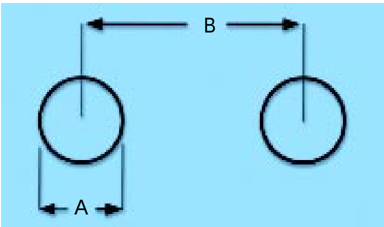
Technical techniques: A primer for transmission lines

Part I—An understanding of transmission lines and tips on using them as transformers and filters can help techs properly configure feedlines and even solve some problems.

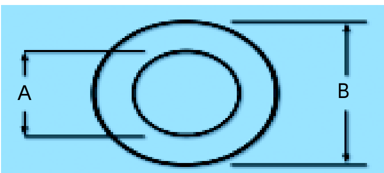
By Patrick E. Buller

Transmission lines carry RF from point to point within radio equipment, between pieces of equipment and from equipment to antennas. They also can be configured as filters and impedance transformers. In simple terms, a transmission line connects the source of energy to the load.



$$Z = 276\log\frac{2B}{A}$$

Figure 1. Balanced two-wire lines: formula for determining impedance of a two-wire transmission line. (*A* and *B* are the same units.)



$$Z = 138\log\frac{B}{A}$$

Figure 2. Characteristic impedance of an air-insulated *coaxial* line can be found by the above formula. (*B* and *A* are the same units.)

- $VSWR = E_{MAX}/E_{MIN}$
- $SWR = Z_{INPUT}/Z_{LOAD}$
- $$SWR = \frac{1 + \sqrt{\dfrac{\text{REFLECTED POWER}}{\text{FORWARD POWER}}}}{1 - \sqrt{\dfrac{\text{REFLECTED POWER}}{\text{FORWARD POWER}}}}$$

Figure 3. Standing wave ratio.

Transmission lines are either *balanced* or *unbalanced*. A two-wire transmission line becomes balanced when each conductor has equal impedance relative to ground or to its surroundings. An unbalanced transmission line has one conductor grounded, or exposed to the outside elements in greater magnitudes than the other conductor.

The impedance value is a function of conductor diameter and spacing between the two conductors. Impedance can be lowered by increasing the diameters, decreasing the spacing between the two conductors or both (see Figure 1). The most common balanced line impedances of today are 300Ω and 450Ω twin lead and 124Ω twinax (balanced coax cable). Seventy-five-ohm cable was common prior to the 1950s because most wire antennas were halfwave center-fed dipoles with impedances near 75Ω.

In an emergency, common 16 gauge lamp (zip) cord would suffice as a dipole transmission line. However, the sun deteriorates this type of cable when used for years at a time. Open-wire transmission line is more common for ham radio stations, not commercial or public safety facilities.

Coax cable

Co means "same or identical," and *axial-axis* means a "center point or point of common rotation." *Coaxial cable* is an unbalanced transmission line. Figure 2 shows the relationship of two conductors and the formula for determining the impedance of a coaxial line.

The center conductor must be kept evenly spaced inside the outer conductor, usually by a *separator*, or *media*. Common media include ceramic insulators (beads), spiral dielectric, polyethylene, fluorinated ethylene propylene-FEP (known as foam) Teflon and air or inert gas with separator beads.

Velocity factor

The media surrounding the center conductor slows the travel of RF energy. How much depends on the material used. The ratio of the time it takes for RF to travel through free space compared to the time it takes to travel through cable is called the velocity factor *vp*. The lower the value of *vp*, the longer it takes RF to reach the end of the cable. Common *vp* values are 0.66 for standard cable, 0.78 for foam, 0.82 for airfoam and 0.98–0.99 for air or inert gas.

All cables cut to a wavelength will be physically shorter than a free-space wavelength. For example, a halfwave at 150MHz is 39.36 inches. Using RG8/U cable, (*vp*–0.66), the physical halfwave cable length would be 39.36 × 0.66 =25.98 inches.

Velocity factors become important when coax cables are used to feed phased arrays and to interconnect cavities and duplexers. They

Buller is a special projects engineer for Tacoma Power, Tacoma, WA. For many years, he served as an electronics design engineer for the Washington State Patrol. He is a member of IEEE, NARTE, APCO and ARRL, and he is a Fellow of the Radio Club of America. His email address is *W7rqt@msn.com.*

are also important when a time domain reflectometer is used to find cable faults.

Impedance

A transmission line impedance can also be determined by $(L/C)^{1/2}$ or by Ohm's law, and would be found by measuring the voltage and current at the sending end of a line of infinite length. In practical terms, for cables shorter than infinity, an adjustable resistance can be added at the end and adjusted to a value that provides the same input voltage and current relationship of the infinite length. This value when measured, will equal the characteristic impedance of the line.

A second method for determining impedance is to terminate any length of cable in its characteristic impedance, resulting in no reflected energy. That way, maximum transfer of energy takes place. Any load connected to a transmission line with an impedance different from the line's characteristic impedance results in a standing wave pattern.

The input of cable measuring hundreds of wavelengths would have virtually no reflected energy and would appear to have an impedance input equal to its characteristic impedance. An example is 500 feet of RG58/U fed with 450MHz of energy. It would show an impedance of 50Ω and minimal reflected power because almost all of the energy would dissipate as it travels the length of the line. It would be an inexpensive dummy load.

The cable TV industry uses this concept in multiple distribution points where taps on the coax cable appear along the length of the cable. An amplifier supplying several volts of signal at the head end is sufficient to overcome the losses, and the loss of the cable terminates the amplifier.

VSWR

Voltage standing wave ratio was the first method for transmission line measurement. If the load absorbs all of the energy sent down the transmission line, no energy returns.

To measure this effect, a detector (often a voltage probe) is moved along the line, maintaining uniform distance from the line, noting the voltage change, if any, as the probe moves along and parallel to the transmission line. The change *Vmax/Vmin* equals the VSWR. The purpose of this test is to determine how closely the load matches the line. The distance between each voltage minimum equals the halfwave length of the transmission line frequency, not the applied frequency. This measured distance, compared to the applied frequency (wavelength), yields the velocity of propagation, *vp*. The movable probe method is used today mostly as a laboratory method and is most suitable when using the Smith Chart.

Determining SWR by reflected power

Today's methods for measuring forward power and reverse power at a point on the transmission line include:

- ❏ applying the formula shown in Figure 3.
- ❏ measuring forward and reverse power in dB and comparing the ratio of dBs, i.e. 25dB return loss.
- ❏ measuring power with a reflectometer and adding to the power reading the coupling loss of the device.

Reflected power is 180° out of phase from the forward wave as shown in Figure 4. To demonstrate this phenomenon, attach a rope or line to a fixed point, like a wall or doorknob, and with your wrist thrust a forward-looking wave. Note that immediately thereafter, a reflected wave will come back to you in the reverse mode. This demonstrates the principle by which directional couplers operate.

Figure 5 is a diagram of a directional coupler that consists of two short transmission lines in close proximity. Line *L2* is a transmission line that has its own characteristic impedance terminated by a resistor *R*. Power traveling in *L1* from left to right induces energy in *L2*, but this energy is dissipated in resistor *R*.

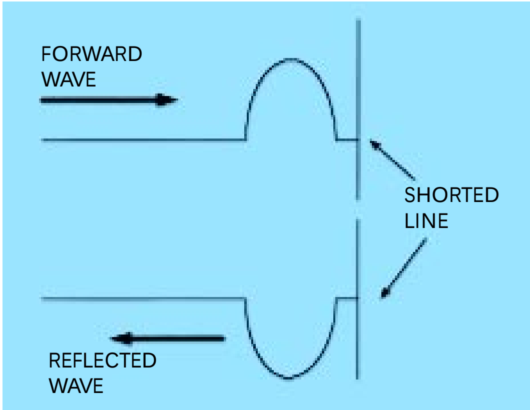


Figure 4. Reflected wave is 180° out of phase from the forward wave. It may lead or lag, depending on type of reactance load.

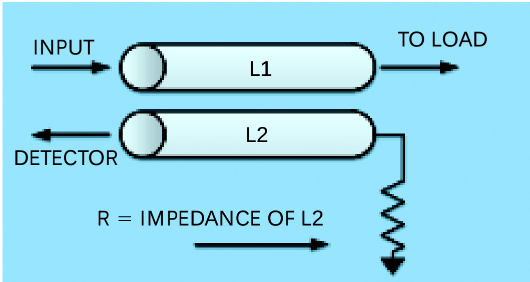


Figure 5. Directional coupler: This arrangement detects reflected power. Forward power can be measured by reversing power flow in *L1*.

If the load is not equal to the impedance of line *L1*, energy will be reflected back on *L1* and in turn coupled to *L2* and on to the detector. Reflected power in this example is measured.

If the input power and load were connected in reverse, the detector would then measure forward power.

If *L2* were physically reversed, keeping the input power on the left, forward power would then be measured.

This example explains how popular wattmeters operate. *L1* is the center conductor of the transmission line of the wattmeter. The rotatable slug is made up of *L2*, resistor *R* and a diode that connects to the meter calibrated in watts. Rotating the slug samples power in either the forward or reverse direction. Note

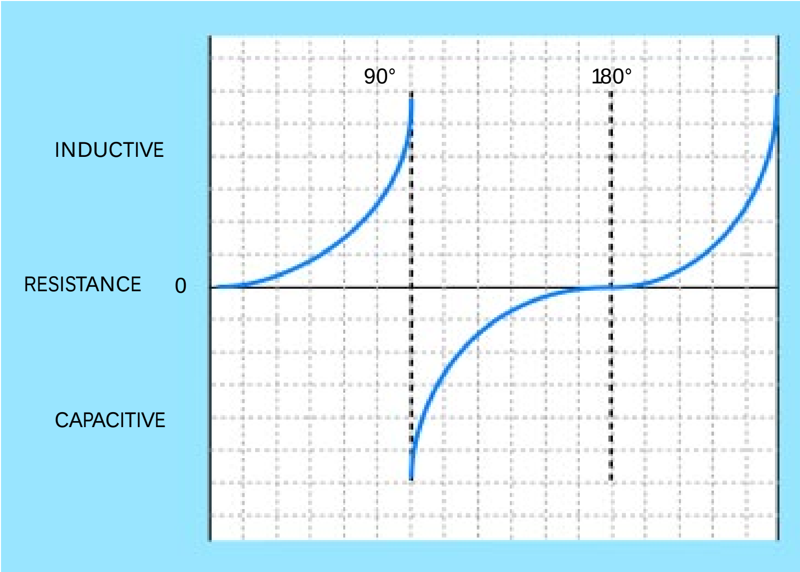


Figure 6. Graph showing shorted transmission line.

that the direction arrow on the slug corresponds to the detector side of *L2*, in Figure 5.

Directional couplers are useful in checking site noise or repeater de-sense. The benefit is that the reference signal generator is sent to the receiver, not to the antenna. Directional couplers are available from megahertz to gigahertz, the latter in the form of rigid waveguide components.

Transmission lines as stubs

A transmission line, when added to another transmission line in either series or parallel, can provide impedance matching. A transmission line that has a short circuit on one end will exhibit reactive components depending on its electrical length as shown in Figure 6. A quarterwave line shorted at one end has a high impedance at the opposite end—meaning it can be connected in parallel on a transmission line of the same impedance without affecting the line. If a halfwave shorted line were connected, the effect would be the same as placing a short on the transmission line at that point.

Another way of looking at this concept is that a quarterwave stub shorts out any second (or even) harmonic. All odd harmonics will be seen as high impedance.

Referring to Figure 6, the following can be stated: A short on one end of a quarterwave is open at the other end. A short on the end of a halfwave is a short at the other end.

The same result is observed when the cable is lengthened in any multiple of half-wavelengths.

The phase of the waveform shifts by 90° at a quarterwave, 180° at a halfwave and 360° at one wavelength of transmission line. Transmission line stubs can therefore be either open circuit, short circuit or terminated—all too often, *poorly* terminated.

Transmission lines as helpers

A length of open-end coax connected as shown in Figure 7A adds reactance according to its electrical length. Coax cable can be changed artificially by adding capacitive reactance to the open end of a stub to achieve the exact reactance desired as shown in Figure 7B. This short length of cable can be “tuned” by a variable capacitor connected between the center and outer conductor on the “open end” that electrically changes the cable length. The net effect is a series, low-impedance circuit connected at that point.

This is also a handy device for tuning a transmission line to measure what effect a cable would have when cut to the exact length. The capacity-tuned line is often used for tuning the coupling link of a cavity. It usually consists of a rigid outer and center conductor with a movable dielectric that has the same effect as a variable capacitor.

A tuned cable connected by a "tee" can reduce interference when there is at least a 2:1 frequency difference between the desired signal and the interfering one. The bandwidth is a function of the diameter of the cable.

Transmission lines as transformers

The quarterwave transformer is useful for changing impedances. It can take the form of either a balanced line or a coax transmission line. Use the formula $Zline = (Za \times Zb)^{1/2}$, where Za is the impedance desired and Zb is the impedance to be matched. Combining two 50Ω impedances yields 25Ω. $(50\times25)^{1/2} = 35.5\Omega$ cable. This result can be achieved with two parallel 72Ω cables or with 35Ω cable. In either case, this 35.5Ω quarter-wave *electrical* length of cable connected to the parallel 50Ω devices transforms 25Ω to 50Ω.

Another way of solving the same problem is to change each of the 50Ω devices to 100Ω so that when they are connected in parallel, the net is a 50Ω point. The quarterwave cable would then have the impedance of $(50\times100)^{1/2} = 71\Omega$. Any of these methods can be used. They are found mostly in antenna-combining units where two or more antenna elements are combined to one 50Ω common feedpoint.

Another method of impedance matching is to make the quarterwave transformer out of rigid tubing. The trick is to find the right diameter for the center conductor. Using the previous example, here's how to find the right size for the hardware. Assume a quarterwave-long 35Ω transformer is desired, and we have a tube with an outer diameter of 1 inch, inside 0.78 inch. Use the formula of Figure 2 with Zo of 35 = 138log B/A where B is 0.78 inch and A is found to be 0.435 inch. A $^{7}/_{16}$ inch rod would serve the purpose.

The complete transformer will be a $^{3}/_{4}$ inch pipe with a $^{7}/_{16}$ inch diameter center rod with a coax fitting on one end of this coax line, and the opposite end will have two coax connectors in parallel to this quarterwave rigid pipe. The combination forms a matching transformer with high-power capabilities. These devices are listed in catalogs as *power splitters* or *hybrid combiners*. Now you know the secret to making your own, inexpensively.

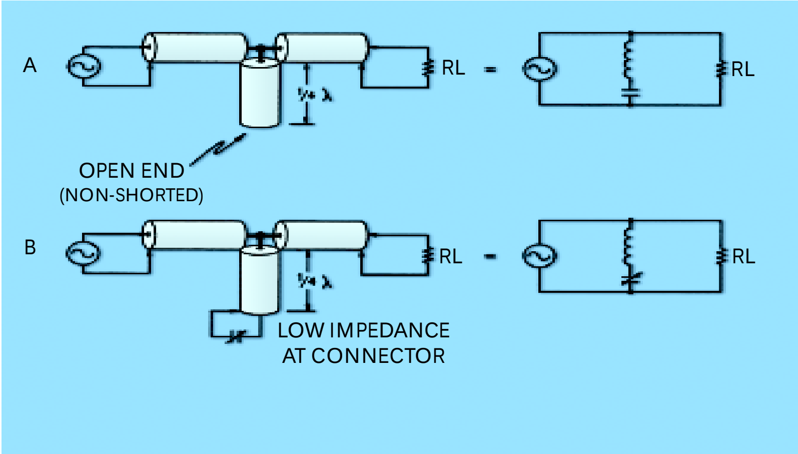


Figure 7a. Open-end stub: Not a complete open circuit, it has some radiation. 7b. Increasing capacity will lower frequency of low impedance. This method has a lower *Q*.

Balanced transformers

A further modification of the quarterwave transformer gives it a balanced output. If another larger diameter pipe were placed over this 1 inch pipe, say a $1^{1}/_{2}$ inch pipe (making the combination "triaxial"), and if it were grounded or connected to the feedpoint, the result would be a balanced 35Ω output because of the decoupling effect of the $1^{1}/_{2}$ inch pipe as shown in Figure 8A.

Coax baluns (BALanced to UNbalanced) offer another method of obtaining balanced lines as shown in Figure 8B and 8C. Figure 8B is a 1:4 impedance step-up because the current divides at the junction point, leaving half of the total current feeding each line of the balanced port. In this example, the output impedance would be 200Ω. Figure 8C has no current division, therefore offers a 1:1 impedance transformation. The additional coax cable alongside converts the common ground point to high impedance because of the quarterwave transformation from a short to an open. These kinds of balanced transmission line transformers are effective tools in matching broadside arrays fed with coax cable.

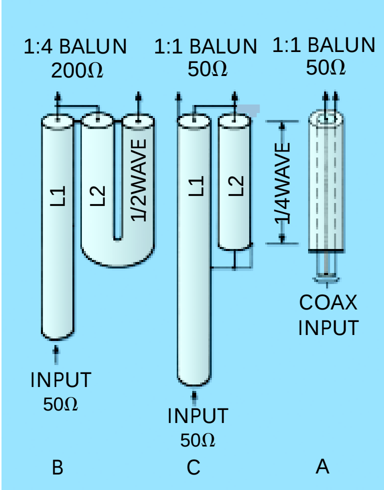


Figure 8. Coax balun. BALanced to UNbalanced. Z_L = L1 = L2, all cases.

With a basic understanding of transmission lines and some helpful tricks for using them as transformers and filters, you can configure feedlines properly and solve some problems along the way. ■