20.2 Choosing a Transmission Line

Making the best choice for a particular installation requires balancing the properties of the three common types of feed lines used by amateurs — coaxial, parallel-conductor or open-wire, and hardline — along with cost. The primary electrical considerations for feed line are characteristic impedance and loss. Mechanical concerns include weight, suitability for exposure to weather or soil, and interaction with other cables and conductors. When evaluating cost, be sure to include the cost of connectors and any auxiliary costs such as baluns and waterproofing materials.

The entire antenna system, composed of the feed line, tuners or matching networks and the antenna itself, must be included when evaluating what type of line to use. Along with loss, the effects of SWR on maximum voltage in the system must be considered if high power will be used, especially if high SWR is anticipated.

Multiband antenna systems, such as non-resonant wire antennas, can present quite a challenge because of the range of SWR values and the wide range of frequencies of use. As an example of the considerations involved, the article "Multiband Operation with Open-wire Line" is included with the downloadable supplemental content. By following the general process of modeling or calculation and evaluation with different types of feed line, reasonable choices can be made that result in satisfactory performance.

20.2.1 Effect of Loss

For most types of line and for modest values of SWR, the additional line loss due to SWR is of little concern. As the line's loss increases at higher frequencies, the total line loss (the sum of matched-line loss and additional loss due to SWR) can be surprisingly large at high values of SWR.

Because of losses in a transmission line, the measured SWR at the input of the line is lower than the SWR measured at the load end of the line. This does *not* mean that the load is absorbing any more power. Line loss absorbs power as it travels to the load and again on its way back to the generator, so the difference between the generator output power and the power returning from the load is higher than for a lossless line. Thus, P_r/P_f is smaller than at the load and so is the measured SWR.

For example, RG-213 solid-dielectric coax cable exhibits a matched-line loss at 28 MHz of 1.14 dB per 100 ft. A 250 ft length of this cable has a matched-line loss of 1.14 × 250/100 = 2.86 dB. Assume that we measure the SWR at the load as 6:1, the total mismatched line loss from equation 11 is 5.32 dB.

The additional loss due to the 6:1 SWR at 28 MHz is 5.32 − 2.86 = 2.46 dB. The SWR at the input of the 250 ft line is only 2.2:1, because line loss has masked the true magnitude of SWR (6:1) at the load end of the line.

The losses increase if coax with a larger matched-line loss is used under the same conditions. For example, RG-58A coaxial cable is about one-half the diameter of RG-213, and it has a matched-line loss of 2.81 dB/ 100 ft at 28 MHz. A 250 ft length of RG-58A has a total matched-line loss of 7.0 dB. With a 6:1 SWR at the load, the additional loss due to SWR is 3.0 dB, for a total loss of 10.0 dB. The additional cable loss due to the mismatch reduces the SWR measured at the input of the line to 1.33:1. An unsuspecting operator measuring the SWR at his transmitter might well believe that everything is just fine, when in truth only about 10% of the transmitter power is getting to the antenna! Be suspicious of very low SWR readings for an antenna fed with a long length of coaxial cable, especially if the SWR remains low across a wide frequency range. Most antennas have narrow SWR bandwidths, and the SWR *should* change across a band.

Transmission Lines for Microwave Frequencies

While low-loss waveguide is generally used to carry microwave frequency signals for long distances, *semi-rigid* coaxial cable — essentially miniature hardline — is used for connections inside and between pieces of equipment in the shack. Working with this type of cable requires special techniques, addressed in the supplemental article "Microwave Plumbing" with this book's online supplemental content. More information on microwave construction techniques is available in the **Construction Techniques** chapter and in the "Microwavelengths" columns by Paul Wade, W1GHZ in *QST*, available on-line to ARRL members.

On the other hand, if expensive [illegible] diameter 50 Ω hardline cable is [illegible] 28 MHz, the matched-line loss is only [illegible] 100 ft. For 250 ft of this hardline, the [illegible] line loss is 0.475 dB, and the additi[illegible] due to a 6:1 SWR is 0.793 dB. Thus, [illegible] loss is 1.27 dB.

At the upper end of the HF spectrum [illegible] the transmitter and antenna are sep[illegible] a long transmission line, the use of [illegible] coax may prove to be a very poor co[illegible] strategy. Adding a 1500 W linear [illegible] (providing 8.7 dB of gain over a 200 W [illegible] mitter), to offset the loss in RG-58A [illegible] to hardline, would cost a great deal [illegible] higher-quality coax. Furthermore, [illegible] *mitting* amplifier can boost *receiver* [illegible] ity — loss in the line has the same [illegible] putting an attenuator in front of the [illegible]

At the lower end of the HF spec[illegible] 3.5 MHz, the amount of loss in comm[illegible] lines is less of a problem for the [illegible] SWR values typical on this band. For [illegible] consider an 80 meter dipole cut for the [illegible] of the band at 3.75 MHz. It exhibits [illegible] of about 6:1 at the 3.5 and 4.0 M[illegible] of the band. At 3.5 MHz, 250 ft of [illegible] small-diameter coax has an addition[illegible] 2.1 dB for this SWR, giving a total [illegible] of 4.0 dB. If larger-diameter RG-21[illegible] used instead, the additional loss due [illegible] is 1.3 dB, for a total loss of 2.2 dB. [illegible] an acceptable level of loss for most [illegible] operators.

The loss situation gets dramaticall[illegible] as the frequency increases into the [illegible] UHF regions. At 146 MHz, the tota[illegible] 250 ft of RG-58A with a 6:1 SWR [illegible] is 21.4 dB, 10.1 dB for RG-213A, an[illegible] for ⅞ inch, 50 Ω hardline. At VHF an[illegible] low SWR is essential to keep line lo[illegible] even for the best coaxial cable. The [illegible] of transmission line must be kept [illegible] practical at these frequencies.

Table 20.1 lists some common[illegible] coax cables showing feet per dB [illegible] frequency. The table can help with [illegible]

Table 20.1
Length in Feet for 1 dB of Matched Loss

MHz	*1.8*	*3.6*	*7.1*	*14.2*	*21.2*	*28.4*	*50.1*	*144*	*440*	[illegible]
RG-58	179	122	83	59	50	42	30	18	9	[illegible]
RG-8X	257	181	128	90	74	63	47	27	14	[illegible]
RG-213	397	279	197	137	111	95	69	38	19	[illegible]
LMR-400	613	436	310	219	179	154	115	67	38	[illegible]
9913	625	435	320	220	190	155	110	62	37	[illegible]
EC4-50				290		202		87		[illegible]
EC5-50				787		548		239		[illegible]
450 Ω OWL*	1065	758	547	391	322	279	213			
600 Ω OWL**	4550	3030	2130	1430	1150	980	715			

**Wireman #551, 400 Ω characteristic impedance*
***Conductors #12 AWG*

lection of coax cable by comparing lengths that result in 1 dB of loss for different types of cable. The larger the value in the table, the less loss in the cable per unit length. (See also Table 23-3 and 23-4 in the *ARRL Antenna Book* for information on more types of cable.) Determine the length of line your installation requires and the maximum acceptable amount of line loss in dB. Divide the total line length by the *maximum* acceptable loss to calculate the *minimum* acceptable length of line with 1 dB of loss. From the table, select a cable type that has a length per 1 dB of loss that is greater than the minimum acceptable length.

Example — An installation requires 400 feet of feed line at 14 MHz with a maximum acceptable value of 3 dB of loss. This requires cable with a minimum of 400 / 3 = 133 feet per dB of loss. Find a cable in Table 20.1 that shows more than 133 feet for 1 dB of loss at 14.2 MHz. RG-213 has the highest acceptable loss at this frequency: 137 ft / dB of loss.

Don't forget that you can combine types of cable and accessories to lower the total system cost while still meeting performance requirements. For example, it is common to use a single low-loss cable from the shack to a distant tower with multiple antennas. At the tower, an antenna switch then selects short runs of less-expensive cable to the various antennas.

20.2.2 Practical Considerations

Either coaxial cable or open-wire transmission or feed line is used to connect the transmitter and antenna. There are pros and cons for each type of feed line. Coax is the common choice because it is readily available, its characteristic impedance is close to that of a center-fed dipole, and it may be easily routed through or along walls and among other cables. Where a very long feed line is required or the antenna is to be used at frequencies for which the feed point impedance is high, the increased RF loss and low working voltage (compared to that of open-wire line) make it a poor choice. Hardline is the preferred choice at VHF and higher frequencies when the line losses for flexible coax would be too high. It is often used for very long line lengths at HF, as well. Refer to the **Component Data and References** chapter for information that will help you evaluate the RF loss of coaxial cable at different lengths and SWR.

Note that most traditional RG-type designations are no longer MIL-spec and are only general references to the cable's construction and characteristics. For example, cable advertised as RG-213 is actually "RG-213 Type" and may have characteristics quite different from the original RG-213 specification. Use the manufacturer's part number to determine the actual performance specifications.

COAXIAL CABLE

Coaxial cable is mechanically much easier to use than open-wire line. Because of the excellent shielding afforded by its outer shield, coax can be installed along a metal tower leg or taped together with numerous other cables, with virtually no interaction or crosstalk. Coax can be used with a rotatable antenna without worrying about shorting or twisting the conductors, which might happen with an open-wire line.

Coaxial cable used in the amateur service is, for the most part, made with solid polyethylene (PE), extended or "foamed" polyethylene (FPE), and solid Teflon (TFE) center insulation. (Teflon dielectric coax is often used at VHF and UHF frequencies due to its low loss characteristics.)

Class 2 PVC (P2) noncontaminating outer jackets are designed for long-life outdoor installations. Class 1 PVC (P1) outer jackets are not recommended for outdoor installations. (See the table of coaxial cables in the **Component Data and References** chapter.) Coax and hardline can be buried underground, especially if run in plastic piping (with suitable drain holes) so that ground water and soil chemicals cannot easily deteriorate the cable. A cable with an outer jacket of polyethylene (PE) rather than polyvinyl chloride (PVC) is recommended for direct-bury installations.

Respect coax's power-handling ratings. Cables such as RG-58 and RG-59 are suitable for power levels up to 300 W with low SWR. RG-8X cable can handle higher power and there are a number of variations of this type of cable. For legal-limit power or moderate SWR, use the larger diameter cables that are 0.4 inches in diameter or larger. Subminiature cables, such as RG-174, are useful for very short lengths at low power levels, but the high RF losses associated with these cables make them unsuitable for most uses as antenna feed lines. In these applications, a PTFE (Teflon) insulated cable is a better choice.

Bending Coax

Bending coax is acceptable as long as the radius of the bend is larger than the specified minimum bending radius. For example, a common minimum bending radius specification for RG-8 is 4 inches (8 times the cable diameter). Coax with more rigid shield materials will have a larger bending radius.

Bending the coax tighter than the minimum bending radius can cause impedance "bumps" in the line by distorting the geometry of the conductors. It can also cause the center conductor to migrate through the plastic insulation and eventually short to the outer shield. This is caused by several preventable conditions.

A major culprit for foam-insulation coax is bending the cable with a tight radius. Baluns are often made by wrapping several turns of coax into a tight bundle with a tight radius, either as a coiled-coax choke or through ferrite cores. Coaxial cable stubs might be wrapped into a coil of small radius to keep them small overall and out of the way. Coax is sometimes coiled up just to use up extra length.

The forces pushing on the center conductor from coiling are aggravated by self-heating from cable loss — a direct function of the amount of power applied and SWR. RG-8X is not rated for 1500 W but lots of amateurs use it successfully at that power level. RG-8X gets warm to the touch at 1500 W. Increasing internal temperature softens the foam which facilitates center conductor migration. Tight radius bends taken together with heating are a recipe for an eventual short circuit. Tightly coiled baluns used outdoors receive solar heating in addition to self-heating and a tight bend radius. A balun made and used this way has a very high probability of shorting out over time — particularly when used at high power.

Avoiding center conductor migration is easy: don't use sharp bends, particularly at high power. Use solid dielectric coax to make tightly coiled coaxial baluns and if stubs must be coiled up, use solid dielectric coax for those too. Use up spare foam coax length by laying it flat on the floor and avoiding sharp radius turns or bends.

Burying Coax

There are several reasons why you might choose to bury coax. One is that direct burial cable is virtually free from storm and UV damage, and usually has lower maintenance cost than cable that is out in the open. Another reason might be aesthetics; a buried cable will be acceptable in almost all communities. Also, being underground reduces common-mode feed line current on the outside of the shield, helping to reduce inter-station interference and RFI. Buried cable is also less susceptible to lightning.

Although any cable can be buried, a cable that is specifically designed for direct burial will have a longer life. The best cable to use is one that has a high-density polyethylene jacket because it is both nonporous and will take a relatively high amount of compressive loads. "Flooded" direct burial cables contain an additional moisture barrier of non-conductive grease under the jacket; this allows the material to leak out, thus "healing" small jacket penetrations. (These can be messy to work with when installing connectors.)

Here are some direct burial guidelines:

1) Because the outer jacket is the cable's first line of defense, any steps that can be taken to protect it will go a long way toward maintaining the internal quality of the cable.

2) Bury the cable in sand or finely pulverized dirt, without sharp stones, cinders, or rubble. If the soil in the trench does not meet these requirements, tamp four to six inches of sand into the trench, lay the cable and tamp another six to eleven inches of sand

above it. A pressure-treated board placed in the trench above the sand prior to backfilling will provide some protection against subsequent damage that could be caused by digging or driving stakes.

3) Lay the cable in the trench with some slack. A tightly stretched cable is more likely to be damaged as the fill material is tamped.

4) Examine the cable as it is being installed to be sure the jacket has not been damaged during storage or by being dragged across over sharp edges.

5) You may want to consider burying it in plastic pipe or conduit. Be careful to drill holes in the bottom of the pipe at all low spots so that any moisture can drain out. While PVC pipe or conduit provides a mechanical barrier, water incursion is practically guaranteed — you can't keep it out. It will leak in directly or condense from moisture in the air. Use the perforated type so that any water will just drain out harmlessly. Plastic drain pipe with drain holes also works well.

6) It is important that direct burial is below the frost line to avoid damage by the expansion and contraction of the earth during freezing and thawing of the soil and any water surrounding the buried cables.

Connecting to and Weatherproofing Coax

Most manufacturers use some type of feed point system that accepts a PL-259 or N connector. Some antennas require you to split the coax and attach the shield and center conductor to machine screws attachment points on the driven element. The exposed end of the coax is very difficult to seal; indeed, it's nearly impossible. Water will wick down the outer shield and into your shack unless you take great pains to weatherproof it. Coating the entire pigtail and attachment terminals with Liquid Electrical Tape or some other conformal sealant is a good approach, although UV will degrade such coatings over time. Another approach for HF beams is to use a "Budwig HQ-1" style insulator with the integral SO-239 and wires for connecting to the terminals. As always, follow the manufacturer's directions.

With many beam antennas, the feed point is out of reach from the tower and should be connected to a jumper just long enough to reach from the feed point to the antenna mast. That way, the feed line connection and waterproofing can be done at the most convenient location. If you ever have to remove the antenna in the future you can just disconnect the jumper and lower the antenna.

The biggest mistake amateurs make with coaxial cable is improper weatherproofing. (See **Figure 28.18** in the **Safety** chapter, showing one way to do it properly.) First, use high-quality electrical tape, such as 3M Scotch 33+ or Scotch 88 (same as 33+ but 1.5 mil thicker). Avoid inexpensive utility tape. Before weatherproofing, tighten the connector (use pliers carefully to seat threaded connectors — hand-tight isn't good enough), and apply two wraps of tape around the joint.

When you're done making a tape wrap, sever the tape with a knife or tear it very carefully — do not stretch the tape until it breaks. This invariably leads to "flagging" in which the end of the tape loosens and blows around in the wind. Let the tape relax before applying the next layer and finishing the wrap.

Begin by applying two wraps of electrical tape around the joint. Next put a layer of butyl rubber vapor wrap over the joint. (3M Butyl Mastic Tape 2212 is one such material. This butyl rubber tape is also usually available in the electrical section of hardware and home improvement stores.) Finally, add two more layers of regular tape over the vapor wrap, creating a professional-quality joint that will never leak. Finally, if the coax is vertical, be sure to wrap the final layer so that the tape is going up the cable as shown in Figure 28.18. In that way, the layers will act like roofing shingles, shedding water off the connection. Wrapping it top to bottom will guide water between the layers of tape.

An alternative method suggested by K4ZA begins with a wrap of "military grade" Teflon tape — a thread wrapping tape thicker than what you'll find at your local hardware store. (McMaster-Carr #6802K44) Over that, install a layer of Scotch 130C (liner-less rubber sealing tape), using a 50% wrap (half the tape width is overlapped). Cover that with a layer of either Scotch 33+ or Scotch 88. Taken apart, 20-year-old joints have revealed connectors with like new appearance.

A recent product for coax joints is shrink-fit tubing impregnated with hot-melt glue along the inside. As you apply heat to the shrink-fit tubing, it shrinks while the glue melts and oozes inside between the fitting and the tubing. It not only keeps the tubing from slipping, but it also fills in the voids in the joint and provides an additional seal. It's an expensive alternative (approximately $1 per inch) but is very simple to use and remove if necessary.

Do not use silicone sealant that gives off acetic acid (a vinegary smell) and absorbs water when curing. Acid and water will migrate into the connection causing problems later. Use only aquarium-type sealants or Dow-Corning 3145 for reliable connections. Be aware that once cured, silicone sealants are very hard to remove from connectors — practically impossible.

OPEN-WIRE LINE

The most common open-wire transmission lines are *ladder line* (also known as *window line*) and *twin-lead*. Since the conductors are not shielded, two-wire lines are affected by their environment. Use standoffs and insulators to keep the line several inches from structures or other conductors. Ladder line has very low loss (twin-lead has a little more), and it can stand very high voltages (created by high SWR) as long as the insulators are clean. Twin-lead can be used at power levels up to 300 W and ladder line to the full legal power limit.

The characteristic impedance of open-wire line varies from 300 Ω for twin-lead to 450 to 600 Ω for most ladder and window line. The common 450 Ω window line with plastic insulation and 1" spacing has a characteristic impedance of approximately 360 to [illegible] and velocity factor (VF) of approximately [illegible] depending on the manufacturer and [illegible] used. The solid plastic insulation also [illegible] that rain, snow, or ice will affect the line's Z_0 and VF, typically dropping both by [illegible] 3% when the line is wet, according to a paper by Wes Stewart, N7WS (**k6mhe.com/[illegible]Ladder_Line.pdf**). This variability [illegible] that if precise characteristics are [illegible] Z_0 and VF should be measured for the line to be used.

When used with 1/2 λ dipoles, the resulting moderate to high SWR [illegible] impedance-matching unit at the [illegible] The low RF losses of open-wire [illegible] this an acceptable situation on the HF [illegible]

Ladder line is available with both [illegible] perweld and stranded copper conductors. The solid conductor types tend to be less [illegible] but will break if flexed repeatedly [illegible] from being blown around in the wind. [illegible] that reason, stranded conductor ladder [illegible] preferred, but if solid conductor ladder [illegible] used, be sure to provide adequate [illegible] support to provide stress relief and [illegible] against flexing.

CONTROL CABLES

In addition to coaxial cables, [illegible] will have some sort of control cable [illegible] tors, antenna switches, or other [illegible] The manufacturer should provide [illegible] is necessary and again, you should [illegible] their specifications.

Multi-conductor cables are not [illegible] waterproof as coaxial cable. The [illegible] usually just a plastic sleeve around [illegible] wires. If the jacket is nicked or cut, [illegible] easily get in and collect at the [illegible] of the cable. If the water does not [illegible] will fill the cable jacket all the way [illegible] station where it will run out the [illegible] of the cable. For this reason, it is [illegible] make a drip loop in the cable [illegible] the station and make a small slice [illegible] the jacket to allow any accumulated [illegible] to leak out.

In the case of rotator cables, [illegible] are sensitive to voltage drop [illegible] should be used. For really long [illegible] amateurs use THHN house wire [illegible]