Eye Diagrams and Sampling Oscilloscopes

Most people are familiar with an oscilloscope display of repetitive waveforms such as sine, square, or triangle waves. These are known as *single-value* displays because each point in the time axis has only a single voltage value associated with it.

When analyzing a digital telecommunication waveform, single-value displays are not very useful. Real communications signals are not repetitive, but consist of random or pseudorandom patterns of ones and zeros. A single-value display can only show a few of the many different possible one-zero combinations. Pattern dependent problems such as slow rise time or excessive overshoot will be overlooked if they don't occur in the small segment of the waveform appearing on the display. For example, the amount of overshoot on the zero-to-one transition of a SONET laser transmitter depends on the exact pattern preceding it.

An eye diagram (Fig. 1) overcomes the limitations of a single-value display by overlapping all of the possible one-zero combinations on the oscilloscope screen. Eye diagrams are *multivalued* displays because each point in the time axis has multiple voltage values associated with it.
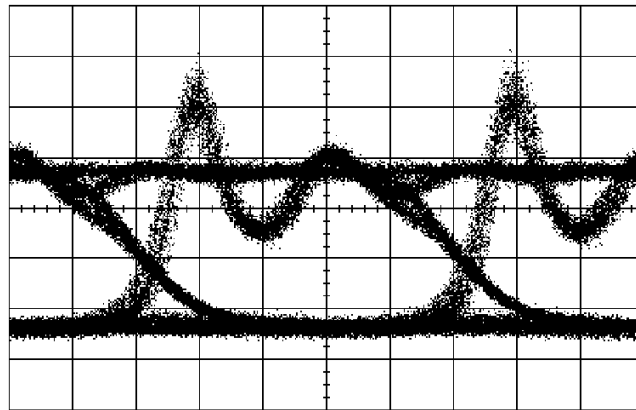

Fig. 1. *Eye diagram of a laser directly modulated at 2.48832 Gbits/s.*

An eye diagram is generated on an oscilloscope using the setup of Fig. 2. The data signal is applied to the oscilloscope's vertical input and a separate trigger signal is applied to its trigger input. Ideally, the trigger signal is a repetitive waveform at the clock rate of the data, although the data signal itself can also be used as a trigger signal in noncritical applications.
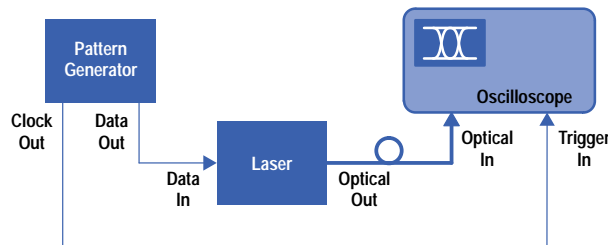

Fig. 2. *Block diagram for eye diagram testing.*

The oscilloscope triggers on the first clock transition after its trigger circuit is armed. Upon triggering, it captures whatever data waveform is present at the vertical input and displays it on the screen. The oscilloscope is set for infinite persistence so that subsequent waveforms will continue to add to the display.

For a short period of time after triggering, the oscilloscope is unable to retrigger while the circuitry resets. At the conclusion of this trigger dead time, the oscilloscope triggers on the next clock transition. The data pattern at this instant will probably be different from the previous one, so the display will now be a combination of the two patterns. This process continues so that eventually, after many trigger events, all the different one-zero combinations will overlap on the screen.

To analyze waveform properties accurately the oscilloscope must have a bandwidth at least three times the data rate, and preferably much more. At high data rates, this leads to an additional complicating factor. Wide-bandwidth single-shot oscilloscopes capable of capturing an entire waveform at once simply aren't economically available, so sampling oscilloscopes must be used instead. Sampling oscilloscopes make use of the concept of *equivalent time* to achieve effective bandwidths up to 50 GHz.

Instead of capturing an entire waveform on each trigger, the sampling oscilloscope measures only the instantaneous amplitude of the wave-form at the sampling instant (Fig. 3). On the first trigger event the oscilloscope samples the waveform immediately and displays the value at the very left edge of the screen. On the next trigger event, it delays slightly before sampling the data. The amount of this delay depends on the number of horizontal data points on the screen and on the selected sweep speed. It is determined by the relation:

$$D = \frac{1}{n-1} \times T,$$

where D is the delay time between successive points, n is the number of points on the screen, and T is the full-screen sweep time. For example, if the full screen sweep time is 10 nanoseconds and the display has 451 horizontal points, then the delay is (1/450) $\times$ 10 ns, or 22.2 ps. The amplitude sampled at this instant is displayed one point to the right of the original sample. On each subsequent trigger event the oscilloscope adds an ever-increasing delay before sampling, so that the trace builds up from left to right across the screen.
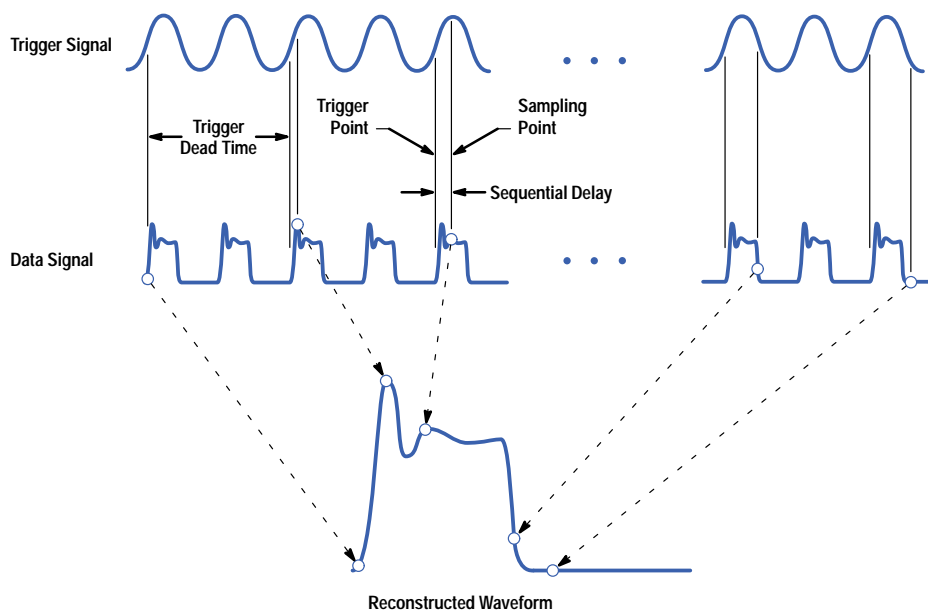

Fig. 3. *Concept of sequential sampling.*

The trade-off in using a sampling oscilloscope is a loss of information about the exact waveform characteristics. When sampling a repetitive waveform such as a sine wave, this doesn't usually pose a problem; the screen display shows a sine wave that is a sampled representation of the original waveform. When sampling a random data pattern, however, the eye diagram appears as a series of disconnected dots. All information about the exact nature of the individual waveforms is lost, so if the eye diagram shows excessive overshoot or slow rise time, the exact data pattern causing the problem can't be identified. This is why Hewlett-Packard incorporated the HP Eyeline display mode into the HP 83480 (see *Article 2*). First developed for the HP 71501 eye diagram analyzer,[1] the eyeline display allows the individual data patterns making up the eye diagram to be seen.

Reference

1. C.M. Miller, "High-Speed Digital Transmitter Characterization Using Eye Diagram Analysis," *Hewlett-Packard Journal*, Vol. 45, no. 4, August 1994, pp. 29-37.