internally, or can be routed to these ADC inputs and their external pins. The OA output signals can also be routed to ADC inputs A1 (OA0), A3 (OA1), or A5 (OA2) and the corresponding external pin. The OA output is also connected to an internal R-ladder with the OAFCx bits. The R-ladder tap is selected with the OAFBRx bits to provide programmable gain amplifier functionality.

Table 20-1 shows the OA output and feedback routing configurations. When OAFCx = 0 the OA is in general-purpose mode and feedback is achieved externally to the device. When OAFCx > 0 and when OAADCx = 00 or 11, the output of the OA is kept internal to the device. When OAFCx > 0 and OAADCx = 01 or 10, the OA output is routed both internally and externally.

Table 20-1. OA Output Configurations

OAFCx	OAADCx	OA Output and Feedback Routing
= 0	x0	OAxOUT connected to external pins and ADC input A1, A3, or A5.
= 0	x1	OAxOUT connected to external pins and ADC input A12, A13, or A14.
> 0	00	OAxOUT used for internal routing only.
> 0	01	OAxOUT connected to external pins and ADC input A12, A13, or A14.
> 0	10	OAxOUT connected to external pins and ADC input A1, A3, or A5.
> 0	11	OAxOUT connected internally to ADC input A12, A13 , or A14. External A12, A13, or A14 pin connections are disconnected from the ADC.

20.2.4 OA Configurations

The OA can be configured for different amplifier functions with the OAFCx bits as listed in Table 20-2.

Table 20-2. OA Mode Select

OAFCx	OA Mode
000	General-purpose opamp
001	Unity gain buffer for three-opamp differential amplifier
010	Unity gain buffer
011	Comparator
100	Non-inverting PGA amplifier
101	Cascaded non-inverting PGA amplifier
110	Inverting PGA amplifier
111	Differential amplifier

20.2.4.1 General Purpose Opamp Mode

In this mode the feedback resistor ladder is isolated from the OAx and the OAxCTL0 bits define the signal routing. The OAx inputs are selected with the OAPx and OANx bits. The OAx output is connected to the ADC input channel as selected by the OAxCTL0 bits.

20.2.4.2 Unity Gain Mode for Differential Amplifier

In this mode the output of the OAx is connected to the inverting input of the OAx providing a unity gain buffer. The non-inverting input is selected by the OAPx bits. The external connection for the inverting input is disabled and the OANx bits are don't care. The output of the OAx is also routed through the resistor ladder as part of the three-opamp differential amplifier. This mode is only for construction of the three-opamp differential amplifier.

20.2.4.3 Unity Gain Mode

In this mode the output of the OAx is connected to the inverting input of the OAx providing a unity gain buffer. The non-inverting input is selected by the OAPx bits. The external connection for the inverting input is disabled and the OANx bits are don't care. The OAx output is connected to the ADC input channel as selected by the OAxCTL0 bits.

20.2.4.4 Comparator Mode

In this mode the output of the OAx is isolated from the resistor ladder. R_{TOP} is connected to AV_{SS} and R_{BOTTOM} is connected to AV_{CC} when OARRIP = 0. When OARRIP = 1, the connection of the resistor ladder is reversed. R_{TOP} is connected to AV_{CC} and R_{BOTTOM} is connected to $AV_{SS.}$ The OAxTAP signal is connected to the inverting input of the OAx providing a comparator with a programmable threshold voltage selected by the OAFBRx bits. The non-inverting input is selected by the OAPx bits. Hysteresis can be added by an external positive feedback resistor. The external connection for the inverting input is disabled and the OANx bits are don't care. The OAx output is connected to the ADC input channel as selected by the OAxCTL0 bits.

20.2.4.5 Non-Inverting PGA Mode

In this mode the output of the OAx is connected to R_{TOP} and R_{BOTTOM} is connected to AV_{SS}. The OAxTAP signal is connected to the inverting input of the OAx providing a non-inverting amplifier configuration with a programmable gain of [1+OAxTAP ratio]. The OAxTAP ratio is selected by the OAFBRx bits. If the OAFBRx bits = 0, the gain is unity. The non-inverting input is selected by the OAPx bits. The external connection for the inverting input is disabled and the OANx bits are don't care. The OAx output is connected to the ADC input channel as selected by the OAxCTL0 bits.

20.2.4.6 Cascaded Non-Inverting PGA Mode

This mode allows internal routing of the OA signals to cascade two or three OA in non-inverting mode. In this mode the non-inverting input of the OAx is connected to OA2OUT (OA0), OA0OUT (OA1), or OA1OUT (OA2) when OAPx = 11. The OAx outputs are connected to the ADC input channel as selected by the OAxCTL0 bits.

20.2.4.7 Inverting PGA Mode

In this mode the output of the OAx is connected to R_{TOP} and R_{BOTTOM} is connected to an analog multiplexer that multiplexes the OAxI0, OAxI1, OAxIA, or the output of one of the remaining OAs, selected with the OANx bits. The OAxTAP signal is connected to the inverting input of the OAx providing an inverting amplifier with a gain of -OAxTAP ratio. The OAxTAP ratio is selected by the OAFBRx bits. The non-inverting input is selected by the OAPx bits. The OAx output is connected to the ADC input channel as selected by the OAxCTL0 bits.

NOTE: Using OAx Negative Input Simultaneously as ADC Input

When the pin connected to the negative input multiplexer is also used as an input to the ADC, conversion errors up to 5 mV may be observed due to internal wiring voltage drops.

20.2.4.8 Differential Amplifier Mode

This mode allows internal routing of the OA signals for a two-opamp or three-opamp instrumentation amplifier. Figure 20-2 shows a two-opamp configuration with OA0 and OA1. In this mode the output of the OAx is connected to R_{TOP} by routing through another OAx in the Inverting PGA mode. R_{BOTTOM} is unconnected providing a unity gain buffer. This buffer is combined with one or two remaining OAx to form the differential amplifier. The OAx output is connected to the ADC input channel as selected by the OAxCTL0 bits.

Figure 20-2 shows an example of a two-opamp differential amplifier using OA0 and OA1. The control register settings and are shown in Table 20-3. The gain for the amplifier is selected by the OAFBRx bits for OA1 and is shown in Table 20-4. The OAx interconnections are shown in Figure 20-3.

Table 20-3. Two-Opamp Differential Amplifier Control Register Settings

Register	Settings (binary)
OA0CTL0	xx xx xx 0 0
OA0CTL1	000 111 0 x
OA1CTL0	11 xx xx x x
OA1CTL1	xxx 110 0 x

Table 20-4. Two-Opamp Differential Amplifier Gain Settings

OA1 OAFBRx	Gain
000	0
001	1/3
010	1
011	1 2/3
100	3
101	4 1/3
110	7
111	15

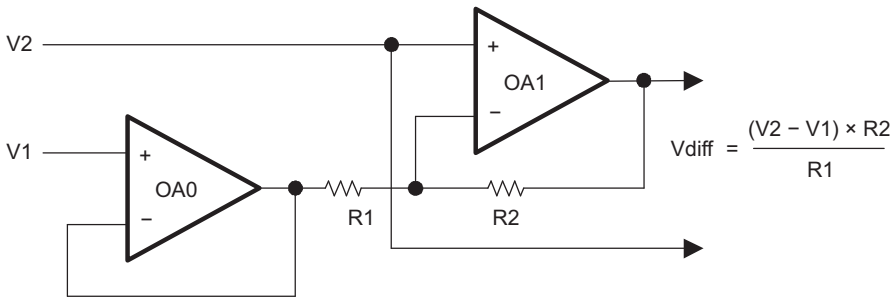


Figure 20-2. Two-Opamp Differential Amplifier

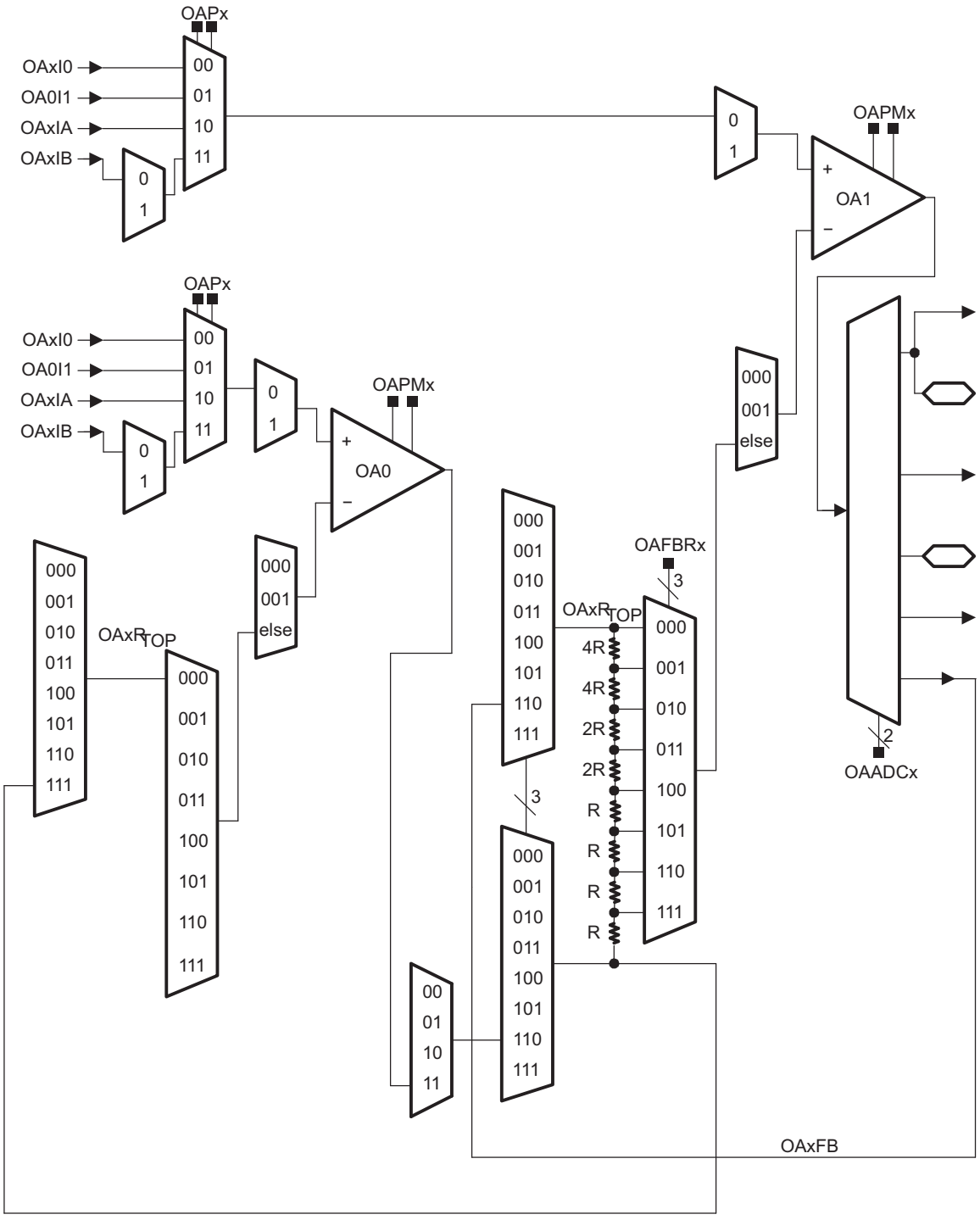


Figure 20-3. Two-Opamp Differential Amplifier OAx Interconnections

Figure 20-4 shows an example of a three-opamp differential amplifier using OA0, OA1 and OA2 (Three opamps are not available on all devices. See device-specific data sheet for implementation.). The control register settings are shown in Table 20-5. The gain for the amplifier is selected by the OAFBRx bits of OA0 and OA2. The OAFBRx settings for both OA0 and OA2 must be equal. The gain settings are shown in Table 20-6. The OAx interconnections are shown in Figure 20-5.

Table 20-5. Three-Opamp Differential Amplifier Control Register Settings

Register	Settings (binary)
OA0CTL0	xx xx xx 0 0
OA0CTL1	xxx 001 0 x
OA1CTL0	xx xx xx 0 0
OA1CTL1	000 111 0 x
OA2CTL0	11 11 xx x x
OA2CTL1	xxx 110 0 x

Table 20-6. Three-Opamp Differential Amplifier Gain Settings

OA0/OA2 OAFBRx	Gain
000	0
001	1/3
010	1
011	1 2/3
100	3
101	4 1/3
110	7
111	15

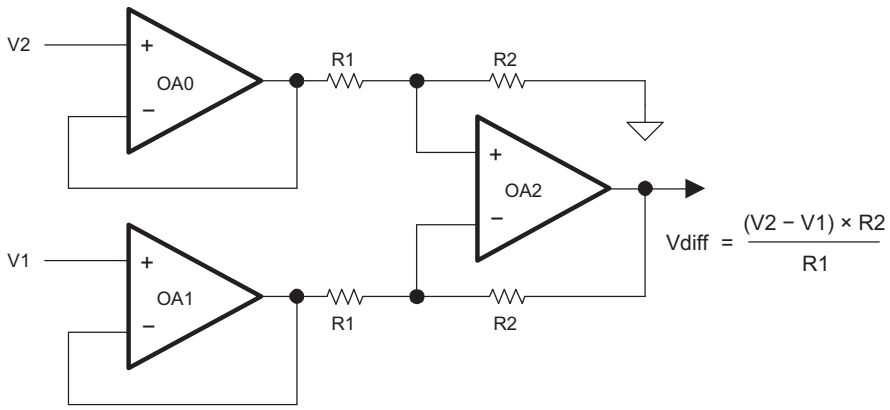


Figure 20-4. Three-Opamp Differential Amplifier

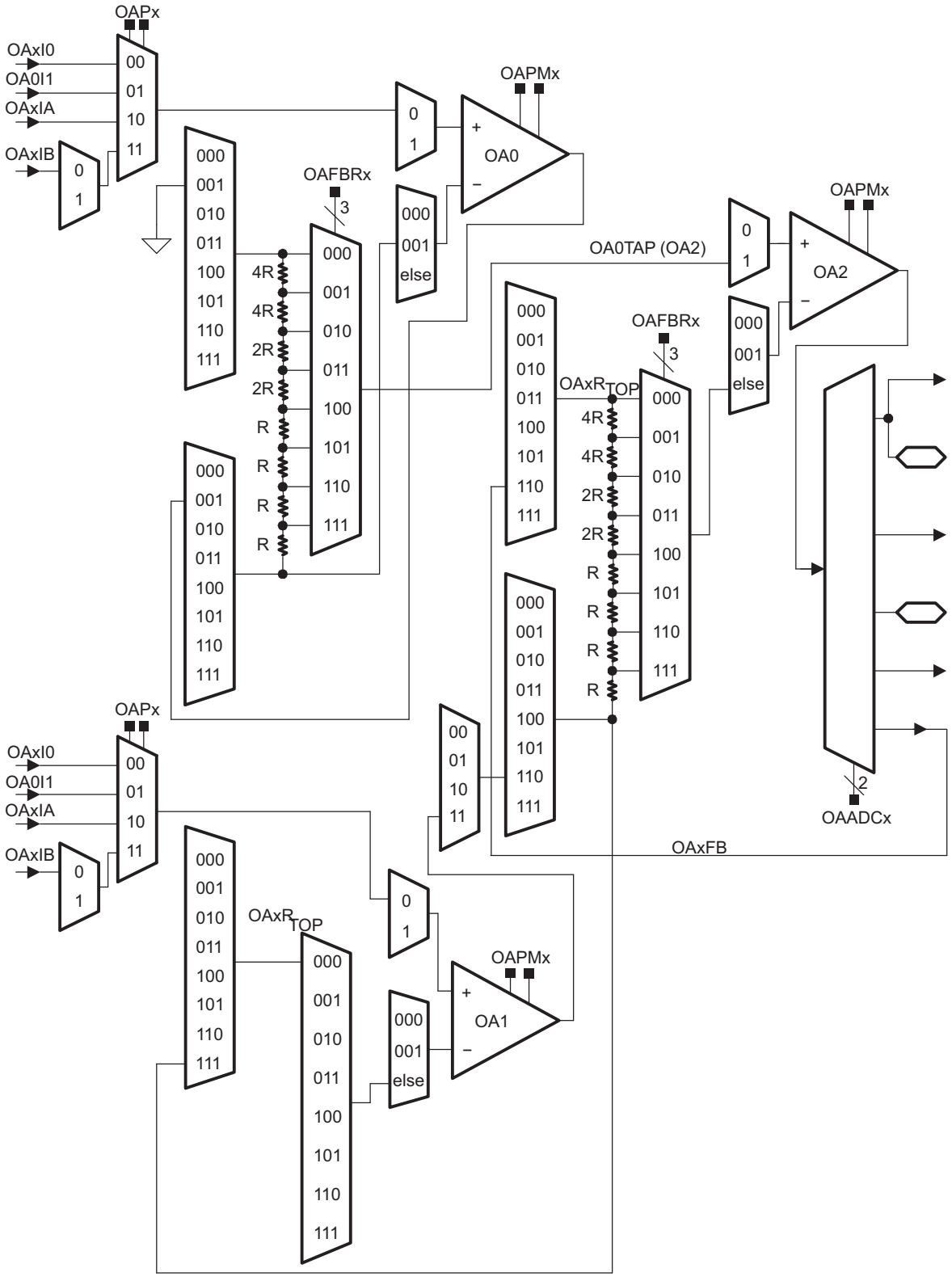


Figure 20-5. Three-Opamp Differential Amplifier OAx Interconnections

20.3 OA Registers

The OA registers are listed in Table 20-7.

Table 20-7. OA Registers

Register	Short Form	Register Type	Address	Initial State
OA0 control register 0	OA0CTL0	Read/write	0C0h	Reset with POR
OA0 control register 1	OA0CTL1	Read/write	0C1h	Reset with POR
OA1 control register 0	OA1CTL0	Read/write	0C2h	Reset with POR
OA1 control register 1	OA1CTL1	Read/write	0C3h	Reset with POR
OA2 control register 0	OA2CTL0	Read/write	0C4h	Reset with POR
OA2 control register 1	OA2CTL1	Read/write	0C5h	Reset with POR

20.3.1 OAxCTL0, Opamp Control Register 0

7	6	5	4	3	2	1	0
OANx		**OAPx**		**OAPMx**		**OAADCx**	
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

OANx Bits 7-6 Inverting input select. These bits select the input signal for the OA inverting input.

00 OAxI0

01 OAxI1

10 OAxIA (see the device-specific data sheet for connected signal)

11 OAxIB (see the device-specific data sheet for connected signal)

OAPx Bits 5-4 Non-inverting input select. These bits select the input signal for the OA non-inverting input.

00 OAxI0

01 OA0I1

10 OAxIA (see the device-specific data sheet for connected signal)

11 OAxIB (see the device-specific data sheet for connected signal)

OAPMx Bits 3-2 Slew rate select. These bits select the slew rate vs. current consumption for the OA.

00 Off, output high Z

01 Slow

10 Medium

11 Fast

OAADCx Bits 1-0 OA output select. These bits, together with the OAFCx bits, control the routing of the OAx output when OAPMx > 0.

When OAFCx = 0:

00 OAxOUT connected to external pins and ADC input A1, A3, or A5

01 OAxOUT connected to external pins and ADC input A12, A13, or A14

10 OAxOUT connected to external pins and ADC input A1, A3, or A5

11 OAxOUT connected to external pins and ADC input A12, A13, or A14

When OAFCx > 0:

00 OAxOUT used for internal routing only

01 OAxOUT connected to external pins and ADC input A12, A13, or A14

10 OAxOUT connected to external pins and ADC input A1, A3, or A5

11 OAxOUT connected internally to ADC input A12, A13 , or A14. External A12, A13, or A14 pin connections are disconnected from the ADC.

20.3.2 OAxCTL1, Opamp Control Register 1

7	6	5	4	3	2	1	0
OAFBRx			**OAFCx**			**OANEXT**	**OARRIP**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

OAFBRx Bits 7-5 OAx feedback resistor select

- 000 Tap 0 - 0R/16R
- 001 Tap 1 - 4R/12R
- 010 Tap 2 - 8R/8R
- 011 Tap 3 - 10R/6R
- 100 Tap 4 - 12R/4R
- 101 Tap 5 - 13R/3R
- 110 Tap 6 - 14R/2R
- 111 Tap 7 - 15R/1R

OAFCx Bits 4-2 OAx function control. This bit selects the function of OAx

- 000 General purpose opamp
- 001 Unity gain buffer for three-opamp differential amplifier
- 010 Unity gain buffer
- 011 Comparator
- 100 Non-inverting PGA amplifier
- 101 Cascaded non-inverting PGA amplifier
- 110 Inverting PGA amplifier
- 111 Differential amplifier

OANEXT Bit 1 OAx inverting input externally available. This bit, when set, connects the inverting OAx input to the external pin when the integrated resistor network is used.

- 0 OAx inverting input not externally available
- 1 OAx inverting input externally available

OARRIP Bit 0 OAx reverse resistor connection in comparator mode

- 0 R_{TOP} is connected to AV_{SS} and R_{BOTTOM} is connected to AV_{CC} when OAFCx = 3
- 1 R_{TOP} is connected to AV_{CC} and R_{BOTTOM} is connected to AV_{SS} when OAFCx = 3.

Comparator_A+

Comparator_A+ is an analog voltage comparator. This chapter describes the operation of the Comparator_A+ of the 2xx family.

Topic **Page**

21.1 Comparator_A+ Introduction

The Comparator_A+ module supports precision slope analog-to-digital conversions, supply voltage supervision, and monitoring of external analog signals.

Features of Comparator_A+ include:

- Inverting and non-inverting terminal input multiplexer
- Software selectable RC-filter for the comparator output
- Output provided to Timer_A capture input
- Software control of the port input buffer
- Interrupt capability
- Selectable reference voltage generator
- Comparator and reference generator can be powered down
- Input Multiplexer

The Comparator_A+ block diagram is shown in Figure 21-1.

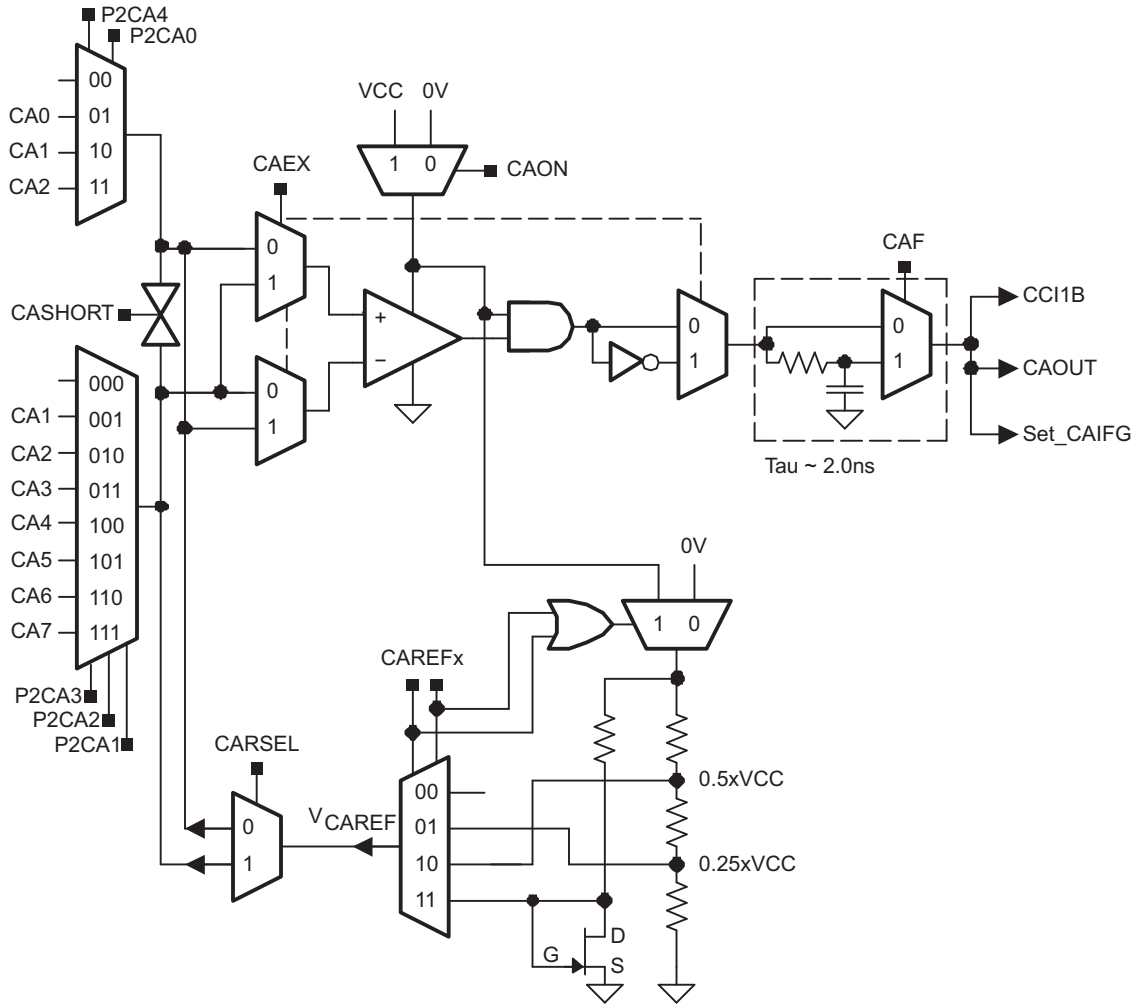


Figure 21-1. Comparator_A+ Block Diagram

NOTE: **MSP430G2210:** Channels 2, 5, 6, and 7 are available. Other channels should not be enabled.

21.2 Comparator_A+ Operation

The Comparator_A+ module is configured with user software. The setup and operation of Comparator_A+ is discussed in the following sections.

21.2.1 Comparator

The comparator compares the analog voltages at the + and - input terminals. If the + terminal is more positive than the - terminal, the comparator output CAOUT is high. The comparator can be switched on or off using control bit CAON. The comparator should be switched off when not in use to reduce current consumption. When the comparator is switched off, the CAOUT is always low.

21.2.2 Input Analog Switches

The analog input switches connect or disconnect the two comparator input terminals to associated port pins using the P2CAx bits. Both comparator terminal inputs can be controlled individually. The P2CAx bits allow:

- Application of an external signal to the + and - terminals of the comparator
- Routing of an internal reference voltage to an associated output port pin

Internally, the input switch is constructed as a T-switch to suppress distortion in the signal path.

NOTE: Comparator Input Connection

When the comparator is on, the input terminals should be connected to a signal, power, or ground. Otherwise, floating levels may cause unexpected interrupts and increased current consumption.

NOTE: MSP430G2210: Comparator channels 0, 1, 3, and 4 are implemented but not available at the device pins. To avoid floating inputs, these comparator inputs should not be enabled.

The CAEX bit controls the input multiplexer, exchanging which input signals are connected to the comparator's + and - terminals. Additionally, when the comparator terminals are exchanged, the output signal from the comparator is inverted. This allows the user to determine or compensate for the comparator input offset voltage.

21.2.3 Input Short Switch

The CASHORT bit shorts the comparator_A+ inputs. This can be used to build a simple sample-and-hold for the comparator as shown in Figure 21-2.

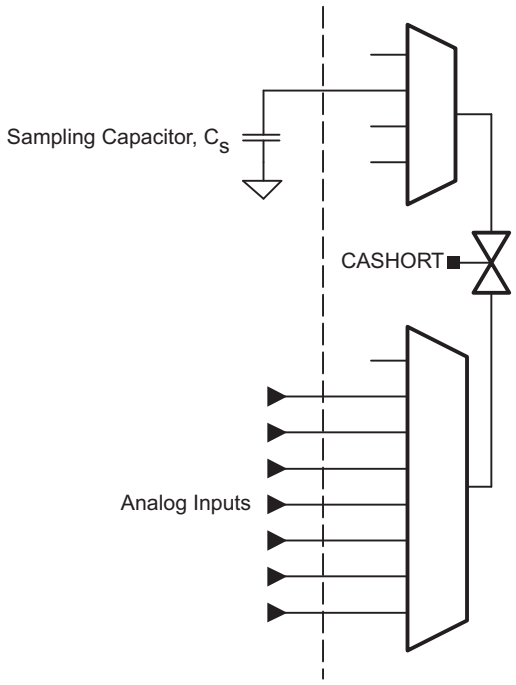


Figure 21-2. Comparator_A+ Sample-And-Hold

The required sampling time is proportional to the size of the sampling capacitor (C_S), the resistance of the input switches in series with the short switch (R_i), and the resistance of the external source (R_S). The total internal resistance (R_I) is typically in the range of 2 to 10 kΩ. The sampling capacitor C_S should be greater than 100 pF. The time constant, Tau, to charge the sampling capacitor C_S can be calculated with the following equation:

$$Tau = (R_I + R_S) \times C_S$$

Depending on the required accuracy 3 to 10 Tau should be used as a sampling time. With 3 Tau the sampling capacitor is charged to approximately 95% of the input signals voltage level, with 5 Tau it is charge to more than 99% and with 10 Tau the sampled voltage is sufficient for 12-bit accuracy.

21.2.4 Output Filter

The output of the comparator can be used with or without internal filtering. When control bit CAF is set, the output is filtered with an on-chip RC-filter.

Any comparator output oscillates if the voltage difference across the input terminals is small. Internal and external parasitic effects and cross coupling on and between signal lines, power supply lines, and other parts of the system are responsible for this behavior as shown in Figure 21-3. The comparator output oscillation reduces accuracy and resolution of the comparison result. Selecting the output filter can reduce errors associated with comparator oscillation.

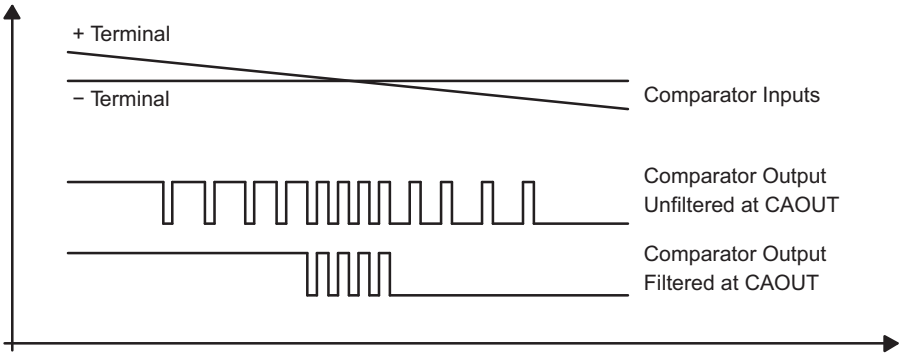


Figure 21-3. RC-Filter Response at the Output of the Comparator

21.2.5 Voltage Reference Generator

The voltage reference generator is used to generate V_{CAREF},which can be applied to either comparator input terminal. The CAREFx bits control the output of the voltage generator. The CARSEL bit selects the comparator terminal to which V_{CAREF} is applied. If external signals are applied to both comparator input terminals, the internal reference generator should be turned off to reduce current consumption. The voltage reference generator can generate a fraction of the device's V_{CC} or a fixed transistor threshold voltage of ~0.55 V.

21.2.6 Comparator_A+, Port Disable Register CAPD

The comparator input and output functions are multiplexed with the associated I/O port pins, which are digital CMOS gates. When analog signals are applied to digital CMOS gates, parasitic current can flow from VCC to GND. This parasitic current occurs if the input voltage is near the transition level of the gate. Disabling the port pin buffer eliminates the parasitic current flow and therefore reduces overall current consumption.

The CAPDx bits, when set, disable the corresponding pin input and output buffers as shown in Figure 21-4. When current consumption is critical, any port pin connected to analog signals should be disabled with its CAPDx bit.

Selecting an input pin to the comparator multiplexer with the P2CAx bits automatically disables the input and output buffers for that pin, regardless of the state of the associated CAPDx bit.

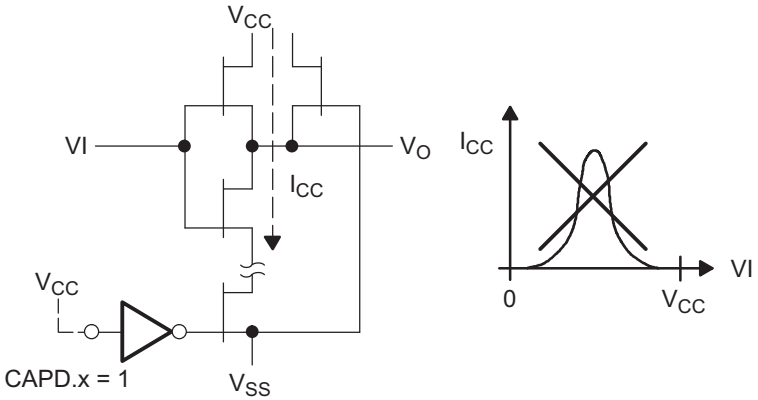


Figure 21-4. Transfer Characteristic and Power Dissipation in a CMOS Inverter/Buffer

NOTE: **MSP430G2210:**The channels 0, 1, 3, an 4 are implemented by not available at pins. To avoid floating inputs these inputs should not be used.

21.2.7 Comparator_A+ Interrupts

One interrupt flag and one interrupt vector are associated with the Comparator_A+ as shown in Figure 21-5. The interrupt flag CAIFG is set on either the rising or falling edge of the comparator output, selected by the CAIES bit. If both the CAIE and the GIE bits are set, then the CAIFG flag generates an interrupt request. The CAIFG flag is automatically reset when the interrupt request is serviced or may be reset with software.

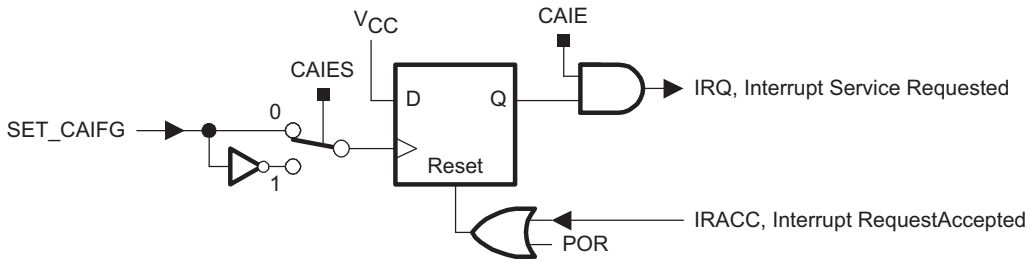


Figure 21-5. Comparator_A+ Interrupt System

21.2.8 Comparator_A+ Used to Measure Resistive Elements

The Comparator_A+ can be optimized to precisely measure resistive elements using single slope analog-to-digital conversion. For example, temperature can be converted into digital data using a thermistor, by comparing the thermistor's capacitor discharge time to that of a reference resistor as shown in Figure 21-6. A reference resister Rref is compared to Rmeas.

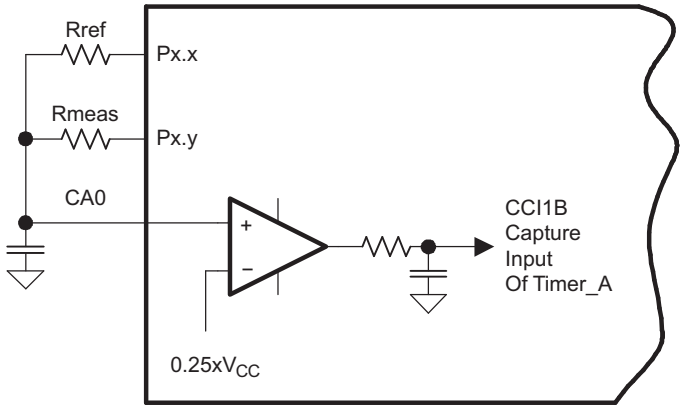


Figure 21-6. Temperature Measurement System

The MSP430 resources used to calculate the temperature sensed by Rmeas are:

- Two digital I/O pins to charge and discharge the capacitor.
- I/O set to output high (V_{CC}) to charge capacitor, reset to discharge.
- I/O switched to high-impedance input with CAPDx set when not in use.
- One output charges and discharges the capacitor via Rref.
- One output discharges capacitor via Rmeas.
- The + terminal is connected to the positive terminal of the capacitor.
- The - terminal is connected to a reference level, for example 0.25 x V_{CC}.
- The output filter should be used to minimize switching noise.
- CAOUT used to gate Timer_A CCI1B, capturing capacitor discharge time.

More than one resistive element can be measured. Additional elements are connected to CA0 with available I/O pins and switched to high impedance when not being measured.

The thermistor measurement is based on a ratiometric conversion principle. The ratio of two capacitor discharge times is calculated as shown in Figure 21-7.

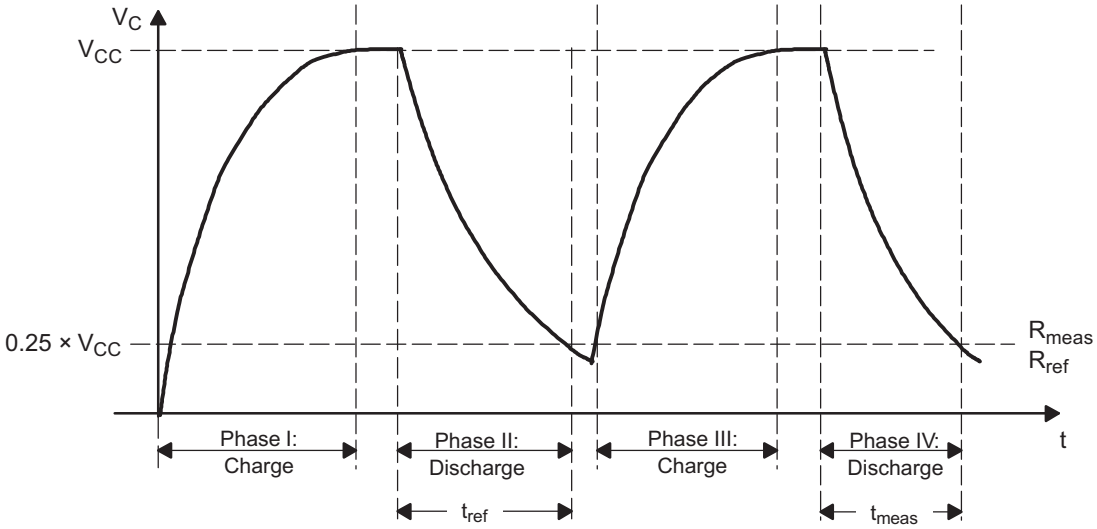


Figure 21-7. Timing for Temperature Measurement Systems

The V_{CC} voltage and the capacitor value should remain constant during the conversion, but are not critical since they cancel in the ratio:

$$\frac{N_{meas}}{N_{ref}} = \frac{-R_{meas} \times C \times \ln \frac{V_{ref}}{V_{CC}}}{-R_{ref} \times C \times \ln \frac{V_{ref}}{V_{CC}}}$$

$$\frac{N_{meas}}{N_{ref}} = \frac{R_{meas}}{R_{ref}}$$

$$R_{meas} = R_{ref} \times \frac{N_{meas}}{N_{ref}}$$

21.3 Comparator_A+ Registers

The Comparator_A+ registers are listed in Table 21-1.

Table 21-1. Comparator_A+ Registers

Register	Short Form	Register Type	Address	Initial State
Comparator_A+ control register 1	CACTL1	Read/write	059h	Reset with POR
Comparator_A+ control register 2	CACTL2	Read/write	05Ah	Reset with POR
Comparator_A+ port disable	CAPD	Read/write	05Bh	Reset with POR

21.3.1 CACTL1, Comparator_A+ Control Register 1

7	6	5	4	3	2	1	0
CAEX	**CARSEL**	**CAREFx**		**CAON**	**CAIES**	**CAIE**	**CAIFG**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

CAEX Bit 7 Comparator_A+ exchange. This bit exchanges the comparator inputs and inverts the comparator output.

CARSEL Bit 6 Comparator_A+ reference select. This bit selects which terminal the V_{CAREF} is applied to.

When CAEX = 0:

0 V_{CAREF} is applied to the + terminal

1 V_{CAREF} is applied to the - terminal

When CAEX = 1:

0 V_{CAREF} is applied to the - terminal

1 V_{CAREF} is applied to the + terminal

CAREF Bits 5-4 Comparator_A+ reference. These bits select the reference voltage V_{CAREF}.

00 Internal reference off. An external reference can be applied.

01 $0.25 \times V_{CC}$

10 $0.50 \times V_{CC}$

11 Diode reference is selected

CAON Bit 3 Comparator_A+ on. This bit turns on the comparator. When the comparator is off it consumes no current. The reference circuitry is enabled or disabled independently.

0 Off

1 On

CAIES Bit 2 Comparator_A+ interrupt edge select

0 Rising edge

1 Falling edge

CAIE Bit 1 Comparator_A+ interrupt enable

0 Disabled

1 Enabled

CAIFG Bit 0 The Comparator_A+ interrupt flag

0 No interrupt pending

1 Interrupt pending

21.3.2 CACTL2, Comparator_A+, Control Register

7	6	5	4	3	2	1	0
CASHORT	**P2CA4**	**P2CA3**	**P2CA2**	**P2CA1**	**P2CA0**	**CAF**	**CAOUT**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	r-(0)

CASHORT	Bit 7	Input short. This bit shorts the + and - input terminals. 0 Inputs not shorted 1 Inputs shorted
P2CA4	Bit 6	Input select. This bit together with P2CA0 selects the + terminal input when CAEX = 0 and the - terminal input when CAEX = 1.
P2CA3[(1)] **P2CA2** **P2CA1**	Bits 5-3	Input select. These bits select the - terminal input when CAEX = 0 and the + terminal input when CAEX = 1. 000 No connection 001 CA1 010 CA2 011 CA3 100 CA4 101 CA5 110 CA6 111 CA7
P2CA0	Bit 2	Input select. This bit, together with P2CA4, selects the + terminal input when CAEX = 0 and the - terminal input when CAEX = 1. 00 No connection 01 CA0 10 CA1 11 CA2
CAF	Bit 1	Comparator_A+ output filter 0 Comparator_A+ output is not filtered 1 Comparator_A+ output is filtered
CAOUT	Bit 0	Comparator_A+ output. This bit reflects the value of the comparator output. Writing this bit has no effect.

(1) **MSP430G2210**: Only channels 2, 5, 6, and 7 are available. Other channels should not be selected.

21.3.3 CAPD, Comparator_A+, Port Disable Register

7	6	5	4	3	2	1	0
CAPD7	**CAPD6**	**CAPD5**	**CAPD4**	**CAPD3**	**CAPD2**	**CAPD1**	**CAPD0**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

CAPDx[(1)]	Bits 7-0	Comparator_A+ port disable. These bits individually disable the input buffer for the pins of the port associated with Comparator_A+. For example, if CA0 is on pin P2.3, the CAPDx bits can be used to individually enable or disable each P2.x pin buffer. CAPD0 disables P2.0, CAPD1 disables P2.1, etc. 0 The input buffer is enabled. 1 The input buffer is disabled.

(1) **MSP430G2210**: Channels 2, 5, 6, and 7 are available. Other channels should not be disabled.

ADC10

The ADC10 module is a high-performance 10-bit analog-to-digital converter. This chapter describes the operation of the ADC10 module of the 2xx family in general. There are device with less than eight external input channels.

Topic **Page**

22.1 ADC10 Introduction

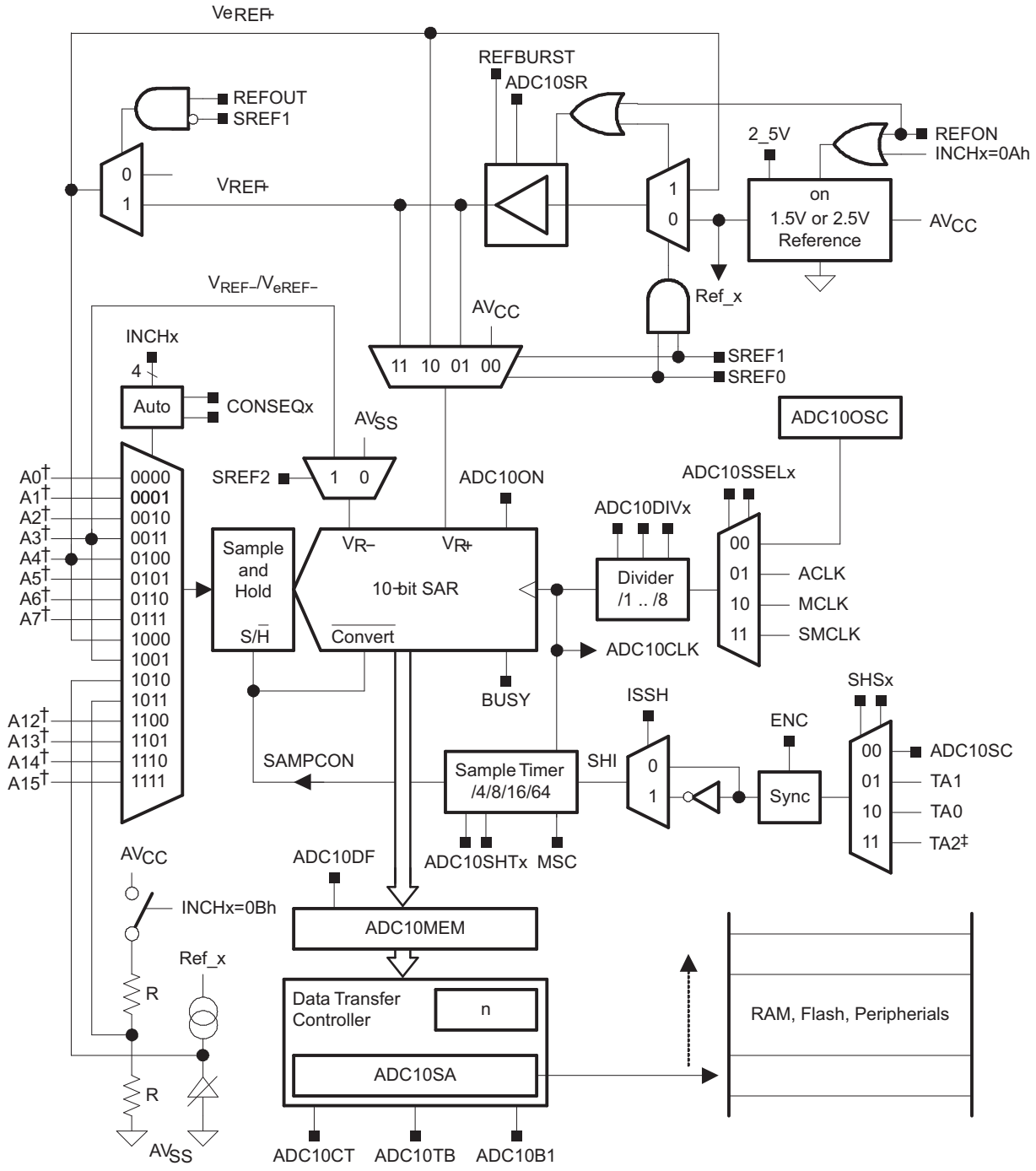
The ADC10 module supports fast, 10-bit analog-to-digital conversions. The module implements a 10-bit SAR core, sample select control, reference generator, and data transfer controller (DTC).

The DTC allows ADC10 samples to be converted and stored anywhere in memory without CPU intervention. The module can be configured with user software to support a variety of applications.

ADC10 features include:

- Greater than 200-ksps maximum conversion rate
- Monotonic 10-bit converter with no missing codes
- Sample-and-hold with programmable sample periods
- Conversion initiation by software or Timer_A
- Software selectable on-chip reference voltage generation (1.5 V or 2.5 V)
- Software selectable internal or external reference
- Up to eight external input channels (twelve on MSP430F22xx devices)
- Conversion channels for internal temperature sensor, V_{CC}, and external references
- Selectable conversion clock source
- Single-channel, repeated single-channel, sequence, and repeated sequence conversion modes
- ADC core and reference voltage can be powered down separately
- Data transfer controller for automatic storage of conversion results

The block diagram of ADC10 is shown in Figure 22-1.



†Channels A12-A15 are available in MSP430F22xx devices only. Channels A12-A15 tied to channel A11 in other devices. Not all channels are available in all devices.
‡TA1 on MSP430F20x2, MSP430G2x31, and MSP430G2x30 devices

Figure 22-1. ADC10 Block Diagram

22.2 ADC10 Operation

The ADC10 module is configured with user software. The setup and operation of the ADC10 is discussed in the following sections.

22.2.1 10-Bit ADC Core

The ADC core converts an analog input to its 10-bit digital representation and stores the result in the ADC10MEM register. The core uses two programmable/selectable voltage levels (V_{R+} and V_{R-}) to define the upper and lower limits of the conversion. The digital output (N_{ADC}) is full scale (03FFh) when the input signal is equal to or higher than V_{R+}, and zero when the input signal is equal to or lower than V_{R-}. The input channel and the reference voltage levels (V_{R+} and V_{R-}) are defined in the conversion-control memory. Conversion results may be in straight binary format or 2s-complement format. The conversion formula for the ADC result when using straight binary format is:

$$N_{ADC} = 1023 \times \frac{V_{IN} - V_{R-}}{V_{R+} - V_{R-}}$$

The ADC10 core is configured by two control registers, ADC10CTL0 and ADC10CTL1. The core is enabled with the ADC10ON bit. With few exceptions the ADC10 control bits can only be modified when ENC = 0. ENC must be set to 1 before any conversion can take place.

22.2.1.1 Conversion Clock Selection

The ADC10CLK is used both as the conversion clock and to generate the sampling period. The ADC10 source clock is selected using the ADC10SSELx bits and can be divided from 1 to 8 using the ADC10DIVx bits. Possible ADC10CLK sources are SMCLK, MCLK, ACLK, and internal oscillator ADC10OSC .

The ADC10OSC, generated internally, is in the 5-MHz range, but varies with individual devices, supply voltage, and temperature. See the device-specific data sheet for the ADC10OSC specification.

The user must ensure that the clock chosen for ADC10CLK remains active until the end of a conversion. If the clock is removed during a conversion, the operation does not complete, and any result is invalid.

22.2.2 ADC10 Inputs and Multiplexer

The eight external and four internal analog signals are selected as the channel for conversion by the analog input multiplexer. The input multiplexer is a break-before-make type to reduce input-to-input noise injection that can result from channel switching (see Figure 22-2). The input multiplexer is also a T-switch to minimize the coupling between channels. Channels that are not selected are isolated from the A/D, and the intermediate node is connected to analog ground (V_{SS}) so that the stray capacitance is grounded to help eliminate crosstalk.

The ADC10 uses the charge redistribution method. When the inputs are internally switched, the switching action may cause transients on the input signal. These transients decay and settle before causing errant conversion.

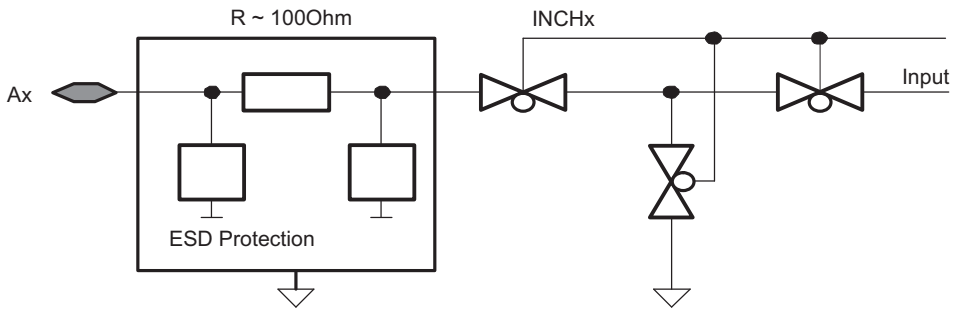


Figure 22-2. Analog Multiplexer

22.2.2.1 Analog Port Selection

The ADC10 external inputs Ax, V_{eREF+},and V_{REF-} share terminals with general purpose I/O ports, which are digital CMOS gates (see the device-specific data sheet). When analog signals are applied to digital CMOS gates, parasitic current can flow from VCC to GND. This parasitic current occurs if the input voltage is near the transition level of the gate. Disabling the port pin buffer eliminates the parasitic current flow and therefore reduces overall current consumption. The ADC10AEx bits provide the ability to disable the port pin input and output buffers.

```
; P2.3 on MSP430F22xx device configured for analog input
   BIS.B   #08h,&ADC10AE0   ; P2.3 ADC10 function and enable
```

Devices which don't have all the ADC10 external inputs channels Ax or V_{eREF+}/V_{REF+} and V_{eREF-}/V_{REF-} available at device pins must not alter the default register bit configuration of the not available pins. See device specific data sheet.

22.2.3 Voltage Reference Generator

The ADC10 module contains a built-in voltage reference with two selectable voltage levels. Setting REFON = 1 enables the internal reference. When REF2_5V = 1, the internal reference is 2.5 V. When REF2_5V = 0, the reference is 1.5 V. The internal reference voltage may be used internally (REFOUT = 0) and, when REFOUT = 1, externally on pin V_{REF+}. REFOUT = 1 should only be used if the pins $V_{REF+}$and V_{REF-} are available as device pins.

External references may be supplied for V_{R+} and V_{R-} through pins A4 and A3 respectively. When external references are used, or when V_{CC} is used as the reference, the internal reference may be turned off to save power.

An external positive reference V_{eREF+} can be buffered by setting SREF0 = 1 and SREF1 = 1 (only devices with V_{eREF+} pin). This allows using an external reference with a large internal resistance at the cost of the buffer current. When REFBURST = 1 the increased current consumption is limited to the sample and conversion period.

External storage capacitance is not required for the ADC10 reference source as on the ADC12.

22.2.3.1 Internal Reference Low-Power Features

The ADC10 internal reference generator is designed for low power applications. The reference generator includes a band-gap voltage source and a separate buffer. The current consumption of each is specified separately in the device-specific data sheet. When REFON = 1, both are enabled and when REFON = 0 both are disabled. The total settling time when REFON becomes set is approximately 30 µs.

When REFON = 1, but no conversion is active, the buffer is automatically disabled and automatically re-enabled when needed. When the buffer is disabled, it consumes no current. In this case, the bandgap voltage source remains enabled.

When REFOUT = 1, the REFBURST bit controls the operation of the internal reference buffer. When REFBURST = 0, the buffer is on continuously, allowing the reference voltage to be present outside the device continuously. When REFBURST = 1, the buffer is automatically disabled when the ADC10 is not actively converting and is automatically re-enabled when needed.

The internal reference buffer also has selectable speed versus power settings. When the maximum conversion rate is below 50 ksps, setting ADC10SR = 1 reduces the current consumption of the buffer approximately 50%.

22.2.4 Auto Power-Down

The ADC10 is designed for low power applications. When the ADC10 is not actively converting, the core is automatically disabled and is automatically re-enabled when needed. The ADC10OSC is also automatically enabled when needed and disabled when not needed. When the core or oscillator is disabled, it consumes no current.

22.2.5 Sample and Conversion Timing

An analog-to-digital conversion is initiated with a rising edge of sample input signal SHI. The source for SHI is selected with the SHSx bits and includes the following:

- The ADC10SC bit
- The Timer_A Output Unit 1
- The Timer_A Output Unit 0
- The Timer_A Output Unit 2

The polarity of the SHI signal source can be inverted with the ISSH bit. The SHTx bits select the sample period t_{sample} to be 4, 8, 16, or 64 ADC10CLK cycles. The sampling timer sets SAMPCON high for the selected sample period after synchronization with ADC10CLK.Total sampling time is t_{sample} plus t_{sync}.The high-to-low SAMPCON transition starts the analog-to-digital conversion, which requires 13 ADC10CLK cycles as shown in Figure 22-3.

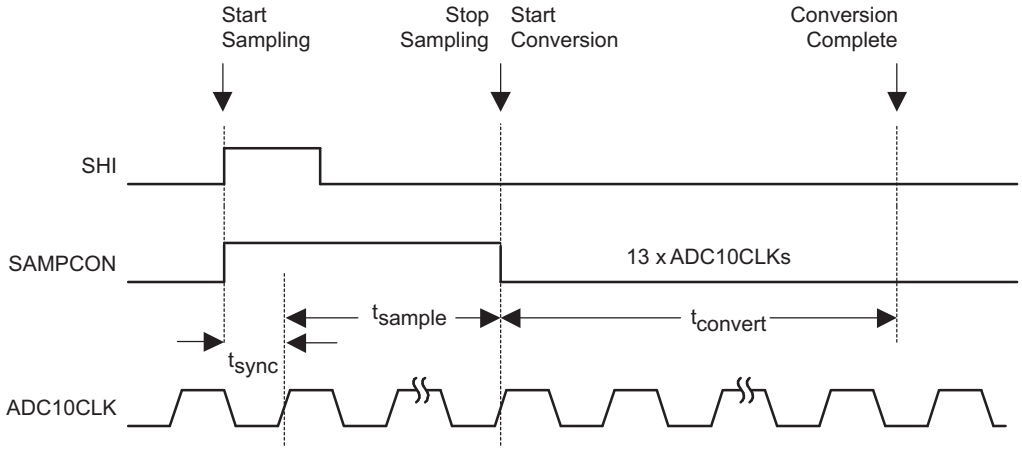


Figure 22-3. Sample Timing

22.2.5.1 Sample Timing Considerations

When SAMPCON = 0 all Ax inputs are high impedance. When SAMPCON = 1, the selected Ax input can be modeled as an RC low-pass filter during the sampling time t_{sample}, as shown in Figure 22-4. An internal MUX-on input resistance R_I (2 kΩ maximum) in series with capacitor C_I (27 pF maximum) is seen by the source. The capacitor C_I voltage V_C must be charged to within ½ LSB of the source voltage V_S for an accurate 10-bit conversion.

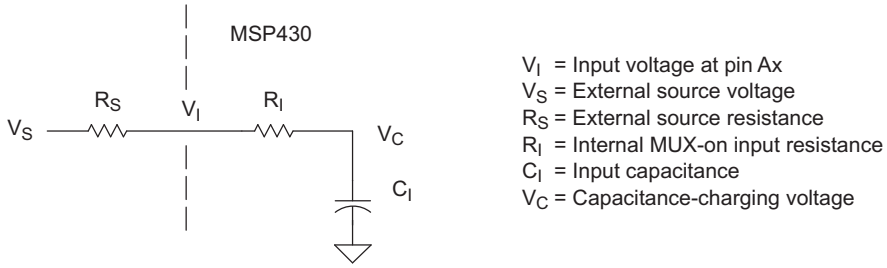


Figure 22-4. Analog Input Equivalent Circuit

The resistance of the source R_S and R_I affect t_{sample}.The following equations can be used to calculate the minimum sampling time for a 10-bit conversion.

$$t_{sample} > (R_S + R_I) \times \ln(2^{11}) \times C_I$$

Substituting the values for R_I and C_I given above, the equation becomes:

$$t_{sample} > (R_S + 2\ k\Omega) \times 7.625 \times 27\ pF$$

For example, if R_S is 10 kΩ, t_{sample} must be greater than 2.47 µs.

When the reference buffer is used in burst mode, the sampling time must be greater than the sampling time calculated and the settling time of the buffer, $t_{REFBURST}$:

$$t_{sample} > \begin{cases} (R_S + R_I) \times \ln(2^{11}) \times C_I \\ t_{REFBURST} \end{cases}$$

For example, if V_{Ref} is 1.5 V and R_S is 10 kΩ, t_{sample} must be greater than 2.47 µs when ADC10SR = 0, or 2.5 µs when ADC10SR = 1. See the device-specific data sheet for parameters.

To calculate the buffer settling time when using an external reference, the formula is:

$t_{REFBURST} = S_R \times V_{Ref} - 0.5\ \mu s$

Where:

SR = Buffer slew rate (~1 µs/V when ADC10SR = 0 and ~2 µs/V when ADC10SR = 1)

V_{Ref} = External reference voltage

22.2.6 Conversion Modes

The ADC10 has four operating modes selected by the CONSEQx bits as discussed in Table 22-1.

Table 22-1. Conversion Mode Summary

CONSEQx	Mode	Operation
00	Single channel single-conversion	A single channel is converted once.
01	Sequence-of-channels	A sequence of channels is converted once.
10	Repeat single channel	A single channel is converted repeatedly.
11	Repeat sequence-of-channels	A sequence of channels is converted repeatedly.

22.2.6.1 Single-Channel Single-Conversion Mode

A single channel selected by INCHx is sampled and converted once. The ADC result is written to ADC10MEM. Figure 22-5 shows the flow of the single-channel, single-conversion mode. When ADC10SC triggers a conversion, successive conversions can be triggered by the ADC10SC bit. When any other trigger source is used, ENC must be toggled between each conversion.

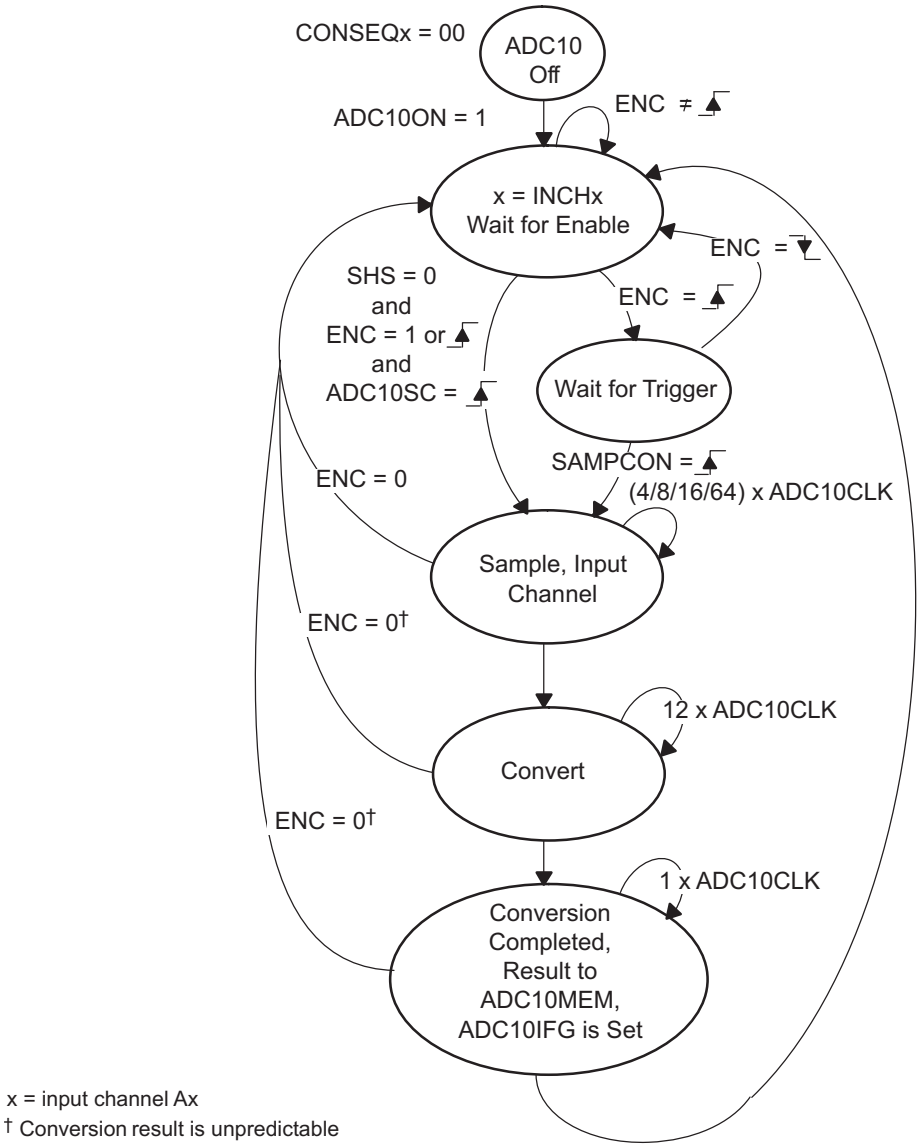


Figure 22-5. Single-Channel Single-Conversion Mode

22.2.6.2 Sequence-of-Channels Mode

A sequence of channels is sampled and converted once. The sequence begins with the channel selected by INCHx and decrements to channel A0. Each ADC result is written to ADC10MEM. The sequence stops after conversion of channel A0. Figure 22-6 shows the sequence-of-channels mode. When ADC10SC triggers a sequence, successive sequences can be triggered by the ADC10SC bit. When any other trigger source is used, ENC must be toggled between each sequence.

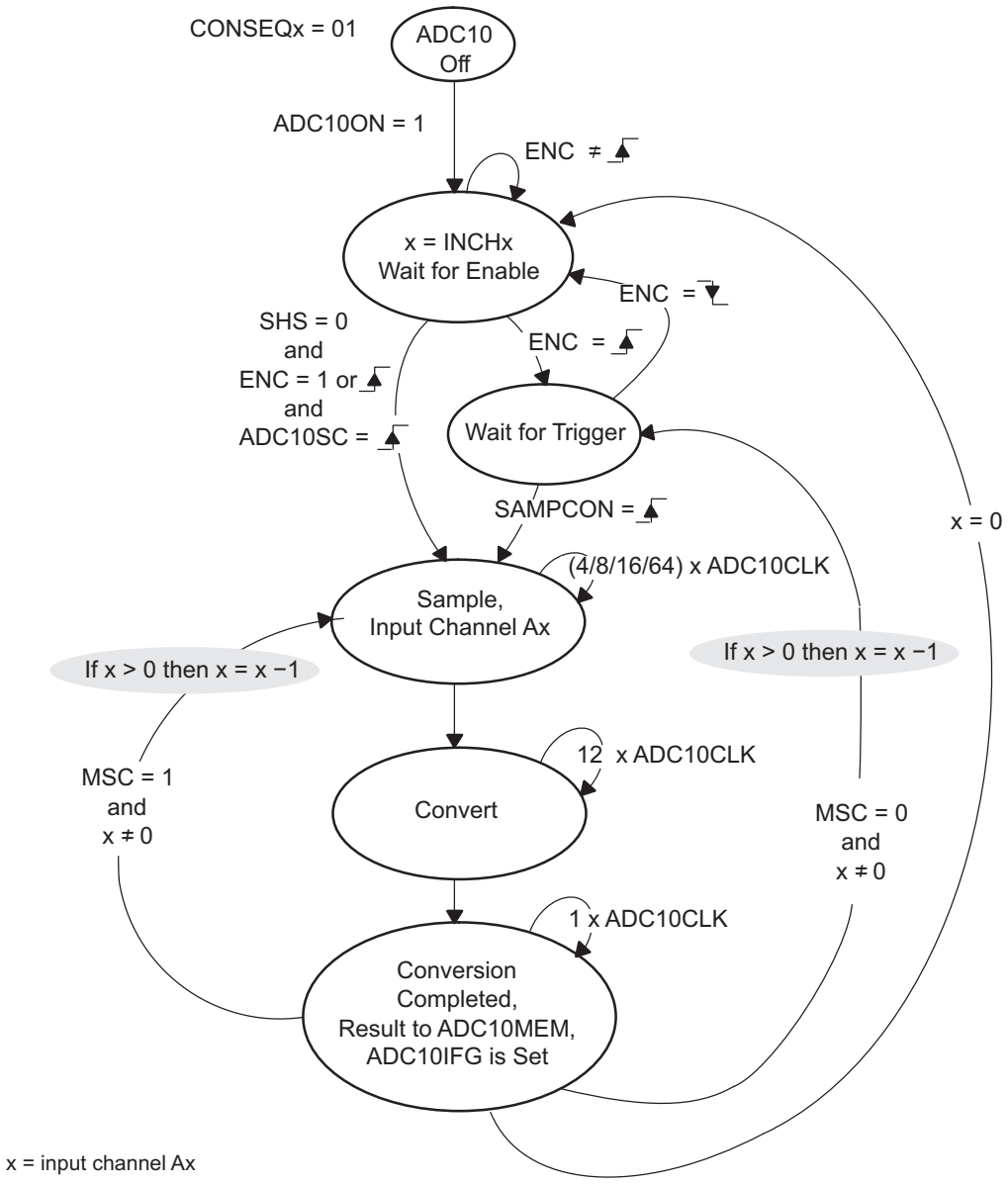


Figure 22-6. Sequence-of-Channels Mode

22.2.6.3 Repeat-Single-Channel Mode

A single channel selected by INCHx is sampled and converted continuously. Each ADC result is written to ADC10MEM. Figure 22-7 shows the repeat-single-channel mode.

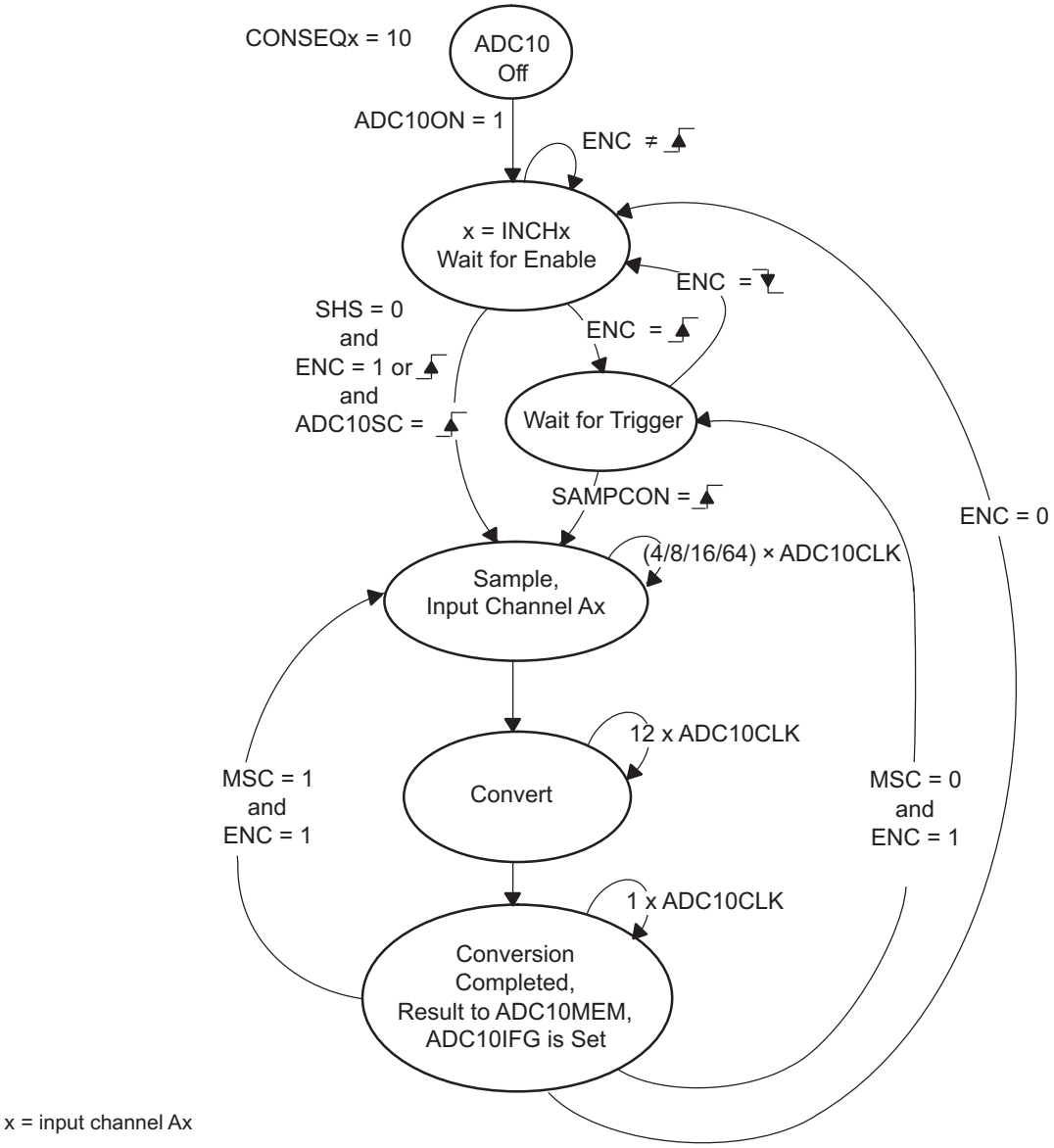


Figure 22-7. Repeat-Single-Channel Mode

22.2.6.4 Repeat-Sequence-of-Channels Mode

A sequence of channels is sampled and converted repeatedly. The sequence begins with the channel selected by INCHx and decrements to channel A0. Each ADC result is written to ADC10MEM. The sequence ends after conversion of channel A0, and the next trigger signal re-starts the sequence. Figure 22-8 shows the repeat-sequence-of-channels mode.

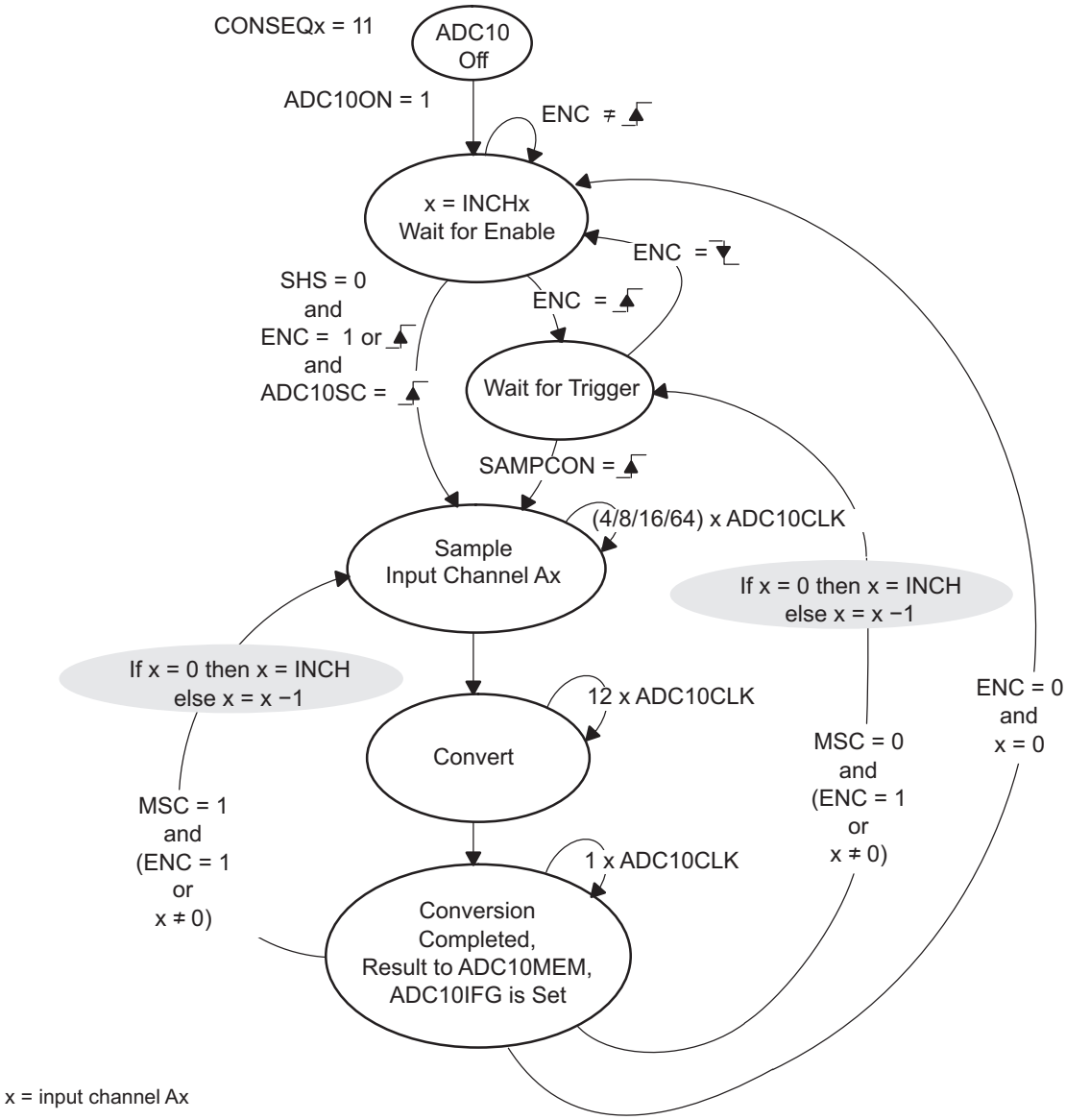


Figure 22-8. Repeat-Sequence-of-Channels Mode

22.2.6.5 Using the MSC Bit

To configure the converter to perform successive conversions automatically and as quickly as possible, a multiple sample and convert function is available. When MSC = 1 and CONSEQx > 0, the first rising edge of the SHI signal triggers the first conversion. Successive conversions are triggered automatically as soon as the prior conversion is completed. Additional rising edges on SHI are ignored until the sequence is completed in the single-sequence mode or until the ENC bit is toggled in repeat-single-channel, or repeated-sequence modes. The function of the ENC bit is unchanged when using the MSC bit.

22.2.6.6 Stopping Conversions

Stopping ADC10 activity depends on the mode of operation. The recommended ways to stop an active conversion or conversion sequence are:

- Resetting ENC in single-channel single-conversion mode stops a conversion immediately and the results are unpredictable. For correct results, poll the ADC10BUSY bit until reset before clearing ENC.
- Resetting ENC during repeat-single-channel operation stops the converter at the end of the current conversion.
- Resetting ENC during a sequence or repeat sequence mode stops the converter at the end of the sequence.
- Any conversion mode may be stopped immediately by setting the CONSEQx = 0 and resetting the ENC bit. Conversion data is unreliable.

22.2.7 ADC10 Data Transfer Controller

The ADC10 includes a data transfer controller (DTC) to automatically transfer conversion results from ADC10MEM to other on-chip memory locations. The DTC is enabled by setting the ADC10DTC1 register to a nonzero value.

When the DTC is enabled, each time the ADC10 completes a conversion and loads the result to ADC10MEM, a data transfer is triggered. No software intervention is required to manage the ADC10 until the predefined amount of conversion data has been transferred. Each DTC transfer requires one CPU MCLK. To avoid any bus contention during the DTC transfer, the CPU is halted, if active, for the one MCLK required for the transfer.

A DTC transfer must not be initiated while the ADC10 is busy. Software must ensure that no active conversion or sequence is in progress when the DTC is configured:

```
; ADC10 activity test
           BIC.W   #ENC,&ADC10CTL0   ;
busy_test  BIT.W   #BUSY,&ADC10CTL1  ;
           JNZ     busy_test        ;
           MOV.W   #xxx,&ADC10SA     ; Safe
           MOV.B   #xx,&ADC10DTC1    ;
; continue setup
```

22.2.7.1 One-Block Transfer Mode

The one-block mode is selected if the ADC10TB is reset. The value n in ADC10DTC1 defines the total number of transfers for a block. The block start address is defined anywhere in the MSP430 address range using the 16-bit register ADC10SA. The block ends at ADC10SA + 2n – 2. The one-block transfer mode is shown in Figure 22-9.

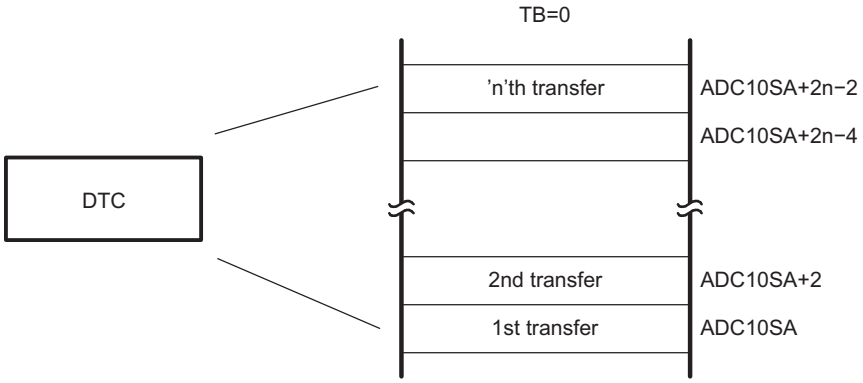


Figure 22-9. One-Block Transfer

The internal address pointer is initially equal to ADC10SA and the internal transfer counter is initially equal to 'n'. The internal pointer and counter are not visible to software. The DTC transfers the word-value of ADC10MEM to the address pointer ADC10SA. After each DTC transfer, the internal address pointer is incremented by two and the internal transfer counter is decremented by one.

The DTC transfers continue with each loading of ADC10MEM, until the internal transfer counter becomes equal to zero. No additional DTC transfers occur until a write to ADC10SA. When using the DTC in the one-block mode, the ADC10IFG flag is set only after a complete block has been transferred. Figure 22-10 shows a state diagram of the one-block mode.

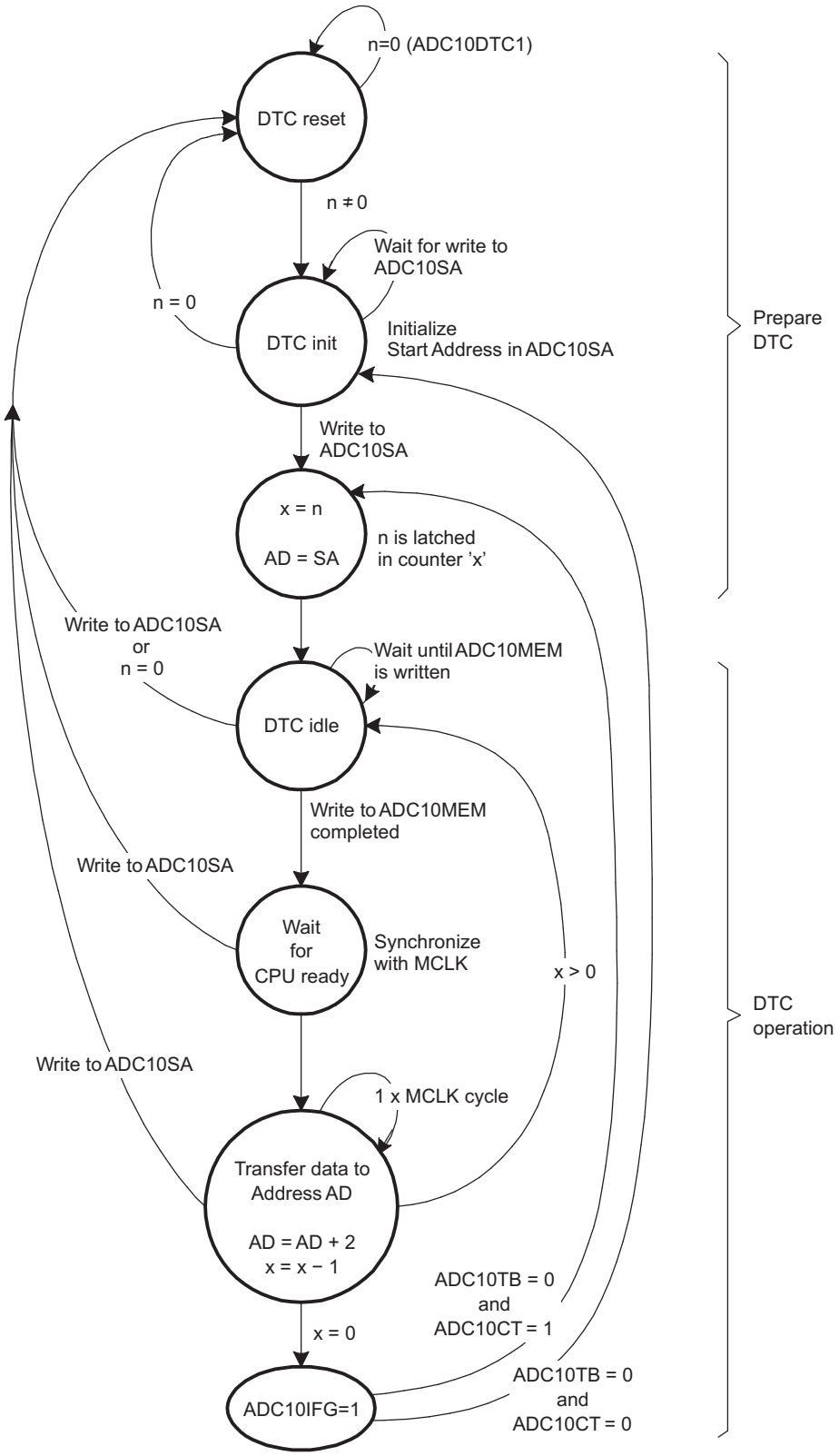


Figure 22-10. State Diagram for Data Transfer Control in One-Block Transfer Mode

22.2.7.2 Two-Block Transfer Mode

The two-block mode is selected if the ADC10TB bit is set. The value n in ADC10DTC1 defines the number of transfers for one block. The address range of the first block is defined anywhere in the MSP430 address range with the 16-bit register ADC10SA. The first block ends at ADC10SA+2n-2. The address range for the second block is defined as SA+2n to SA+4n-2. The two-block transfer mode is shown in Figure 22-11.

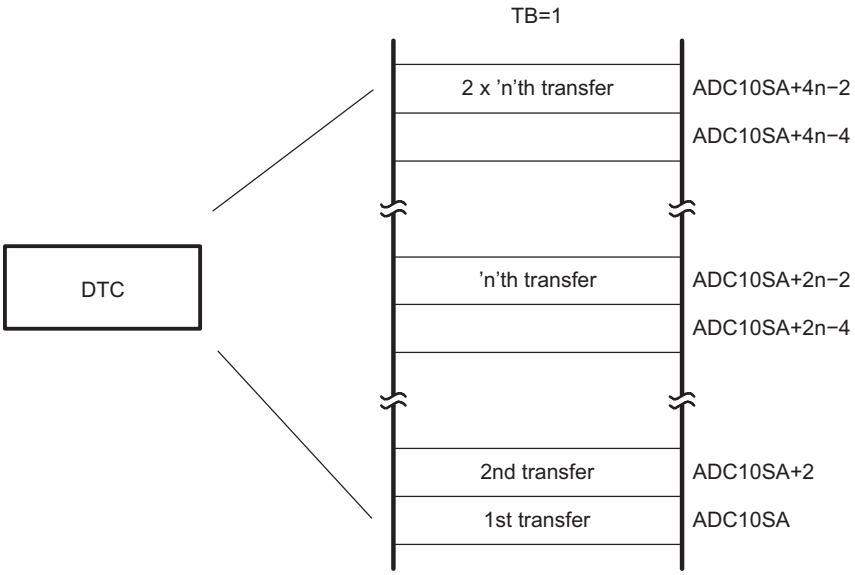


Figure 22-11. Two-Block Transfer

The internal address pointer is initially equal to ADC10SA and the internal transfer counter is initially equal to 'n'. The internal pointer and counter are not visible to software. The DTC transfers the word-value of ADC10MEM to the address pointer ADC10SA. After each DTC transfer the internal address pointer is incremented by two and the internal transfer counter is decremented by one.

The DTC transfers continue, with each loading of ADC10MEM, until the internal transfer counter becomes equal to zero. At this point, block one is full and both the ADC10IFG flag the ADC10B1 bit are set. The user can test the ADC10B1 bit to determine that block one is full.

The DTC continues with block two. The internal transfer counter is automatically reloaded with 'n'. At the next load of the ADC10MEM, the DTC begins transferring conversion results to block two. After n transfers have completed, block two is full. The ADC10IFG flag is set and the ADC10B1 bit is cleared. User software can test the cleared ADC10B1 bit to determine that block two is full. Figure 22-12 shows a state diagram of the two-block mode.

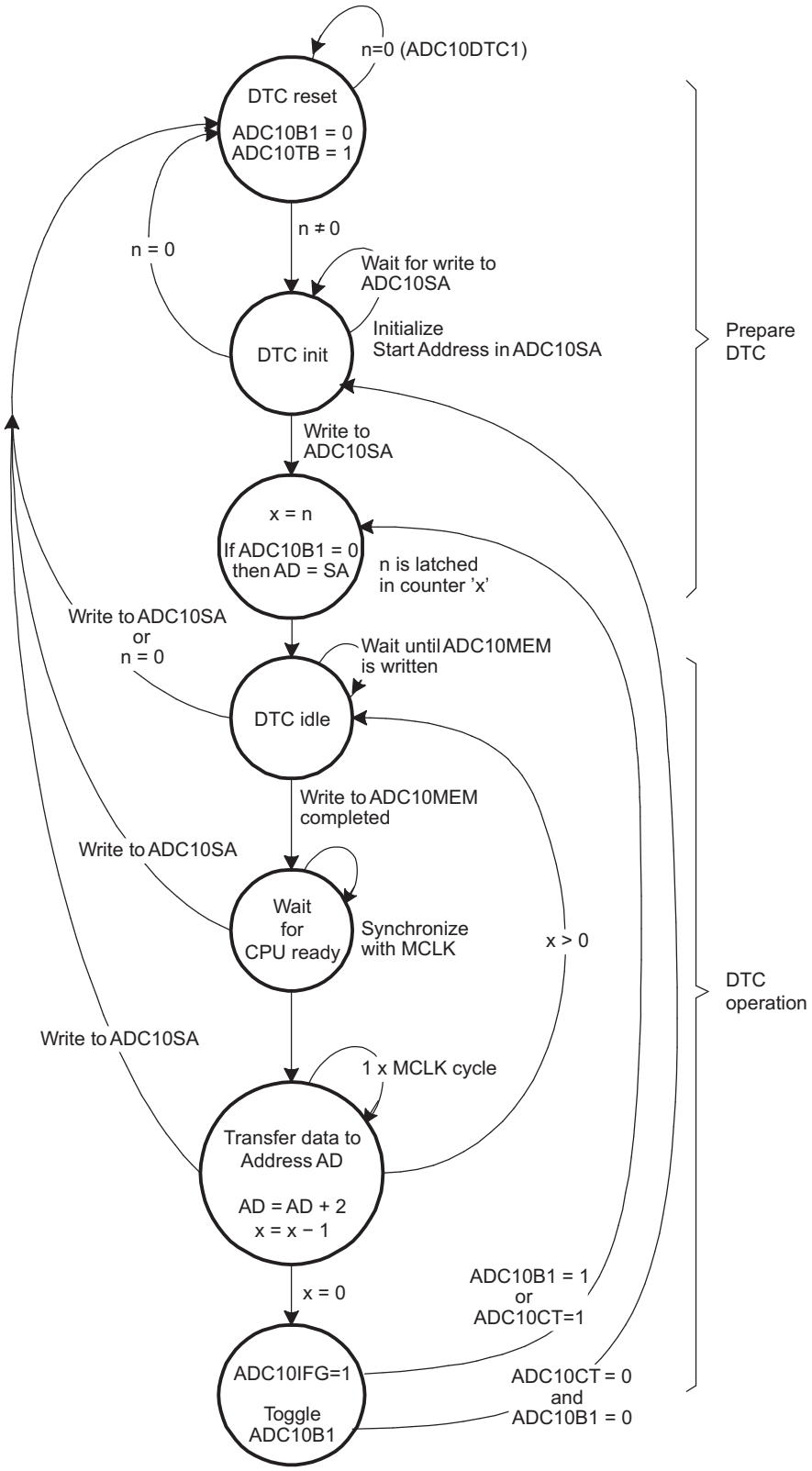


Figure 22-12. State Diagram for Data Transfer Control in Two-Block Transfer Mode

22.2.7.3 Continuous Transfer

A continuous transfer is selected if ADC10CT bit is set. The DTC does not stop after block one (in one-block mode) or block two (in two-block mode) has been transferred. The internal address pointer and transfer counter are set equal to ADC10SA and n respectively. Transfers continue starting in block one. If the ADC10CT bit is reset, DTC transfers cease after the current completion of transfers into block one (in one-block mode) or block two (in two-block mode) have been transferred.

22.2.7.4 DTC Transfer Cycle Time

For each ADC10MEM transfer, the DTC requires one or two MCLK clock cycles to synchronize, one for the actual transfer (while the CPU is halted), and one cycle of wait time. Because the DTC uses MCLK, the DTC cycle time is dependent on the MSP430 operating mode and clock system setup.

If the MCLK source is active but the CPU is off, the DTC uses the MCLK source for each transfer, without re-enabling the CPU. If the MCLK source is off, the DTC temporarily restarts MCLK, sourced with DCOCLK, only during a transfer. The CPU remains off, and MCLK is again turned off after the DTC transfer. The maximum DTC cycle time for all operating modes is show in Table 22-2.

Table 22-2. Maximum DTC Cycle Time

CPU Operating Mode	Clock Source	Maximum DTC Cycle Time
Active mode	MCLK = DCOCLK	3 MCLK cycles
Active mode	MCLK = LFXT1CLK	3 MCLK cycles
Low-power mode LPM0/1	MCLK = DCOCLK	4 MCLK cycles
Low-power mode LPM3/4	MCLK = DCOCLK	4 MCLK cycles + 2 µs(1)
Low-power mode LPM0/1	MCLK = LFXT1CLK	4 MCLK cycles
Low-power mode LPM3	MCLK = LFXT1CLK	4 MCLK cycles
Low-power mode LPM4	MCLK = LFXT1CLK	4 MCLK cycles + 2 µs(1)

(1) The additional 2 µs are needed to start the DCOCLK. See the device-specific data sheet for parameters.

22.2.8 Using the Integrated Temperature Sensor

To use the on-chip temperature sensor, select the analog input channel INCHx = 1010. Any other configuration is done as if an external channel was selected, including reference selection, conversion-memory selection, etc.

The typical temperature sensor transfer function is shown in Figure 22-13. When using the temperature sensor, the sample period must be greater than 30 µs. The temperature sensor offset error is large. Deriving absolute temperature values in the application requires calibration. See the device-specific data sheet for the parameters. See Section 24.2.2.1 for the calibration equations.

Selecting the temperature sensor automatically turns on the on-chip reference generator as a voltage source for the temperature sensor. However, it does not enable the V_{REF+} output or affect the reference selections for the conversion. The reference choices for converting the temperature sensor are the same as with any other channel.

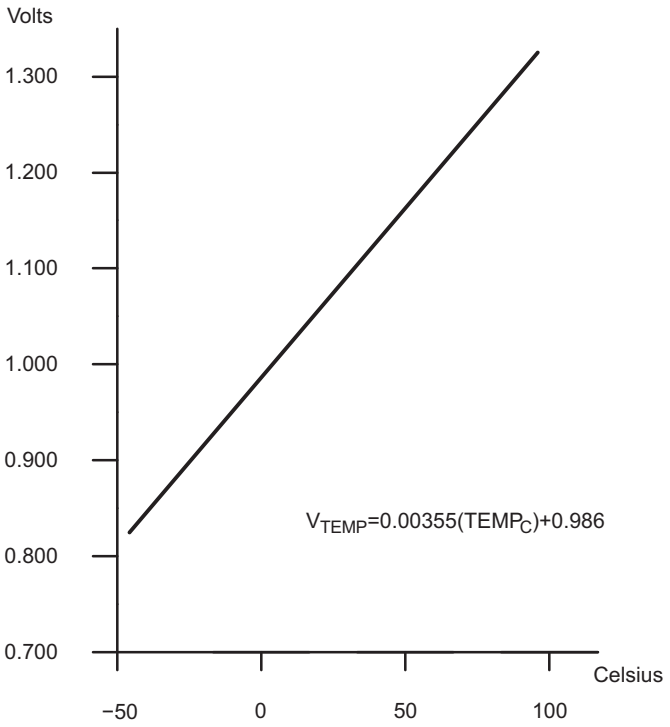


Figure 22-13. Typical Temperature Sensor Transfer Function

22.2.9 ADC10 Grounding and Noise Considerations

As with any high-resolution ADC, appropriate printed-circuit-board layout and grounding techniques should be followed to eliminate ground loops, unwanted parasitic effects, and noise.

Ground loops are formed when return current from the A/D flows through paths that are common with other analog or digital circuitry. If care is not taken, this current can generate small, unwanted offset voltages that can add to or subtract from the reference or input voltages of the A/D converter. The connections shown in Figure 22-14 and Figure 22-15 help avoid this.

In addition to grounding, ripple and noise spikes on the power supply lines due to digital switching or switching power supplies can corrupt the conversion result. A noise-free design is important to achieve high accuracy.

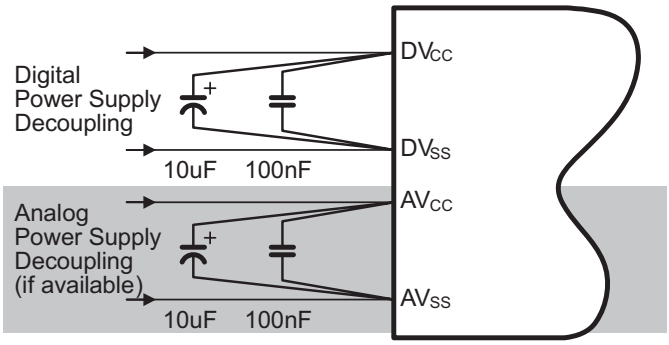


Figure 22-14. ADC10 Grounding and Noise Considerations (Internal V_{REF})

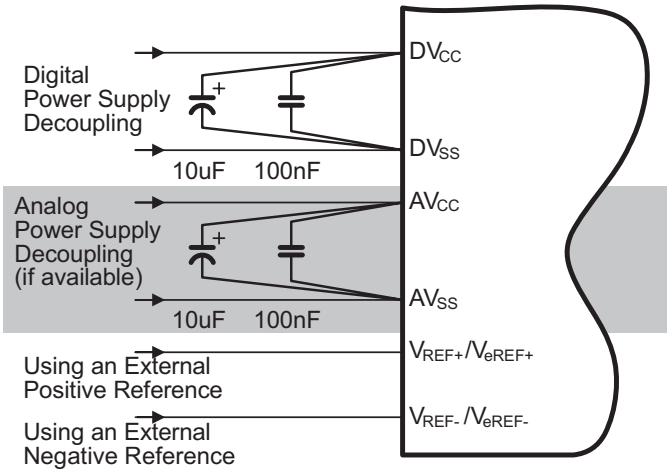


Figure 22-15. ADC10 Grounding and Noise Considerations (External V_{REF})

22.2.10 ADC10 Interrupts

One interrupt and one interrupt vector are associated with the ADC10 as shown in Figure 22-16. When the DTC is not used (ADC10DTC1 = 0), ADC10IFG is set when conversion results are loaded into ADC10MEM. When DTC is used (ADC10DTC1 > 0), ADC10IFG is set when a block transfer completes and the internal transfer counter n = 0. If both the ADC10IE and the GIE bits are set, then the ADC10IFG flag generates an interrupt request. The ADC10IFG flag is automatically reset when the interrupt request is serviced, or it may be reset by software.

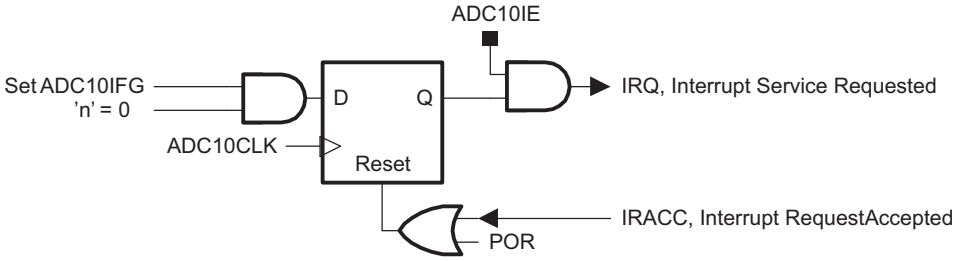


Figure 22-16. ADC10 Interrupt System

22.3 ADC10 Registers

The ADC10 registers are listed in Table 22-3.

Table 22-3. ADC10 Registers

Register	Short Form	Register Type	Address	Initial State
ADC10 input enable register 0	ADC10AE0	Read/write	04Ah	Reset with POR
ADC10 input enable register 1	ADC10AE1	Read/write	04Bh	Reset with POR
ADC10 control register 0	ADC10CTL0	Read/write	01B0h	Reset with POR
ADC10 control register 1	ADC10CTL1	Read/write	01B2h	Reset with POR
ADC10 memory	ADC10MEM	Read	01B4h	Unchanged
ADC10 data transfer control register 0	ADC10DTC0	Read/write	048h	Reset with POR
ADC10 data transfer control register 1	ADC10DTC1	Read/write	049h	Reset with POR
ADC10 data transfer start address	ADC10SA	Read/write	01BCh	0200h with POR

22.3.1 ADC10CTL0, ADC10 Control Register 0

15	14	13	12	11	10	9	8
SREFx			**ADC10SHTx**		**ADC10SR**	**REFOUT**	**REFBURST**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
MSC	**REF2_5V**	**REFON**	**ADC10ON**	**ADC10IE**	**ADC10IFG**	**ENC**	**ADC10SC**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Can be modified only when ENC = 0

SREFx Bits 15-13 Select reference.

- 000 $V_{R+} = V_{CC}$ and $V_{R-} = V_{SS}$
- 001 $V_{R+} = V_{REF+}$ and $V_{R-} = V_{SS}$
- 010 $V_{R+} = V_{eREF+}$ and $V_{R-} = V_{SS}$. Devices with V_{eREF+} only.
- 011 V_{R+} = Buffered V_{eREF+} and $V_{R-} = V_{SS}$. Devices with V_{eREF+} pin only.
- 100 $V_{R+} = V_{CC}$ and $V_{R-} = V_{REF-}/ V_{eREF-}$. Devices with V_{eREF-} pin only.
- 101 $V_{R+} = V_{REF+}$ and $V_{R-} = V_{REF-}/ V_{eREF-}$. Devices with $V_{eREF+/-}$ pins only.
- 110 $V_{R+} = V_{eREF+}$ and $V_{R-} = V_{REF-}/ V_{eREF-}$. Devices with $V_{eREF+/-}$ pins only.
- 111 V_{R+} = Buffered V_{eREF+} and $V_{R-} = V_{REF-}/ V_{eREF-}$. Devices with $V_{eREF+/-}$ pins only.

ADC10SHTx Bits 12-11 ADC10 sample-and-hold time

- 00 4 × ADC10CLKs
- 01 8 × ADC10CLKs
- 10 16 × ADC10CLKs
- 11 64 × ADC10CLKs

ADC10SR Bit 10 ADC10 sampling rate. This bit selects the reference buffer drive capability for the maximum sampling rate. Setting ADC10SR reduces the current consumption of the reference buffer.

- 0 Reference buffer supports up to ~200 ksps
- 1 Reference buffer supports up to ~50 ksps

REFOUT Bit 9 Reference output

- 0 Reference output off
- 1 Reference output on. Devices with V_{eREF+} / V_{REF+} pin only.

REFBURST Bit 8 Reference burst.

- 0 Reference buffer on continuously
- 1 Reference buffer on only during sample-and-conversion

MSC Bit 7 Multiple sample and conversion. Valid only for sequence or repeated modes.

- 0 The sampling requires a rising edge of the SHI signal to trigger each sample-and-conversion.
- 1 The first rising edge of the SHI signal triggers the sampling timer, but further sample-and-conversions are performed automatically as soon as the prior conversion is completed

REF2_5V Bit 6 Reference-generator voltage. REFON must also be set.

- 0 1.5 V
- 1 2.5 V

REFON Bit 5 Reference generator on

- 0 Reference off
- 1 Reference on

ADC10ON Bit 4 ADC10 on

- 0 ADC10 off
- 1 ADC10 on

ADC10IE Bit 3 ADC10 interrupt enable

- 0 Interrupt disabled
- 1 Interrupt enabled

ADC10IFG	Bit 2	ADC10 interrupt flag. This bit is set if ADC10MEM is loaded with a conversion result. It is automatically reset when the interrupt request is accepted, or it may be reset by software. When using the DTC this flag is set when a block of transfers is completed. 0 No interrupt pending 1 Interrupt pending
ENC	Bit 1	Enable conversion 0 ADC10 disabled 1 ADC10 enabled
ADC10SC	Bit 0	Start conversion. Software-controlled sample-and-conversion start. ADC10SC and ENC may be set together with one instruction. ADC10SC is reset automatically. 0 No sample-and-conversion start 1 Start sample-and-conversion

22.3.2 ADC10CTL1, ADC10 Control Register 1

15	14	13	12	11	10	9	8
INCHx				**SHSx**		**ADC10DF**	**ISSH**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
ADC10DIVx			**ADC10SSELx**		**CONSEQx**		**ADC10BUSY**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	r-0

Can be modified only when ENC = 0

INCHx Bits 15-12 Input channel select. These bits select the channel for a single-conversion or the highest channel for a sequence of conversions. Only available ADC channels should be selected. See device specific data sheet.

- 0000 A0
- 0001 A1
- 0010 A2
- 0011 A3
- 0100 A4
- 0101 A5
- 0110 A6
- 0111 A7
- 1000 V_{eREF+}
- 1001 V_{REF-}/V_{eREF-}
- 1010 Temperature sensor
- 1011 $(V_{CC} - V_{SS}) / 2$
- 1100 $(V_{CC} - V_{SS}) / 2$, A12 on MSP430F22xx devices
- 1101 $(V_{CC} - V_{SS}) / 2$, A13 on MSP430F22xx devices
- 1110 $(V_{CC} - V_{SS}) / 2$, A14 on MSP430F22xx devices
- 1111 $(V_{CC} - V_{SS}) / 2$, A15 on MSP430F22xx devices

SHSx Bits 11-10 Sample-and-hold source select.

- 00 ADC10SC bit
- 01 Timer_A.OUT1 (1)
- 10 Timer_A.OUT0 (1)
- 11 Timer_A.OUT2 (Timer_A.OUT1 on MSP430F20x0, MSP430G2x31, and MSP430G2x30 devices) (1)

ADC10DF Bit 9 ADC10 data format

- 0 Straight binary
- 1 2s complement

ISSH Bit 8 Invert signal sample-and-hold

- 0 The sample-input signal is not inverted.
- 1 The sample-input signal is inverted.

ADC10DIVx Bits 7-5 ADC10 clock divider

- 000 /1
- 001 /2
- 010 /3
- 011 /4
- 100 /5
- 101 /6
- 110 /7
- 111 /8

ADC10SSELx Bits 4-3 ADC10 clock source select

- 00 ADC10OSC
- 01 ACLK
- 10 MCLK
- 11 SMCLK

(1) Timer triggers are from Timer0_Ax if more than one timer module exists on the device.

CONSEQx	Bits 2-1	Conversion sequence mode select
	00	Single-channel-single-conversion
	01	Sequence-of-channels
	10	Repeat-single-channel
	11	Repeat-sequence-of-channels
ADC10BUSY	Bit 0	ADC10 busy. This bit indicates an active sample or conversion operation
	0	No operation is active.
	1	A sequence, sample, or conversion is active.

22.3.3 ADC10AE0, Analog (Input) Enable Control Register 0

7	6	5	4	3	2	1	0
ADC10AE0x							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

ADC10AE0x	Bits 7-0	ADC10 analog enable. These bits enable the corresponding pin for analog input. BIT0 corresponds to A0, BIT1 corresponds to A1, etc. The analog enable bit of not implemented channels should not be programmed to 1.
	0	Analog input disabled
	1	Analog input enabled

22.3.4 ADC10AE1, Analog (Input) Enable Control Register 1 (MSP430F22xx only)

7	6	5	4	3	2	1	0
ADC10AE1x				**Reserved**			
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

ADC10AE1x	Bits 7-4	ADC10 analog enable. These bits enable the corresponding pin for analog input. BIT4 corresponds to A12, BIT5 corresponds to A13, BIT6 corresponds to A14, and BIT7 corresponds to A15. The analog enable bit of not implemented channels should not be programmed to 1.
	0	Analog input disabled
	1	Analog input enabled
Reserved	Bits 3-0	Reserved

22.3.5 ADC10MEM, Conversion-Memory Register, Binary Format

15	14	13	12	11	10	9	8
0	0	0	0	0	0	**Conversion Results**	
r0	r0	r0	r0	r0	r0	r	r

7	6	5	4	3	2	1	0
Conversion Results							
r	r	r	r	r	r	r	r

Conversion Results	Bits 15-0	The 10-bit conversion results are right justified, straight-binary format. Bit 9 is the MSB. Bits 15-10 are always 0.

22.3.6 ADC10MEM, Conversion-Memory Register, 2s Complement Format

15	14	13	12	11	10	9	8
Conversion Results							
r	r	r	r	r	r	r	r
7	6	5	4	3	2	1	0
Conversion Results		0	0	0	0	0	0
r	r	r0	r0	r0	r0	r0	r0

Conversion Results Bits 15-0 The 10-bit conversion results are left-justified, 2s complement format. Bit 15 is the MSB. Bits 5-0 are always 0.

22.3.7 ADC10DTC0, Data Transfer Control Register 0

7	6	5	4	3	2	1	0
Reserved				**ADC10TB**	**ADC10CT**	**ADC10B1**	**ADC10FETCH**
r0	r0	r0	r0	rw-(0)	rw-(0)	r-(0)	rw-(0)

Reserved Bits 7-4 Reserved. Always read as 0.

ADC10TB Bit 3 ADC10 two-block mode

- 0 One-block transfer mode
- 1 Two-block transfer mode

ADC10CT Bit 2 ADC10 continuous transfer

- 0 Data transfer stops when one block (one-block mode) or two blocks (two-block mode) have completed.
- 1 Data is transferred continuously. DTC operation is stopped only if ADC10CT cleared, or ADC10SA is written to.

ADC10B1 Bit 1 ADC10 block one. This bit indicates for two-block mode which block is filled with ADC10 conversion results. ADC10B1 is valid only after ADC10IFG has been set the first time during DTC operation. ADC10TB must also be set.

- 0 Block 2 is filled
- 1 Block 1 is filled

ADC10FETCH Bit 0 This bit should normally be reset.

22.3.8 ADC10DTC1, Data Transfer Control Register 1

7	6	5	4	3	2	1	0
DTC Transfers							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

DTC Transfers Bits 7-0 DTC transfers. These bits define the number of transfers in each block.

- 0 DTC is disabled
- 01h-0FFh Number of transfers per block

22.3.9 ADC10SA, Start Address Register for Data Transfer

15	14	13	12	11	10	9	8
ADC10SAx							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
ADC10SAx							0
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	r0

ADC10SAx	Bits 15-1	ADC10 start address. These bits are the start address for the DTC. A write to register ADC10SA is required to initiate DTC transfers.
Unused	Bit 0	Unused, Read only. Always read as 0.

ADC12

The ADC12 module is a high-performance 12-bit analog-to-digital converter. This chapter describes the ADC12 of the MSP430x2xx device family.

Topic **Page**

23.1 ADC12 Introduction

The ADC12 module supports fast 12-bit analog-to-digital conversions. The module implements a 12-bit SAR core, sample select control, reference generator, and a 16-word conversion-and-control buffer. The conversion-and-control buffer allows up to 16 independent ADC samples to be converted and stored without any CPU intervention.

ADC12 features include:

- Greater than 200-ksps maximum conversion rate
- Monotonic 12-bit converter with no missing codes
- Sample-and-hold with programmable sampling periods controlled by software or timers
- Conversion initiation by software, Timer_A, or Timer_B
- Software selectable on-chip reference voltage generation (1.5 V or 2.5 V)
- Software selectable internal or external reference
- Eight individually configurable external input channels
- Conversion channels for internal temperature sensor, AV_{CC}, and external references
- Independent channel-selectable reference sources for both positive and negative references
- Selectable conversion clock source
- Single-channel, repeat-single-channel, sequence, and repeat-sequence conversion modes
- ADC core and reference voltage can be powered down separately
- Interrupt vector register for fast decoding of 18 ADC interrupts
- 16 conversion-result storage registers

The block diagram of ADC12 is shown in Figure 23-1.

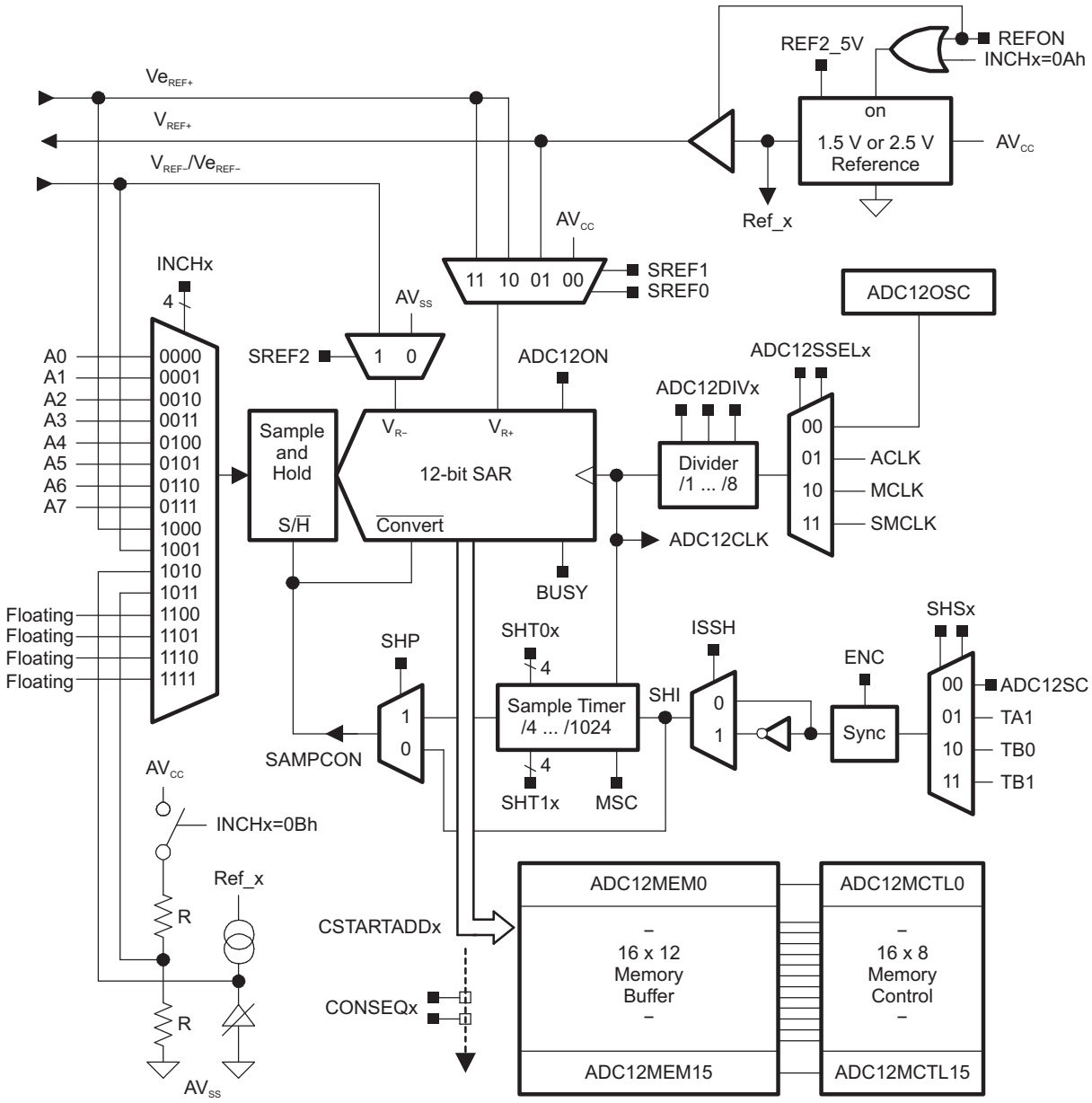


Figure 23-1. ADC12 Block Diagram

23.2 ADC12 Operation

The ADC12 module is configured with user software. The setup and operation of the ADC12 is discussed in the following sections.

23.2.1 12-Bit ADC Core

The ADC core converts an analog input to its 12-bit digital representation and stores the result in conversion memory. The core uses two programmable/selectable voltage levels (V_{R+} and V_{R-}) to define the upper and lower limits of the conversion. The digital output (N_{ADC}) is full scale (0FFFh) when the input signal is equal to or higher than V_{R+}, and the digital output is zero when the input signal is equal to or lower than V_{R-}. The input channel and the reference voltage levels (V_{R+} and V_{R-}) are defined in the conversion-control memory. The conversion formula for the ADC result N_{ADC} is:

$$N_{ADC} = 4095 \times \frac{V_{IN} - V_{R-}}{V_{R+} - V_{R-}}$$

The ADC12 core is configured by two control registers, ADC12CTL0 and ADC12CTL1. The core is enabled with the ADC12ON bit. The ADC12 can be turned off when not in use to save power. With few exceptions, the ADC12 control bits can only be modified when ENC = 0. ENC must be set to 1 before any conversion can take place.

23.2.1.1 Conversion Clock Selection

The ADC12CLK is used both as the conversion clock and to generate the sampling period when the pulse sampling mode is selected. The ADC12 source clock is selected using the ADC12SSELx bits and can be divided from 1 through 8 using the ADC12DIVx bits. Possible ADC12CLK sources are SMCLK, MCLK, ACLK, and an internal oscillator ADC12OSC.

The ADC12OSC is generated internally and is in the 5-MHz range, but the frequency varies with individual devices, supply voltage, and temperature. See the device-specific data sheet for the ADC12OSC specification.

The application must ensure that the clock chosen for ADC12CLK remains active until the end of a conversion. If the clock is removed during a conversion, the operation does not complete and any result is invalid.

23.2.2 ADC12 Inputs and Multiplexer

The eight external and four internal analog signals are selected as the channel for conversion by the analog input multiplexer. The input multiplexer is a break-before-make type to reduce input-to-input noise injection that can result from channel switching (see Figure 23-2). The input multiplexer is also a T-switch to minimize the coupling between channels. Channels that are not selected are isolated from the A/D, and the intermediate node is connected to analog ground (AV_{SS}) so that the stray capacitance is grounded to help eliminate crosstalk.

The ADC12 uses the charge redistribution method. When the inputs are internally switched, the switching action may cause transients on the input signal. These transients decay and settle before causing errant conversion.

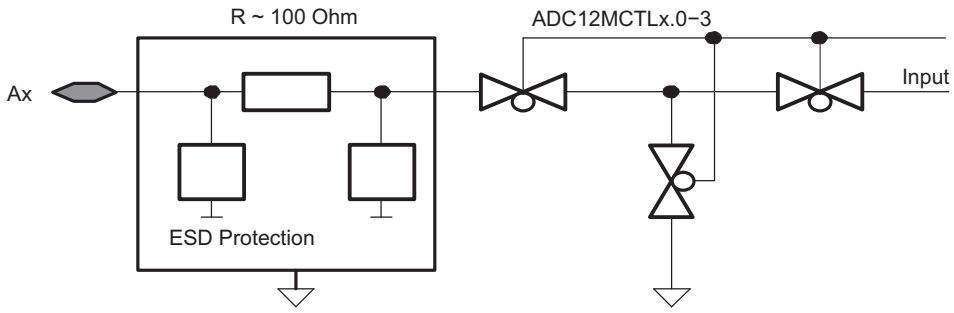


Figure 23-2. Analog Multiplexer

23.2.2.1 Analog Port Selection

The ADC12 inputs are multiplexed with the port P6 pins, which are digital CMOS gates. When analog signals are applied to digital CMOS gates, parasitic current can flow from VCC to GND. This parasitic current occurs if the input voltage is near the transition level of the gate. Disabling the port pin buffer eliminates the parasitic current flow and, therefore, reduces overall current consumption. The P6SELx bits provide the ability to disable the port pin input and output buffers.

```
; P6.0 and P6.1 configured for analog input
      BIS.B   #3h,&P6SEL   ; P6.1 and P6.0 ADC12 function
```

23.2.3 Voltage Reference Generator

The ADC12 module contains a built-in voltage reference with two selectable voltage levels, 1.5 V and 2.5 V. Either of these reference voltages may be used internally and externally on pin V_{REF+}.

Setting REFON = 1 enables the internal reference. When REF2_5V = 1, the internal reference is 2.5 V. When REF2_5V = 0, the reference is 1.5 V. The reference can be turned off to save power when not in use.

For proper operation, the internal voltage reference generator must be supplied with storage capacitance across V_{REF+} and AV_{SS}. The recommended storage capacitance is a parallel combination of 10-µF and 0.1-µF capacitors. From turn-on, a maximum of 17 ms must be allowed for the voltage reference generator to bias the recommended storage capacitors. If the internal reference generator is not used for the conversion, the storage capacitors are not required.

NOTE: Reference Decoupling

Approximately 200 µA is required from *any* reference used by the ADC12 while the two LSBs are being resolved during a conversion. A parallel combination of 10-µF and 0.1-µF capacitors is recommended for *any* reference as shown in Figure 23-11.

External references may be supplied for V_{R+} and V_{R-} through pins V_{eREF+} and V_{REF-}/V_{eREF-} respectively.

23.2.4 Sample and Conversion Timing

An analog-to-digital conversion is initiated with a rising edge of the sample input signal SHI. The source for SHI is selected with the SHSx bits and includes the following:

- The ADC12SC bit
- The Timer_A Output Unit 1
- The Timer_B Output Unit 0
- The Timer_B Output Unit 1

The polarity of the SHI signal source can be inverted with the ISSH bit. The SAMPCON signal controls the sample period and start of conversion. When SAMPCON is high, sampling is active. The high-to-low SAMPCON transition starts the analog-to-digital conversion, which requires 13 ADC12CLK cycles. Two different sample-timing methods are defined by control bit SHP, extended sample mode and pulse mode.

23.2.4.1 Extended Sample Mode

The extended sample mode is selected when SHP = 0. The SHI signal directly controls SAMPCON and defines the length of the sample period t_{sample}. When SAMPCON is high, sampling is active. The high-to-low SAMPCON transition starts the conversion after synchronization with ADC12CLK (see Figure 23-3).

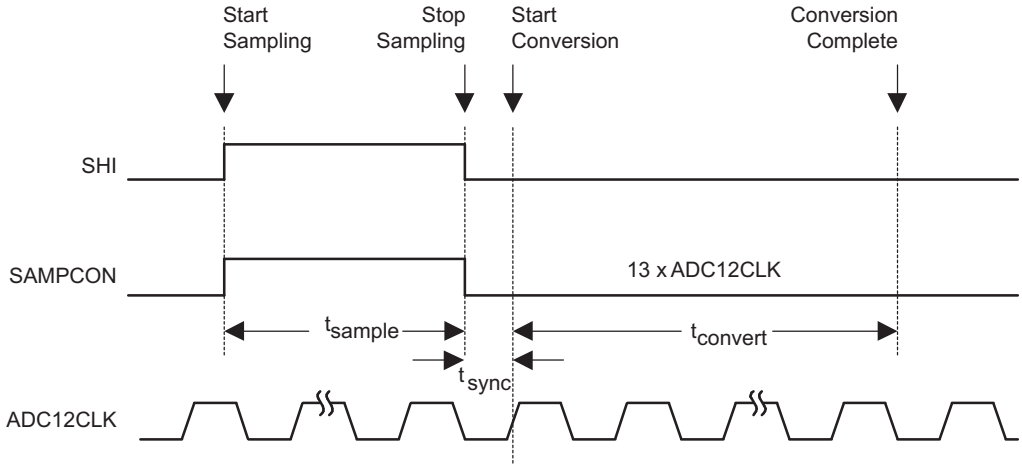


Figure 23-3. Extended Sample Mode

23.2.4.2 Pulse Sample Mode

The pulse sample mode is selected when SHP = 1. The SHI signal is used to trigger the sampling timer. The SHT0x and SHT1x bits in ADC12CTL0 control the interval of the sampling timer that defines the SAMPCON sample period t_{sample}. The sampling timer keeps SAMPCON high after synchronization with AD12CLK for a programmed interval t_{sample}. The total sampling time is t_{sample} plus t_{sync} (see Figure 23-4).

The SHTx bits select the sampling time in 4x multiples of ADC12CLK. SHT0x selects the sampling time for ADC12MCTL0 to 7 and SHT1x selects the sampling time for ADC12MCTL8 to 15.

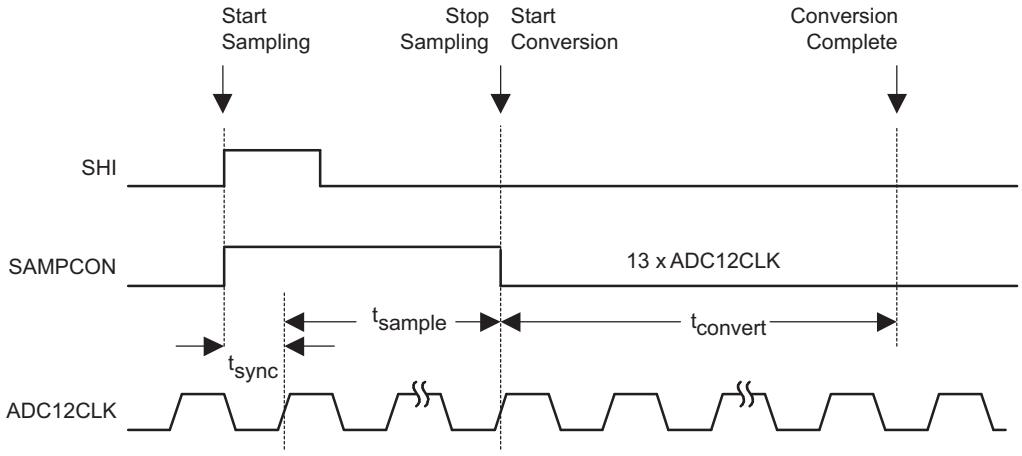


Figure 23-4. Pulse Sample Mode

23.2.4.3 Sample Timing Considerations

When SAMPCON = 0, all Ax inputs are high impedance. When SAMPCON = 1, the selected Ax input can be modeled as an RC low-pass filter during the sampling time t_{sample}, as shown in Figure 23-5. An internal MUX-on input resistance R_I (maximum of 2 kΩ) in series with capacitor C_I (maximum of 40 pF) is seen by the source. The capacitor C_I voltage (V_C) must be charged to within 1/2 LSB of the source voltage (V_S) for an accurate 12-bit conversion.

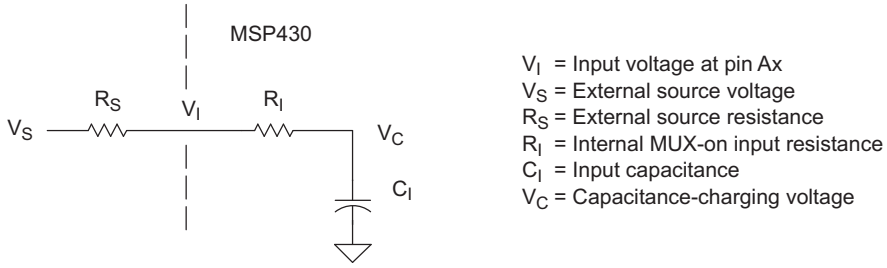


Figure 23-5. Analog Input Equivalent Circuit

The resistance of the source R_S and R_I affect t_{sample}. The following equation can be used to calculate the minimum sampling time t_{sample} for a 12-bit conversion:

$$t_{sample} > (R_S + R_I) \times \ln(2^{13}) \times C_I + 800 \text{ ns}$$

Substituting the values for R_I and C_I given above, the equation becomes:

$$t_{sample} > (R_S + 2 \text{ k}\Omega) \times 9.011 \times 40 \text{ pF} + 800 \text{ ns}$$

For example, if R_S is 10 kΩ, t_{sample} must be greater than 5.13 µs.

23.2.5 Conversion Memory

There are 16 ADC12MEMx conversion memory registers to store conversion results. Each ADC12MEMx is configured with an associated ADC12MCTLx control register. The SREFx bits define the voltage reference and the INCHx bits select the input channel. The EOS bit defines the end of sequence when a sequential conversion mode is used. A sequence rolls over from ADC12MEM15 to ADC12MEM0 when the EOS bit in ADC12MCTL15 is not set.

The CSTARTADDx bits define the first ADC12MCTLx used for any conversion. If the conversion mode is single-channel or repeat-single-channel the CSTARTADDx points to the single ADC12MCTLx to be used.

If the conversion mode selected is either sequence-of-channels or repeat-sequence-of-channels, CSTARTADDx points to the first ADC12MCTLx location to be used in a sequence. A pointer, not visible to software, is incremented automatically to the next ADC12MCTLx in a sequence when each conversion completes. The sequence continues until an EOS bit in ADC12MCTLx is processed; this is the last control byte processed.

When conversion results are written to a selected ADC12MEMx, the corresponding flag in the ADC12IFGx register is set.

23.2.6 ADC12 Conversion Modes

The ADC12 has four operating modes selected by the CONSEQx bits as shown in Table 23-1.

Table 23-1. Conversion Mode Summary

CONSEQx	Mode	Operation
00	Single channel single-conversion	A single channel is converted once.
01	Sequence-of-channels	A sequence of channels is converted once.
10	Repeat-single-channel	A single channel is converted repeatedly.
11	Repeat-sequence-of-channels	A sequence of channels is converted repeatedly.

23.2.6.1 Single-Channel Single-Conversion Mode

A single channel is sampled and converted once. The ADC result is written to the ADC12MEMx defined by the CSTARTADDx bits. Figure 23-6 shows the flow of the single-channel, single-conversion mode. When ADC12SC triggers a conversion, successive conversions can be triggered by the ADC12SC bit. When any other trigger source is used, ENC must be toggled between each conversion.

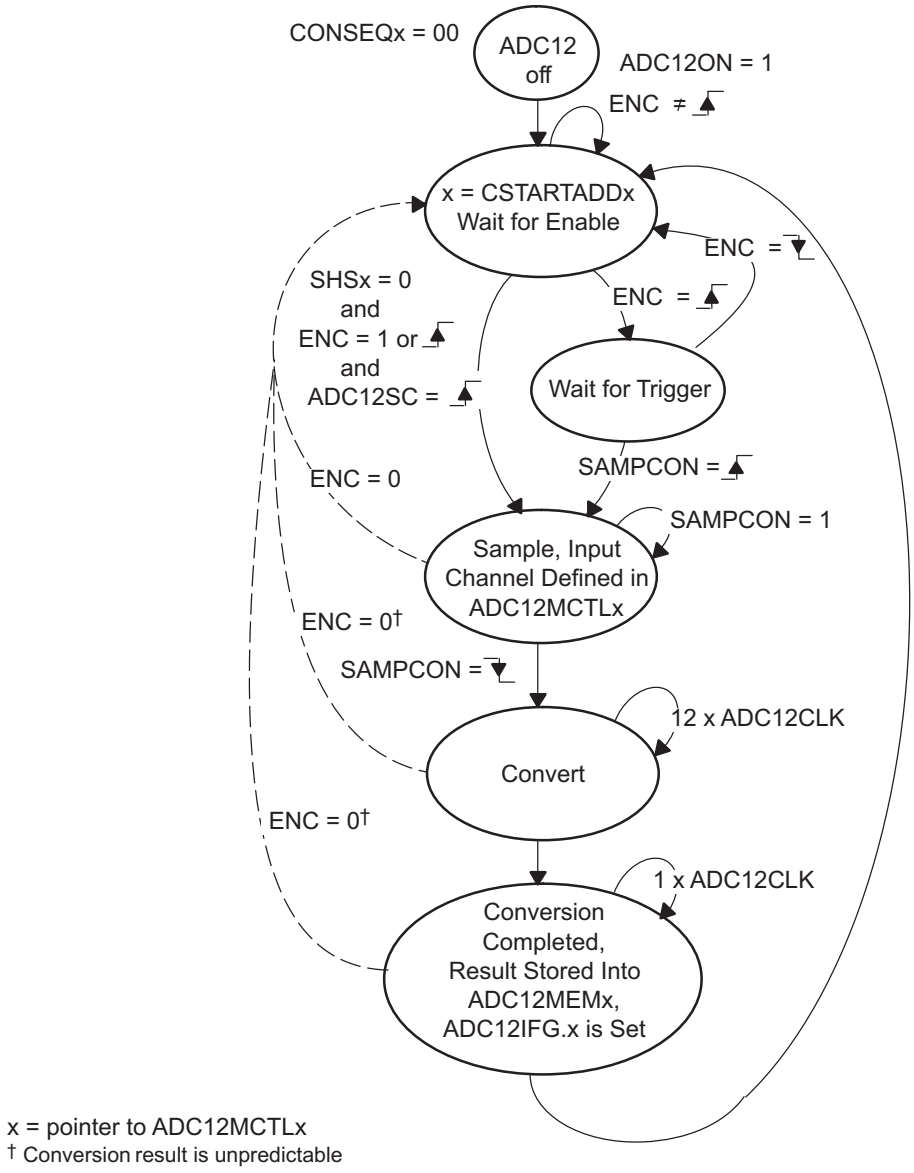


Figure 23-6. Single-Channel, Single-Conversion Mode

23.2.6.2 Sequence-of-Channels Mode

A sequence of channels is sampled and converted once. The ADC results are written to the conversion memories starting with the ADCMEMx defined by the CSTARTADDx bits. The sequence stops after the measurement of the channel with a set EOS bit. Figure 23-7 shows the sequence-of-channels mode. When ADC12SC triggers a sequence, successive sequences can be triggered by the ADC12SC bit. When any other trigger source is used, ENC must be toggled between each sequence.

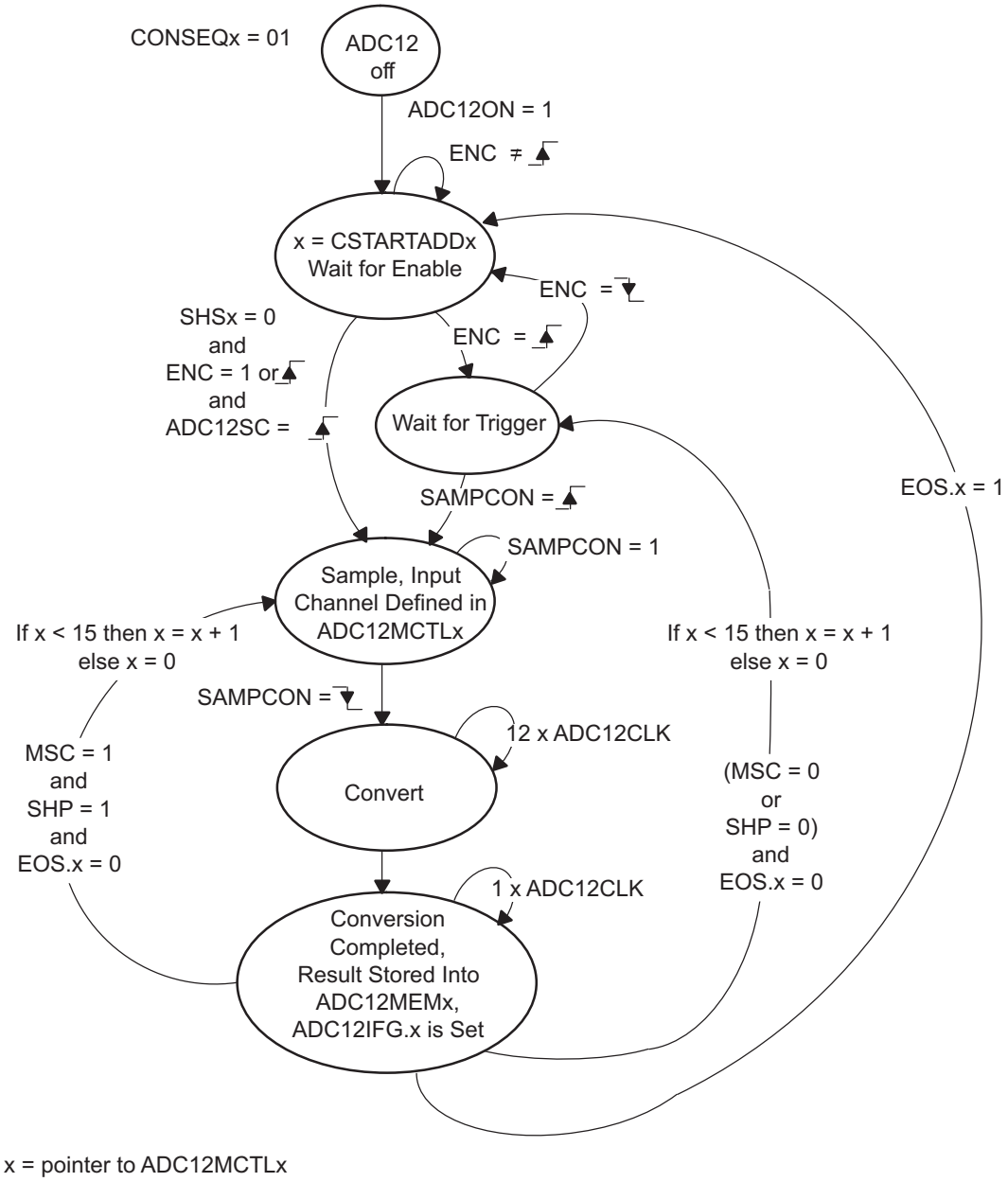


Figure 23-7. Sequence-of-Channels Mode

23.2.6.3 Repeat-Single-Channel Mode

A single channel is sampled and converted continuously. The ADC results are written to the ADC12MEMx defined by the CSTARTADDx bits. It is necessary to read the result after the completed conversion, because only one ADC12MEMx memory is used and is overwritten by the next conversion. Figure 23-8 shows repeat-single-channel mode.

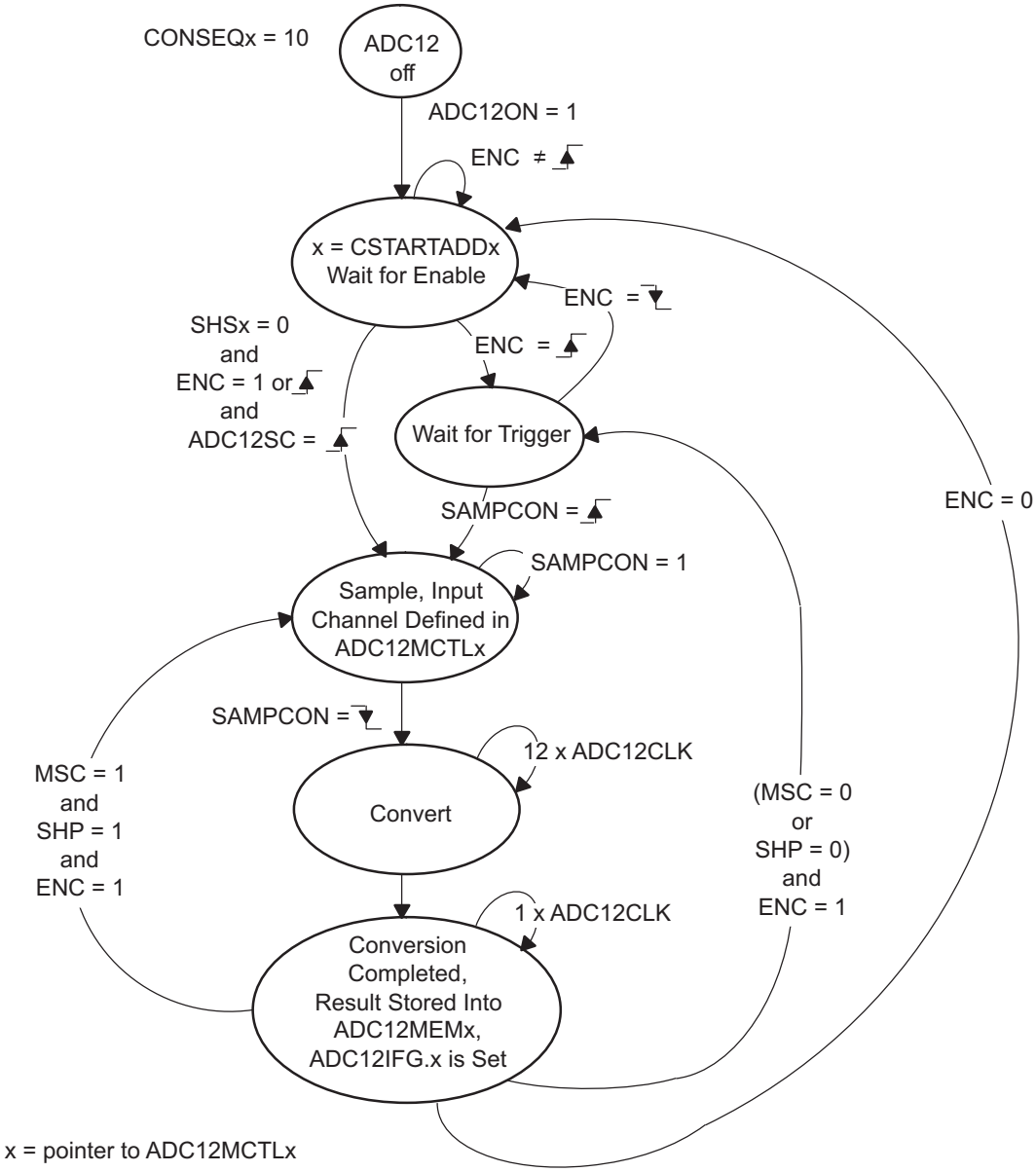


Figure 23-8. Repeat-Single-Channel Mode

23.2.6.4 Repeat-Sequence-of-Channels Mode

A sequence of channels is sampled and converted repeatedly. The ADC results are written to the conversion memories starting with the ADC12MEMx defined by the CSTARTADDx bits. The sequence ends after the measurement of the channel with a set EOS bit, and the next trigger signal re-starts the sequence. Figure 23-9 shows the repeat-sequence-of-channels mode.

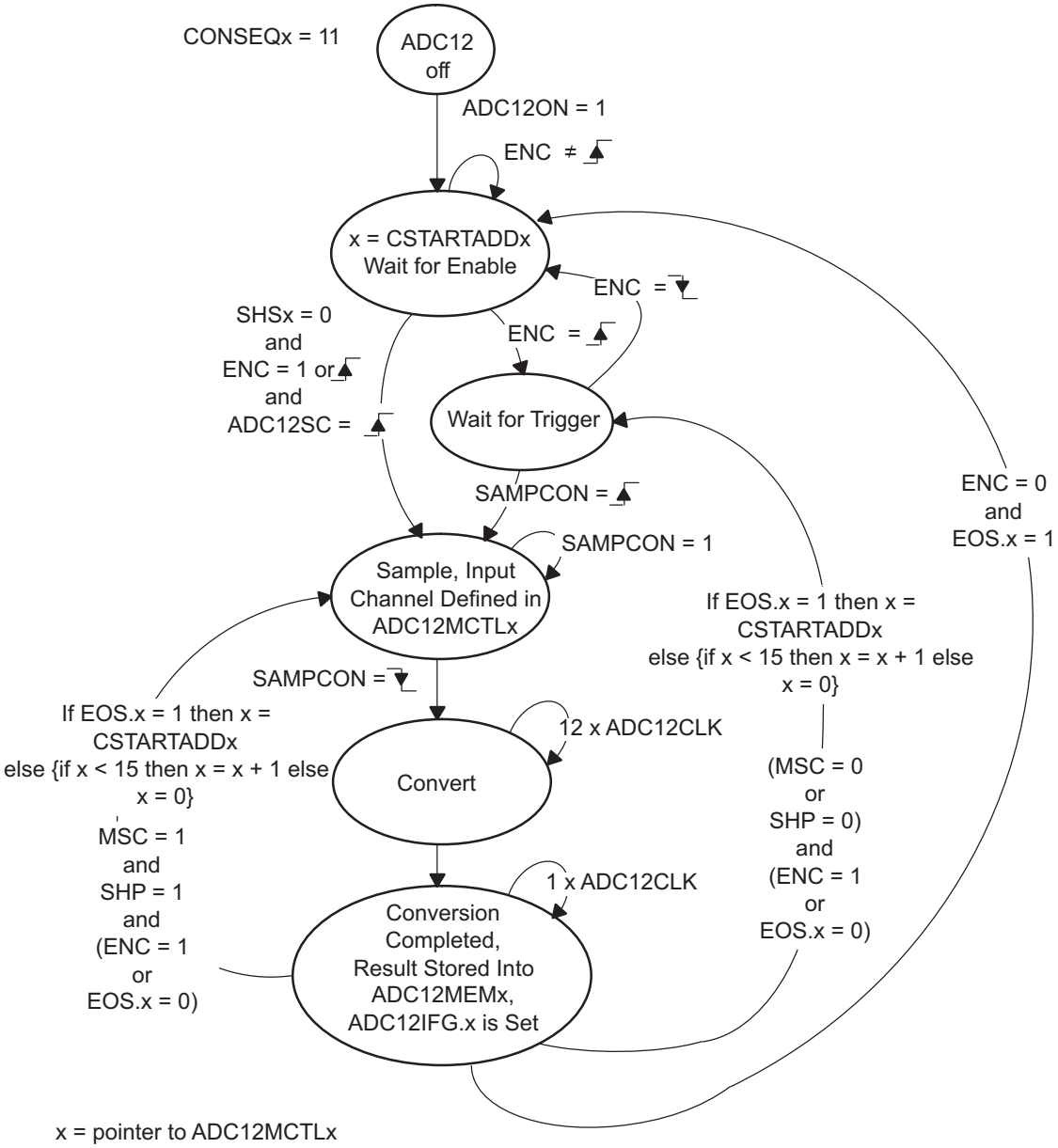


Figure 23-9. Repeat-Sequence-of-Channels Mode

23.2.6.5 Using the Multiple Sample and Convert (MSC) Bit

To configure the converter to perform successive conversions automatically and as quickly as possible, a multiple sample and convert function is available. When MSC = 1, CONSEQx > 0, and the sample timer is used, the first rising edge of the SHI signal triggers the first conversion. Successive conversions are triggered automatically as soon as the prior conversion is completed. Additional rising edges on SHI are ignored until the sequence is completed in the single-sequence mode or until the ENC bit is toggled in repeat-single-channel or repeated-sequence modes. The function of the ENC bit is unchanged when using the MSC bit.

23.2.6.6 Stopping Conversions

Stopping ADC12 activity depends on the mode of operation. The recommended ways to stop an active conversion or conversion sequence are:

- Resetting ENC in single-channel single-conversion mode stops a conversion immediately and the results are unpredictable. For correct results, poll the busy bit until it is reset before clearing ENC.
- Resetting ENC during repeat-single-channel operation stops the converter at the end of the current conversion.
- Resetting ENC during a sequence or repeat-sequence mode stops the converter at the end of the sequence.
- Any conversion mode may be stopped immediately by setting the CONSEQx = 0 and resetting ENC bit. In this case, conversion data are unreliable.

NOTE: No EOS Bit Set For Sequence

If no EOS bit is set and a sequence mode is selected, resetting the ENC bit does not stop the sequence. To stop the sequence, first select a single-channel mode and then reset ENC.

23.2.7 Using the Integrated Temperature Sensor

To use the on-chip temperature sensor, select the analog input channel INCHx = 1010. Any other configuration is done as if an external channel was selected, including reference selection, conversion-memory selection, etc.

The typical temperature sensor transfer function is shown in Figure 23-10. When using the temperature sensor, the sample period must be greater than 30 µs. The temperature sensor offset error can be large and needs to be calibrated for most applications. See the device-specific data sheet for parameters. See Section 24.2.2.1 for the calibration equations.

Selecting the temperature sensor automatically turns on the on-chip reference generator as a voltage source for the temperature sensor. However, it does not enable the V_{REF+} output or affect the reference selections for the conversion. The reference choices for converting the temperature sensor are the same as with any other channel.

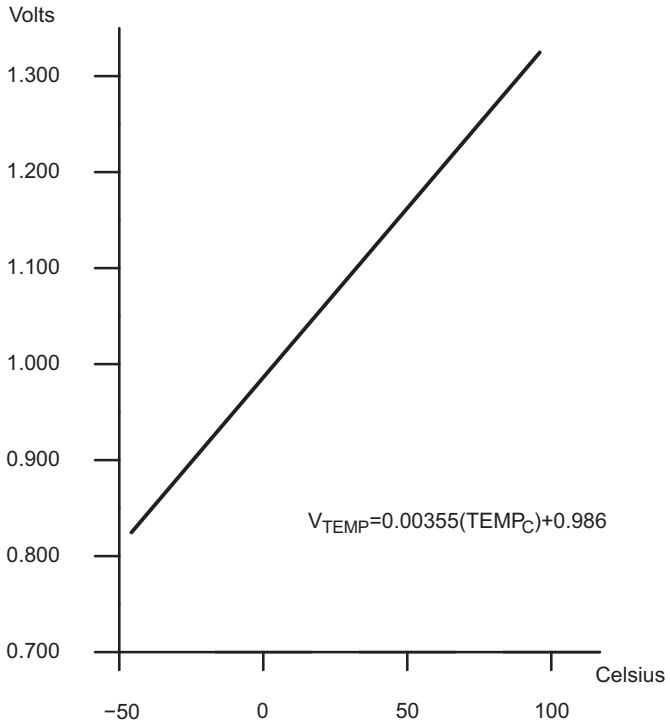


Figure 23-10. Typical Temperature Sensor Transfer Function

23.2.8 ADC12 Grounding and Noise Considerations

As with any high-resolution ADC, appropriate printed-circuit-board layout and grounding techniques should be followed to eliminate ground loops, unwanted parasitic effects, and noise.

Ground loops are formed when return current from the A/D flows through paths that are common with other analog or digital circuitry. If care is not taken, this current can generate small unwanted offset voltages that can add to or subtract from the reference or input voltages of the A/D converter. The connections shown in Figure 23-11 help avoid this.

In addition to grounding, ripple and noise spikes on the power supply lines due to digital switching or switching power supplies can corrupt the conversion result. A noise-free design using separate analog and digital ground planes with a single-point connection is recommend to achieve high accuracy.

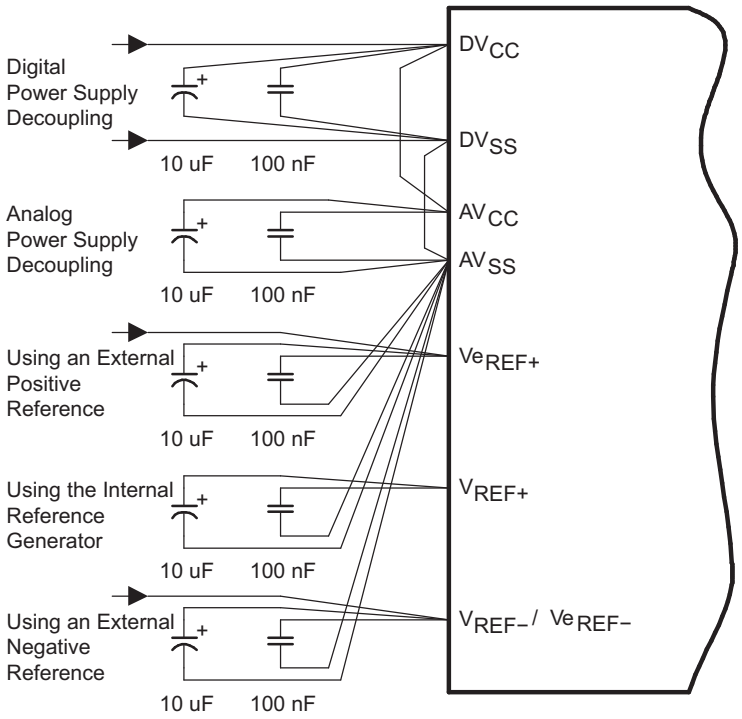


Figure 23-11. ADC12 Grounding and Noise Considerations

23.2.9 ADC12 Interrupts

The ADC12 has 18 interrupt sources:

- ADC12IFG0 to ADC12IFG15
- ADC12OV, ADC12MEMx overflow
- ADC12TOV, ADC12 conversion time overflow

The ADC12IFGx bits are set when their corresponding ADC12MEMx memory register is loaded with a conversion result. An interrupt request is generated if the corresponding ADC12IEx bit and the GIE bit are set. The ADC12OV condition occurs when a conversion result is written to any ADC12MEMx before its previous conversion result was read. The ADC12TOV condition is generated when another sample-and-conversion is requested before the current conversion is completed. The DMA is triggered after the conversion in single channel modes or after the completion of a sequence-of-channel modes.

23.2.9.1 ADC12IV, Interrupt Vector Generator

All ADC12 interrupt sources are prioritized and combined to source a single interrupt vector. The interrupt vector register ADC12IV is used to determine which enabled ADC12 interrupt source requested an interrupt.

The highest priority enabled ADC12 interrupt generates a number in the ADC12IV register (see Section 23.3.7). This number can be evaluated or added to the program counter to automatically enter the appropriate software routine. Disabled ADC12 interrupts do not affect the ADC12IV value.

Any access (read or write) of the ADC12IV register automatically resets the ADC12OV condition or the ADC12TOV condition if either was the highest pending interrupt. Neither interrupt condition has an accessible interrupt flag. The ADC12IFGx flags are not reset by an ADC12IV access. ADC12IFGx bits are reset automatically by accessing their associated ADC12MEMx register or may be reset with software.

If another interrupt is pending after servicing of an interrupt, another interrupt is generated. For example, if the ADC12OV and ADC12IFG3 interrupts are pending when the interrupt service routine accesses the ADC12IV register, the ADC12OV interrupt condition is reset automatically. After the RETI instruction of the interrupt service routine is executed, the ADC12IFG3 generates another interrupt.

23.2.9.2 ADC12 Interrupt Handling Software Example

Example 23-1 shows the recommended use of ADC12IV and the handling overhead. The ADC12IV value is added to the PC to automatically jump to the appropriate routine.

The numbers at the right margin show the necessary CPU cycles for each instruction. The software overhead for different interrupt sources includes interrupt latency and return-from-interrupt cycles, but not the task handling itself. The latencies are:

- ADC12IFG0 to ADC12IFG14, ADC12TOV, and ADC12OV: 16 cycles
- ADC12IFG15: 14 cycles

The interrupt handler for ADC12IFG15 shows a way to check immediately if a higher prioritized interrupt occurred during the processing of ADC12IFG15. This saves nine cycles if another ADC12 interrupt is pending.

Example 23-1. Interrupt Handling

```
; Interrupt handler for ADC12.
INT_ADC12              ; Enter Interrupt Service Routine    6
   ADD    &ADC12IV,PC  ; Add offset to PC                   3
   RETI                ; Vector 0: No interrupt            5
   JMP    ADOV         ; Vector 2: ADC overflow            2
   JMP    ADTOV        ; Vector 4: ADC timing overflow     2
   JMP    ADM0         ; Vector 6: ADC12IFG0               2
      ...              ; Vectors 8-32                      2
   JMP    ADM14        ; Vector 34: ADC12IFG14             2
;
; Handler for ADC12IFG15 starts here. No JMP required.
;
ADM15   MOV   &ADC12MEM15,xxx  ; Move result, flag is reset
        ...                    ; Other instruction needed?
        JMP   INT_ADC12        ; Check other int pending
;
;   ADC12IFG14-ADC12IFG1 handlers go here
;
ADM0    MOV   &ADC12MEM0,xxx   ; Move result, flag is reset
        ...                    ; Other instruction needed?
        RETI                   ; Return                    5
;
ADTOV   ...                    ; Handle Conv. time overflow
        RETI                   ; Return                    5
;
ADOV    ...                    ; Handle ADCMEMx overflow
        RETI                   ; Return                    5
```

23.3 ADC12 Registers

The ADC12 registers are listed in Table 23-2.

Table 23-2. ADC12 Registers

Register	Short Form	Register Type	Address	Initial State
ADC12 control register 0	ADC12CTL0	Read/write	01A0h	Reset with POR
ADC12 control register 1	ADC12CTL1	Read/write	01A2h	Reset with POR
ADC12 interrupt flag register	ADC12IFG	Read/write	01A4h	Reset with POR
ADC12 interrupt enable register	ADC12IE	Read/write	01A6h	Reset with POR
ADC12 interrupt vector word	ADC12IV	Read	01A8h	Reset with POR
ADC12 memory 0	ADC12MEM0	Read/write	0140h	Unchanged
ADC12 memory 1	ADC12MEM1	Read/write	0142h	Unchanged
ADC12 memory 2	ADC12MEM2	Read/write	0144h	Unchanged
ADC12 memory 3	ADC12MEM3	Read/write	0146h	Unchanged
ADC12 memory 4	ADC12MEM4	Read/write	0148h	Unchanged
ADC12 memory 5	ADC12MEM5	Read/write	014Ah	Unchanged
ADC12 memory 6	ADC12MEM6	Read/write	014Ch	Unchanged
ADC12 memory 7	ADC12MEM7	Read/write	014Eh	Unchanged
ADC12 memory 8	ADC12MEM8	Read/write	0150h	Unchanged
ADC12 memory 9	ADC12MEM9	Read/write	0152h	Unchanged
ADC12 memory 10	ADC12MEM10	Read/write	0154h	Unchanged
ADC12 memory 11	ADC12MEM11	Read/write	0156h	Unchanged
ADC12 memory 12	ADC12MEM12	Read/write	0158h	Unchanged
ADC12 memory 13	ADC12MEM13	Read/write	015Ah	Unchanged
ADC12 memory 14	ADC12MEM14	Read/write	015Ch	Unchanged
ADC12 memory 15	ADC12MEM15	Read/write	015Eh	Unchanged
ADC12 memory control 0	ADC12MCTL0	Read/write	080h	Reset with POR
ADC12 memory control 1	ADC12MCTL1	Read/write	081h	Reset with POR
ADC12 memory control 2	ADC12MCTL2	Read/write	082h	Reset with POR
ADC12 memory control 3	ADC12MCTL3	Read/write	083h	Reset with POR
ADC12 memory control 4	ADC12MCTL4	Read/write	084h	Reset with POR
ADC12 memory control 5	ADC12MCTL5	Read/write	085h	Reset with POR
ADC12 memory control 6	ADC12MCTL6	Read/write	086h	Reset with POR
ADC12 memory control 7	ADC12MCTL7	Read/write	087h	Reset with POR
ADC12 memory control 8	ADC12MCTL8	Read/write	088h	Reset with POR
ADC12 memory control 9	ADC12MCTL9	Read/write	089h	Reset with POR
ADC12 memory control 10	ADC12MCTL10	Read/write	08Ah	Reset with POR
ADC12 memory control 11	ADC12MCTL11	Read/write	08Bh	Reset with POR
ADC12 memory control 12	ADC12MCTL12	Read/write	08Ch	Reset with POR
ADC12 memory control 13	ADC12MCTL13	Read/write	08Dh	Reset with POR
ADC12 memory control 14	ADC12MCTL14	Read/write	08Eh	Reset with POR
ADC12 memory control 15	ADC12MCTL15	Read/write	08Fh	Reset with POR

23.3.1 ADC12CTL0, ADC12 Control Register 0

15	14	13	12	11	10	9	8
SHT1x				**SHT0x**			
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
MSC	**REF2_5V**	**REFON**	**ADC120N**	**ADC12OVIE**	**ADC12TOVIE**	**ENC**	**ADC12SC**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Can be modified only when ENC = 0

SHT1x Bits 15-12 Sample-and-hold time. These bits define the number of ADC12CLK cycles in the sampling period for registers ADC12MEM8 to ADC12MEM15.

- 0000 4 ADC12CLK cycles
- 0001 8 ADC12CLK cycles
- 0010 16 ADC12CLK cycles
- 0011 32 ADC12CLK cycles
- 0100 64 ADC12CLK cycles
- 0101 96 ADC12CLK cycles
- 0110 128 ADC12CLK cycles
- 0111 192 ADC12CLK cycles
- 1000 256 ADC12CLK cycles
- 1001 384 ADC12CLK cycles
- 1010 512 ADC12CLK cycles
- 1011 768 ADC12CLK cycles
- 1100 1024 ADC12CLK cycles
- 1101 1024 ADC12CLK cycles
- 1110 1024 ADC12CLK cycles
- 1111 1024 ADC12CLK cycles

SHT0x Bits 11-8 Sample-and-hold time. These bits define the number of ADC12CLK cycles in the sampling period for registers ADC12MEM0 to ADC12MEM7.

- 0000 4 ADC12CLK cycles
- 0001 8 ADC12CLK cycles
- 0010 16 ADC12CLK cycles
- 0011 32 ADC12CLK cycles
- 0100 64 ADC12CLK cycles
- 0101 96 ADC12CLK cycles
- 0110 128 ADC12CLK cycles
- 0111 192 ADC12CLK cycles
- 1000 256 ADC12CLK cycles
- 1001 384 ADC12CLK cycles
- 1010 512 ADC12CLK cycles
- 1011 768 ADC12CLK cycles
- 1100 1024 ADC12CLK cycles
- 1101 1024 ADC12CLK cycles
- 1110 1024 ADC12CLK cycles
- 1111 1024 ADC12CLK cycles

MSC Bit 7 Multiple sample and conversion. Valid only for sequence or repeated modes.

- 0 The sampling timer requires a rising edge of the SHI signal to trigger each sample-and-conversion.
- 1 The first rising edge of the SHI signal triggers the sampling timer, but further sample-and-conversions are performed automatically as soon as the prior conversion is completed.

REF2_5V Bit 6 Reference generator voltage. REFON must also be set.

- 0 1.5 V
- 1 2.5 V

REFON	Bit 5	Reference generator on
		0 Reference off
		1 Reference on
ADC12ON	Bit 4	ADC12 on
		0 ADC12 off
		1 ADC12 on
ADC12OVIE	Bit 3	ADC12MEMx overflow-interrupt enable. The GIE bit must also be set to enable the interrupt.
		0 Overflow interrupt disabled
		1 Overflow interrupt enabled
ADC12TOVIE	Bit 2	ADC12 conversion-time-overflow interrupt enable. The GIE bit must also be set to enable the interrupt.
		0 Conversion time overflow interrupt disabled
		1 Conversion time overflow interrupt enabled
ENC	Bit 1	Enable conversion
		0 ADC12 disabled
		1 ADC12 enabled
ADC12SC	Bit 0	Start conversion. Software-controlled sample-and-conversion start. ADC12SC and ENC may be set together with one instruction. ADC12SC is reset automatically.
		0 No sample-and-conversion-start
		1 Start sample-and-conversion

23.3.2 ADC12CTL1, ADC12 Control Register 1

15	14	13	12	11	10	9	8
CSTARTADDx				**SHSx**		**SHP**	**ISSH**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
ADC12DIVx			**ADC12SSELx**		**CONSEQx**		**ADC12BUSY**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Can be modified only when ENC = 0

CSTARTADDx Bits 15-12 Conversion start address. These bits select which ADC12 conversion-memory register is used for a single conversion or for the first conversion in a sequence. The value of CSTARTADDx is 0 to 0Fh, corresponding to ADC12MEM0 to ADC12MEM15.

SHSx Bits 11-10 Sample-and-hold source select

- 00 ADC12SC bit
- 01 Timer_A.OUT1
- 10 Timer_B.OUT0
- 11 Timer_B.OUT1

SHP Bit 9 Sample-and-hold pulse-mode select. This bit selects the source of the sampling signal (SAMPCON) to be either the output of the sampling timer or the sample-input signal directly.

- 0 SAMPCON signal is sourced from the sample-input signal.
- 1 SAMPCON signal is sourced from the sampling timer.

ISSH Bit 8 Invert signal sample-and-hold

- 0 The sample-input signal is not inverted.
- 1 The sample-input signal is inverted.

ADC12DIVx Bits 7-5 ADC12 clock divider

- 000 /1
- 001 /2
- 010 /3
- 011 /4
- 100 /5
- 101 /6
- 110 /7
- 111 /8

ADC12SSELx Bits 4-3 ADC12 clock source select

- 00 ADC12OSC
- 01 ACLK
- 10 MCLK
- 11 SMCLK

CONSEQx Bits 2-1 Conversion sequence mode select

- 00 Single-channel, single-conversion
- 01 Sequence-of-channels
- 10 Repeat-single-channel
- 11 Repeat-sequence-of-channels

ADC12BUSY Bit 0 ADC12 busy. This bit indicates an active sample or conversion operation.

- 0 No operation is active.
- 1 A sequence, sample, or conversion is active.

23.3.3 ADC12MEMx, ADC12 Conversion Memory Registers

15	14	13	12	11	10	9	8
0	0	0	0	Conversion Results			
r0	r0	r0	r0	rw	rw	rw	rw
7	6	5	4	3	2	1	0
Conversion Results							
rw	rw	rw	rw	rw	rw	rw	rw

Conversion Results	Bits 15-0	The 12-bit conversion results are right-justified. Bit 11 is the MSB. Bits 15-12 are always 0. Writing to the conversion memory registers corrupts the results.

23.3.4 ADC12MCTLx, ADC12 Conversion Memory Control Registers

7	6	5	4	3	2	1	0
EOS	SREFx			INCHx			
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Can be modified only when ENC = 0

EOS	Bit 7	End of sequence. Indicates the last conversion in a sequence.	
		0	Not end of sequence
		1	End of sequence
SREFx	Bits 6-4	Select reference	
		000	$V_{R+} = AV_{CC}$ and $V_{R-} = AV_{SS}$
		001	$V_{R+} = V_{REF+}$ and $V_{R-} = AV_{SS}$
		010	$V_{R+} = V_{eREF+}$ and $V_{R-} = AV_{SS}$
		011	$V_{R+} = V_{eREF+}$ and $V_{R-} = AV_{SS}$
		100	$V_{R+} = AV_{CC}$ and $V_{R-} = V_{REF-}/ V_{eREF-}$
		101	$V_{R+} = V_{REF+}$ and $V_{R-} = V_{REF-}/ V_{eREF-}$
		110	$V_{R+} = V_{eREF+}$ and $V_{R-} = V_{REF-}/ V_{eREF-}$
		111	$V_{R+} = V_{eREF+}$ and $V_{R-} = V_{REF-}/ V_{eREF-}$
INCHx	Bits 3-0	Input channel select	
		0000	A0
		0001	A1
		0010	A2
		0011	A3
		0100	A4
		0101	A5
		0110	A6
		0111	A7
		1000	V_{eREF+}
		1001	V_{REF-}/V_{eREF-}
		1010	Temperature diode
		1011	$(AV_{CC} - AV_{SS}) / 2$
		1100	GND
		1101	GND
		1110	GND
		1111	GND

23.3.5 ADC12IE, ADC12 Interrupt Enable Register

15	14	13	12	11	10	9	8
ADC12IE15	**ADC12IE14**	**ADC12IE13**	**ADC12IE12**	**ADC12IE11**	**ADC12IE10**	**ADC12IFG9**	**ADC12IE8**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
ADC12IE7	**ADC12IE6**	**ADC12IE5**	**ADC12IE4**	**ADC12IE3**	**ADC12IE2**	**ADC12IE1**	**ADC12IE0**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

ADC12IEx Bits 15-0 Interrupt enable. These bits enable or disable the interrupt request for the ADC12IFGx bits.

0 Interrupt disabled

1 Interrupt enabled

23.3.6 ADC12IFG, ADC12 Interrupt Flag Register

15	14	13	12	11	10	9	8
ADC12IFG15	**ADC12IFG14**	**ADC12IFG13**	**ADC12IFG12**	**ADC12IFG11**	**ADC12IFG10**	**ADC12IFG9**	**ADC12IFG8**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
ADC12IFG7	**ADC12IFG6**	**ADC12IFG5**	**ADC12IFG4**	**ADC12IFG3**	**ADC12IFG2**	**ADC12IFG1**	**ADC12IFG0**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

ADC12IFGx Bits 15-0 ADC12MEMx Interrupt flag. These bits are set when corresponding ADC12MEMx is loaded with a conversion result. The ADC12IFGx bits are reset if the corresponding ADC12MEMx is accessed, or may be reset with software.

0 No interrupt pending

1 Interrupt pending

23.3.7 ADC12IV, ADC12 Interrupt Vector Register

15	14	13	12	11	10	9	8
0	0	0	0	0	0	0	0
r0	r0	r0	r0	r0	r0	r0	r0

7	6	5	4	3	2	1	0
0	0	**ADC12IVx**					0
r0	r0	r-(0)	r-(0)	r-(0)	r-(0)	r-(0)	r0

ADC12IVx Bits 15-0 ADC12 interrupt vector value

ADC12IV Contents	Interrupt Source	Interrupt Flag	Interrupt Priority
000h	No interrupt pending	-	
002h	ADC12MEMx overflow	-	Highest
004h	Conversion time overflow	-	
006h	ADC12MEM0 interrupt flag	ADC12IFG0	
008h	ADC12MEM1 interrupt flag	ADC12IFG1	
00Ah	ADC12MEM2 interrupt flag	ADC12IFG2	
00Ch	ADC12MEM3 interrupt flag	ADC12IFG3	
00Eh	ADC12MEM4 interrupt flag	ADC12IFG4	
010h	ADC12MEM5 interrupt flag	ADC12IFG5	
012h	ADC12MEM6 interrupt flag	ADC12IFG6	
014h	ADC12MEM7 interrupt flag	ADC12IFG7	
016h	ADC12MEM8 interrupt flag	ADC12IFG8	
018h	ADC12MEM9 interrupt flag	ADC12IFG9	
01Ah	ADC12MEM10 interrupt flag	ADC12IFG10	
01Ch	ADC12MEM11 interrupt flag	ADC12IFG11	
01Eh	ADC12MEM12 interrupt flag	ADC12IFG12	
020h	ADC12MEM13 interrupt flag	ADC12IFG13	
022h	ADC12MEM14 interrupt flag	ADC12IFG14	
024h	ADC12MEM15 interrupt flag	ADC12IFG15	Lowest

TLV Structure

The Tag-Length-Value (TLV) structure is used in selected MSP430x2xx devices to provide device-specific information in the device's flash memory SegmentA, such as calibration data. For the device-dependent implementation, see the device-specific data sheet.

Topic **Page**

24.1 TLV Introduction

The TLV structure stores device-specific data in SegmentA. The SegmentA content of an example device is shown in Table 24-1.

Table 24-1. Example SegmentA Structure

Word Address	Upper Byte	Lower Byte	Tag Address and Offset
0x10FE	CALBC1_1MHZ	CALDCO_1MHZ	0x10F6 + 0x0008
0x10FC	CALBC1_8MHZ	CALDCO_8MHZ	0x10F6 + 0x0006
0x10FA	CALBC1_12MHZ	CALDCO_12MHZ	0x10F6 + 0x0004
0x10F8	CALBC1_16MHZ	CALDCO_16MHZ	0x10F6 + 0x0002
0x10F6	0x08 (LENGTH)	TAG_DCO_30	0x10F6
0x10F4	0xFF	0xFF	
0x10F2	0xFF	0xFF	
0x10F0	0xFF	0xFF	
0x10EE	0xFF	0xFF	
0x10EC	0x08 (LENGTH)	TAG_EMPTY	0x10EC
0x10EA	CAL_ADC_25T85		0x10DA + 0x0010
0x10E8	CAL_ADC_25T30		0x10DA + 0x000E
0x10E6	CAL_ADC_25VREF_FACTOR		0x10DA + 0x000C
0x10E4	CAL_ADC_15T85		0x10DA + 0x000A
0x10E2	CAL_ADC_15T30		0x10DA + 0x0008
0x10E0	CAL_ADC_15VREF_FACTOR		0x10DA + 0x0006
0x10DE	CAL_ADC_OFFSET		0x10DA + 0x0004
0x10DC	CAL_ADC_GAIN_FACTOR		0x10DA + 0x0002
0x10DA	0x10 (LENGTH)	TAG_ADC12_1	0x10DA
0x10D8	0xFF	0xFF	
0x10D6	0xFF	0xFF	
0x10D4	0xFF	0xFF	
0x10D2	0xFF	0xFF	
0x10D0	0xFF	0xFF	
0x10CE	0xFF	0xFF	
0x10CC	0xFF	0xFF	
0x10CA	0xFF	0xFF	
0x10C8	0xFF	0xFF	
0x10C6	0xFF	0xFF	
0x10C4	0xFF	0xFF	
0x10C2	0x16 (LENGTH)	TAG_EMPTY	0x10C2
0x10C0	2s complement of bit-wise XOR		0x10C0

The first two bytes of SegmentA (0x10C0 and 0x10C1) hold the checksum of the remainder of the segment (addresses 0x10C2 to 0x10FF).

The first tag is located at address 0x10C2 and, in this example, is the TAG_EMPTY tag. The following byte (0x10C3) holds the length of the following structure. The length of this TAG_EMPTY structure is 0x16 and, therefore, the next tag, TAG_ADC12_1, is found at address 0x10DA. Again, the following byte holds the length of the TAG_ADC12_1 structure.

The TLV structure maps the entire address range 0x10C2 to 0x10FF of the SegmentA. A program routine looking for tags starting at the SegmentA address 0x10C2 can extract all information even if it is stored at a different (device-specific) absolute address.

24.2 Supported Tags

Each device contains a subset of the tags shown in Table 24-2. See the device-specific data sheet for details.

Table 24-2. Supported Tags (Device Specific)

Tag	Description	Value
TAG_EMPTY	Identifies an unused memory area	0xFE
TAG_DCO_30	Calibration values for the DCO at room temperature and DV_{CC} = 3 V	0x01
TAG_ADC12_1	Calibration values for the ADC12 module	0x08
TAG_ADC10_1	Calibration values for the ADC10 module	0x08

24.2.1 DCO Calibration TLV Structure

For DCO calibration, the BCS+ registers (BCSCTL1 and DCOCTL) are used. The values stored in the flash information memory SegmentA are written to the BCS+ registers (see Table 24-3).

Table 24-3. DCO Calibration Data (Device Specific)

Label	Description	Offset
CALBC1_1MHZ	Value for the BCSCTL1 register for 1 MHz, T_A = 25°C	0x07
CALDCO_1MHZ	Value for the DCOCTL register for 1 MHz, T_A = 25°C	0x06
CALBC1_8MHZ	Value for the BCSCTL1 register for 8 MHz, T_A = 25°C	0x05
CALDCO_8MHZ	Value for the DCOCTL register for 8 MHz, T_A = 25°C	0x04
CALBC1_12MHZ	Value for the BCSCTL1 register for 12 MHz, T_A = 25°C	0x03
CALDCO_12MHZ	Value for the DCOCTL register for 12 MHz, T_A = 25°C	0x02
CALBC1_16MHZ	Value for the BCSCTL1 register for 16 MHz, T_A = 25°C	0x01
CALDCO_16MHZ	Value for the DCOCTL register for 16 MHz, T_A = 25°C	0x00

The calibration data for the DCO is available in all 2xx devices and is stored at the same absolute addresses. The device-specific SegmentA content is applied using the absolute addressing mode if the sample code shown in Example 24-1 is used.

Example 24-1. Code Example Using Absolute Addressing Mode

```
; Calibrate the DCO to 1 MHz
      CLR.B   &DCOCTL                 ; Select lowest DCOx
                                      ; and MODx settings
      MOV.B   &CALBC1_1MHZ,&BCSCTL1   ; Set RSELx
      MOV.B   &CALDCO_1MHZ,&DCOCTL    ; Set DCOx and MODx
```

The TLV structure allows use of the address of the TAG_DCO_30 tag to address the DCO registers. Example 24-2 shows how to address the DCO calibration data using the TAG_DCO_30 tag.

Example 24-2. Code Example Using the TLV Structure

```
; Calibrate the DCO to 8 MHz
; It is assumed that R10 contains the address of the TAG_DCO_30 tag
      CLR.B   &DCOCTL           ; Select lowest DCOx and
                                ; MODx settings
      MOV.B   7(R10),&BCSCTL1   ; Set RSEL
      MOV.B   6(R10),&DCOCTL    ; Set DCOx and MODx
```

24.2.2 TAG_ADC12_1 Calibration TLV Structure

The calibration data for the ADC12 module consists of eight words (see Table 24-4).

Table 24-4. TAG_ADC12_1 Calibration Data (Device Specific)

Label	Description	Offset
CAL_ADC_25T85	VREF2_5 = 1, T_A = 85°C ± 2°C, 12-bit conversion result	0x0E
CAL_ADC_25T30	VREF2_5 = 1, T_A = 30°C ± 2°C, 12-bit conversion result	0x0C
CAL_ADC_25VREF_FACTOR	VREF2_5 = 1, T_A = 30°C ± 2°C	0x0A
CAL_ADC_15T85	VREF2_5 = 0, T_A = 85°C ± 2°C, 12-bit conversion result	0x08
CAL_ADC_15T30	VREF2_5 = 0, T_A = 30°C ± 2°C, 12-bit conversion result	0x06
CAL_ADC_15VREF_FACTOR	VREF2_5 = 0, T_A = 30°C ± 2°C	0x04
CAL_ADC_OFFSET	VeREF = 2.5 V, T_A = 85°C ± 2°C, $f_{ADC12CLK}$ = 5 MHz	0x02
CAL_ADC_GAIN_FACTOR	VeREF = 2.5 V, T_A = 85°C ± 2°C, $f_{ADC12CLK}$ = 5 MHz	0x00

24.2.2.1 Temperature Sensor Calibration Data

The temperature sensor is calibrated using the internal voltage references. Each reference voltage (1.5 V and 2.5 V) contains a measured value for two temperatures, 30°C±2°C and 85°C±2°C and are stored in the TLV structure at the respective SegmentA location (see Table 24-4). The characteristic equation of the temperature sensor voltage, in mV, is:

$$V_{SENSE} = TC_{SENSOR} \times Temp + V_{SENSOR} \quad (1)$$

The temperature coefficient, TC_{SENSOR}in mV/°C, represents the slope of the equation. V_{SENSOR}, in mV, represents the y-intercept of the equation. Temp, in °C, is the temperature of interest.

The temperature (Temp, °C) can be computed as follows for each of the reference voltages used in the ADC measurement:

$$Temp = (ADC(raw) - CAL\_ADC\_15T30) \times \left(\frac{85 - 30}{CAL\_ADC\_15T85 - CAL\_ADC\_15T30} \right) + 30$$

$$Temp = (ADC(raw) - CAL\_ADC\_25T30) \times \left(\frac{85 - 30}{CAL\_ADC\_25T85 - CAL\_ADC\_25T30} \right) + 30 \quad (2)$$

24.2.2.2 Integrated Voltage Reference Calibration Data

The reference voltages (VREF2_5 = 0 and 1) are measured at room temperature. The measured value is normalized by 1.5 V or 2.5 V before stored into the flash information memory SegmentA.

CAL_ADC_15VREF_FACTOR = (Ve_{REF} / 1.5 V) × 2^{15}

The conversion result is corrected by multiplying it with the CAL_ADC_15VREF_FACTOR (or CAL_ADC_25VREF_FACTOR) and dividing the result by 2^{15}.

ADC(corrected) = ADC(raw) × CAL_ADC_15VREF_FACTOR × (1 / 2^{15})

24.2.2.3 Example Using the Reference Calibration

In the following example, the integrated 1.5-V reference voltage is used during a conversion.

- Conversion result: 0x0100
- Reference voltage calibration factor (CAL_ADC_15VREF_FACTOR): 0x7BBB

The following steps show an example of how the ADC12 conversion result can be corrected by using the hardware multiplier:

1. Multiply the conversion result by 2 (this step simplifies the final division).
2. Multiply the result by CAL_ADC_15VREF_FACTOR.
3. Divide the result by 2^{16} (use the upper word of the 32-bit multiplication result RESHI).

In the example:

1. 0x0100 × 0x0002 = 0x0200
2. 0x0200 × 0x7BBB = 0x00F7_7600
3. 0x00F7_7600 ÷ 0x0001_0000 = 0x0000_00F7 (= 247)

The code example using the hardware multiplier follows.

```
; The ADC conversion result is stored in ADC12MEM0
; It is assumed that R9 contains the address of the
; TAG_ADC12_1.
; The corrected value is available in ADC_COR
      MOV.W   &ADC12MEM0,R10    ; move result to R10
      RLA.W   R10               ; R10 x 2
      MOV.W   R10,&MPY          ; unsigned multiply OP1
      MOV.W   CAL_ADC_15VREF_FACTOR(R9),&OP2
                                ; calibration value OP2
      MOV.W   &RESHI,&ADC_COR   ; result: upper 16-bit MPY
```

24.2.2.4 Offset and Gain Calibration Data

The offset of the ADC12 is determined and stored as a twos-complement number in SegmentA. The offset error correction is done by adding the CAL_ADC_OFFSET to the conversion result.

ADC(offset_corrected) = ADC(raw) + CAL_ADC_OFFSET

The gain of the ADC12, stored at offset 0x00, is calculated by the following equation.

CAL_ADC_GAIN_FACTOR = (1 / GAIN) × 2^{15}

The conversion result is gain corrected by multiplying it with the CAL_ADC_GAIN_FACTOR and dividing the result by 2^{15}.

ADC(gain_corrected) = ADC(raw) × CAL_ADC_GAIN_FACTOR × (1 / 2^{15})

If both gain and offset are corrected, the gain correction is done first.

ADC(gain_corrected) = ADC(raw) × CAL_ADC_GAIN_FACTOR × (1 / 2^{15})

ADC(final) = ADC(gain_corrected) + CAL_ADC_OFFSET

24.2.2.5 Example Using Gain and Offset Calibration

In the following example, an external reference voltage is used during a conversion.

- Conversion result: 0x0800 (= 2048)
- Gain calibration factor: 0x7FE0 (gain error: +2 LSB)
- Offset calibration: 0xFFFE (2s complement of -2)

The following steps show an example of how the ADC12 conversion result is corrected by using the hardware multiplier:

1. Multiply the conversion result by 2 (this step simplifies the final division).
2. Multiply the result by CAL_ADC_GAIN_FACTOR.
3. Divide the result by 2^{16} (use the upper word of the 32-bit multiplication result RESHI)
4. Add CAL_ADC_OFFSET to the result.

In the example:

1. 0x0800 × 0x0002 = 0x1000
2. 0x1000 × 0x8010 = 0x0801_0000
3. 0x0801_0000 ÷ 0x0001_0000 = 0x0000_0801 (= 2049)
4. 0x801 + 0xFFFE = 0x07FF (= 2047)

The code example using the hardware multiplier follows.

```
; The ADC conversion result is stored in ADC12MEM0
; It is assumed that R9 contains the address of the TAG_ADC12_1.
```

```
; The corrected value is available in ADC_COR
      MOV.W   &ADC12MEM0,R10    ; move result to R10
      RLA.W   R10               ; R10 * 2
      MOV.W   R10,&MPY          ; unsigned multiply OP1
      MOV.W   CAL_ADC_GAIN_FACTOR(R9),&OP2
                                ; calibration value OP2
      MOV.W   &RESHI,&ADC_COR   ; use upper 16-bit MPY
      ADD.W   CAL_ADC_OFFSET(R9),&ADC_COR
                                ; add offset correction
```

24.3 Checking Integrity of SegmentA

The 64-byte SegmentA contains a 2-byte checksum of the data stored at 0x10C2 up to 0x10FF at addresses 0x10C0 and 0x10C1. The checksum is a bit-wise XOR of 31 words stored in the twos-complement data format.

A code example to calculate the checksum follows.

```
; Checking the SegmentA integrity by calculating the 2's
; complement of the 31 words at 0x10C2 - 0x10FE.
; It is assumed that the SegmentA Start Address is stored
; in R10. R11 is initialized to 0x00.
; The label TLV_CHKSUM is set to 0x10C0.
       ADD.W   #2,R10            ; Skip the checksum
LP0    XOR.W   @R10+,R11         ; Add a word to checksum
       CMP.W   #0x10FF,R10       ; Last word included?
       JN      LP0               ; No, add more data
       ADD.W   &TLV_CHKSUM,R11   ; Add checksum
       JNZ     CSNOK             ; Checksum not ok
       ...                       ; Use SegmentA data
CSNOK  ...                       ; Do not use SegmentA Data
```

24.4 Parsing TLV Structure of Segment A

Example code to analyze SegmentA follows.

```
; It is assumed that the SegmentA start address
; is stored in R10.

LP1   ADD.W   #2,R10              ; Skip two bytes
      CMP.W   #0x10FF,R10         ; SegmentA end reached?
      JGE     DONE                ; Yes, done

      CMP.B   #TAG_EMPTY,0(R10)   ; TAG_EMPTY?
      JNZ     T1                  ; No, continue
      JMP     LP2                 ; Yes, done with TAG_EMPTY

T1    CMP.B   #TAG_ADC12_1,0(R10) ; TAG_ADC12_1?
      JNZ     T2                  ; No, continue
      ...                         ; Yes, found TAG_ADC12_1
      JMP     LP2                 ; Done with TAG_ADC12_1

T2    CMP.B   #DCO_30,0(R10)      ; TAG_DCO_30?
      JNZ     T3                  ; No, continue
      CLR.B   &DCOCTL             ; Select lowest DCOx
      MOV.B   7(R10),&BCSCTL1     ; Yes, use e.g. 8MHz data and
      MOV.B   6(R10),&DCOCTL      ; set DCOx and MODx
      JMP     LP2                 ; Done with TAG_DCO_30

T3    ...                         ; Test for "next tag"
      ...                         ;
      JMP     LP2                 ; Done with "next tag"
```

```
LP2   MOV.B   1(R10),R11          ; Store LENGTH in R11
      ADD.W   R11,R10             ; Add LENGTH to R10
      JMP     LP1                 ; Jump to continue analysis
DONE                              ;
```

DAC12

The DAC12 module is a 12-bit voltage-output digital-to-analog converter (DAC). This chapter describes the operation of the DAC12 module of the MSP430x2xx device family.

Topic **Page**

25.1 DAC12 Introduction

The DAC12 module is a 12-bit voltage-output DAC. The DAC12 can be configured in 8-bit or 12-bit mode and may be used in conjunction with the DMA controller. When multiple DAC12 modules are present, they may be grouped together for synchronous update operation.

Features of the DAC12 include:

- 12-bit monotonic output
- 8-bit or 12-bit voltage output resolution
- Programmable settling time vs power consumption
- Internal or external reference selection
- Straight binary or 2s compliment data format
- Self-calibration option for offset correction
- Synchronized update capability for multiple DAC12 modules

NOTE: Multiple DAC12 Modules

Some devices may integrate more than one DAC12 module. If more than one DAC12 is present on a device, the multiple DAC12 modules operate identically.

Throughout this chapter, nomenclature appears such as DAC12_xDAT or DAC12_xCTL to describe register names. When this occurs, the x is used to indicate which DAC12 module is being discussed. In cases where operation is identical, the register is simply referred to as DAC12_xCTL.

The block diagram of the DAC12 module is shown in Figure 25-1.

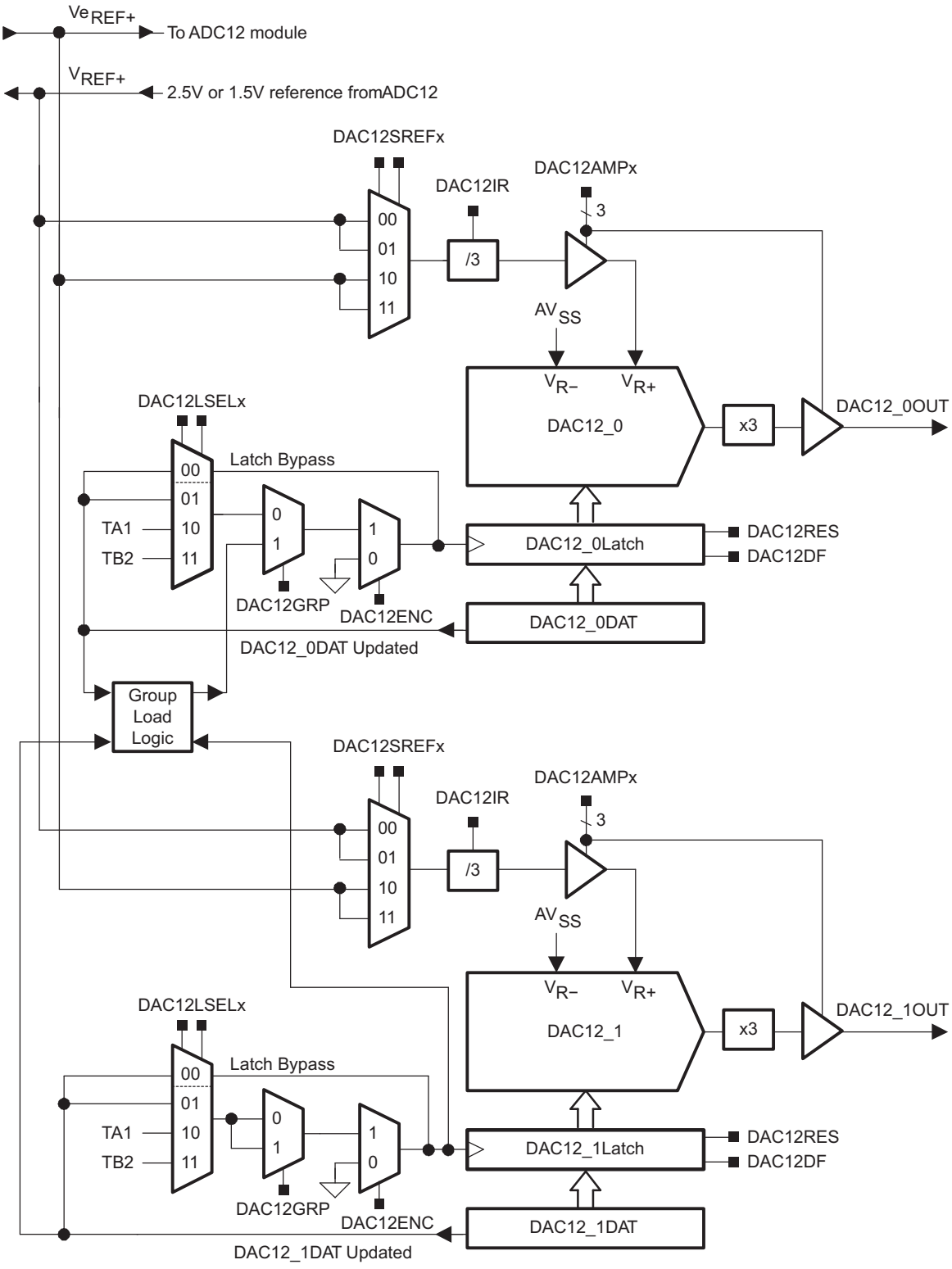


Figure 25-1. DAC12 Block Diagram

25.2 DAC12 Operation

The DAC12 module is configured with user software. The setup and operation of the DAC12 is discussed in the following sections.

25.2.1 DAC12 Core

The DAC12 can be configured to operate in 8-bit or 12-bit mode using the DAC12RES bit. The full-scale output is programmable to be 1x or 3x the selected reference voltage via the DAC12IR bit. This feature allows the user to control the dynamic range of the DAC12. The DAC12DF bit allows the user to select between straight binary data and 2s-compliment data for the DAC. When using straight binary data format, the formula for the output voltage is given in Table 25-1.

Table 25-1. DAC12 Full-Scale Range (V_{REF} = V_{eREF+} or V_{REF+})

Resolution	DAC12RES	DAC12IR	Output Voltage Formula
12 bit	0	0	$V_{OUT} = V_{REF} \times 3 \times \frac{DAC12\_xDAT}{4096}$
12 bit	0	1	$V_{OUT} = V_{REF} \times \frac{DAC12\_xDAT}{4096}$
8 bit	1	0	$V_{OUT} = V_{REF} \times 3 \times \frac{DAC12\_xDAT}{256}$
8 bit	1	1	$V_{OUT} = V_{REF} \times \frac{DAC12\_xDAT}{256}$

In 8-bit mode, the maximum useable value for DAC12_xDAT is 0FFh. In 12-bit mode, the maximum useable value for DAC12_xDAT is 0FFFh. Values greater than these may be written to the register, but all leading bits are ignored.

25.2.1.1 DAC12 Port Selection

The DAC12 outputs are multiplexed with the port P6 pins and ADC12 analog inputs, and also the V_{eREF+} pins. When DAC12AMPx > 0, the DAC12 function is automatically selected for the pin, regardless of the state of the associated PxSELx and PxDIRx bits. The DAC12OPS bit selects between the P6 pins and the V_{eREF+} pins for the DAC outputs. For example, when DAC12OPS = 0, DAC12_0 outputs on P6.6 and DAC12_1 outputs on P6.7. When DAC12OPS = 1, DAC12_0 outputs on V_{eREF+} and DAC12_1 outputs on P6.5. See the port pin schematic in the device-specific data sheet for more details.

25.2.2 DAC12 Reference

The reference for the DAC12 is configured to use either an external reference voltage or the internal 1.5-V/2.5-V reference from the ADC12 module with the DAC12SREFx bits. When DAC12SREFx = {0,1} the V_{REF+} signal is used as the reference and when DAC12SREFx = {2,3} the V_{eREF+} signal is used as the reference.

To use the ADC12 internal reference, it must be enabled and configured via the applicable ADC12 control bits.

25.2.2.1 DAC12 Reference Input and Voltage Output Buffers

The reference input and voltage output buffers of the DAC12 can be configured for optimized settling time vs power consumption. Eight combinations are selected using the DAC12AMPx bits. In the low/low setting, the settling time is the slowest, and the current consumption of both buffers is the lowest. The medium and high settings have faster settling times, but the current consumption increases. See the device-specific data sheet for parameters.

25.2.3 Updating the DAC12 Voltage Output

The DAC12_xDAT register can be connected directly to the DAC12 core or double buffered. The trigger for updating the DAC12 voltage output is selected with the DAC12LSELx bits.

When DAC12LSELx = 0 the data latch is transparent and the DAC12_xDAT register is applied directly to the DAC12 core. the DAC12 output updates immediately when new DAC12 data is written to the DAC12_xDAT register, regardless of the state of the DAC12ENC bit.

When DAC12LSELx = 1, DAC12 data is latched and applied to the DAC12 core after new data is written to DAC12_xDAT. When DAC12LSELx = 2 or 3, data is latched on the rising edge from the Timer_A CCR1 output or Timer_B CCR2 output respectively. DAC12ENC must be set to latch the new data when DAC12LSELx > 0.

25.2.4 DAC12_xDAT Data Format

The DAC12 supports both straight binary and 2s compliment data formats. When using straight binary data format, the full-scale output value is 0FFFh in 12-bit mode (0FFh in 8-bit mode) as shown in Figure 25-2.

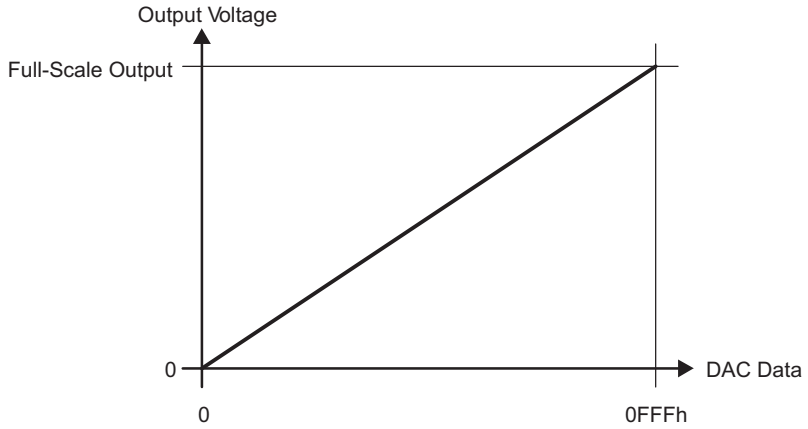


Figure 25-2. Output Voltage vs DAC12 Data, 12-Bit, Straight Binary Mode

When using 2s-compliment data format, the range is shifted such that a DAC12_xDAT value of 0800h (0080h in 8-bit mode) results in a zero output voltage, 0000h is the mid-scale output voltage, and 07FFh (007Fh for 8-bit mode) is the full-scale voltage output (see Figure 25-3).

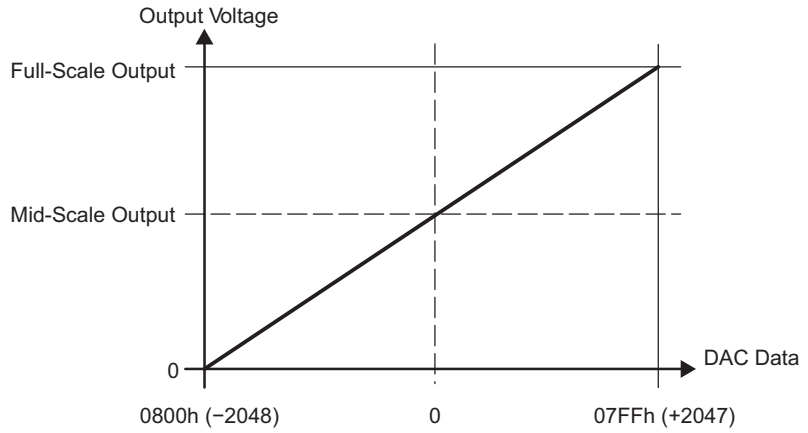


Figure 25-3. Output Voltage vs DAC12 Data, 12-Bit, 2s-Compliment Mode

25.2.5 DAC12 Output Amplifier Offset Calibration

The offset voltage of the DAC12 output amplifier can be positive or negative. When the offset is negative, the output amplifier attempts to drive the voltage negative but cannot do so. The output voltage remains at zero until the DAC12 digital input produces a sufficient positive output voltage to overcome the negative offset voltage, resulting in the transfer function shown in Figure 25-4.

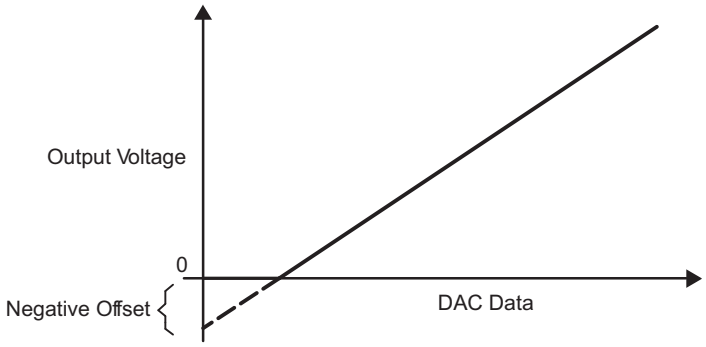


Figure 25-4. Negative Offset

When the output amplifier has a positive offset, a digital input of zero does not result in a zero output voltage. The DAC12 output voltage reaches the maximum output level before the DAC12 data reaches the maximum code. This is shown in Figure 25-5.

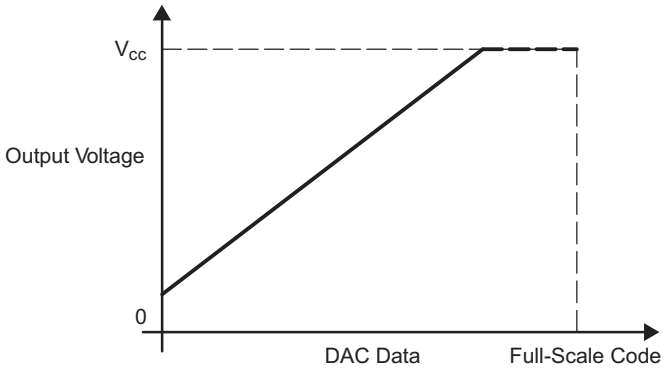


Figure 25-5. Positive Offset

The DAC12 has the capability to calibrate the offset voltage of the output amplifier. Setting the DAC12CALON bit initiates the offset calibration. The calibration should complete before using the DAC12. When the calibration is complete, the DAC12CALON bit is automatically reset. The DAC12AMPx bits should be configured before calibration. For best calibration results, port and CPU activity should be minimized during calibration.

25.2.6 Grouping Multiple DAC12 Modules

Multiple DAC12s can be grouped together with the DAC12GRP bit to synchronize the update of each DAC12 output. Hardware ensures that all DAC12 modules in a group update simultaneously independent of any interrupt or NMI event.

DAC12_0 and DAC12_1 are grouped by setting the DAC12GRP bit of DAC12_0. The DAC12GRP bit of DAC12_1 is don't care. When DAC12_0 and DAC12_1 are grouped:

- The DAC12_1 DAC12LSELx bits select the update trigger for both DACs
- The DAC12LSELx bits for both DACs must be > 0
- The DAC12ENC bits of both DACs must be set to 1

When DAC12_0 and DAC12_1 are grouped, both DAC12_xDAT registers must be written to before the outputs update, even if data for one or both of the DACs is not changed. Figure 25-6 shows a latch-update timing example for grouped DAC12_0 and DAC12_1.

When DAC12_0 DAC12GRP = 1 and both DAC12_x DAC12LSELx > 0 and either DAC12ENC = 0, neither DAC12 updates.

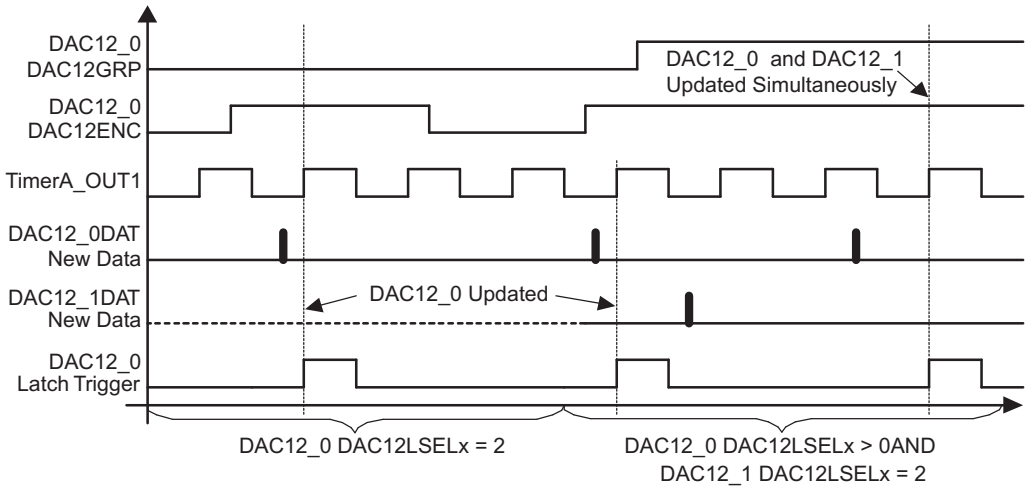


Figure 25-6. DAC12 Group Update Example, Timer_A3 Trigger

NOTE: DAC12 Settling Time

The DMA controller is capable of transferring data to the DAC12 faster than the DAC12 output can settle. The user must assure the DAC12 settling time is not violated when using the DMA controller. See the device-specific data sheet for parameters.

25.2.7 DAC12 Interrupts

The DAC12 interrupt vector is shared with the DMA controller on some devices (see device-specific data sheet for interrupt assignment). In this case, software must check the DAC12IFG and DMAIFG flags to determine the source of the interrupt.

The DAC12IFG bit is set when DAC12LSELx > 0 and DAC12 data is latched from the DAC12_xDAT register into the data latch. When DAC12LSELx = 0, the DAC12IFG flag is not set.

A set DAC12IFG bit indicates that the DAC12 is ready for new data. If both the DAC12IE and GIE bits are set, the DAC12IFG generates an interrupt request. The DAC12IFG flag is not reset automatically. It must be reset by software.

25.3 DAC12 Registers

The DAC12 registers are listed in Table 25-2.

Table 25-2. DAC12 Registers

Register	Short Form	Register Type	Address	Initial State
DAC12_0 control	DAC12_0CTL	Read/write	01C0h	Reset with POR
DAC12_0 data	DAC12_0DAT	Read/write	01C8h	Reset with POR
DAC12_1 control	DAC12_1CTL	Read/write	01C2h	Reset with POR
DAC12_1 data	DAC12_1DAT	Read/write	01CAh	Reset with POR

25.3.1 DAC12_xCTL, DAC12 Control Register

15	14	13	12	11	10	9	8
DAC12OPS	**DAC12SREFx**		**DAC12RES**	**DAC12LSELx**		**DAC12CALON**	**DAC12IR**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
DAC12AMPx			**DAC12DF**	**DAC12IE**	**DAC12IFG**	**DAC12ENC**	**DAC12GRP**
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Can be modified only when DAC12ENC = 0

DAC12OPS Bit 15 DAC12 output select
- 0 DAC12_0 output on P6.6, DAC12_1 output on P6.7
- 1 DAC12_0 output on V_{eREF+}, DAC12_1 output on P6.5

DAC12SREFx Bits 14-13 DAC12 select reference voltage
- 00 V_{REF+}
- 01 V_{REF+}
- 10 V_{eREF+}
- 11 V_{eREF+}

DAC12RES Bit 12 DAC12 resolution select
- 0 12-bit resolution
- 1 8-bit resolution

DAC12LSELx Bits 11-10 DAC12 load select. Selects the load trigger for the DAC12 latch. DAC12ENC must be set for the DAC to update, except when DAC12LSELx = 0.
- 00 DAC12 latch loads when DAC12_xDAT written (DAC12ENC is ignored)
- 01 DAC12 latch loads when DAC12_xDAT written, or, when grouped, when all DAC12_xDAT registers in the group have been written.
- 10 Rising edge of Timer_A.OUT1 (TA1)
- 11 Rising edge of Timer_B.OUT2 (TB2)

DAC12CALON Bit 9 DAC12 calibration on. This bit initiates the DAC12 offset calibration sequence and is automatically reset when the calibration completes.
- 0 Calibration is not active
- 1 Initiate calibration/calibration in progress

DAC12IR Bit 8 DAC12 input range. This bit sets the reference input and voltage output range.
- 0 DAC12 full-scale output = 3x reference voltage
- 1 DAC12 full-scale output = 1x reference voltage

DAC12AMPx Bits 7-5 DAC12 amplifier setting. These bits select settling time vs current consumption for the DAC12 input and output amplifiers.

DAC12AMPx	Input Buffer	Output Buffer
000	Off	DAC12 off, output high Z
001	Off	DAC12 off, output 0 V
010	Low speed/current	Low speed/current
011	Low speed/current	Medium speed/current
100	Low speed/current	High speed/current
101	Medium speed/current	Medium speed/current
110	Medium speed/current	High speed/current
111	High speed/current	High speed/current

DAC12DF Bit 4 DAC12 data format
- 0 Straight binary
- 1 2s complement

DAC12IE Bit 3 DAC12 interrupt enable
- 0 Disabled
- 1 Enabled

DAC12IFG	Bit 2	DAC12 Interrupt flag
		0 No interrupt pending
		1 Interrupt pending
DAC12ENC	Bit 1	DAC12 enable conversion. This bit enables the DAC12 module when DAC12LSELx > 0. when DAC12LSELx = 0, DAC12ENC is ignored.
		0 DAC12 disabled
		1 DAC12 enabled
DAC12GRP	Bit 0	DAC12 group. Groups DAC12_x with the next higher DAC12_x. Not used for DAC12_1.
		0 Not grouped
		1 Grouped

25.3.2 DAC12_xDAT, DAC12 Data Register

15	14	13	12	11	10	9	8
0	0	0	0	**DAC12 Data**			
r(0)	r(0)	r(0)	r(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
DAC12 Data							
rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)	rw-(0)

Unused	Bits 15-12	Unused. These bits are always 0 and do not affect the DAC12 core.
DAC12 Data	Bits 11-0	DAC12 data

DAC12 Data Format	DAC12 Data
12-bit binary	The DAC12 data are right-justified. Bit 11 is the MSB.
12-bit 2s complement	The DAC12 data are right-justified. Bit 11 is the MSB (sign).
8-bit binary	The DAC12 data are right-justified. Bit 7 is the MSB. Bits 11-8 are don't care and do not affect the DAC12 core.
8-bit 2s complement	The DAC12 data are right-justified. Bit 7 is the MSB (sign). Bits 11-8 are don't care and do not affect the DAC12 core.

SD16_A

The SD16_A module is a single-converter 16-bit sigma-delta analog-to-digital conversion module with high impedance input buffer. This chapter describes the SD16_A. The SD16_A module is implemented in the MSP430x20x3 devices.

Topic **Page**

26.1 SD16_A Introduction

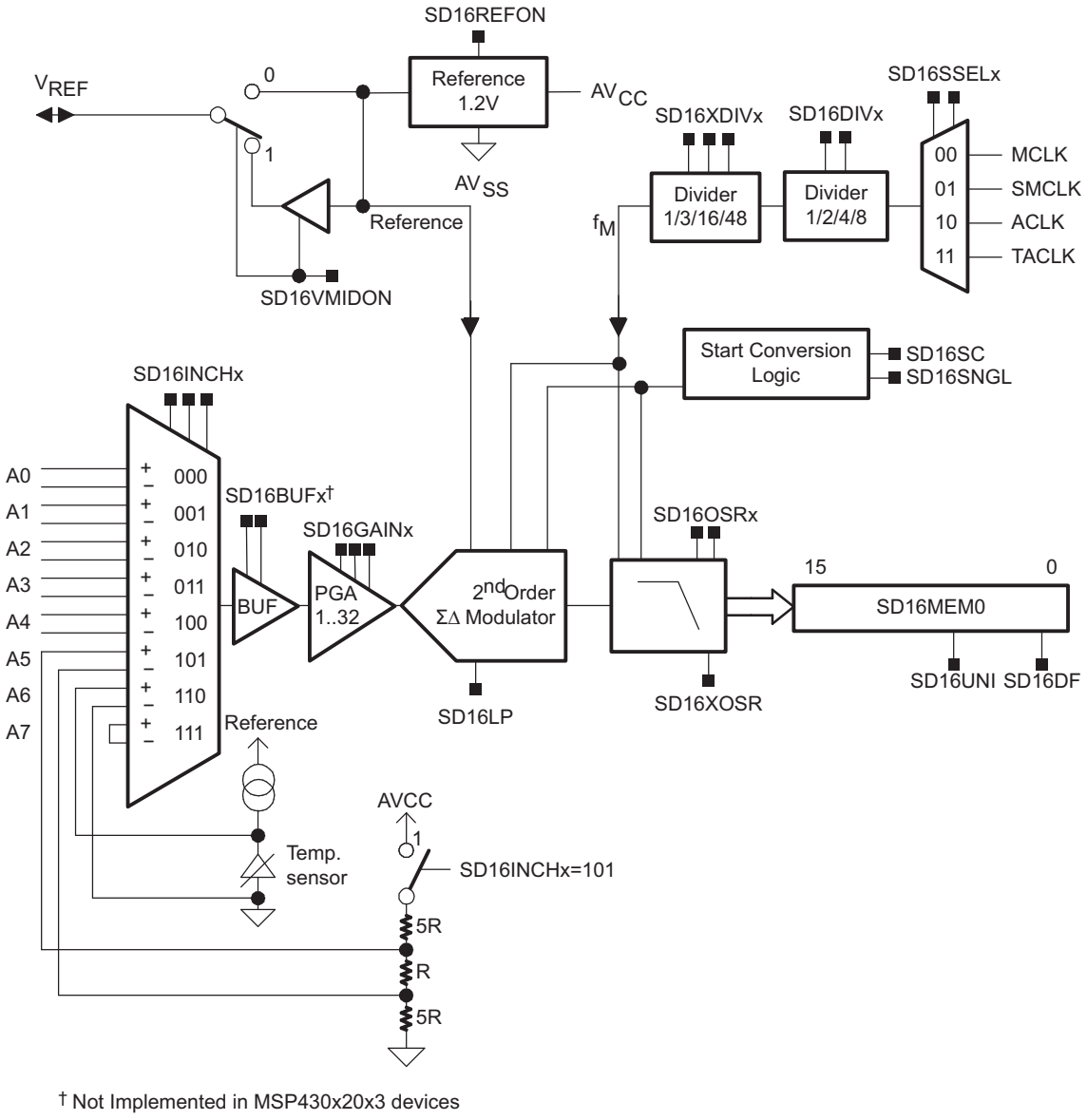
The SD16_A module consists of one sigma-delta analog-to-digital converter with a high-impedance input buffer and an internal voltage reference. It has up to eight fully differential multiplexed analog input pairs including a built-in temperature sensor and a divided supply voltage. The converter is based on a second-order oversampling sigma-delta modulator and digital decimation filter. The decimation filter is a comb type filter with selectable oversampling ratios of up to 1024. Additional filtering can be done in software.

The high impedance input buffer is not implemented in MSP430x20x3 devices.

Features of the SD16_A include:

- 16-bit sigma-delta architecture
- Up to eight multiplexed differential analog inputs per channel(The number of inputs is device dependent, see the device-specific data sheet.)
- Software selectable on-chip reference voltage generation (1.2 V)
- Software selectable internal or external reference
- Built-in temperature sensor
- Up to 1.1-MHz modulator input frequency
- High impedance input buffer(not implemented on all devices, see the device-specific data sheet)
- Selectable low-power conversion mode

The block diagram of the SD16_A module is shown in Figure 26-1.



† Not Implemented in MSP430x20x3 devices

Figure 26-1. SD16_A Block Diagram

26.2 SD16_A Operation

The SD16_A module is configured with user software. The setup and operation of the SD16_A is discussed in the following sections.

26.2.1 ADC Core

The analog-to-digital conversion is performed by a 1-bit second-order sigma-delta modulator. A single-bit comparator within the modulator quantizes the input signal with the modulator frequency f_M. The resulting 1-bit data stream is averaged by the digital filter for the conversion result.

26.2.2 Analog Input Range and PGA

The full-scale input voltage range for each analog input pair is dependent on the gain setting of the programmable gain amplifier of each channel. The maximum full-scale range is $\pm V_{FSR}$ where V_{FSR} is defined by:

$$V_{FSR} = \frac{V_{REF}/2}{GAIN_{PGA}}$$

For a 1.2-V reference, the maximum full-scale input range for a gain of 1 is:

$$\pm V_{FSR} = \frac{1.2\ V/2}{1} = \pm 0.6\ V$$

See the device-specific data sheet for full-scale input specifications.

26.2.3 Voltage Reference Generator

The SD16_A module has a built-in 1.2-V reference. It is enabled by the SD16REFON bit. When using the internal reference an external 100-nF capacitor connected from V_{REF} to AV_{SS} is recommended to reduce noise. The internal reference voltage can be used off-chip when SD16VMIDON = 1. The buffered output can provide up to 1 mA of drive. When using the internal reference off-chip, a 470-nF capacitor connected from V_{REF} to AV_{SS} is required. See the device-specific data sheet for parameters.

An external voltage reference can be applied to the V_{REF} input when SD16REFON and SD16VMIDON are both reset.

26.2.4 Auto Power-Down

The SD16_A is designed for low power applications. When the SD16_A is not actively converting, it is automatically disabled and automatically re-enabled when a conversion is started. The reference is not automatically disabled, but can be disabled by setting SD16REFON = 0. When the SD16_A or reference are disabled, they consume no current.

26.2.5 Analog Input Pair Selection

The SD16_A can convert up to 8 differential input pairs multiplexed into the PGA. Up to five analog input pairs (A0-A4) are available externally on the device. A resistive divider to measure the supply voltage is available using the A5 multiplexer input. An internal temperature sensor is available using the A6 multiplexer input.

Input A7 is a shorted connection between the + and - input pair and can be used to calibrate the offset of the SD16_A input stage. Note that the measured offset depends on the impedance of the external circuitry; thus, the actual offset seen at any of the analog inputs may be different.

26.2.5.1 Analog Input Setup

The analog input is configured using the SD16INCTL0 and the SD16AE registers. The SD16INCHx bits select one of eight differential input pairs of the analog multiplexer. The gain for the PGA is selected by the SD16GAINx bits. A total of six gain settings are available. The SD16AEx bits enable or disable the analog input pin. Setting any SD16AEx bit disables the multiplexed digital circuitry for the associated pin. See the device-specific data sheet for pin diagrams.

During conversion any modification to the SD16INCHx and SD16GAINx bits will become effective with the next decimation step of the digital filter. After these bits are modified, the next three conversions may be invalid due to the settling time of the digital filter. This can be handled automatically with the SD16INTDLYx bits. When SD16INTDLY = 00h, conversion interrupt requests will not begin until the fourth conversion after a start condition.

On devices implementing the high impedance input buffer it can be enabled using the SD16BUFx bits. The speed settings are selected based on the SD16_A modulator frequency as shown in Table 26-1.

Table 26-1. High Input Impedance Buffer

SD16BUFx	Buffer	SD16 Modulator Frequency f_M
00	Buffer disabled	
01	Low speed/current	f_M < 200 kHz
10	Medium speed/current	200 kHz < f_M < 700 kHz
11	High speed/current	700 kHz < f_M < 1.1 MHz

An external RC anti-aliasing filter is recommended for the SD16_A to prevent aliasing of the input signal. The cutoff frequency should be < 10 kHz for a 1-MHz modulator clock and OSR = 256. The cutoff frequency may set to a lower frequency for applications that have lower bandwidth requirements.

26.2.6 Analog Input Characteristics

The SD16_A uses a switched-capacitor input stage that appears as an impedance to external circuitry as shown in Figure 26-2.

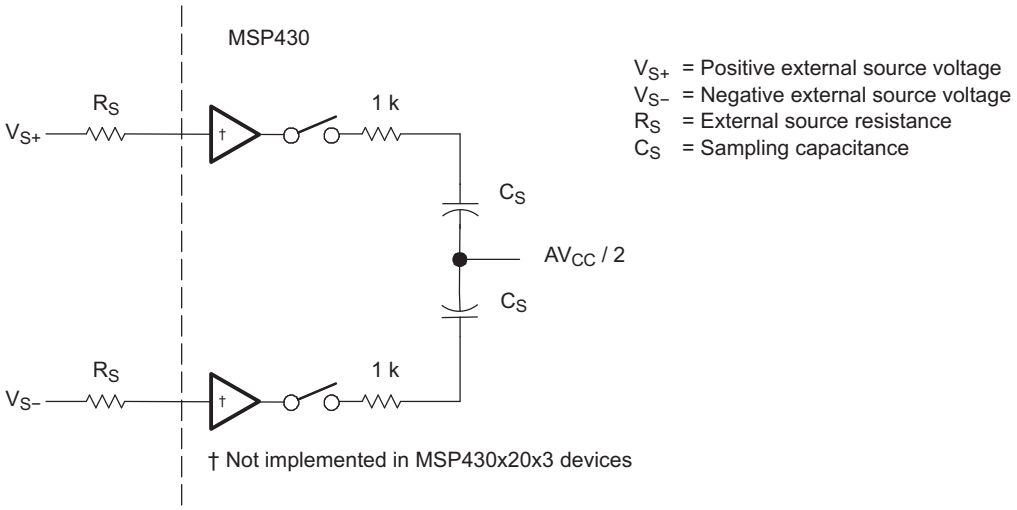


Figure 26-2. Analog Input Equivalent Circuit

When the buffers are used, R_S does not affect the sampling frequency f_S. However, when the buffers are not used or are not present on the device, the maximum sampling frequency f_S may be calculated from the minimum settling time $t_{Settling}$ of the sampling circuit given by:

$$t_{Settling} \geq (R_S + 1\,k\Omega) \times C_S \times \ln\left(\frac{GAIN \times 2^{17} \times V_{Ax}}{V_{REF}}\right)$$

where

$$f_S = \frac{1}{2 \times t_{Settling}} \quad \text{and} \quad V_{Ax} = \max\left(\left|\frac{AV_{CC}}{2} - V_{S+}\right|, \left|\frac{AV_{CC}}{2} - V_{S-}\right|\right)$$

with V_{S+} and V_{S-} referenced to AV_{SS}.

C_S varies with the gain setting as shown in Table 26-2.

Table 26-2. Sampling Capacitance

PGA Gain	Sampling Capacitance, C_S
1	1.25 pF
2, 4	2.5 pF
8	5 pF
16, 32	10 pF

26.2.7 Digital Filter

The digital filter processes the 1-bit data stream from the modulator using a $SINC^3$ comb filter. The transfer function is described in the z-Domain by:

$$H(z) = \left(\frac{1}{OSR} \times \frac{1 - z^{-OSR}}{1 - z^{-1}} \right)^3$$

and in the frequency domain by:

$$H(f) = \left[\frac{\text{sinc}\left(OSR \times \pi \times \frac{f}{f_M} \right)}{\text{sinc}\left(\pi \times \frac{f}{f_M} \right)} \right]^3 = \left[\frac{1}{OSR} \times \frac{\sin\left(OSR \times \pi \times \frac{f}{f_M} \right)}{\sin\left(\pi \times \frac{f}{f_M} \right)} \right]^3$$

where the oversampling rate, OSR, is the ratio of the modulator frequency f_M to the sample frequency f_S. Figure 26-3 shows the filter's frequency response for an OSR of 32. The first filter notch is at $f_S = f_M/OSR$. The notch's frequency can be adjusted by changing the modulator's frequency, f_M, using SD16SSELx and SD16DIVx and the oversampling rate using the SD16OSRx and SD16XOSR bits.

The digital filter for each enabled ADC channel completes the decimation of the digital bit-stream and outputs new conversion results to the SD16MEM0 register at the sample frequency f_S.

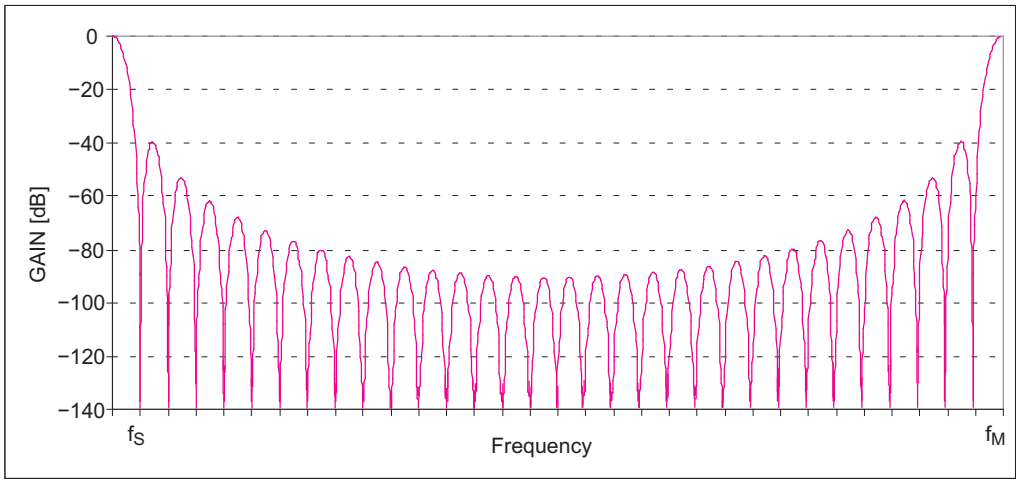


Figure 26-3. Comb Filter Frequency Response With OSR = 32

Figure 26-4 shows the digital filter step response and conversion points. For step changes at the input after start of conversion a settling time must be allowed before a valid conversion result is available. The SD16INTDLYx bits can provide sufficient filter settling time for a full-scale change at the ADC input. If the step occurs synchronously to the decimation of the digital filter the valid data will be available on the third conversion. An asynchronous step will require one additional conversion before valid data is available.

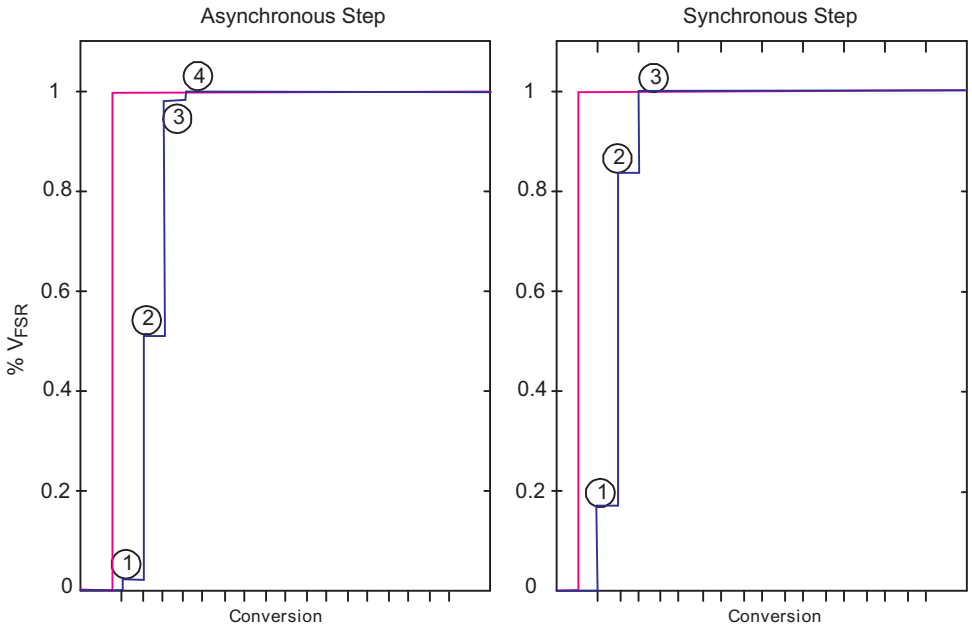


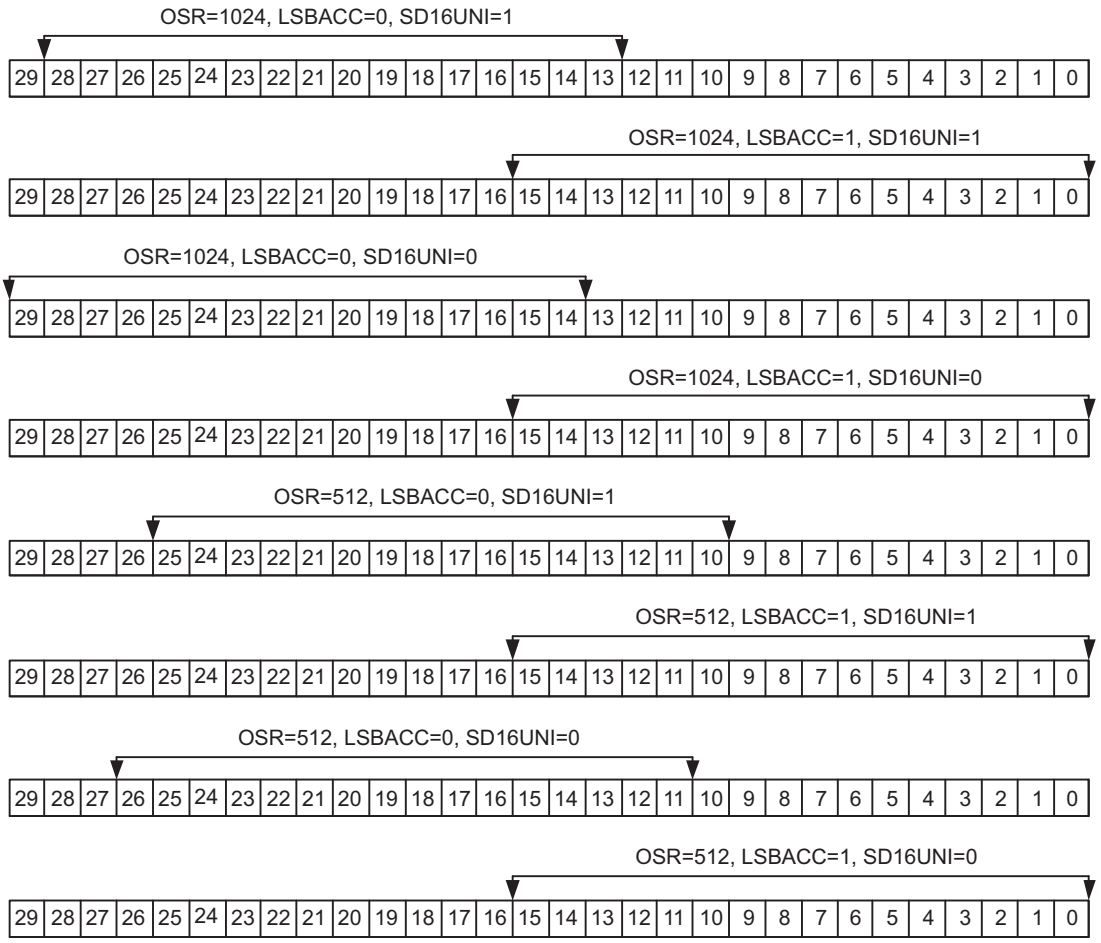
Figure 26-4. Digital Filter Step Response and Conversion Points

26.2.7.1 Digital Filter Output

The number of bits output by the digital filter is dependent on the oversampling ratio and ranges from 15 to 30 bits. Figure 26-5 shows the digital filter output and their relation to SD16MEM0 for each OSR, LSBACC, and SD16UNI setting. For example, for OSR = 1024, LSBACC = 0, and SD16UNI = 1, the SD16MEM0 register contains bits 28 - 13 of the digital filter output. When OSR = 32, the one (SD16UNI = 0) or two (SD16UNI=1) LSBs are always zero.

The SD16LSBACC and SD16LSBTOG bits give access to the least significant bits of the digital filter output. When SD16LSBACC = 1 the 16 least significant bits of the digital filter's output are read from SD16MEM0 using word instructions. The SD16MEM0 register can also be accessed with byte instructions returning only the 8 least significant bits of the digital filter output.

When SD16LSBTOG = 1 the SD16LSBACC bit is automatically toggled each time SD16MEM0 is read. This allows the complete digital filter output result to be read with two reads of SD16MEM0. Setting or clearing SD16LSBTOG does not change SD16LSBACC until the next SD16MEM0 access.



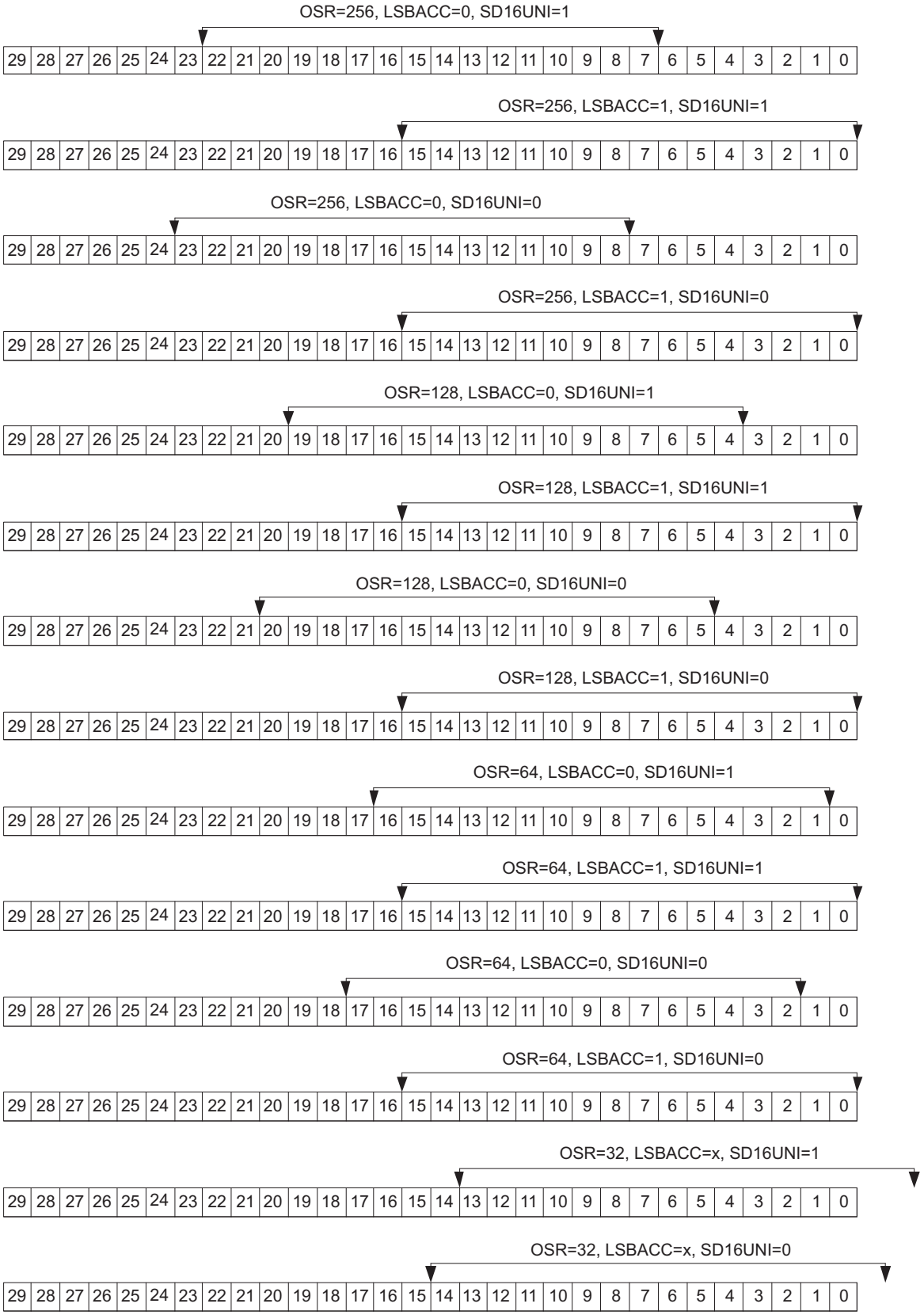


Figure 26-5. Used Bits of Digital Filter Output

26.2.8 Conversion Memory Register: SD16MEM0

The SD16MEM0 register is associated with the SD16_A channel. Conversion results are moved to the SD16MEM0 register with each decimation step of the digital filter. The SD16IFG bit is set when new data is written to SD16MEM0. SD16IFG is automatically cleared when SD16MEM0 is read by the CPU or may be cleared with software.

26.2.8.1 Output Data Format

The output data format is configurable in two's complement, offset binary or unipolar mode as shown in Table 26-3. The data format is selected by the SD16DF and SD16UNI bits.

Table 26-3. Data Format

SD16UNI	SD16DF	Format	Analog Input	SD16MEM0[1]	Digital Filter Output (OSR = 256)
0	0	Bipolar Offset Binary	+FSR	FFFF	FFFFFF
			ZERO	8000	800000
			-FSR	0000	000000
0	1	Bipolar Twos Compliment	+FSR	7FFF	7FFFFF
			ZERO	0000	000000
			-FSR	8000	800000
1	0	Unipolar	+FSR	FFFF	FFFFFF
			ZERO	0000	800000
			-FSR	0000	000000

(1) Independent of SD16OSRx and SD16XOSR settings; SD16LSBACC = 0.

NOTE: Offset Measurements and Data Format

Any offset measurement done either externally or using the internal differential pair A7 would be appropriate only when the channel is operating under bipolar mode with SD16UNI = 0.

Figure 26-6 shows the relationship between the full-scale input voltage range from $-V_{FSR}$ to $+V_{FSR}$ and the conversion result. The data formats are illustrated.

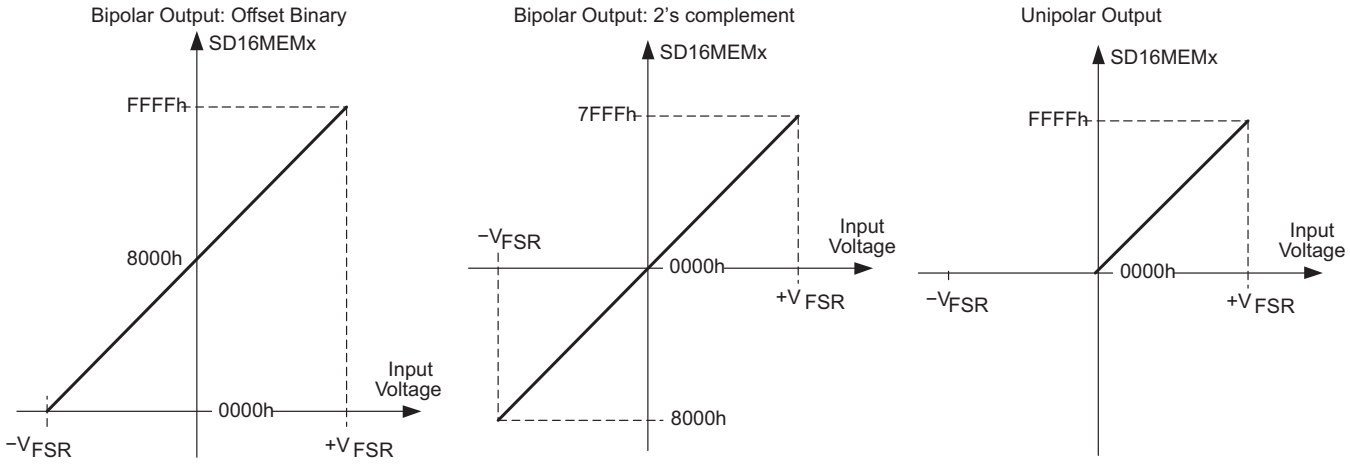


Figure 26-6. Input Voltage vs Digital Output

26.2.9 Conversion Modes

The SD16_A module can be configured for two modes of operation, listed in Table 26-4. The SD16SNGL bit selects the conversion mode.

Table 26-4. Conversion Mode Summary

SD16SNGL	Mode	Operation
1	Single conversion	The channel is converted once.
0	Continuous conversion	The channel is converted continuously.

26.2.9.1 Single Conversion

Setting the SD16SC bit of the channel initiates one conversion on that channel when SD16SNGL = 1. The SD16SC bit will automatically be cleared after conversion completion.

Clearing SD16SC before the conversion is completed immediately stops conversion of the channel, the channel is powered down and the corresponding digital filter is turned off. The value in SD16MEM0 can change when SD16SC is cleared. It is recommended that the conversion data in SD16MEM0 be read prior to clearing SD16SC to avoid reading an invalid result.

26.2.9.2 Continuous Conversion

When SD16SNGL = 0 continuous conversion mode is selected. Conversion of the channel will begin when SD16SC is set and continue until the SD16SC bit is cleared by software.

Clearing SD16SC immediately stops conversion of the selected channel, the channel is powered down and the corresponding digital filter is turned off. The value in SD16MEM0 can change when SD16SC is cleared. It is recommended that the conversion data in SD16MEM0 be read prior to clearing SD16SC to avoid reading an invalid result.

Figure 26-7 shows conversion operation.

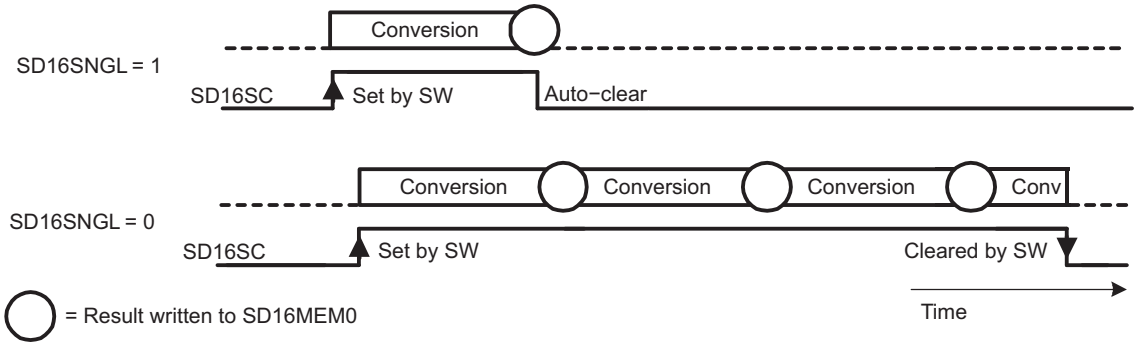


Figure 26-7. Single Channel Operation

26.2.10 Using the Integrated Temperature Sensor

To use the on-chip temperature sensor, the user selects the analog input pair SD16INCHx = 110 and sets SD16REFON = 1. Any other configuration is done as if an external analog input pair was selected, including SD16INTDLYx and SD16GAINx settings. Because the internal reference must be on to use the temperature sensor, it is not possible to use an external reference for the conversion of the temperature sensor voltage. Also, the internal reference will be in contention with any used external reference. In this case, the SD16VMIDON bit may be set to minimize the affects of the contention on the conversion.

The typical temperature sensor transfer function is shown in Figure 26-8. When switching inputs of an SD16_A channel to the temperature sensor, adequate delay must be provided using SD16INTDLYx to allow the digital filter to settle and assure that conversion results are valid. The temperature sensor offset error can be large, and may need to be calibrated for most applications. See device-specific data sheet for temperature sensor parameters.

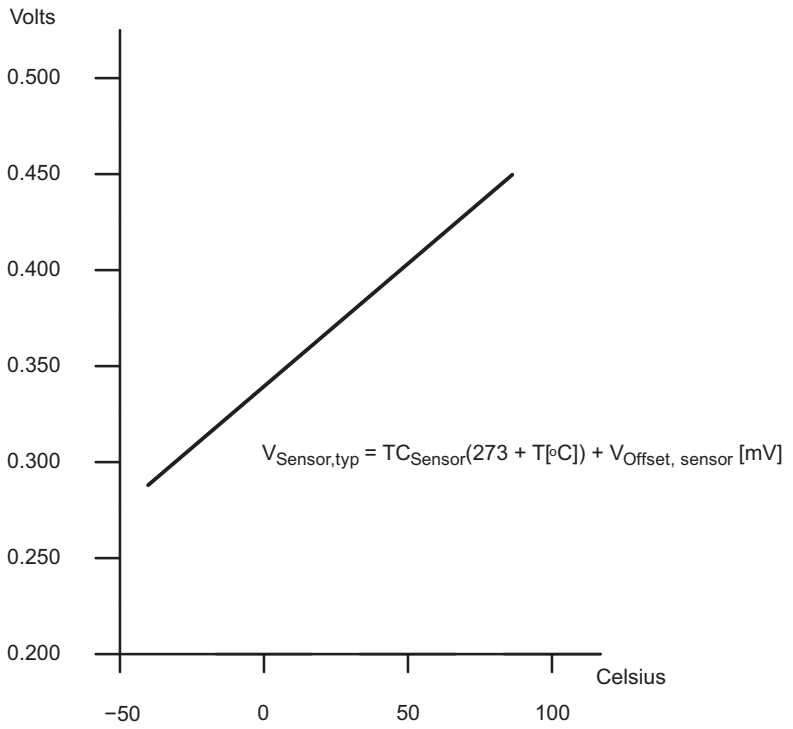


Figure 26-8. Typical Temperature Sensor Transfer Function

26.2.11 Interrupt Handling

The SD16_A has 2 interrupt sources for its ADC channel:

- SD16IFG
- SD16OVIFG

The SD16IFG bit is set when the SD16MEM0 memory register is written with a conversion result. An interrupt request is generated if the corresponding SD16IE bit and the GIE bit are set. The SD16_A overflow condition occurs when a conversion result is written to SD16MEM0 location before the previous conversion result was read.

26.2.11.1 SD16IV, Interrupt Vector Generator

All SD16_A interrupt sources are prioritized and combined to source a single interrupt vector. SD16IV is used to determine which enabled SD16_A interrupt source requested an interrupt. The highest priority SD16_A interrupt request that is enabled generates a number in the SD16IV register (see register description). This number can be evaluated or added to the program counter to automatically enter the appropriate software routine. Disabled SD16_A interrupts do not affect the SD16IV value.

Any access, read or write, of the SD16IV register has no effect on the SD16OVIFG or SD16IFG flags. The SD16IFG flags are reset by reading the SD16MEM0 register or by clearing the flags in software. SD16OVIFG bits can only be reset with software.

If another interrupt is pending after servicing of an interrupt, another interrupt is generated. For example, if the SD16OVIFG and one or more SD16IFG interrupts are pending when the interrupt service routine accesses the SD16IV register, the SD16OVIFG interrupt condition is serviced first and the corresponding flag(s) must be cleared in software. After the RETI instruction of the interrupt service routine is executed, the highest priority SD16IFG pending generates another interrupt request.

26.2.11.2 Interrupt Delay Operation

The SD16INTDLYx bits control the timing for the first interrupt service request for the corresponding channel. This feature delays the interrupt request for a completed conversion by up to four conversion cycles allowing the digital filter to settle prior to generating an interrupt request. The delay is applied each time the SD16SC bit is set or when the SD16GAINx or SD16INCHx bits for the channel are modified. SD16INTDLYx disables overflow interrupt generation for the channel for the selected number of delay cycles. Interrupt requests for the delayed conversions are not generated during the delay.

26.3 SD16_A Registers

The SD16_A registers are listed in Table 26-5.

Table 26-5. SD16_A Registers

Register	Short Form	Register Type	Address	Initial State
SD16_A control	SD16CTL	Read/write	0100h	Reset with PUC
SD16_A interrupt vector	SD16IV	Read/write	0110h	Reset with PUC
SD16_A channel 0 control	SD16CCTL0	Read/write	0102h	Reset with PUC
SD16_A conversion memory	SD16MEM0	Read/write	0112h	Reset with PUC
SD16_A input control	SD16INCTL0	Read/write	0B0h	Reset with PUC
SD16_A analog enable	SD16AE	Read/write	0B7h	Reset with PUC

26.3.1 SD16CTL, SD16_A Control Register

15	14	13	12	11	10	9	8
Reserved				**SD16XDIVx**			**SD16LP**
r0	r0	r0	r0	rw-0	rw-0	rw-0	rw-0
7	6	5	4	3	2	1	0
SD16DIVx		**SD16SSELx**		**SD16VMIDON**	**SD16REFON**	**SD16OVIE**	**Reserved**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	r0

Reserved	Bits 15-12	Reserved
SD16XDIVx	Bits 11-9	SD16_A clock divider
		000 /1
		001 /3
		010 /16
		011 /48
		1xx Reserved
SD16LP	Bit 8	Low power mode. This bit selects a reduced speed, reduced power mode
		0 Low-power mode is disabled
		1 Low-power mode is enabled. The maximum clock frequency for the SD16_A is reduced.
SD16DIVx	Bits 7-6	SD16_A clock divider
		00 /1
		01 /2
		10 /4
		11 /8
SD16SSELx	Bits 5-4	SD16_A clock source select
		00 MCLK
		01 SMCLK
		10 ACLK
		11 External TACLK
SD16VMIDON	Bit 3	VMID buffer on
		0 Off
		1 On
SD16REFON	Bit 2	Reference generator on
		0 Reference off
		1 Reference on
SD16OVIE	Bit 1	SD16_A overflow interrupt enable. The GIE bit must also be set to enable the interrupt.
		0 Overflow interrupt disabled
		1 Overflow interrupt enabled
Reserved	Bit 0	Reserved

26.3.2 SD16CCTL0, SD16_A Control Register 0

15	14	13	12	11	10	9	8
Reserved	**SD16BUFx**[1]		**SD16UNI**	**SD16XOSR**	**SD16SNGL**	**SD16OSRx**	
r0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0
7	6	5	4	3	2	1	0
SD16LSBTOG	**SD16LSBACC**	**SD16OVIFG**	**SD16DF**	**SD16IE**	**SD16IFG**	**SD16SC**	**Reserved**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	r-0

Reserved	Bit 15	Reserved
SD16BUFx	Bits 14-13	High-impedance input buffer mode
		00 Buffer disabled
		01 Slow speed/current
		10 Medium speed/current
		11 High speed/current
SD16UNI	Bit 12	Unipolar mode select
		0 Bipolar mode
		1 Unipolar mode
SD16XOSR	Bit 11	Extended oversampling ratio. This bit, along with the SD16OSRx bits, select the oversampling ratio. See SD16OSRx bit description for settings.
SD16SNGL	Bit 10	Single conversion mode select
		0 Continuous conversion mode
		1 Single conversion mode
SD16OSRx	Bits 9-8	Oversampling ratio
		When SD16XOSR = 0
		00 256
		01 128
		10 64
		11 32
		When SD16XOSR = 1
		00 512
		01 1024
		10 Reserved
		11 Reserved
SD16LSBTOG	Bit 7	LSB toggle. This bit, when set, causes SD16LSBACC to toggle each time the SD16MEM0 register is read.
		0 SD16LSBACC does not toggle with each SD16MEM0 read
		1 SD16LSBACC toggles with each SD16MEM0 read
SD16LSBACC	Bit 6	LSB access. This bit allows access to the upper or lower 16-bits of the SD16_A conversion result.
		0 SD16MEMx contains the most significant 16-bits of the conversion.
		1 SD16MEMx contains the least significant 16-bits of the conversion.
SD16OVIFG	Bit 5	SD16_A overflow interrupt flag
		0 No overflow interrupt pending
		1 Overflow interrupt pending
SD16DF	Bit 4	SD16_A data format
		0 Offset binary
		1 2's complement
SD16IE	Bit 3	SD16_A interrupt enable
		0 Disabled
		1 Enabled
SD16IFG	Bit 2	SD16_A interrupt flag. SD16IFG is set when new conversion results are available. SD16IFG is automatically reset when the corresponding SD16MEMx register is read, or may be cleared with software.
		0 No interrupt pending
		1 Interrupt pending

(1) Reserved in MSP430x20x3 devices

SD16SC	Bit 1	SD16_A start conversion
		0 No conversion start
		1 Start conversion
Reserved	Bit 0	Reserved

26.3.3 SD16INCTL0, SD16_A Input Control Register

7	6	5	4	3	2	1	0
SD16INTDLYx		**SD16GAINx**			**SD16INCHx**		
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

SD16INTDLYx	Bits 7-6	Interrupt delay generation after conversion start. These bits select the delay for the first interrupt after conversion start.
		00 Fourth sample causes interrupt
		01 Third sample causes interrupt
		10 Second sample causes interrupt
		11 First sample causes interrupt
SD16GAINx	Bits 5-3	SD16_A preamplifier gain
		000 x1
		001 x2
		010 x4
		011 x8
		100 x16
		101 x32
		110 Reserved
		111 Reserved
SD16INCHx	Bits 2-0	SD16_A channel differential pair input
		000 A0
		001 A1
		010 A2
		011 A3
		100 A4
		101 A5 - (AV_{CC} - AV_{SS}) / 11
		110 A6 - Temperature Sensor
		111 A7 - Short for PGA offset measurement

26.3.4 SD16MEM0, SD16_A Conversion Memory Register

15	14	13	12	11	10	9	8
Conversion Results							
r	r	r	r	r	r	r	r
7	6	5	4	3	2	1	0
Conversion Results							
r	r	r	r	r	r	r	r

Conversion Results Bits 15-0 Conversion Results. The SD16MEMx register holds the upper or lower 16-bits of the digital filter output, depending on the SD16LSBACC bit.

26.3.5 SD16AE, SD16_A Analog Input Enable Register

7	6	5	4	3	2	1	0
SD16AE7	**SD16AE6**	**SD16AE5**	**SD16AE4**	**SD16AE3**	**SD16AE2**	**SD16AE1**	**SD16AE0**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

SD16AEx Bits 7-0 SD16_A analog enable

0 External input disabled. Negative inputs are internally connected to VSS.

1 External input enabled.

26.3.6 SD16IV, SD16_A Interrupt Vector Register

15	14	13	12	11	10	9	8
0	0	0	0	0	0	0	0
r0	r0	r0	r0	r0	r0	r0	r0
7	6	5	4	3	2	1	0
0	0	0	**SD16IVx**				0
r0	r0	r0					r0

SD16IVx Bits 15-0 SD16_A interrupt vector value

SD16IV Contents	Interrupt Source	Interrupt Flag	Interrupt Priority
000h	No interrupt pending	-	
002h	SD16MEMx overflow	SD16CCTLx SD16OVIFG	Highest
004h	SD16_A interrupt	SD16CCTL0 SD16IFG	
006h	Reserved	-	
008h	Reserved	-	
00Ah	Reserved	-	
00Ch	Reserved	-	
00Eh	Reserved	-	
010h	Reserved	-	Lowest

SD24_A

The SD24_A module is a multichannel 24-bit sigma-delta analog-to-digital converter (ADC). This chapter describes the SD24_A of the MSP430x2xx family.

Topic **Page**

27.1 SD24_A Introduction

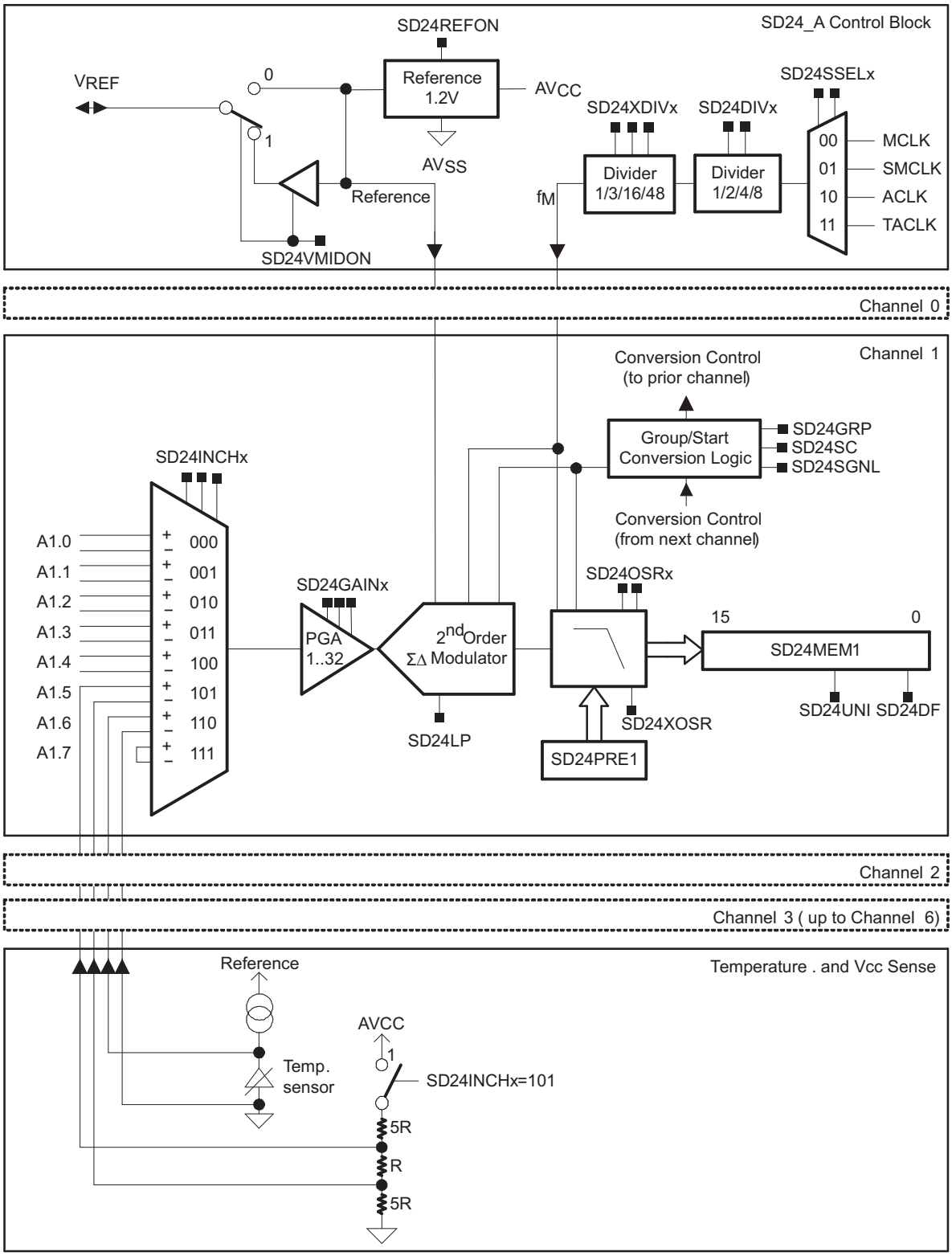
The SD24_A module consists of up to seven independent sigma-delta analog-to-digital converters, referred to as channels, and an internal voltage reference. Each channel has up to eight fully differential multiplexed analog input pairs including a built-in temperature sensor and a divided supply voltage. The converters are based on second-order oversampling sigma-delta modulators and digital decimation filters. The decimation filters are comb-type filters with selectable oversampling ratios of up to 1024. Additional filtering can be done in software.

The digital filter output of SD24_A can range from 15 bits to 30 bits, based on the oversampling ratio. The default oversampling ratio is 256, which results in 24-bit output from the digital filter. The 16 most significant bits of the filter are captured in the SD24_A conversion memory register and, by setting SD24LSBACC = 1, the 16 least significant bits of the filter output can be read (see Section 27.2.7 for details).

Features of the SD24_A include:

- Up to seven independent, simultaneously-sampling ADC channels (the number of channels is device dependent, see the device-specific data sheet)
- Up to eight multiplexed differential analog inputs per channel (the number of inputs is device dependent, see the device-specific data sheet)
- Software selectable on-chip reference voltage generation (1.2 V)
- Software selectable internal or external reference
- Built-in temperature sensor accessible by all channels
- Up to 1.1-MHz modulator input frequency
- High impedance input buffer (not implemented on all devices, see the device-specific data sheet)
- Selectable low-power conversion mode

The block diagram of the SD24_A module is shown in Figure 27-1.



NOTE: Ax.1 to Ax.4 not available on all devices. See device-specific data sheet.

Figure 27-1. Block Diagram of the SD24_A

27.2 SD24_A Operation

The SD24_A module is configured with user software. The setup and operation of the SD24_A is discussed in the following sections.

27.2.1 ADC Core

The analog-to-digital conversion is performed by a 1-bit second-order sigma-delta modulator. A single-bit comparator within the modulator quantizes the input signal with the modulator frequency f_M. The resulting 1-bit data stream is averaged by the digital filter for the conversion result.

27.2.2 Analog Input Range and PGA

The full-scale input voltage range for each analog input pair is dependent on the gain setting of the programmable gain amplifier of each channel. The maximum full-scale range is $\pm V_{FSR}$ where V_{FSR} is defined by:

$$V_{FSR} = \frac{V_{REF}/2}{GAIN_{PGA}}$$

For a 1.2-V reference, the maximum full-scale input range for a gain of 1 is:

$$\pm V_{FSR} = \frac{1.2\ V/2}{1} = \pm 0.6\ V$$

See the device-specific data sheet for full-scale input specifications.

27.2.3 Voltage Reference Generator

The SD24_A module has a built-in 1.2-V reference. It can be used for each SD24_A channel and is enabled by the SD24REFON bit. When using the internal reference an external 100-nF capacitor connected from V_{REF} to AV_{SS} is recommended to reduce noise. The internal reference voltage can be used off-chip when SD24VMIDON = 1. The buffered output can provide up to 1 mA of drive. When using the internal reference off-chip, a 470-nF capacitor connected from V_{REF} to AV_{SS} is required. See device-specific data sheet for parameters.

An external voltage reference can be applied to the V_{REF} input when SD24REFON and SD24VMIDON are both reset.

27.2.4 Auto Power-Down

The SD24_A is designed for low-power applications. When the SD24_A is not actively converting, it is automatically disabled and automatically re-enabled when a conversion is started. The reference is not automatically disabled, but it can be disabled by setting SD24REFON = 0. When the SD24_A or reference are disabled, they consume no current.

27.2.5 Analog Input Pair Selection

The SD24_A can convert up to eight differential input pairs multiplexed into the PGA. Up to five analog input pairs (A0 to A4) are available externally on the device. A resistive divider to measure the supply voltage is available using the A5 multiplexer input. An internal temperature sensor is available using the A6 multiplexer input.

Input A7 is a shorted connection between the + and – input pair and can be used to calibrate the offset of the SD24_A input stage. Note that the measured offset depends on the impedance of the external circuitry; thus, the actual offset seen at any of the analog inputs may be different.

27.2.5.1 Analog Input Setup

The analog input of each channel is configured using the SD24INCTLx register. These settings can be independently configured for each SD24_A channel.

The SD24INCHx bits select one of eight differential input pairs of the analog multiplexer. The gain for each PGA is selected by the SD24GAINx bits. A total of six gain settings are available.

On some devices SD24AEx bits are available to enable or disable the analog input pin. Setting any SD24AEx bit disables the multiplexed digital circuitry for the associated pin. See the device-specific data sheet for pin diagrams.

During conversion any modification to the SD24INCHx and SD24GAINx bits will become effective with the next decimation step of the digital filter. After these bits are modified, the next three conversions may be invalid due to the settling time of the digital filter. This can be handled automatically with the SD24INTDLYx bits. When SD24INTDLY = 00h, conversion interrupt requests will not begin until the fourth conversion after a start condition.

On devices implementing the high impedance input buffer it can be enabled using the SD24BUFx bits. The speed settings are selected based on the SD24_A modulator frequency as shown in Table 27-1.

Table 27-1. High Input Impedance Buffer

SD24BUFx	Buffer	SD24 Modulator Frequency, f_M
00	Buffer disabled	
01	Low speed/current	f_M < 200 kHz
10	Medium speed/current	200 kHz < f_M < 700 kHz
11	High speed/current	700 kHz < f_M < 1.1 MHz

An external RC anti-aliasing filter is recommended for the SD24_A to prevent aliasing of the input signal. The cutoff frequency should be less than 10 kHz for a 1-MHz modulator clock and OSR = 256. The cutoff frequency may set to a lower frequency for applications that have lower bandwidth requirements.

27.2.6 Analog Input Characteristics

The SD24_A uses a switched-capacitor input stage that appears as an impedance to external circuitry as shown in Figure 27-2.

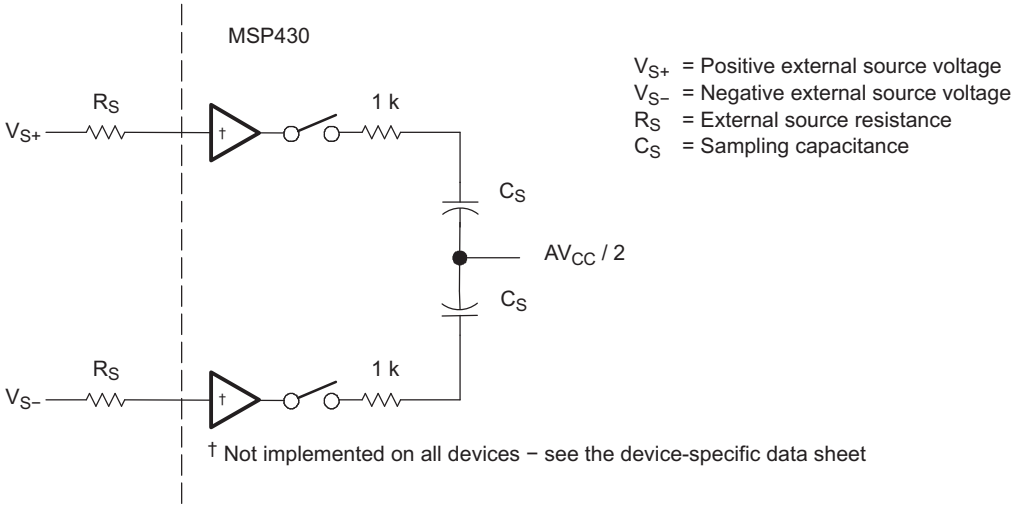


Figure 27-2. Analog Input Equivalent Circuit

When the buffers are used, R_S does not affect the sampling frequency f_S. However, when the buffers are not used or are not present on the device, the maximum modulator frequency f_M may be calculated from the minimum settling time $t_{Settling}$ of the sampling circuit given by:

$$t_{Settling} \geq (R_S + 1\ k\Omega) \times C_S \times \ln\left(\frac{GAIN \times 2^{17} \times V_{Ax}}{V_{REF}}\right)$$

Where,

$$f_M = \frac{1}{2 \times t_{Settling}} \quad \text{and} \quad V_{Ax} = \max\left(\left|\frac{AV_{CC}}{2} - V_{S+}\right|, \left|\frac{AV_{CC}}{2} - V_{S-}\right|\right)$$

with V_{S+} and V_{S-} referenced to AV_{SS}.

C_S varies with the gain setting as shown in Table 27-2.

Table 27-2. Sampling Capacitance

PGA Gain	Sampling Capacitance (C_S)
1	1.25 pF
2, 4	2.5 pF
8	5 pF
16, 32	10 pF

27.2.7 Digital Filter

The digital filter processes the 1-bit data stream from the modulator using a $SINC^3$ comb filter. The transfer function is described in the z-Domain by:

$$H(z) = \left(\frac{1}{OSR} \times \frac{1 - z^{-OSR}}{1 - z^{-1}}\right)^3$$

and in the frequency domain by:

$$H(f) = \left[\frac{\text{sinc}\left(OSR \times \pi \times \frac{f}{f_M}\right)}{\text{sinc}\left(\pi \times \frac{f}{f_M}\right)}\right]^3 = \left[\frac{1}{OSR} \times \frac{\sin\left(OSR \times \pi \times \frac{f}{f_M}\right)}{\sin\left(\pi \times \frac{f}{f_M}\right)}\right]^3$$

where the oversampling rate, OSR, is the ratio of the modulator frequency f_M to the sample frequency f_S. Figure 27-3 shows the filter's frequency response for an OSR of 32. The first filter notch is at $f_S = f_M/OSR$. The notch frequency can be adjusted by changing the modulator frequency, f_M, using SD24SSELx and SD24DIVx and the oversampling rate using the SD24OSRx and SD24XOSR bits.

The digital filter for each enabled ADC channel completes the decimation of the digital bit-stream and outputs new conversion results to the corresponding SD24MEMx register at the sample frequency f_S.

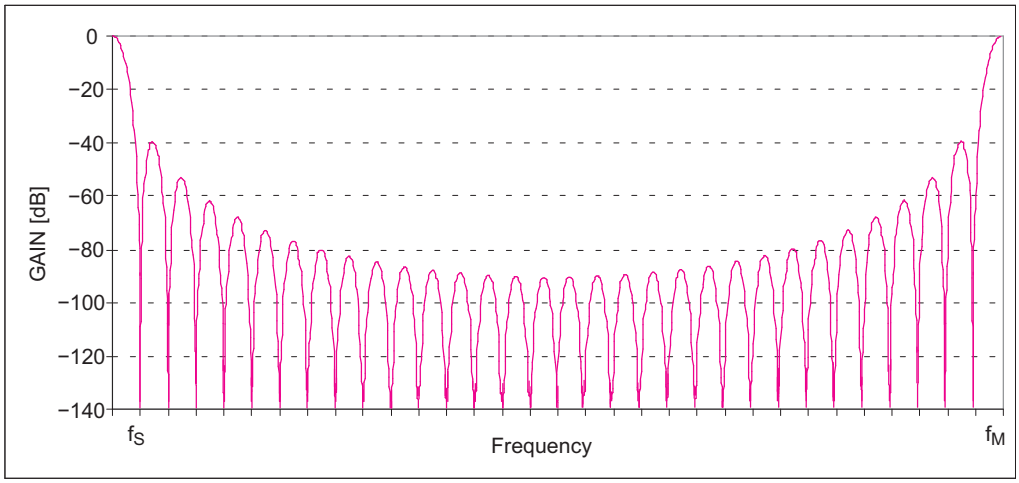


Figure 27-3. Comb Filter Frequency Response With OSR = 32

Figure 27-4 shows the digital filter step response and conversion points. For step changes at the input after start of conversion a settling time must be allowed before a valid conversion result is available. The SD24INTDLYx bits can provide sufficient filter settling time for a full-scale change at the ADC input. If the step occurs synchronously to the decimation of the digital filter the valid data will be available on the third conversion. An asynchronous step will require one additional conversion before valid data is available.

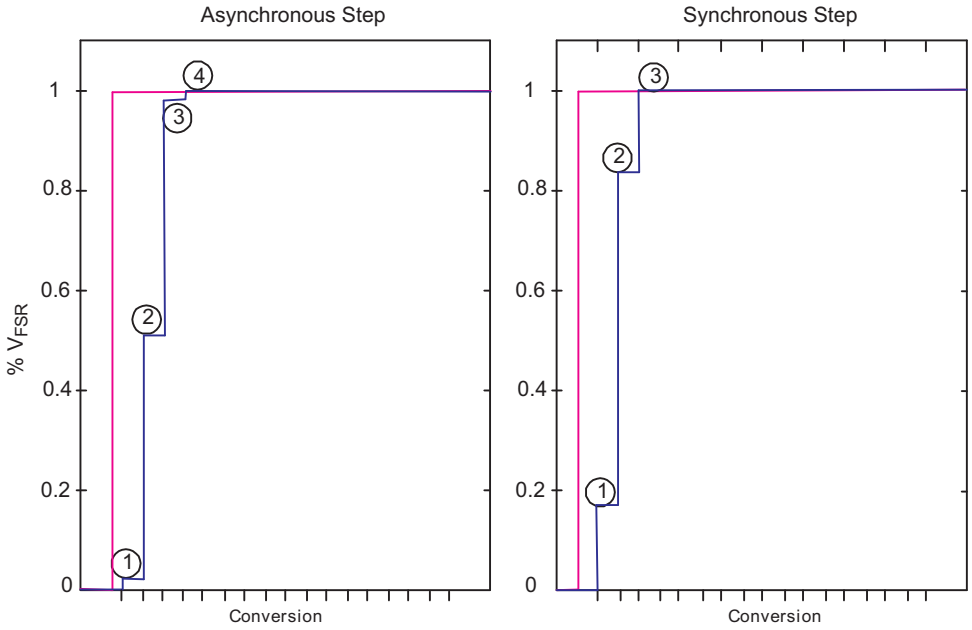


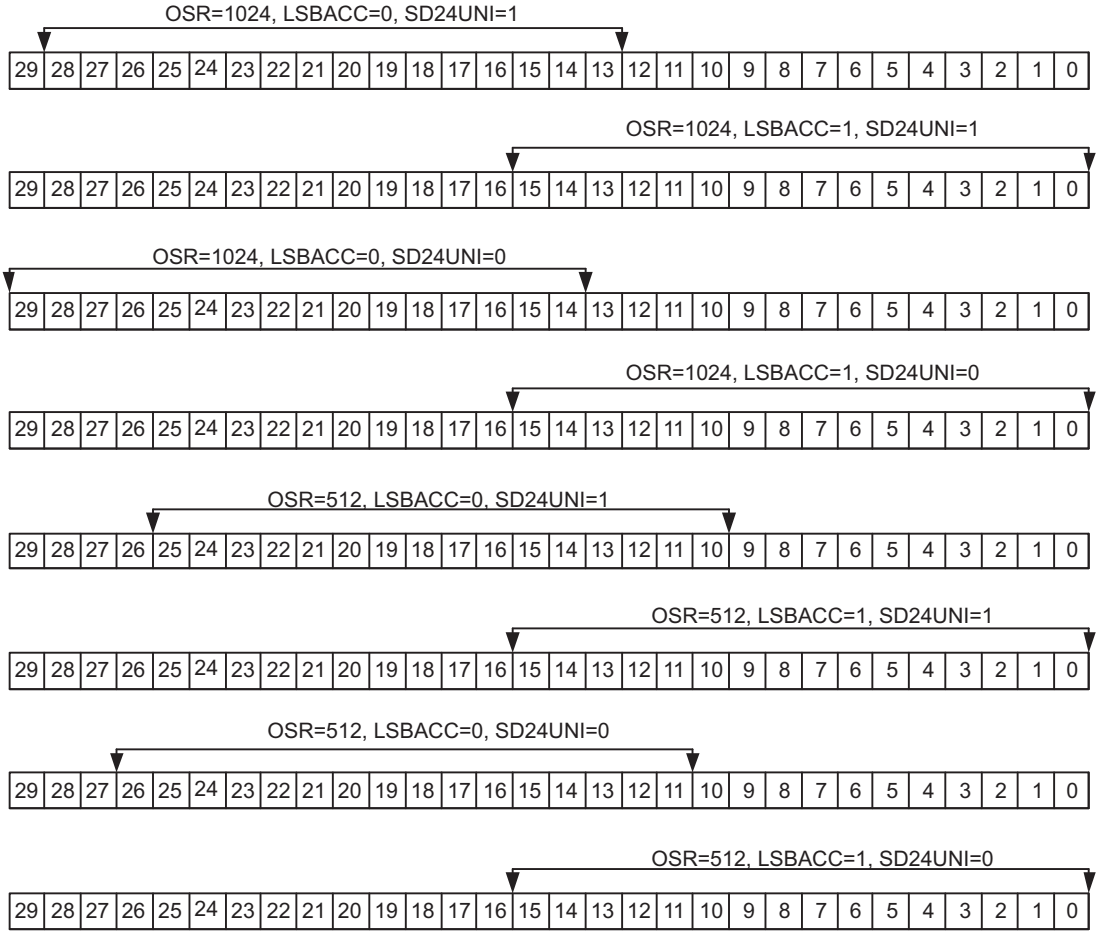
Figure 27-4. Digital Filter Step Response and Conversion Points

27.2.7.1 Digital Filter Output

The number of bits output by the digital filter is dependent on the oversampling ratio and ranges from 15 to 30 bits. Figure 27-5 shows the digital filter output and their relation to SD24MEMx for each OSR, LSBACC, and SD24UNI setting. For example, for OSR = 1024, LSBACC = 0, and SD24UNI = 1, the SD24MEMx register contains bits 28 to 13 of the digital filter output. When OSR = 32, the one (SD24UNI = 0) or two (SD24UNI = 1) LSBs are always zero.

The SD24LSBACC and SD24LSBTOG bits give access to the least significant bits of the digital filter output. When SD24LSBACC = 1 the 16 least significant bits of the digital filter's output are read from SD24MEMx using word instructions. The SD24MEMx register can also be accessed with byte instructions returning only the 8 least significant bits of the digital filter output.

When SD24LSBTOG = 1 the SD24LSBACC bit is automatically toggled each time SD24MEMx is read. This allows the complete digital filter output result to be read with two reads of SD24MEMx. Setting or clearing SD24LSBTOG does not change SD24LSBACC until the next SD24MEMx access.



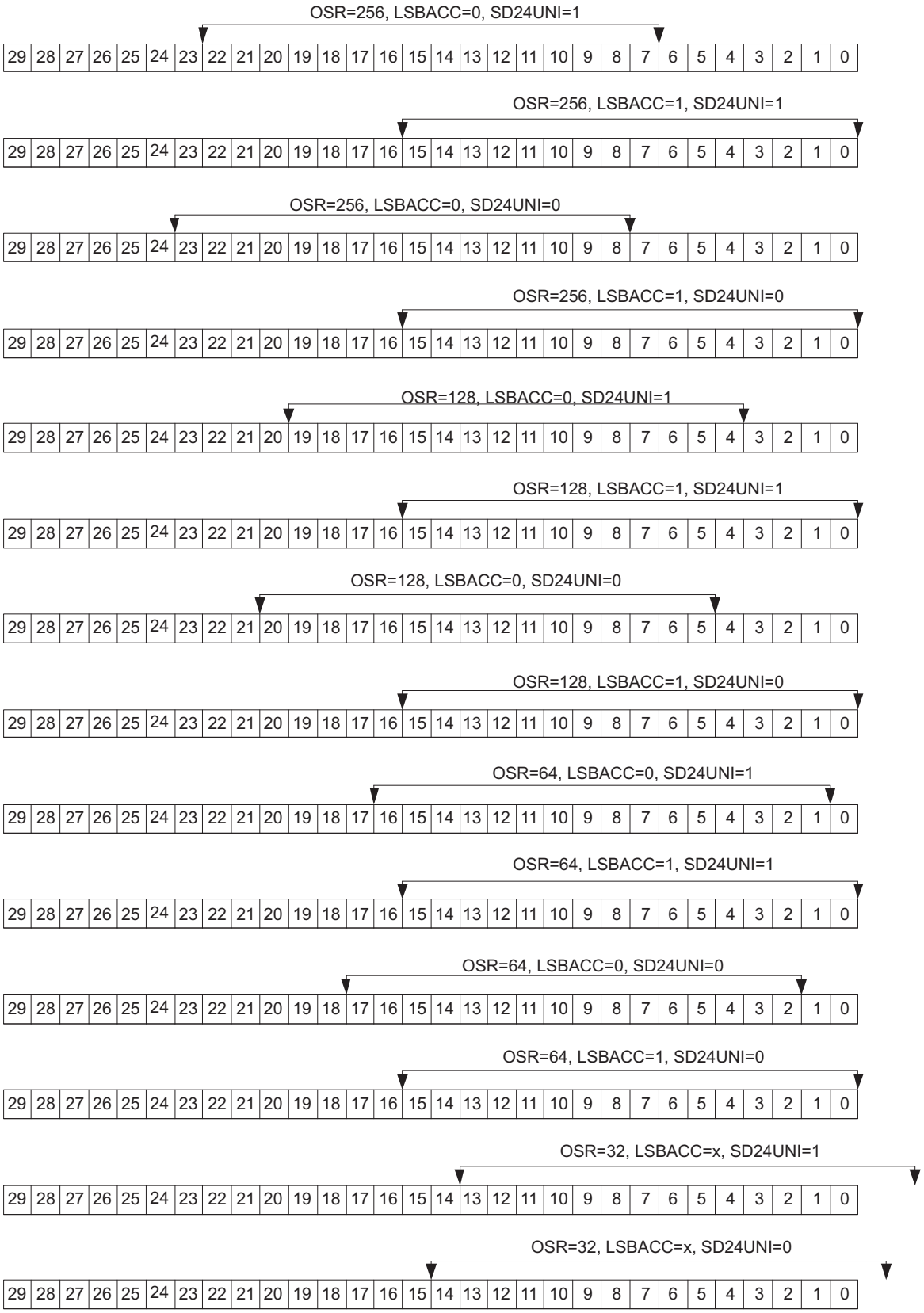


Figure 27-5. Used Bits of Digital Filter Output

27.2.8 Conversion Memory Register: SD24MEMx

One SD24MEMx register is associated with each SD24_A channel. Conversion results are moved to the corresponding SD24MEMx register with each decimation step of the digital filter. The SD24IFG bit is set when new data is written to SD24MEMx. SD24IFG is automatically cleared when SD24MEMx is read by the CPU or may be cleared with software.

27.2.8.1 Output Data Format

The output data format is configurable in twos complement, offset binary or unipolar mode as shown in Table 27-3. The data format is selected by the SD24DF and SD24UNI bits.

Table 27-3. Data Format

SD24UNI	SD24DF	Format	Analog Input	SD24MEMx (1)	Digital Filter Output (OSR = 256)
0	0	Bipolar offset binary	+FSR	FFFF	FFFFFF
			ZERO	8000	800000
			-FSR	0000	000000
0	1	Bipolar twos compliment	+FSR	7FFF	7FFFFF
			ZERO	0000	000000
			-FSR	8000	800000
1	0	Unipolar	+FSR	FFFF	FFFFFF
			ZERO	0000	800000
			-FSR	0000	000000

(1) Independent of SD24OSRx and SD24XOSR settings; SD24LSBACC = 0.

NOTE: Offset Measurements and Data Format

Any offset measurement done either externally or using the internal differential pair A7 would be appropriate only when the channel is operating under bipolar mode with SD24UNI = 0.

If the measured value is to be used in the unipolar mode for offset correction it needs to be multiplied by two.

Figure 27-6 shows the relationship between the full-scale input voltage range from $-V_{FSR}$ to $+V_{FSR}$ and the conversion result. The data formats are illustrated.

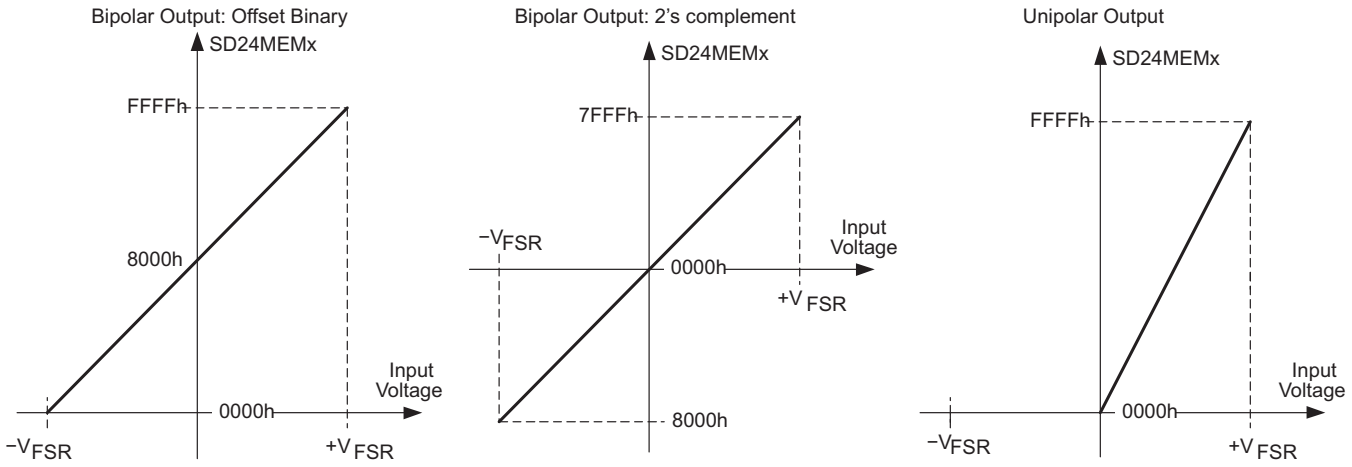


Figure 27-6. Input Voltage vs Digital Output

27.2.9 Conversion Modes

The SD24_A module can be configured for four modes of operation, listed in Table 27-4. The SD24SNGL and SD24GRP bits for each channel selects the conversion mode.

Table 27-4. Conversion Mode Summary

SD24SNGL	SD24GRP (1)	Mode	Operation
1	0	Single channel, Single conversion	A single channel is converted once.
0	0	Single channel, Continuous conversion	A single channel is converted continuously.
1	1	Group of channels, Single conversion	A group of channels is converted once.
0	1	Group of channels, Continuous conversion	A group of channels is converted continuously.

(1) A channel is grouped and is the master channel of the group when SD24GRP = 0 if SD24GRP for the prior channel(s) is set.

27.2.9.1 Single Channel, Single Conversion

Setting the SD24SC bit of a channel initiates one conversion on that channel when SD24SNGL = 1 and it is not grouped with any other channels. The SD24SC bit will automatically be cleared after conversion completion.

Clearing SD24SC before the conversion is completed immediately stops conversion of the selected channel, the channel is powered down and the corresponding digital filter is turned off. The value in SD24MEMx can change when SD24SC is cleared. It is recommended that the conversion data in SD24MEMx be read prior to clearing SD24SC to avoid reading an invalid result.

27.2.9.2 Single Channel, Continuous Conversion

When SD24SNGL = 0 continuous conversion mode is selected. Conversion of the selected channel will begin when SD24SC is set and continue until the SD24SC bit is cleared by software when the channel is not grouped with any other channel.

Clearing SD24SC immediately stops conversion of the selected channel, the channel is powered down and the corresponding digital filter is turned off. The value in SD24MEMx can change when SD24SC is cleared. It is recommended that the conversion data in SD24MEMx be read prior to clearing SD24SC to avoid reading an invalid result.

Figure 27-7 shows single channel operation for single conversion mode and continuous conversion mode.

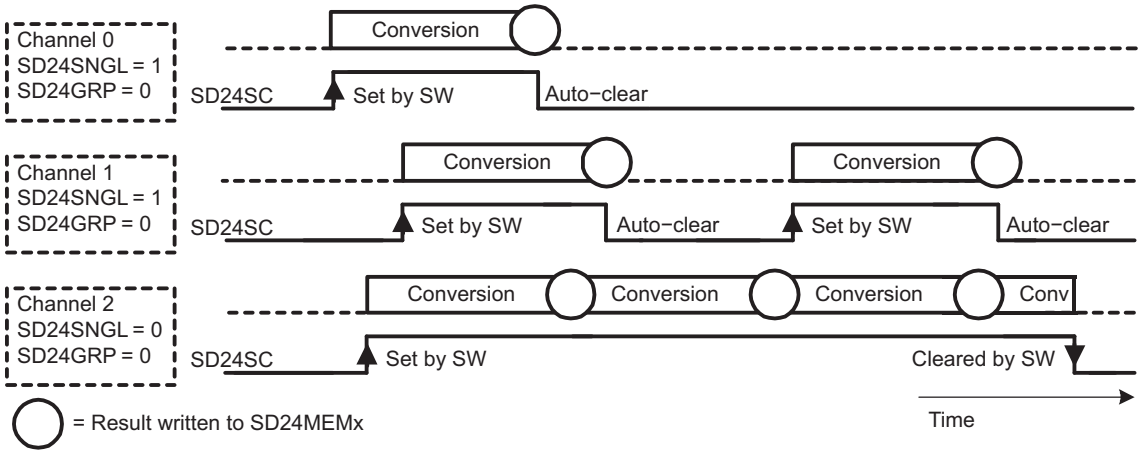


Figure 27-7. Single Channel Operation - Example

27.2.9.3 Group of Channels, Single Conversion

Consecutive SD24_A channels can be grouped together with the SD24GRP bit to synchronize conversions. Setting SD24GRP for a channel groups that channel with the next channel in the module. For example, setting SD24GRP for channel 0 groups that channel with channel 1. In this case, channel 1 is the master channel, enabling and disabling conversion of all channels in the group with its SD24SC bit. The SD24GRP bit of the master channel is always 0. The SD24GRP bit of last channel in SD24_A has no function and is always 0.

When SD24SNGL = 1 for a channel in a group, single conversion mode is selected. A single conversion of that channel will occur synchronously when the master channel SD24SC bit is set. The SD24SC bit of all channels in the group will automatically be set and cleared by SD24SC of the master channel. SD24SC for each channel can also be cleared in software independently.

Clearing SD24SC of the master channel before the conversions are completed immediately stops conversions of all channels in the group, the channels are powered down and the corresponding digital filters are turned off. Values in SD24MEMx can change when SD24SC is cleared. It is recommended that the conversion data in SD24MEMx be read prior to clearing SD24SC to avoid reading an invalid result.

27.2.9.4 Group of Channels, Continuous Conversion

When SD24SNGL = 0 for a channel in a group, continuous conversion mode is selected. Continuous conversion of that channel will occur synchronously when the master channel SD24SC bit is set. SD24SC bits for all grouped channels will be automatically set and cleared with the master channel's SD24SC bit. SD24SC for each channel in the group can also be cleared in software independently.

When SD24SC of a grouped channel is set by software independently of the master, conversion of that channel will automatically synchronize to conversions of the master channel. This ensures that conversions for grouped channels are always synchronous to the master.

Clearing SD24SC of the master channel immediately stops conversions of all channels in the group the channels are powered down and the corresponding digital filters are turned off. Values in SD24MEMx can change when SD24SC is cleared. It is recommended that the conversion data in SD24MEMx be read prior to clearing SD24SC to avoid reading an invalid result.

Figure 27-8 shows grouped channel operation for three SD24_A channels. Channel 0 is configured for single conversion mode, SD24SNGL = 1, and channels 1 and 2 are in continuous conversion mode, SD24SNGL = 0. Channel two, the last channel in the group, is the master channel. Conversions of all channels in the group occur synchronously to the master channel regardless of when each SD24SC bit is set using software.

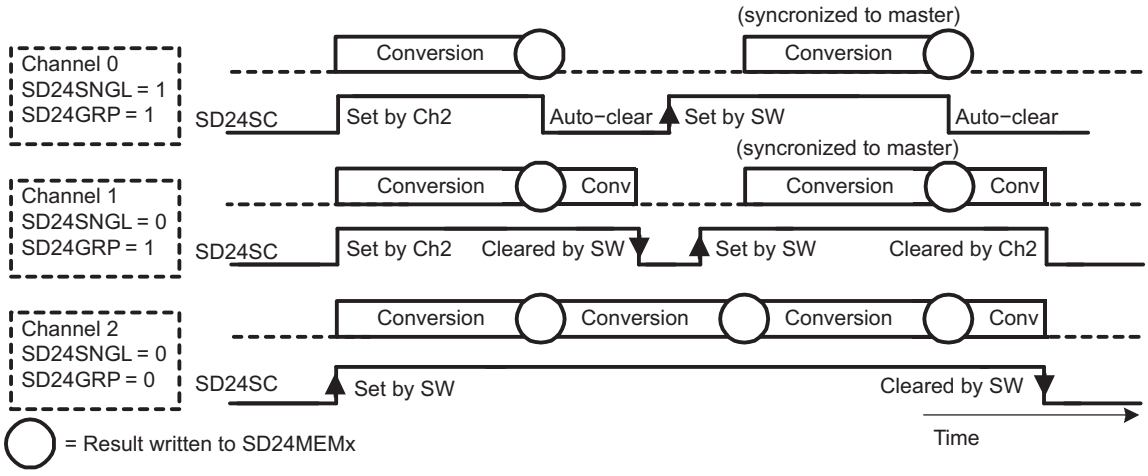


Figure 27-8. Grouped Channel Operation - Example

27.2.10 Conversion Operation Using Preload

When multiple channels are grouped the SD24PREx registers can be used to delay the conversion time frame for each channel. Using SD24PREx, the decimation time of the digital filter is increased by the specified number of f_M clock cycles and can range from 0 to 255. Figure 27-9 shows an example using SD24PREx.

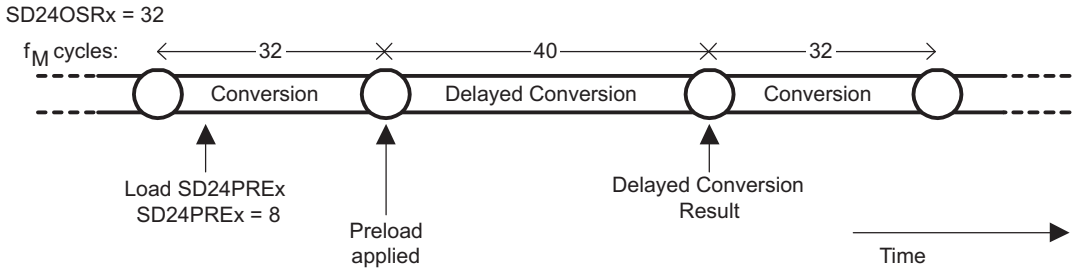


Figure 27-9. Conversion Delay Using Preload - Example

The SD24PREx delay is applied to the beginning of the next conversion cycle after being written. The delay is used on the first conversion after SD24SC is set and on the conversion cycle following each write to SD24PREx. Following conversions are not delayed. After modifying SD24PREx, the next write to SD24PREx should not occur until the next conversion cycle is completed, otherwise the conversion results may be incorrect.

The accuracy of the result for the delayed conversion cycle using SD24PREx is dependent on the length of the delay and the frequency of the analog signal being sampled. For example, when measuring a DC signal, SD24PREx delay has no effect on the conversion result regardless of the duration. The user must determine when the delayed conversion result is useful in their application.

Figure 27-10 shows the operation of grouped channels 0 and 1. The preload register of channel 1 is loaded with zero resulting in immediate conversion whereas the conversion cycle of channel 0 is delayed by setting SD24PRE0 = 8. The first channel 0 conversion uses SD24PREx = 8, shifting all subsequent conversions by eight f_M clock cycles.

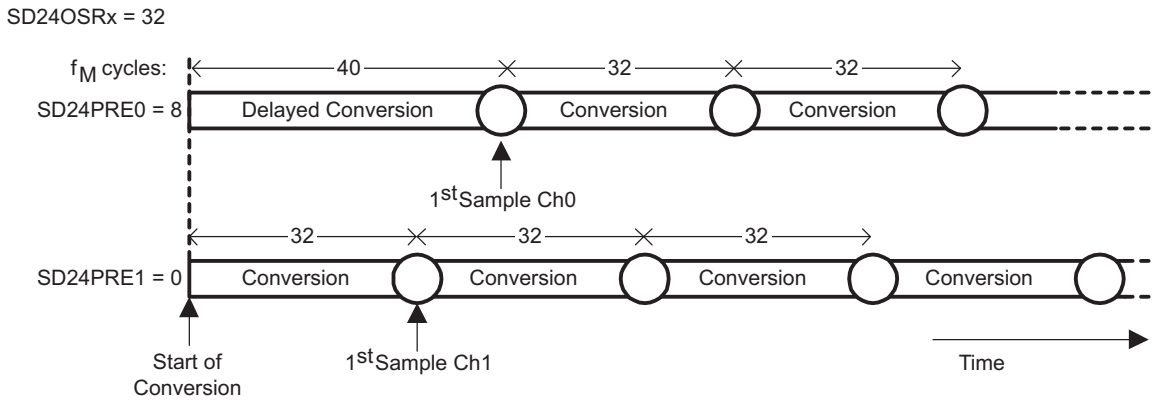


Figure 27-10. Start of Conversion Using Preload - Example

When channels are grouped, care must be taken when a channel or channels operate in single conversion mode or are disabled in software while the master channel remains active. Each time channels in the group are re-enabled and re-synchronize with the master channel, the preload delay for that channel will be reintroduced. Figure 27-11 shows the re-synchronization and preload delays for channels in a group. It is recommended that SD24PREx = 0 for the master channel to maintain a consistent delay between the master and remaining channels in the group when they are re-enabled.

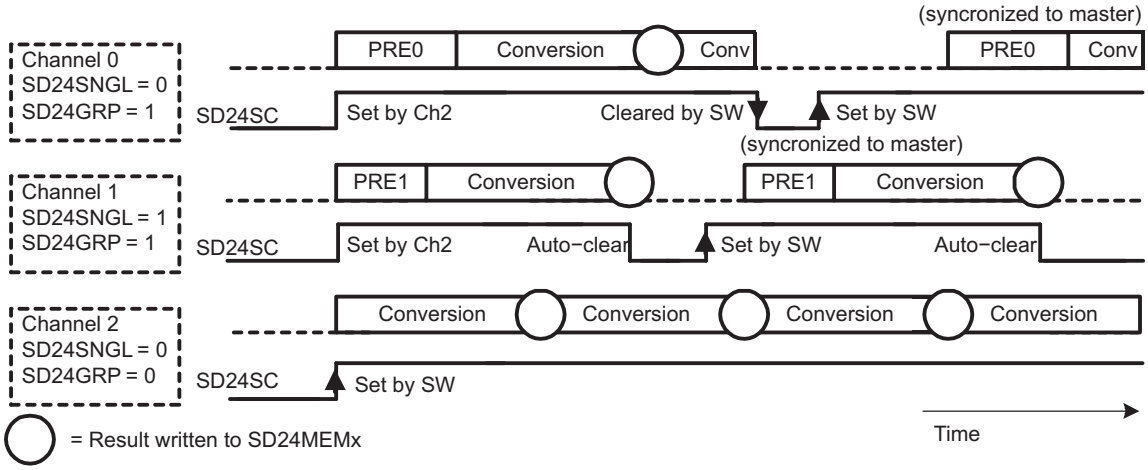


Figure 27-11. Preload and Channel Synchronization

27.2.11 Using the Integrated Temperature Sensor

To use the on-chip temperature sensor, the user selects the analog input pair SD24INCHx = 110 and sets SD24REFON = 1. Any other configuration is done as if an external analog input pair was selected, including SD24INTDLYx and SD24GAINx settings. Because the internal reference must be on to use the temperature sensor, it is not possible to use an external reference for the conversion of the temperature sensor voltage. Also, the internal reference will be in contention with any used external reference. In this case, the SD24VMIDON bit may be set to minimize the affects of the contention on the conversion.

The typical temperature sensor transfer function is shown in Figure 27-12. When switching inputs of an SD24_A channel to the temperature sensor, adequate delay must be provided using SD24INTDLYx to allow the digital filter to settle and assure that conversion results are valid. The temperature sensor offset error can be large, and may need to be calibrated for most applications. See device-specific data sheet for temperature sensor parameters.

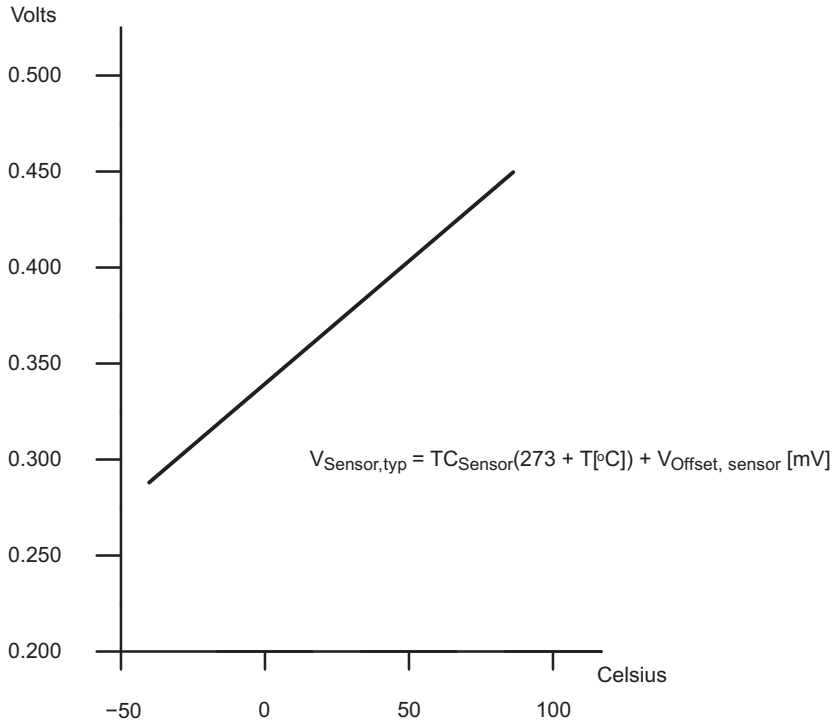


Figure 27-12. Typical Temperature Sensor Transfer Function

27.2.12 Interrupt Handling

The SD24_A has 2 interrupt sources for each ADC channel:

- SD24IFG
- SD24OVIFG

The SD24IFG bits are set when their corresponding SD24MEMx memory register is written with a conversion result. An interrupt request is generated if the corresponding SD24IE bit and the GIE bit are set. The SD24_A overflow condition occurs when a conversion result is written to any SD24MEMx location before the previous conversion result was read.

27.2.12.1 SD24IV, Interrupt Vector Generator

All SD24_A interrupt sources are prioritized and combined to source a single interrupt vector. SD24IV is used to determine which enabled SD24_A interrupt source requested an interrupt. The highest priority SD24_A interrupt request that is enabled generates a number in the SD24IV register (see register description). This number can be evaluated or added to the program counter to automatically enter the appropriate software routine. Disabled SD24_A interrupts do not affect the SD24IV value.

Any access, read or write, of the SD24IV register has no effect on the SD24OVIFG or SD24IFG flags. The SD24IFG flags are reset by reading the associated SD24MEMx register or by clearing the flags in software. SD24OVIFG bits can only be reset with software.

If another interrupt is pending after servicing of an interrupt, another interrupt is generated. For example, if the SD24OVIFG and one or more SD24IFG interrupts are pending when the interrupt service routine accesses the SD24IV register, the SD24OVIFG interrupt condition is serviced first and the corresponding flag(s) must be cleared in software. After the RETI instruction of the interrupt service routine is executed, the highest priority SD24IFG pending generates another interrupt request.

27.2.12.2 Interrupt Delay Operation

The SD24INTDLYx bits control the timing for the first interrupt service request for the corresponding channel. This feature delays the interrupt request for a completed conversion by up to four conversion cycles allowing the digital filter to settle prior to generating an interrupt request. The delay is applied each time the SD24SC bit is set or when the SD24GAINx or SD24INCHx bits for the channel are modified. SD24INTDLYx disables overflow interrupt generation for the channel for the selected number of delay cycles. Interrupt requests for the delayed conversions are not generated during the delay.

27.2.12.3 SD24_A Interrupt Handling Software Example

The following software example shows the recommended use of SD24IV and the handling overhead. The SD24IV value is added to the PC to automatically jump to the appropriate routine.

The numbers at the right margin show the necessary CPU cycles for each instruction. The software overhead for different interrupt sources includes interrupt latency and return-from-interrupt cycles, but not the task handling itself. The latencies are:

- SD24OVIFG, CH0 SD24IFG, CH1 SD24IFG: 16 cycles
- CH2 SD24IFG: 14 cycles

The interrupt handler for channel 2 SD24IFG shows a way to check immediately if a higher prioritized interrupt occurred during the processing of the ISR. This saves nine cycles if another SD24_A interrupt is pending.

```
; Interrupt handler for SD24_A.
INT_SD24               ; Enter Interrupt Service Routine    6
   ADD      &SD24IV,PC  ; Add offset to PC                   3
   RETI                 ; Vector 0: No interrupt            5
   JMP      ADOV        ; Vector 2: ADC overflow            2
   JMP      ADM0        ; Vector 4: CH_0 SD24IFG            2
   JMP      ADM1        ; Vector 6: CH_1 SD24IFG            2
;
; Handler for CH_2 SD24IFG starts here. No JMP required.
;
ADM2   MOV   &SD24MEM2,xxx  ; Move result, flag is reset
       ...                  ; Other instruction needed?
       JMP   INT_SD24       ; Check other int pending       2
;
; Remaining Handlers
;
ADM1   MOV   &SD24MEM1,xxx  ; Move result, flag is reset
       ...                  ; Other instruction needed?
       RETI                 ; Return                        5
;
ADM0   MOV   &SD24MEM0,xxx  ; Move result, flag is reset
       RETI                 ; Return                        5
;
ADOV   ...                  ; Handle SD24MEMx overflow
       RETI                 ; Return                        5
```

27.3 SD24_A Registers

The SD24_A registers are listed in Table 27-5 (registers for channels not implemented are unavailable; see the device-specific data sheet).

Table 27-5. SD24_A Registers

Register	Short Form	Register Type	Address	Initial State
SD24_A Control	SD24CTL	Read/write	0100h	Reset with PUC
SD24_A Interrupt Vector	SD24IV	Read/write	0110h	Reset with PUC
SD24_A Analog Enable(1)	SD24AE	Read/write	0B7h	Reset with PUC
SD24_A Channel 0 Control	SD24CCTL0	Read/write	0102h	Reset with PUC
SD24_A Channel 0 Conversion Memory	SD24MEM0	Read/write	0112h	Reset with PUC
SD24_A Channel 0 Input Control	SD24INCTL0	Read/write	0B0h	Reset with PUC
SD24_A Channel 0 Preload	SD24PRE0	Read/write	0B8h	Reset with PUC
SD24_A Channel 1 Control	SD24CCTL1	Read/write	0104h	Reset with PUC
SD24_A Channel 1 Conversion Memory	SD24MEM1	Read/write	0114h	Reset with PUC
SD24_A Channel 1 Input Control	SD24INCTL1	Read/write	0B1h	Reset with PUC
SD24_A Channel 1 Preload	SD24PRE1	Read/write	0B9h	Reset with PUC
SD24_A Channel 2 Control	SD24CCTL2	Read/write	0106h	Reset with PUC
SD24_A Channel 2 Conversion Memory	SD24MEM2	Read/write	0116h	Reset with PUC
SD24_A Channel 2 Input Control	SD24INCTL2	Read/write	0B2h	Reset with PUC
SD24_A Channel 2 Preload	SD24PRE2	Read/write	0BAh	Reset with PUC
SD24_A Channel 3 Control	SD24CCTL3	Read/write	0108h	Reset with PUC
SD24_A Channel 3 Conversion Memory	SD24MEM3	Read/write	0118h	Reset with PUC
SD24_A Channel 3 Input Control	SD24INCTL3	Read/write	0B3h	Reset with PUC
SD24_A Channel 3 Preload	SD24PRE3	Read/write	0BBh	Reset with PUC
SD24_A Channel 4 Control	SD24CCTL4	Read/write	010Ah	Reset with PUC
SD24_A Channel 4 Conversion Memory	SD24MEM4	Read/write	011Ah	Reset with PUC
SD24_A Channel 4 Input Control	SD24INCTL4	Read/write	0B4h	Reset with PUC
SD24_A Channel 4 Preload	SD24PRE4	Read/write	0BCh	Reset with PUC
SD24_A Channel 5 Control	SD24CCTL5	Read/write	010Ch	Reset with PUC
SD24_A Channel 5 Conversion Memory	SD24MEM5	Read/write	011Ch	Reset with PUC
SD24_A Channel 5 Input Control	SD24INCTL5	Read/write	0B5h	Reset with PUC
SD24_A Channel 5 Preload	SD24PRE5	Read/write	0BDh	Reset with PUC
SD24_A Channel 6 Control	SD24CCTL6	Read/write	010Eh	Reset with PUC
SD24_A Channel 6 Conversion Memory	SD24MEM6	Read/write	011Eh	Reset with PUC
SD24_A Channel 6 Input Control	SD24INCTL6	Read/write	0B6h	Reset with PUC
SD24_A Channel 6 Preload	SD24PRE6	Read/write	0BEh	Reset with PUC

(1) Not implemented on all devices; see the device-specific data sheet.

27.3.1 SD24CTL, SD24_A Control Register

15	14	13	12	11	10	9	8
Reserved				SD24XDIVx			SD24LP
r0	r0	r0	r0	rw-0	rw-0	rw-0	rw-0
7	6	5	4	3	2	1	0
SD24DIVx		SD24SSELx		SD24VMIDON	SD24REFON	SD24OVIE	Reserved
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	r0

Reserved Bits 15-12 Reserved

SD24XDIVx Bits 11-9 SD24_A clock divider
- 00 /1
- 01 /3
- 10 /16
- 11 /48
- 1xx Reserved

SD24LP Bit 8 Low-power mode. This bit selects a reduced-speed reduced-power mode
- 0 Low-power mode is disabled
- 1 Low-power mode is enabled. The maximum clock frequency for the SD24_A is reduced.

SD24DIVx Bits 7-6 SD24_A clock divider
- 00 /1
- 01 /2
- 10 /4
- 11 /8

SD24SSELx Bits 5-4 SD24_A clock source select
- 00 MCLK
- 01 SMCLK
- 10 ACLK
- 11 External TACLK

SD24VMIDON Bit 3 VMID buffer on
- 0 Off
- 1 On

SD24REFON Bit 2 Reference generator on
- 0 Reference off
- 1 Reference on

SD24OVIE Bit 1 SD24_A overflow interrupt enable. The GIE bit must also be set to enable the interrupt.
- 0 Overflow interrupt disabled
- 1 Overflow interrupt enabled

Reserved Bit 0 Reserved

27.3.2 SD24CCTLx, SD24_A Channel x Control Register

15	14	13	12	11	10	9	8
Reserved	**SD24BUFx**[1]		**SD24UNI**	**SD24XOSR**	**SD24SNGL**	**SD24OSRx**	
r0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0
7	6	5	4	3	2	1	0
SD24LSBTOG	**SD24LSBACC**	**SD24OVIFG**	**SD24DF**	**SD24IE**	**SD24IFG**	**SD24SC**	**SD24GRP**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	r(w)-0

Reserved	Bit 15	Reserved
SD24BUFx	Bits 14-13	High-impedance input buffer mode
		00 Buffer disabled
		01 Slow speed/current
		10 Medium speed/current
		11 High speed/current
SD24UNI	Bit 12	Unipolar mode select
		0 Bipolar mode
		1 Unipolar mode
SD24XOSR	Bit 11	Extended oversampling ratio. This bit, along with the SD24OSRx bits, select the oversampling ratio. See SD24OSRx bit description for settings.
SD24SNGL	Bit 10	Single conversion mode select
		0 Continuous conversion mode
		1 Single conversion mode
SD24OSRx	Bits 9-8	Oversampling ratio
		When SD24XOSR = 0
		00 256
		01 128
		10 64
		11 32
		When SD24XOSR = 1
		00 512
		01 1024
		10 Reserved
		11 Reserved
SD24LSBTOG	Bit 7	LSB toggle. This bit, when set, causes SD24LSBACC to toggle each time the SD24MEMx register is read.
		0 SD24LSBACC does not toggle with each SD24MEMx read
		1 SD24LSBACC toggles with each SD24MEMx read
SD24LSBACC	Bit 6	LSB access. This bit allows access to the upper or lower 16-bits of the SD24_A conversion result.
		0 SD24MEMx contains the most significant 16-bits of the conversion.
		1 SD24MEMx contains the least significant 16-bits of the conversion.
SD24OVIFG	Bit 5	SD24_A overflow interrupt flag
		0 No overflow interrupt pending
		1 Overflow interrupt pending
SD24DF	Bit 4	SD24_A data format
		0 Offset binary
		1 2s complement
SD24IE	Bit 3	SD24_A interrupt enable
		0 Disabled
		1 Enabled

(1) Not implemented on all devices (see the device-specific data sheet).Reserved with r0 access if high-impedance buffer not implemented.

SD24IFG	Bit 2	SD24_A interrupt flag. SD24IFG is set when new conversion results are available. SD24IFG is automatically reset when the corresponding SD24MEMx register is read, or may be cleared with software. 0 No interrupt pending 1 Interrupt pending
SD24SC	Bit 1	SD24_A start conversion 0 No conversion start 1 Start conversion
SD24GRP	Bit 0	SD24_A group. Groups SD24_A channel with next higher channel. Not used for the last channel. 0 Not grouped 1 Grouped

27.3.3 SD24INCTLx, SD24_A Channel x Input Control Register

7	6	5	4	3	2	1	0
SD24INTDLYx		**SD24GAINx**			**SD24INCHx**		
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

SD24INTDLYx	Bits 7-6	Interrupt delay generation after conversion start. These bits select the delay for the first interrupt after conversion start. 00 Fourth sample causes interrupt 01 Third sample causes interrupt 10 Second sample causes interrupt 11 First sample causes interrupt
SD24GAINx	Bits 5-3	SD24_A preamplifier gain 000 x1 001 x2 010 x4 011 x8 100 x16 101 x32 110 Reserved 111 Reserved
SD24INCHx	Bits 2-0	SD24_A channel differential pair input. The available selections are device dependent. See the device-specific data sheet. 000 Ax.0 001 Ax.1(1) 010 Ax.2(1) 011 Ax.3(1) 100 Ax.4(1) 101 (AV_{CC} - AV_{SS}) / 11 110 Temperature sensor 111 Short for PGA offset measurement

(1) Ax.1 to Ax.4 not available on all devices (see device-specific data sheet).

27.3.4 SD24MEMx, SD24_A Channel x Conversion Memory Register

15	14	13	12	11	10	9	8
Conversion Results							
r	r	r	r	r	r	r	r
7	6	5	4	3	2	1	0
Conversion Results							
r	r	r	r	r	r	r	r

Conversion Results	Bits 15-0	Conversion results. The SD24MEMx register holds the upper or lower 16-bits of the digital filter output, depending on the SD24LSBACC bit.

27.3.5 SD24PREx, SD24_A Channel x Preload Register

7	6	5	4	3	2	1	0
Preload Value							
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

Preload Value	Bits 7-0	SD24_A digital filter preload value

27.3.6 SD24AE, SD24_A Analog Input Enable Register

7	6	5	4	3	2	1	0
SD24AE7	**SD24AE6**	**SD24AE5**	**SD24AE4**	**SD24AE3**	**SD24AE2**	**SD24AE1**	**SD24AE0**
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

SD24AEx	Bits 7-0	SD24_A analog enable	
		0	External input disabled. Negative inputs are internally connected to VSS.
		1	External input enabled

27.3.7 SD24IV, SD24_A Interrupt Vector Register

15	14	13	12	11	10	9	8
0	**0**	**0**	**0**	**0**	**0**	**0**	**0**
r0	r0	r0	r0	r0	r0	r0	r0

7	6	5	4	3	2	1	0
0	**0**	**0**	**SD24IVx**				**0**
r0	r0	r0	r-0	r-0	r-0	r-0	r0

SD24IVx Bits 15-0 SD24_A interrupt vector value

SD24IV Contents	Interrupt Source	Interrupt Flag	Interrupt Priority
000h	No interrupt pending	-	
002h	SD24MEMx overflow	SD24CCTLx SD24OVIFG(1)	Highest
004h	SD24_A Channel 0 Interrupt	SD24CCTL0 SD24IFG	
006h	SD24_A Channel 1 Interrupt	SD24CCTL1 SD24IFG	
008h	SD24_A Channel 2 Interrupt	SD24CCTL2 SD24IFG	
00Ah	SD24_A Channel 3 Interrupt	SD24CCTL3 SD24IFG	
00Ch	SD24_A Channel 4 Interrupt	SD24CCTL4 SD24IFG	
00Eh	SD24_A Channel 5 Interrupt	SD24CCTL5 SD24IFG	
010h	SD24_A Channel 6 Interrupt	SD24CCTL6 SD24IFG	Lowest

(1) When an SD24_A overflow occurs, the user must check all SD24CCTLx SD24OVIFG flags to determine which channel overflowed.

Embedded Emulation Module (EEM)

This chapter describes the Embedded Emulation Module (EEM) that is implemented in all MSP430 flash devices.

Topic **Page**

28.1 EEM Introduction

Every MSP430 flash-based microcontroller implements an embedded emulation module (EEM). It is accessed and controlled through JTAG. Each implementation is device dependent and is described in section 1.3 *EEM Configurations* and the device-specific data sheet.

In general, the following features are available:

- Non-intrusive code execution with real-time breakpoint control
- Single step, step into and step over functionality
- Full support of all low-power modes
- Support for all system frequencies, for all clock sources
- Up to eight (device dependent) hardware triggers/breakpoints on memory address bus (MAB) or memory data bus (MDB)
- Up to two (device dependent) hardware triggers/breakpoints on CPU register write accesses
- MAB, MDB ,and CPU register access triggers can be combined to form up to eight (device dependent) complex triggers/breakpoints
- Trigger sequencing (device dependent)
- Storage of internal bus and control signals using an integrated trace buffer (device dependent)
- Clock control for timers, communication peripherals, and other modules on a global device level or on a per-module basis during an emulation stop

Figure 28-1 shows a simplified block diagram of the largest currently available 2xx EEM implementation.

For more details on how the features of the EEM can be used together with the IAR Embedded Workbench™ debugger see the application report *Advanced Debugging Using the Enhanced Emulation Module* (SLAA263) at www.msp430.com. Code Composer Essentials (CCE) and most other debuggers supporting MSP430 have the same or a similar feature set. For details see the user's guide of the applicable debugger.

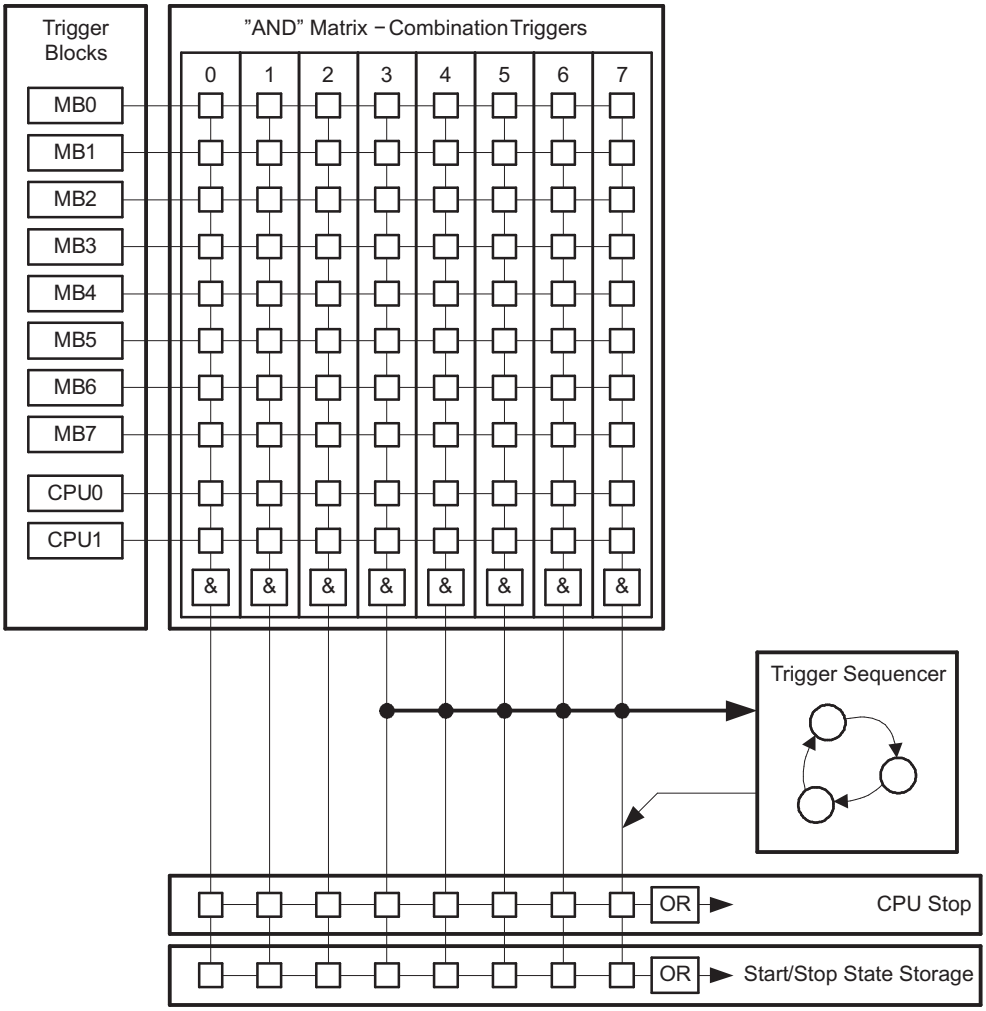


Figure 28-1. Large Implementation of the Embedded Emulation Module (EEM)

28.2 EEM Building Blocks

28.2.1 Triggers

The event control in the EEM of the MSP430 system consists of triggers, which are internal signals indicating that a certain event has happened. These triggers may be used as simple breakpoints, but it is also possible to combine two or more triggers to allow detection of complex events and trigger various reactions besides stopping the CPU.

In general, the triggers can be used to control the following functional blocks of the EEM:

- Breakpoints (CPU stop)
- State storage
- Sequencer

There are two different types of triggers, the memory trigger and the CPU register write trigger.

Each memory trigger block can be independently selected to compare either the MAB or the MDB with a given value. Depending on the implemented EEM the comparison can be =, ≠, ≥, or ≤. The comparison can also be limited to certain bits with the use of a mask. The mask is either bit-wise or byte-wise, depending upon the device. In addition to selecting the bus and the comparison, the condition under which the trigger is active can be selected. The conditions include read access, write access, DMA access, and instruction fetch.

Each CPU register write trigger block can be independently selected to compare what is written into a selected register with a given value. The observed register can be selected for each trigger independently. The comparison can be =, ≠, ≥, or ≤. The comparison can also be limited to certain bits with the use of a bit mask.

Both types of triggers can be combined to form more complex triggers. For example, a complex trigger can signal when a particular value is written into a user-specified address.

28.2.2 Trigger Sequencer

The trigger sequencer allows the definition of a certain sequence of trigger signals before an event is accepted for a break or state storage event. Within the trigger sequencer, it is possible to use the following features:

- Four states (State 0 to State 3)
- Two transitions per state to any other state
- Reset trigger that resets the sequencer to State 0.

The Trigger sequencer always starts at State 0 and must execute to State 3 to generate an action. If State 1 or State 2 are not required, they can be bypassed.

28.2.3 State Storage (Internal Trace Buffer)

The state storage function uses a built-in buffer to store MAB, MDB, and CPU control signal information (that is, read, write, or instruction fetch) in a non-intrusive manner. The built-in buffer can hold up to eight entries. The flexible configuration allows the user to record the information of interest very efficiently.

28.2.4 Clock Control

The EEM provides device dependent flexible clock control. This is useful in applications where a running clock is needed for peripherals after the CPU is stopped (for example, to allow a UART module to complete its transfer of a character or to allow a timer to continue generating a PWM signal).

The clock control is flexible and supports both modules that need a running clock and modules that must be stopped when the CPU is stopped due to a breakpoint.

28.3 EEM Configurations

Table 28-1 gives an overview of the EEM configurations in the MSP430 2xx family. The implemented configuration is device dependent - see the device data sheet.

Table 28-1. 2xx EEM Configurations

Feature	XS	S	M	L
Memory Bus Triggers	2(=, ≠ only)	3	5	8
Memory Bus Trigger Mask for	1) Low byte 2) High byte	1) Low byte 2) High byte	1) Low byte 2) High byte	All 16 or 20 bits
CPU Register-Write Triggers	0	1	1	2
Combination Triggers	2	4	6	8
Sequencer	No	No	Yes	Yes
State Storage	No	No	No	Yes

In general the following features can be found on any 2xx device:

- At least two MAB/MDB triggers supporting:
  - Distinction between CPU, DMA, read, and write accesses
  - =, ≠, ≥, or ≤ comparison (in XS only =, ≠)
- At least two trigger Combination registers
- Hardware breakpoints using the CPU Stop reaction
- Clock control with individual control of module clocks (in some XS configurations the control of module clocks is hardwired)

Revision History

Revision	Comments
SLAU144G	Chapter 5 *Basic Clock Module+*, Added information specific to the MSP430AFE2xx devices: Figure 5-2. Basic Clock Module+ Block Diagram − MSP430AFE2xx Section 5.3, Register BCSCTL3 default Section 5.3.2, 5.3.3, 5.3.4, Available register bits, defaults, and definitions Added chapters: Chapter 18 *USART Peripheral Interface, UART Mode* Chapter 19 *USART Peripheral Interface, SPI Mode* Chapter 27 *SD24_A* Made editorial and format changes throughout.
SLAU144H	Section 2.4, Corrected DCO startup time. Section 8.2.6, Updated pin oscillator information; added Figure 8-1. Section 3.4.6.5, Corrected typo in BIC description. Section 7.2.1, Corrected typo in code example.
SLAU144I	Table 2-3, Changed comments on crystal pins. Section 1.4.1, Corrected addresses for end of Flash/ROM. Section 3.3.5, Changed example figure. Updated descriptions in the following sections: Section 5.1, Section 5.2.1, Section 5.2.2, Section 5.2.3, Section 5.2.5.2,Section 5.2.7.1,Section 5.3.3 (DCOR bit), Section 5.3.4 (FLST1Sx bit). Section 7.3.2 and Section 7.3.4, Added information regarding MSP430G2xx. Section 8.1, Added note regarding MSP430G22x0. Chapter 21, Added notes throughout regarding MSP430G2210. Figure 22-1, Updated block diagram. Section 22.2.2.1, Changed Analog Port Selection description. Section 22.2.3, Changed Voltage Reference Generator description. Section 22.3.1, Updated SREF bit description. Section 22.3.2, Updated INCHx bit description. Figure 23-1, Changed four inputs on center left mux from GND to Floating. Table 24-1, Corrected CALDCO... names. Made editorial changes throughout.
SLAU144J	Figure 3-17, Corrected bottom left bit number. Section 7.2, Corrected minimum number of main memory segments. Section 24.2.2.1, Added temperature sensor calibration equations. Section 26.2.5, Changed description. Section 27.2.5, Changed description.

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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