

## Let's Talk Transmission Lines

### Don't neglect one of the most important parts of your station!

By Edward J. Farmer, AA6ZM

No one wants to discuss transmission lines. Many hams would rather chew aluminum foil. After all, transmission lines are just the cables that link your radios to your antennas. You hook them up and get on the air. Who cares? Boring!

Well, the subject may not have much "sex appeal," but if you want to get maximum performance from your station, give me your attention for a couple of minutes. These lines have a major influence on the results you'll achieve on the air. A little extra knowledge will—literally—take you a long way!

### It's a Question of Impedance

Modern solid state radios expect a *load impedance* of  $50\ \Omega$ , resistive. We want to connect them to an antenna, the feed-point impedance of which can be *anything*. It depends on the antenna design, plus how and where it's installed. In general, the impedance is "complex," meaning it has both resistive and *reactive* components. (Don't worry—we'll discuss reactance in a moment.)

### Antenna Impedance

Even though the electrical properties are "distributed" throughout the antenna, it's easier to think about a *lumped impedance* representing the load present at its feed point. Two resistors in series with an inductor and capacitor is a useful model (see Figure 1).

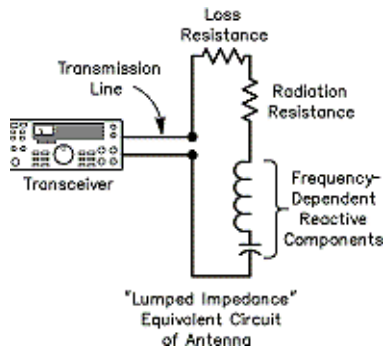


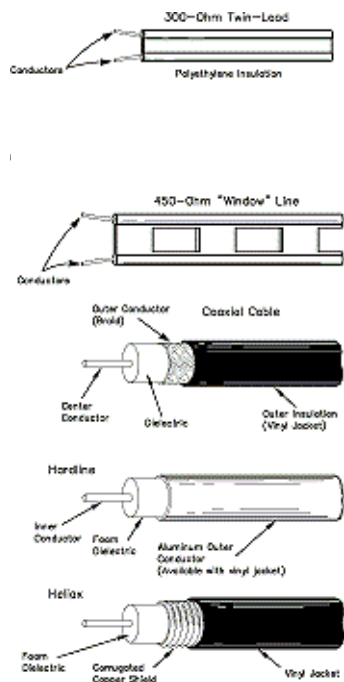
Figure 1—The radio, antenna and transmission line. The object is to get as much power as possible from the radio into the antenna's radiation resistance.

One of the resistors is the desirable *radiation resistance*, which represents the useful work done by the antenna in converting your transmitter's output into radiation that spans states or continents! The other is the *loss resistance* resulting from the resistance of the wire and connections. (Now you know why you need good solder joints and sound mechanical connections on your antenna.) Power consumed in the loss resistance does not increase the RF field—it merely makes heat. The radiation resistance is usually the larger of the two, but in some designs, such as small loops, radiation resistance is so small that loss resistance becomes significant.

*Reactance* is the effect produced by the inductor and capacitor. The net effect can be capacitive or inductive depending on the frequency. An antenna is, after all, a distributed tuned circuit. At resonance, the capacitive reactance is canceled exactly by the inductive reactance and the net effect is simply that of the two resistors. When the operating frequency is below resonance, the capacitive component dominates while above resonance the inductive component dominates. Put another way, wire antennas that are shorter than required for resonance are "capacitive" and antennas that are longer are "inductive."

### Transmission-Line Impedance

Now that you have a grasp of the nature of antenna impedance, let's consider the pathway from the antenna to your radio: the transmission line. Transmission lines (sometimes called *feed lines*) can take many forms (see **Figure 2**).



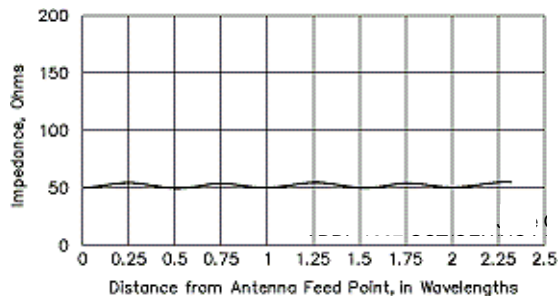
**Figure 2—**These are the most common types of transmission lines you'll encounter in ham applications.

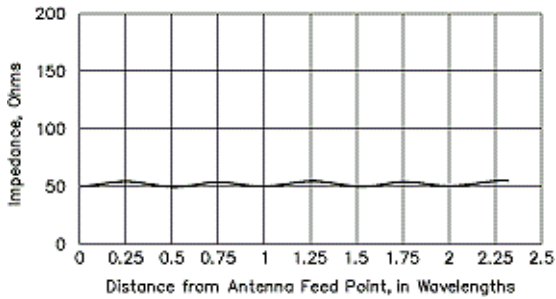
When most hams think of transmission lines, the word "coax" comes to mind. Coax—*coaxial cable*—has an inner conductor surrounded by a concentric shield. Its characteristics are derived from the outer diameter of the center conductor, the inner diameter of the shield and the electrical properties of the medium separating them.

Ladder line (sometimes called *twinlead* or *open-wire* line, depending on the construction) consists of two parallel conductors separated by an insulator, either plastic or simply the air itself. Ladder line also has a characteristic impedance and it is determined by the diameter of the wires, the separation distance, and the insulating material. Twinlead is often used for home TV antennas and has a characteristic impedance of 300 Ω. So-called "window" ladder line is commonly used for amateur work and has a characteristic impedance of 450 Ω. Other types are also available.

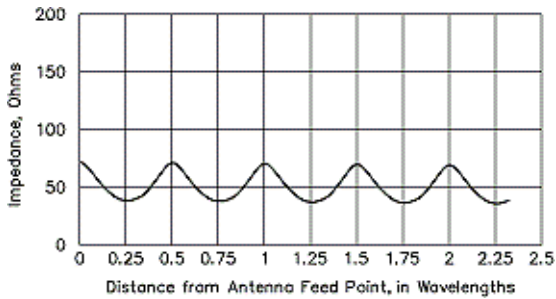
The property of most interest to us is the characteristic impedance, which is the impedance an infinitely long line would present to the transmitter. Since your transmission line is unlikely to be infinitely long, let's see what happens if you take a 50-Ω cable, such as RG-8, and terminate it with a 50-Ω resistor. The RF impedance measured at its source end will be 50 Ω, regardless of the length of the line. (Well, this is only true of lossless lines, but let's not lose sight of the principles involved!)

Most coax used in amateur service has a characteristic impedance of nominally 50 or 75 Ω. **Figure 3** shows how impedance varies along a near-matched 50-Ω line. **Figure 4** repeats the demonstration with the line terminated at 75 Ω. When the load impedance is *greater* than the characteristic impedance, a maximum impedance point occurs every half wavelength from the antenna, and a minimum impedance point occurs at every quarter wavelength point between. When the load impedance is *less* than the characteristic impedance, the maximum and minimum points swap places. Sometimes a difficult-to-match situation can be helped by changing the line length. Doing so changes the impedance seen by the transceiver or antenna tuner (and hopefully gets it within a range the tuner can handle)—*but it does not change the SWR on the line*.





**Figure 3—**This graph shows the variation in impedance along a 50-Ω transmission line as you get farther from the antenna. In this case, the SWR is nearly 1:1 because the antenna is presenting an impedance that is very close to 50 Ω. Notice that the variations are minimal.



**Figure 4—**If we attach a 50-Ω transmission line to an antenna with an impedance of 75 Ω, there are substantial impedance variations along the length of the line!

And what about the effects of lossy lines? As Shakespeare wrote, “...ay, there’s the rub.” All transmission lines have some amount of loss, it’s just a question of how much at what frequencies. The result is always the same: *Some of your power isn’t radiated*. Stir in a high SWR and even *less* of your power is heading for the heavens. Let’s find out why.

### Matching Radios, Transmission Lines, and Antennas

If your transmitter needs to see 50Ω at its output, and you use a coaxial cable with a characteristic impedance of 50 Ω connected to an antenna with a feed-point impedance of 50 Ω, you’re on easy street. The entire system is “matched” and maximum power is transferred from the transmitter into the antenna.

The problem is that antennas don’t always have the common decency to present an impedance of 50 Ω. In fact, the feed-point impedance of a simple half-wave dipole depends on the height above ground, ground conductivity, and, especially, the operating frequency.

When the flow of power from the transmitter encounters an unmatched impedance at the antenna, some of it is reflected back up the transmission line. Try an experiment tonight to understand this concept. Turn on a flashlight in a dark room and aim the beam at the nearest window. The light travels across the room unnoticed and then encounters the window glass. Some of the light passes through, but some of it reflects back toward the flashlight. RF power in a transmission line acts in a similar way when it reaches your antenna.

As the reflected power heads back up the line, it interacts with the forward power to make *standing waves*. It is the ratio of forward to reverse power that you measure with your SWR (standing wave ratio) meter. The standing waves result from the mismatch of impedance between the line and the antenna. The SWR is the same (except for attenuation) everywhere along the line.

A high SWR promotes transmission line loss because the power initially reflected at the load has to make two more trips along the line—back to the antenna tuner or radio, and then back to the load. Thanks to the inherent losses in your transmission line, you’re losing power during each one of these trips. The total loss depends on the length of the line through which the current flows. The higher the SWR and the longer the line, the greater the loss.

In addition, the transmitter-end impedance of the line is no longer the 50 Ω the radio needs. The impedance presented by the transmission line now depends on the impedance of the antenna relative to the line's characteristic impedance *and* the length of the line. If this impedance strays too far from 50 Ω, your transceiver will begin reducing its output—or it may shut down altogether!

One solution to the transceiver shut-down dilemma is to insert a device between the rig and the antenna system (or directly at the antenna itself) that effectively transforms the impedance to 50 Ω. Such a device is known as an *antenna tuner*. It's a collection of inductors and capacitors arranged to form an RF impedance transformer. When properly adjusted (tuned), the input impedance matches the transmitter (or transmission line, if it's placed at the antenna) and the output impedance matches the load.

When placed at the antenna, an antenna tuner provides a 50-Ω impedance at the end of the 50-Ω line that is fed from a 50-Ω transceiver, resulting in a 1:1 SWR on the transmission line and at the radio. Life on an antenna pole is hard for most tuners, so we typically put them near (or build them into) our transceivers. In that case, they match the 50-Ω output of the transceiver to whatever impedance is at the transceiver end of the transmission line. *They do not change the SWR on the line, or the loss it produces. What can we do to reduce the loss?*

## Reducing Transmission Line Losses

Transmission line losses hurt two ways: They waste our transmitter's power and they attenuate the signals we receive. A line loss of 4 dB reduces the output of a 50 W transmitter to 20 W at the antenna. The signals we're trying to hear are also reduced by this same factor of 2.5!

As we've already seen, losses in transmission lines are directly related to their length. Loss data are usually reported in decibels per 100 feet, so one way to reduce line loss is to use less of it. Assuming the line is the shortest possible length, there are two ways to further reduce loss: Reduce the SWR, change to a lower-loss line, or both.

You can reduce the SWR by adjusting the antenna. In the case of a wire dipole, this means either cutting wire or adding wire.

Transmission line loss depends on the type of line and the operating frequency. **Table 1** makes an interesting comparison of transmission line loss under both "matched" and high SWR conditions.

## Table 1—How much power are you really radiating?

Assume that you have a 100-W transceiver connected to one of the transmission lines listed below. How much power (in watts) actually makes it to your antenna? Examples are shown for 80, 10 and 2 meters, with 100 feet of transmission line and SWRs of 1:1 and 6:1 on each of these bands.

Transmission Line Type	3.5 MHz 1:1 SWR	3.5 MHz 6:1 SWR	28 MHz 1:1 SWR	28 MHz 6:1 SWR	146 MHz 1:1 SWR	146 MHz 6:1 SWR
RG-58A	85	65	56	33	22	11
RG-8A	91	79	76	52	48	27
3/4-inch Hardline	98	93	93	81	83	63
450-Ω Ladder line	99	98	98	91	91	79

It's worth noting that ladder line exhibits substantially less loss on the HF bands than just about any other transmission line available. This means you can get away with SWRs on ladder line that would cause intolerable loss with coax. (This pertains to clean, dry twinlead. When the line is wet—and especially when it's wet and dirty—loss becomes much larger. The less polyethylene and the more air between the wires, the better.)

## Let's Summarize...

The object of an antenna is to get RF into and out of the air. Your transmission line plays a critical role in getting this job done. When you shortchange yourself on transmission line, you shortchange your whole station.

As long as an antenna tuner is used, ladder line offers some compelling advantages compared with coaxial cable in almost any medium- or high-frequency application. This is particularly true when you want multiband operation with a single antenna.

When you're working above 50 MHz, remember to use the lowest-loss cable you can afford. The higher you go in frequency, the worse the losses become—even when the SWR is 1:1!

## Unbalanced Transmission Line Currents and Feed-Line Radiation

Center-fed dipoles are *balanced*, which means that they are electrically symmetrical. Ladder line is balanced. If you feed a dipole with ladder line, you have a nicely balanced system. So far, so good.

A coaxial feed line upsets the antenna's balance because the shield ultimately forces a ground at the transmitter. Inside the coax the current in the center conductor is matched by an equal but opposite current on the inside of the shield, resulting in a zero net field. Remember, radiation is produced by RF current flowing through a conductor. If the current in the center conductor and the current on the inside of the shield of the coaxial cable are equal but opposite, then the radiation field from one is canceled by the other resulting in no net radiation. (A similar analysis applies to ladder line.)

But this says nothing about the current that might flow on the *outside* of the coaxial shield. Remember the skin effect? Think about the outside of the shield as a third wire running from the connection point of the shield and antenna back to the connector on the transmitter, and hence to ground. Nothing prevents RF current from flowing on the outside of the shield, thus causing the shield to radiate. How much current flows on the outside of the shield? It depends on the length of the transmission line. A line that is an *integral multiple* of a half wavelength presents a low input impedance and permits current to flow. It's easy to say, "Avoid transmission lines that are integral multiples of a half wavelength," but in practice that's hard to do. The solution is yet another device. This one is known as a *balun*.

The term "balun" is short for "*balanced to unbalanced transformer*." Baluns provide a fixed ratio of impedance transformation and limit the flow of the unbalanced current (the one flowing on the outside of the shield).