TABLE OF CONTENTS

Chapter 23 —
CD-ROM Content

Supplemental Articles
- "Coaxial RF Connectors for Microwaves" by Tom Williams, WA1MBA
- "Hands-On Radio: Open Wire Transmission Lines" by Ward Silver, NØAX
- "Hands-On Radio: SWR and Transmission Line Loss" by Ward Silver, NØAX
- "Multiband Operation with Open-wire Line" by George Cutsogeorge, W2VJN
- "My Feedline Tunes My Antenna" by Byron Goodman W1DX
- RF Connectors and Transmission Line Information — *ARRL Handbook*
- Smith Chart supplement
- "Using RG58 coaxial crimp connectors with RG6 cable" by Garth Jenkinson, VK3BBK

Chapter 23

Transmission Lines

23.1 BASIC THEORY OF TRANSMISSION LINES

The desirability of installing an antenna in a clear space, not too near buildings or power and telephone lines, cannot be stressed too strongly. On the other hand, the transmitter that generates the RF power for driving the antenna is usually, as a matter of necessity, located some distance from the antenna terminals. The connecting link between the two is the RF *transmission line*, feeder or feed line. Its sole purpose is to carry RF power from one place to another, and to do it as efficiently as possible. That is, the ratio of the power *transferred* by the line to the power *lost* in it should be as large as the circumstances permit.

At radio frequencies, every conductor that has appreciable length compared with the wavelength in use *radiates* power — every conductor is an antenna. Special care must be used, therefore, to minimize radiation from the conductors used in RF transmission lines. Without such care, the power radiated by the line may be much larger than that which is lost in the resistance of conductors and dielectrics (insulating materials). Power loss in resistance is inescapable, at least to a degree, but loss by radiation is largely avoidable.

Radiation loss from transmission lines can be prevented by using two conductors arranged and operated so the electromagnetic field from one is balanced everywhere by an equal and opposite field from the other. In such a case, the resultant field is zero everywhere in space — there is no radiation from the line.

For example, **Figure 23.1** shows two parallel conductors having currents I1 and I2 flowing in opposite directions. If the current I1 at point Y on the upper conductor has the same amplitude as the current I2 at the corresponding point X on the lower conductor, the fields set up by the two currents are equal in magnitude. Because the two currents are flowing in opposite directions, the field from I1 at Y is 180° out of phase with the field from I2 at X. However, it takes a measurable interval of time for the field from X to travel to Y. If I1 and I2 are alternating currents, the phase of the field from I1 at Y changes in such a time interval, so at the instant the field from X reaches Y, the two fields at Y are not exactly 180° out of phase. The two fields are exactly 180° out of phase at every point in space only when the two conductors occupy the same space — an obviously impossible condition if they are to remain separate conductors.

The best that can be done is to make the two fields cancel each other as completely as possible. This can be achieved by keeping the distance d between the two conductors small enough so the time interval during which the field from X is moving to Y is a very small part of a cycle. When this is the case, the phase difference between the two fields at any given point is so close to 180° that cancellation is nearly complete.

Practical values of d (the separation between the two conductors) are determined by the physical limitations of line construction. A separation that meets the condition of being "very small" at one frequency may be quite large at another. For example, if d is 6 inches, the phase difference between the two fields at Y is only a fraction of a degree if the frequency is 3.5 MHz. This is because a distance of 6 inches is such a small fraction of a wavelength ($1\ \lambda = 281$ feet) at 3.5 MHz. But at 144 MHz, the phase difference is 26°, and at 420 MHz, it is 77°. In neither of these cases could the two fields be considered to "cancel" each other. Conductor separation must be very small in comparison with the wavelength used; it should never exceed 1% of the wavelength, and smaller separations are desirable. Transmission lines consisting of two parallel conductors as in Figure 23.1F, G, and H are called *open- or parallel-wire lines*, *parallel-conductor lines* or *two-wire lines*.

A second general type of line construction called *coaxial line* (coax, pronounced "KOH-ax") or concentric line is shown in Figures 23.1A, B, C, and D. In coax, one of the conductors is tube-shaped and encloses the other conductor.

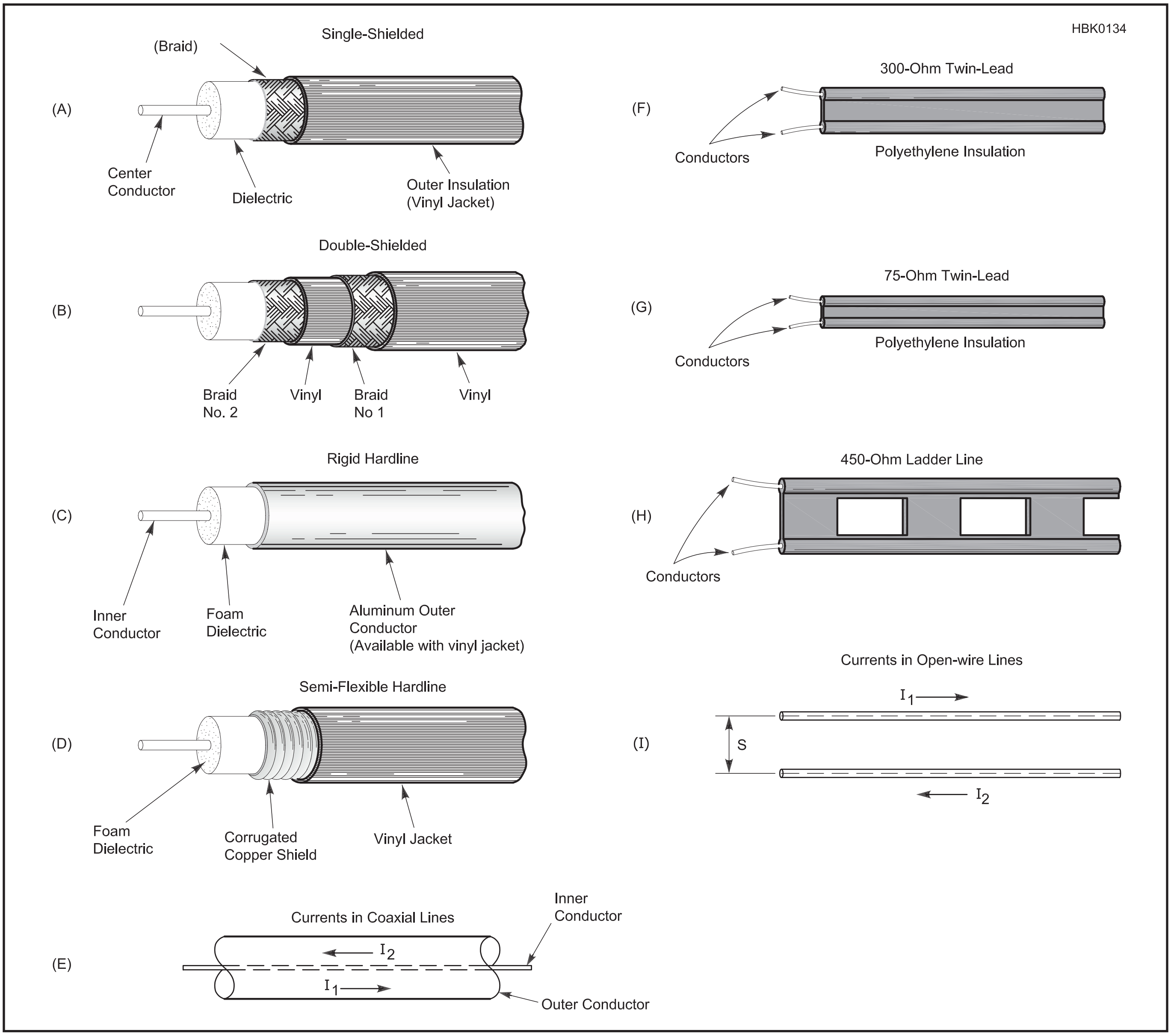


Figure 23.1 — Common types of transmission lines used by amateurs below microwave frequencies. Coaxial cables are shown at A, B, C, and D. Parallel-conductor lines are shown at F, G, and H. Current flow is shown in coaxial cables (E) and parallel-conductor lines (I) as described in the text.

As shown in Figure 23.1E, the current flowing on the inner conductor is balanced by an equal current flowing in the opposite direction on the inside surface of the outer conductor. Because of skin effect, the current on the inner surface of the outer conductor does not penetrate far enough to appear on the outside surface. In fact, the total electromagnetic field outside the coaxial line (as a result of currents flowing on the conductors inside) is always zero, because the outer conductor acts as a shield at radio frequencies. The separation between the inner conductor and the outer conductor is therefore unimportant from the standpoint of reducing radiation.

A third general type of transmission line is the *waveguide*. Waveguides are discussed in the chapter **VHF and UHF Antenna Systems**.

23.1.1 CURRENT FLOW IN LONG LINES

In **Figure 23.2**, imagine that the connection between the battery and the two wires is made instantaneously and then broken. During the time the wires are in contact with the battery terminals, electrons in wire 1 will be attracted to the positive battery terminal and an equal number of electrons in wire 2 will be repelled from the negative terminal. This happens only near the battery terminals at first, because electromagnetic waves do not travel at infinite speed. Some time does elapse before the currents flow at the more extreme parts of the wires. By ordinary standards, the elapsed time is very short. Because the speed of wave travel along the wires may approach the speed of light at 300,000,000 meters per second, it becomes necessary to measure time in millionths

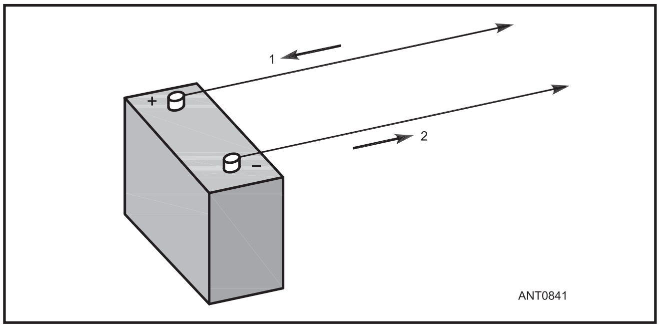


Figure 23.2 — A representation of current flow on a long transmission line.

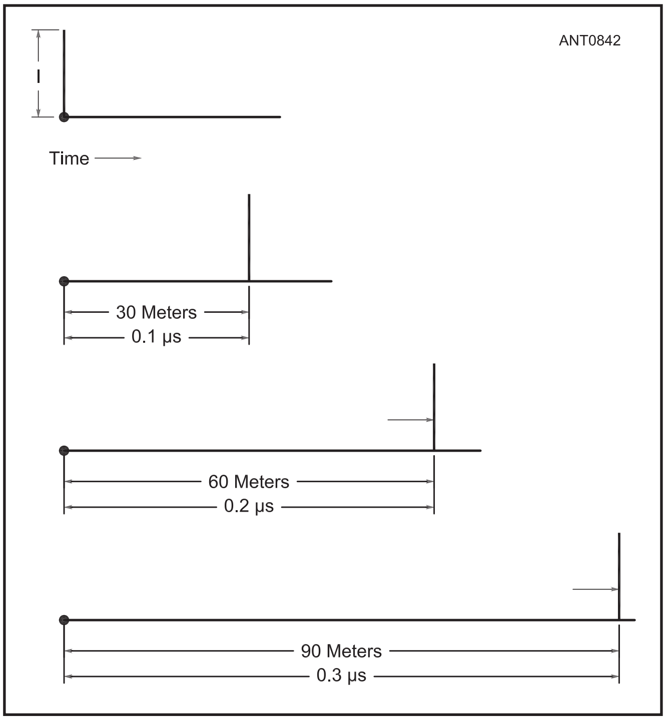


Figure 23.3 — A current pulse traveling along a transmission line at the speed of light would reach the successive positions shown at intervals of 0.1 μs.

of a second (microseconds, μs).

For example, suppose that the contact with the battery is so short that it can be measured in a very small fraction of a microsecond. Then the "pulse" of current that flows at the battery terminals during this time can be represented by the vertical line in **Figure 23.3**. At the speed of light this pulse travels 30 meters along the line in 0.1 μs, 60 meters in 0.2 μs, 90 meters in 0.3 μs, and so on, as far as the line reaches.

The current does not exist all along the wires; it is only present at the point that the pulse has reached in its travel. At this point it is present in both wires, with the electrons moving in one direction in one wire and in the other direction in the other wire. If the line is infinitely long and has no resistance (or other cause of energy loss), the pulse will travel undiminished forever.

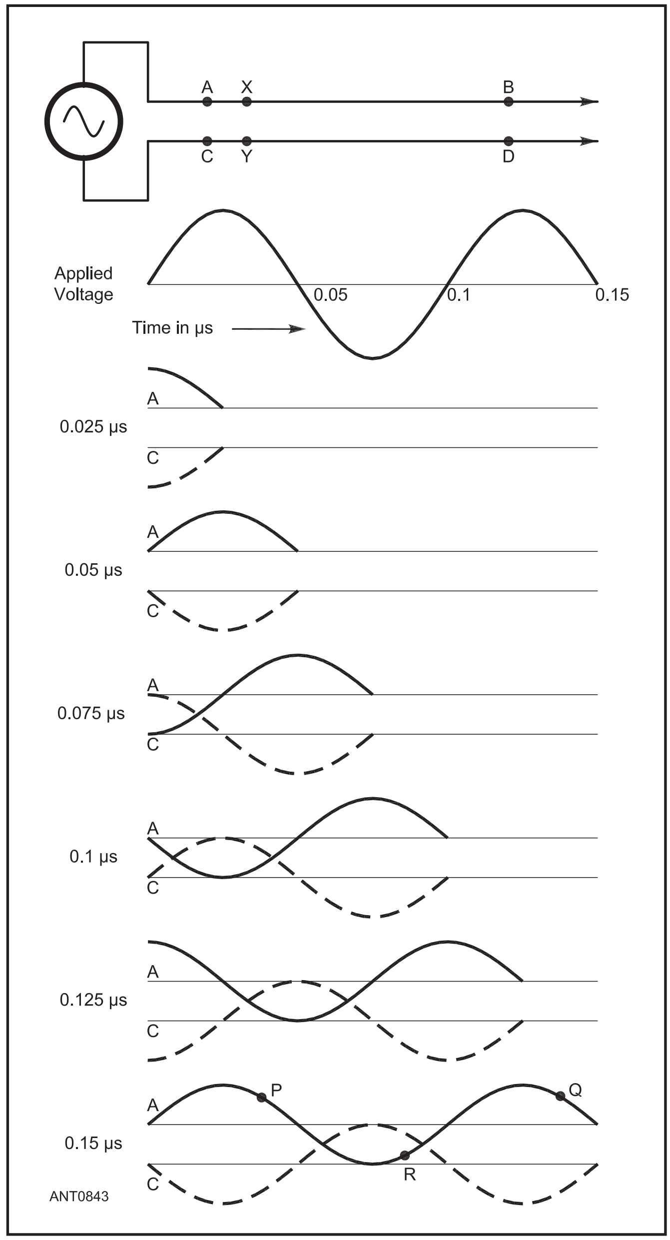


Figure 23.4 — Instantaneous current along a transmission line at successive time intervals. The frequency is 10 MHz; the time for each complete cycle is 0.1 μs.

By extending the example of Figure 23.3, it is not hard to see that if, instead of one pulse, a whole series of them were started on the line at equal time intervals, the pulses would travel along the line with the same time and distance spacing between them, each pulse independent of the others. In fact, each pulse could even have a different amplitude if the battery voltage were varied between pulses. Furthermore, the pulses could be so closely spaced that they touched each other, in which case current would be present everywhere along the line simultaneously.

It follows from this that an alternating voltage applied to the line would give rise to the sort of current flow shown in **Figure 23.4**. If the frequency of the ac voltage is 10,000,000 hertz or 10 MHz, each cycle occupies 0.1 ms, so a complete cycle of current will be present along each 30 meters of line. This is a distance of one wavelength. Any currents at points B and D on the two conductors occur one cycle later in time than the currents at A and C. Put another way, the currents initiated at A and C do not appear at B and D, one wavelength away, until the applied voltage has gone through a complete cycle.

Because the applied voltage is always changing, the currents at A and C change in proportion. The current a short distance away from A and C — for instance, at X and Y — is not the same as the current at A and C. This is because the current at X and Y was caused by a value of voltage that occurred slightly earlier in the cycle. This situation holds true all along the line; at any instant the current anywhere along the line from A to B and C to D is different from the current at any other point on that section of the line.

The remaining series of drawings in Figure 23.4 shows how the instantaneous currents might be distributed if we could take snapshots of them at intervals of ¼ cycle. The current travels out from the input end of the line in waves. At any given point on the line, the current goes through its complete range of ac values in one cycle, just as it does at the input end. Therefore (if there are no losses) an ammeter inserted in either conductor reads exactly the same current at any point along the line, because the ammeter averages the current over a whole cycle. (The phases of the currents at any two separate points are different, but the ammeter cannot show phase.)

23.1.2 VELOCITY OF PROPAGATION

In the example above it was assumed that energy travels along the line at the velocity of light. The actual velocity is very close to that of light only in lines in which the insulation between conductors is air. The presence of dielectrics other than air reduces the velocity.

Current flows at the speed of light only in a vacuum, although the speed in air is close to that in a vacuum. Therefore, the time required for a signal of a given frequency to travel down a length of practical transmission line is *longer* than the time required for the same signal to travel the same distance in free space. Because of this propagation delay, 360° of a given wave exists in a physically shorter distance on a given transmission line than in free space. The exact delay for a given transmission line is a function of the properties of the line, mainly the dielectric constant of the insulating material between the conductors. This delay is expressed in terms of the speed of light (either as a percentage or a decimal fraction), and is referred to as velocity factor (VF). The velocity factor is related to the dielectric constant (ε) by

$$VF = \frac{1}{\sqrt{\varepsilon}} \qquad \text{(Eq 1)}$$

The wavelength in a practical line is always shorter than the wavelength in free space, which has a dielectric constant ε = 1.0. Whenever reference is made to a line as being a half wavelength or quarter wavelength long (λ/2 or λ/4), it is understood that what is meant by this is the *electrical* length of the line. The physical length corresponding to an electrical wavelength on a given line is given by

$$\lambda\ (\text{feet}) = \frac{983.6}{f} \times VF \qquad \text{(Eq 2)}$$

where
f = frequency in MHz
VF = velocity factor

Values of VF for several common types of lines are given later in this chapter. The actual VF of a given cable varies slightly from one production run or manufacturer to another, even though the cables may have exactly the same specifications.

As we shall see later, a quarter-wavelength line is frequently used as an impedance transformer, and so it is convenient to calculate the length of a quarter-wave line directly by

$$\lambda / 4 = \frac{245.9}{f} \times VF \qquad \text{(Eq 2A)}$$

It is important to note that Equation 1 is based on some simplifying assumptions about the cable and the frequency of use. At frequencies below 100 kHz, these assumptions become progressively less valid and VF drops dramatically. This is generally not an issue at amateur frequencies but could become significant when coaxial or twisted-pair transmission lines are used for software-defined radio applications. This is discussed more in the paper "Transmission Lines at Audio Frequencies, and a Bit of History" by Jim Brown, K9YC listed in the Bibliography.

23.1.3 CHARACTERISTIC IMPEDANCE

If the line could be *perfect* — having no resistive losses — a question might arise: What is the amplitude of the current in a pulse applied to this line? Will a larger voltage result in a larger current, or is the current theoretically infinite for an applied voltage, as we would expect from applying Ohm's Law to a circuit without resistance? The answer is that the current does depend directly on the voltage, just as though resistance were present.

The reason for this is that the current flowing in the line is something like the charging current that flows when a battery is connected to a capacitor. That is, the line has capacitance. However, it also has inductance. Both of these are "distributed"

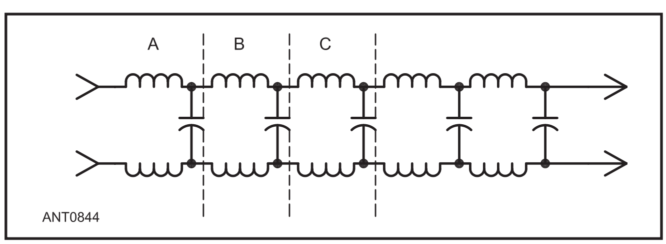


Figure 23.5 — Equivalent of an ideal (lossless) transmission line in terms of ordinary circuit elements (lumped constants). The values of inductance and capacitance depend on the line construction.

But Why 50 Ohms?

Coaxial cable burst on the scene as ham radio rebooted after World War II and the 50 Ω characteristic impedance of RG-8 became the de facto standard from then on. But why 50 Ω? The answer comes from Volume 9 of the MIT Radiation Lab Series, *Microwave Transmission Circuits*, by George L. Ragan, published in 1948. (**web.mit.edu/klund/www/books/radlab.html**) On page 147, after several pages deriving the optimum geometries, Ragan writes, "Obvious economy both in test equipment and in design work can be achieved if a single impedance can be chosen as a compromise standard. It has been found convenient to adopt 50 ohms as an impedance level offering a satisfactory compromise." His Table 4.2 shows the relative loss and power-handling capability loss of 50 Ω air- and polyethylene-insulated lines. The latter achieves better than 50% of the optimum value based either on wavelength or outer conductor size, including 100% of the optimum attenuation. Thus, 50 Ω was selected based on available types and sizes of materials to give good (but mostly not best) performance for both power and loss. (Thanks to Gene Pentecost, W4IMT, for researching this question.)

properties. We may think of the line as being composed of a whole series of small inductors and capacitors, connected as in **Figure 23.5**, where each coil is the inductance of an extremely small section of wire, and the capacitance is that existing between the same two sections. Each series inductor acts to limit the rate at which current can charge the following shunt capacitor, and in so doing establishes a very important property of a transmission line: its *surge impedance*, more commonly known as its *characteristic impedance*. This is abbreviated by convention as Z_0. While relatively constant at RF, Z_0 increases below 100 kHz, becoming much higher at and below audio frequencies as described in the previously noted Bibliography entry for Brown.

23.1.4 TERMINATED LINES

The value of the characteristic impedance is equal to $\sqrt{L/C}$ in a perfect line — that is, one in which the conductors have no resistance and there is no leakage between them — where L and C are the inductance and capacitance, respectively, per unit length of line. The inductance decreases with increasing conductor diameter, and the capacitance decreases with increasing spacing between the conductors. Hence a line with closely spaced large conductors has relatively low characteristic impedance, while one with widely spaced thin conductors has high impedance. Practical values of Z_0 for parallel-conductor lines range from about 200 to 800 Ω. Typical coaxial lines have characteristic impedances from 30 to 100 Ω. Physical constraints on practical wire diameters and spacings limit Z_0 values to these ranges.

In the earlier discussion of current traveling along a transmission line, we assumed that the line was infinitely long. Practical lines have a definite length, and they are terminated in a load at the output or load end (the end to which the power is delivered). In **Figure 23.6**, if the load is a pure resistance of a value equal to the characteristic impedance of a perfect, lossless line, the current traveling along the line to the load finds that the load simply "looks like" more transmission line of the same characteristic impedance.

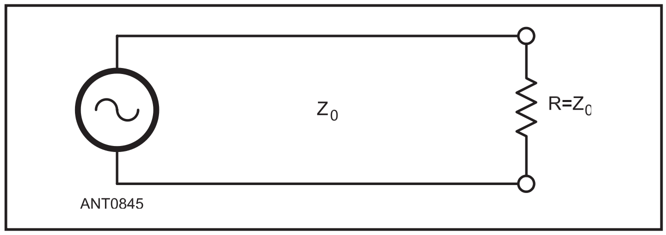


Figure 23.6 — A transmission line terminated in a resistive load equal to the characteristic impedance of the line.

The reason for this can be more easily understood by considering it from another viewpoint. Along a transmission line, power is transferred successively from one elementary section in Figure 23.5 to the next. When the line is infinitely long, this power transfer goes on in one direction — away from the source of power.

From the standpoint of Section B, Figure 23.5, for instance, the power transferred to section C has simply disappeared in C. As far as section B is concerned, it makes no difference whether C has absorbed the power itself or has transferred it along to more transmission line. Consequently, if we substitute a load for section C that has the same electrical characteristics as the transmission line, section B will transfer power into it just as if it were more transmission line. A pure resistance equal to the characteristic impedance of C, which is also the characteristic impedance of the line, meets this condition. It absorbs all the power just as the infinitely long line absorbs all the power transferred by section B.

Matched Lines

A line terminated in a load equal to the complex characteristic line impedance is said to be *matched*. In a matched transmission line, power is transferred outward along the line from the source until it reaches the load, where it is completely absorbed. Thus with either the infinitely long line or its matched counterpart, the impedance presented to the source of power (the line-input impedance) is the same *regardless of the line length*. It is simply equal to the characteristic impedance of the line. The current in such a line is equal to the applied voltage divided by the characteristic impedance, and the power put into it is E^2/Z_0 or I^2Z_0, by Ohm's Law.

Mismatched Lines

Now take the case where the terminating load is *not* equal to Z_0, as in **Figure 23.7**. The load no longer looks like more line to the section of line immediately adjacent. Such a line is said to be *mismatched*. The more the load impedance differs from Z_0, the greater the mismatch. The power reaching the load is not totally absorbed, as it was when the load was equal

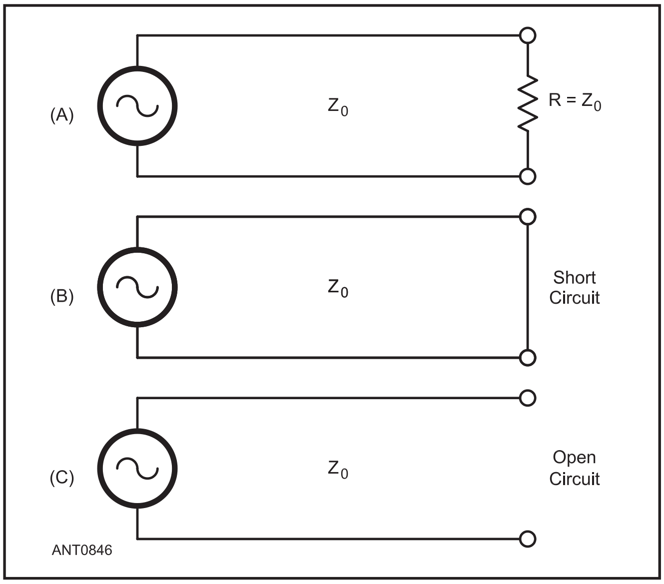


Figure 23.7 — **Mismatched lines; extreme cases. At A, termination not equal to Z_0; at B, short-circuited line; At C, open-circuited line.**

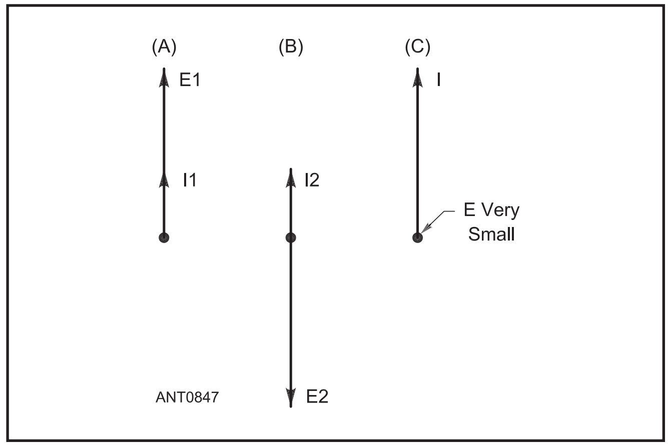


Figure 23.8 — **Voltage and current at the short circuit on a short-circuited line. These vectors show how the incident voltage and current (A) combine with the reflected voltage and current (B) to result in high current and very low voltage in the short circuit (C).**

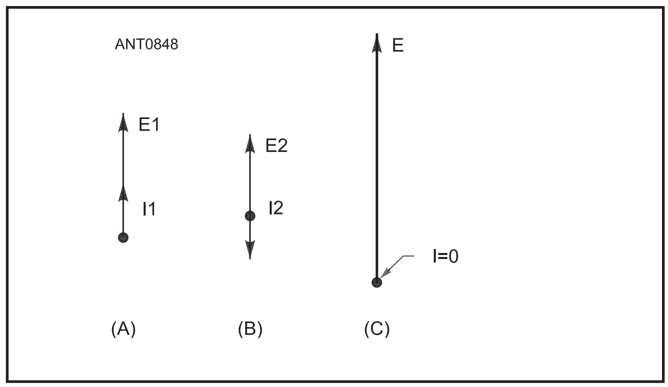


Figure 23.9 — **Voltage and current at the end of an open-circuited line. At A, incident voltage and current; At B, reflected voltage and current; At C, resulting voltage and current.**

to Z_0, because the load requires a voltage to current ratio that is different from the one traveling along the line. The result is that the load absorbs only part of the power reaching it (the *incident* power); the remainder acts as though it had bounced off a wall and starts back along the line toward the source. This is known as *reflected power*, and the greater the mismatch, the larger the percentage of the incident power that is reflected. In the extreme case where the load is zero (a short circuit) or infinity (an open circuit), *all* of the power reaching the end of the line is reflected back toward the source.

Whenever there is a mismatch, power is transferred in both directions along the line. The voltage to current ratio is the same for the reflected power as for the incident power, because this ratio is determined by the Z_0 of the line. The voltage and current travel along the line in both directions in the same wave motion shown in Figure 23.4. If the source of power is an ac generator, the incident (outgoing) voltage and the reflected (returning) voltage are simultaneously present all along the line. The actual voltage at any point along the line is the vector sum of the two components, taking into account the *phases* of each component. The same is true of the current.

The effect of the incident and reflected components on the behavior of the line can be understood more readily by considering first the two limiting cases — the short-circuited line and the open-circuited line. If the line is short-circuited as in Figure 23.7B, the voltage at the end must be zero. Thus the incident voltage must disappear suddenly at the short. It can do this only if the reflected voltage is opposite in phase and of the same amplitude. This is shown by the vectors in **Figure 23.8**. The current, however, does not disappear in the short circuit. In fact, the incident current flows through the short and in addition, there is the reflected component in phase of the same amplitude as the incident current.

The reflected voltage and current must have the same amplitudes as the incident voltage and current, because no power is dissipated in the short circuit; all the power starts back toward the source. Reversing the phase of *either* the current or voltage (but not both) reverses the direction of power flow. In the short-circuited case the phase of the voltage is reversed on reflection, but the phase of the current is not.

If the line is open-circuited (Figure 23.7C) the current must be zero at the end of the line. In this case the reflected current is 180° out of phase with the incident current and has the same amplitude. By reasoning similar to that used in the short-circuited case, the reflected voltage must be in phase with the incident voltage, and must have the same amplitude. Vectors for the open-circuited case are shown in **Figure 23.9**.

Where there is a finite value of resistance (or a combination of resistance and reactance) at the end of the line, as in Figure 23.7A, only part of the power reaching the end of the line is reflected. That is, the reflected voltage and current are smaller than the incident voltage and current. If R is less than Z_0, the reflected and incident voltage are 180° out of phase, just as in the case of the short-circuited line, but the amplitudes are not equal because all of the voltage does not disappear at R. Similarly, if R is greater than Z_0, the reflected and incident currents are 180° out of phase (as they were in the open-circuited line), but all of the current does not appear in R. The amplitudes of the two components are therefore not equal. These two cases are shown in **Figure 23.10**. Note that the resultant current and voltage are in phase in R, because R is a pure resistance.

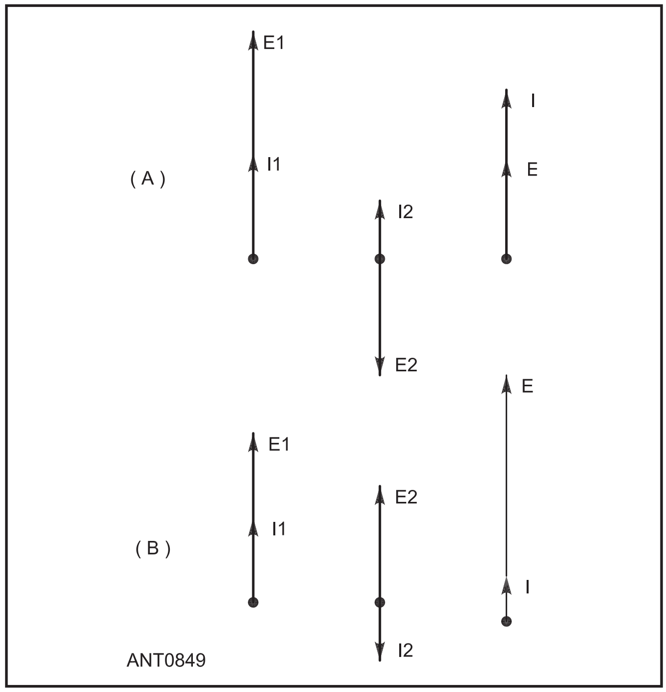


Figure 23.10 — Incident and reflected components of voltage and current when the line is terminated in a pure resistance R not equal to Z_0. In the case shown, the reflected components have half the amplitude of the incident components. At A, R less than Z_0; at B, R greater than Z_0.

Non-resistive Terminations

In most of the preceding discussions, we considered loads containing only resistance. Furthermore, our transmission line was considered to be lossless. Such a resistive load will consume some, if not all, of the power that has been transferred along the line. However, a nonresistive load such as a pure reactance can also terminate a length of line. Such terminations, of course, will consume no power, but will reflect all of the energy arriving at the end of the line. In this case the theoretical SWR (covered later) in the line will be infinite, but in practice, losses in the line will limit the SWR to some finite value at line positions back toward the source.

At first you might think there is little or no point in terminating a line with a nonresistive load. In a later section we shall examine this in more detail, but the value of input impedance depends on the value of the load impedance, on the length of the line, the losses in a practical line, and on the characteristic impedance of the line. There are times when a line terminated in a nonresistive load can be used to advantage, such as in phasing or matching applications. Remote switching of reactive terminations on sections of line can be used to reverse the beam heading of an antenna array, for example. The point of this brief discussion is that a line need not always be terminated in a load that will consume power.

23.2 PRACTICAL TRANSMISSION LINES

23.2.1 ATTENUATION

Every practical line will have some inherent loss, partly because of the resistance of the conductors, partly because power is consumed in the dielectric used for insulating the conductors, and partly because in many cases a small amount of power escapes from the line by radiation. We shall consider here in detail the losses associated with conductor and dielectric losses.

Matched-Line Losses

Power lost in a transmission line is not directly proportional to the line length, but varies logarithmically with the length. That is, if 10% of the input power is lost in a section of line of certain length, 10% of the remaining power will be lost in the next section of the same length, and so on. For this reason it is customary to express line losses in terms of decibels per unit length, since the decibel is a unit of logarithmic ratios. Calculations are very simple because the total loss in a line is found by multiplying the decibel loss per unit length by the total length of the line.

The power lost in a matched line (that is, where the load is equal to the characteristic impedance of the line) is called *matched-line loss*. Matched-line loss is usually expressed in decibels per 100 feet. It is necessary to specify the frequency for which the loss applies, because the loss does vary with frequency.

Conductor and dielectric loss both increase as the operating frequency is increased, but not in the same way. This, together with the fact that the relative amount of each type of loss depends on the actual construction of the line, makes it impossible to give a specific relationship between loss and frequency that will apply to all types of lines.

One relationship that does apply is that for lines made of the same materials (for example, copper and solid polyethylene) higher impedance lines will have lower losses. This

Coaxial Feed Line Loss Coefficients

High-precision calculations of loss in coaxial feed lines require three constants, K0, K1, and K2, which are specified by manufacturers for each type of cable. You may encounter these coefficients in online calculators and other tools for determining feed line characteristics, loss, and so on.

- K0 is associated with the dc resistance of the conductors and does not vary with frequency.
- K1 is associated with the skin effect of the conductors which varies in proportion to the square root of frequency.
- K2 is associated with the dielectric loss which varies directly with frequency.

is because the current is lower in a higher impedance line, reducing resistive (I^2R) losses.

In practice, when selecting a feed line, each type of line must be considered individually. Actual loss values for practical lines are given in a later section of this chapter along with a discussion of how to select a feed line.

One effect of matched-line loss in a real transmission line is that the characteristic impedance, Z_0, becomes complex, with a non-zero reactive component X_0. Thus,

$$Z_0 = R_0 - jX_0 \qquad \text{(Eq 3)}$$

$$X_0 = -R_0 \frac{\alpha}{\beta} \qquad \text{(Eq 4)}$$

where

$$\alpha = \frac{\text{Attenuation (dB / 100feet)} \times 0.1151 \text{ (nepers / dB)}}{\text{100 feet}}$$

the matched-line attenuation, in nepers per unit length (Nepers are a unitless non-logarithmic radio and 1 neper = 8.686 dB.)

$\beta = \frac{2\pi}{\lambda}$, the phase constant in radians/unit length.

The reactive portion of the complex characteristic impedance is always capacitive (that is, its sign is negative) and the value of X_0 is usually small compared to the resistive portion R_0.

23.2.2 REFLECTION COEFFICIENT

The ratio of the reflected voltage at a given point on a transmission line to the incident voltage is called the *voltage reflection coefficient*. The voltage reflection coefficient is also equal to the ratio of the incident and reflected currents. Thus

$$\rho = \frac{E_r}{E_f} = \frac{I_r}{I_f} \qquad \text{(Eq 5)}$$

where

ρ = reflection coefficient
E_r = reflected voltage
E_f = forward (incident) voltage
I_r = reflected current
I_f = forward (incident) current

The reflection coefficient is determined by the relationship between the line Z_0 and the actual load at the terminated end of the line. In most cases, the actual load is not entirely resistive — that is, the load is a complex impedance, consisting of a resistance in series with a reactance, as is the complex characteristic impedance of the transmission line.

The reflection coefficient is thus a complex quantity, having both amplitude and phase, and is generally designated by the Greek letter ρ (rho), or sometimes as Γ (Gamma). The relationship between R_a (the load resistance), X_a (the load reactance), Z_0 (the complex line characteristic impedance, whose real part is R_0 and whose reactive part is X_0) and the complex reflection coefficient ρ is

$$\rho = \frac{Z_a - Z_0}{Z_a + Z_0} = \frac{(R_a \pm jX_a) - (R_0 \pm jX_0)}{(R_a \pm jX_a) + (R_0 \pm jX_0)} \qquad \text{(Eq 6)}$$

For high-quality, low-loss transmission lines at low frequencies, the characteristic impedance Z_0 is almost completely resistive, meaning that $Z_0 \cong R_0$ and $X_0 \cong 0$. The magnitude of the complex reflection coefficient in Eq 6 then simplifies to:

$$|\rho| = \sqrt{\frac{(R_a - R_0)^2 + X_a^2}{(R_a + R_0)^2 + X_a^2}} \qquad \text{(Eq 7)}$$

For example, if the characteristic impedance of a coaxial line at a low operating frequency is 50 Ω and the load impedance is 120 Ω in series with a capacitive reactance of –90 Ω, the magnitude of the reflection coefficient is

$$|\rho| = \sqrt{\frac{(120 - 50)^2 + (-90)^2}{(120 + 50)^2 + (-90)^2}} = 0.593$$

Note that the vertical bars on each side of ρ mean the *magnitude* of rho. If R_a in Eq 7 is equal to R_0 and if X_a is 0, the reflection coefficient, ρ, also is 0. This represents a *matched condition*, where all the energy in the incident wave is transferred to the load. On the other hand, if R_a is 0, meaning that the load has no real resistive part, the reflection coefficient is 1.0, regardless of the value of R_0. This means that all the forward power is reflected, since the load is completely reactive. As we shall see later on, the concept of reflection coefficient is a very useful one to evaluate the impedance seen looking into the input of a mismatched transmission line.

Another representation of the reflection coefficient concept is the *return loss*, which is the reflection coefficient expressed in dB.

$$RL = -20 \log |\rho| \, dB \qquad \text{(Eq 8)}$$

For example, a reflection coefficient of 0.593 is a return loss of –20 log (0.593) = 4.5 dB. (Note that some texts express return loss as negative numbers, but most define it as positive.)

23.2.3 STANDING WAVES

As might be expected, reflection cannot occur at the load without some effect on the voltages and currents all along the line. To keep things simple for a while longer, let us continue to consider only resistive loads, without any reactance. The conclusions we shall reach are valid for transmission lines terminated in complex impedances as well.

The effects are most simply shown by vector diagrams. **Figure 23.11** is an example where the terminating resistance R is less than Z_0. The voltage and current vectors at R are shown in the reference position; they correspond with the vectors in Figure 23.10A, turned 90°. Back along the line from R toward the power source, the incident vectors, E1 and I1, lead the vectors at the load according to their position along the line measured in electrical degrees. (The corresponding distances in fractions of a wavelength are also shown.) The vectors representing reflected voltage and current, E2 and I2, successively lag the same vectors at the load.

This lag is the natural consequence of the direction in which the incident and reflected components are traveling, together with the fact that it takes time for power to be transferred along the line. The resultant voltage E and current I at each of these positions is shown as a dotted arrow. Although the incident and reflected components maintain their respective amplitudes (the reflected component is shown at half the incident-component amplitude in this drawing), their phase relationships vary with position along the line. The phase shift causes both the amplitude and phase of the *resultants* to vary with position on the line.

If the amplitude variations (disregarding phase) of the resultant voltage and current are plotted against position along the line, graphs like those of **Figure 23.12A** will result. If we could go along the line with a voltmeter and ammeter measuring the current and voltage at each point, plotting the collected data would give curves like these. In contrast, if the load matched the Z_0 of the line, similar measurements along the line would show that the voltage is the same everywhere

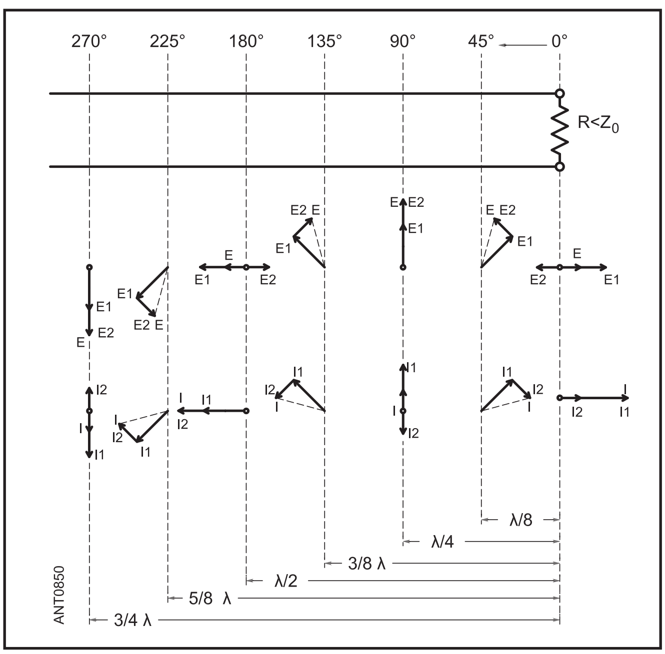


Figure 23.11 — Incident and reflected components at various positions along the transmission line, together with resultant voltages and currents at the same positions. The case shown is for R less than Z_0.

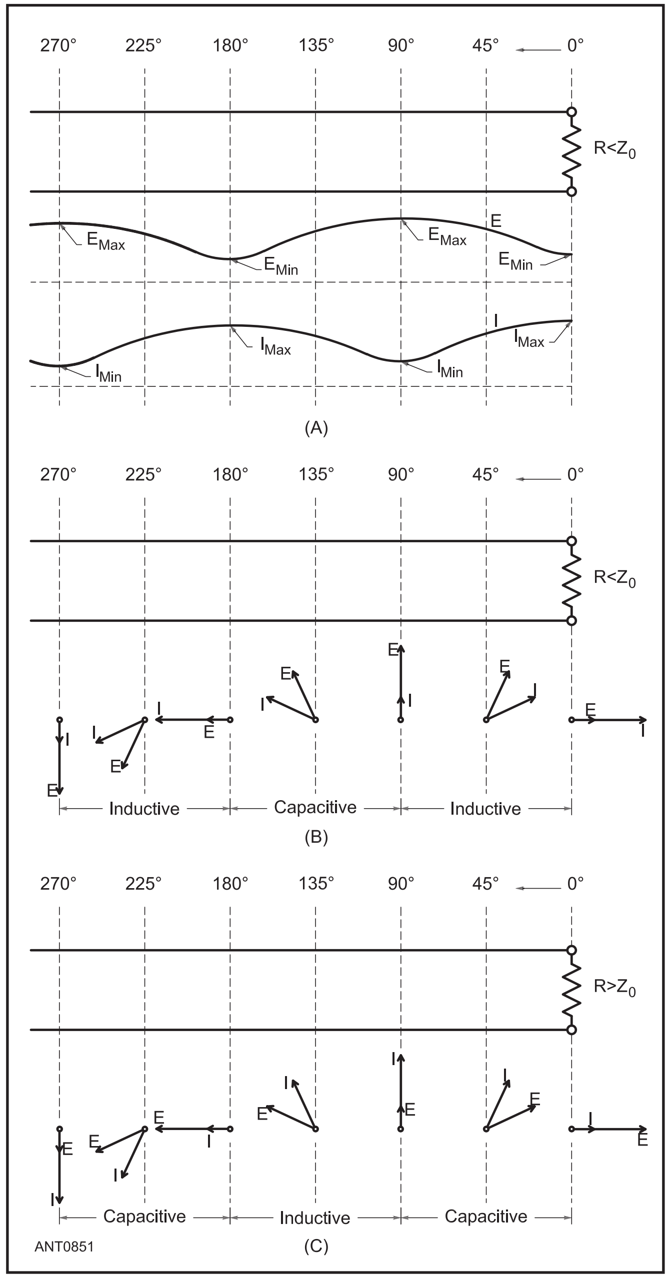


Figure 23.12 — Standing waves of current and voltage along the line for R less than Z_0. At A, resultant voltages and currents along a mismatched line are shown at B and C. At B, R less than Z_0; At C, R greater than Z_0.

(and similarly for the current). The mismatch between load and line is responsible for the variations in amplitude which, because of their stationary, wave-like appearance, are called *standing waves*.

Some general conclusions can be drawn from inspection of the standing-wave curves: At a position 180° ($\lambda/2$) from the load, the voltage and current have the same values they do at the load. At a position 90° from the load, the voltage and current are "inverted." That is, if the voltage is lowest and current highest at the load (when R is less than Z_0), then 90° from the load the voltage reaches its highest value. The current reaches its lowest value at the same point. In the case where R is greater than Z_0, so the voltage is highest and the current lowest at the load, the voltage is lowest and the current is highest 90° from the load.

Note that the conditions at the 90° point also exist at the 270° point ($3\lambda/4$). If the graph were continued on toward the source of power it would be found that this duplication occurs at every point that is an odd multiple of 90º (odd multiple of $\lambda/4$) from the load. Similarly, the voltage and current are the same at every point that is a multiple of 180° (any multiple of $\lambda/2$) away from the load.

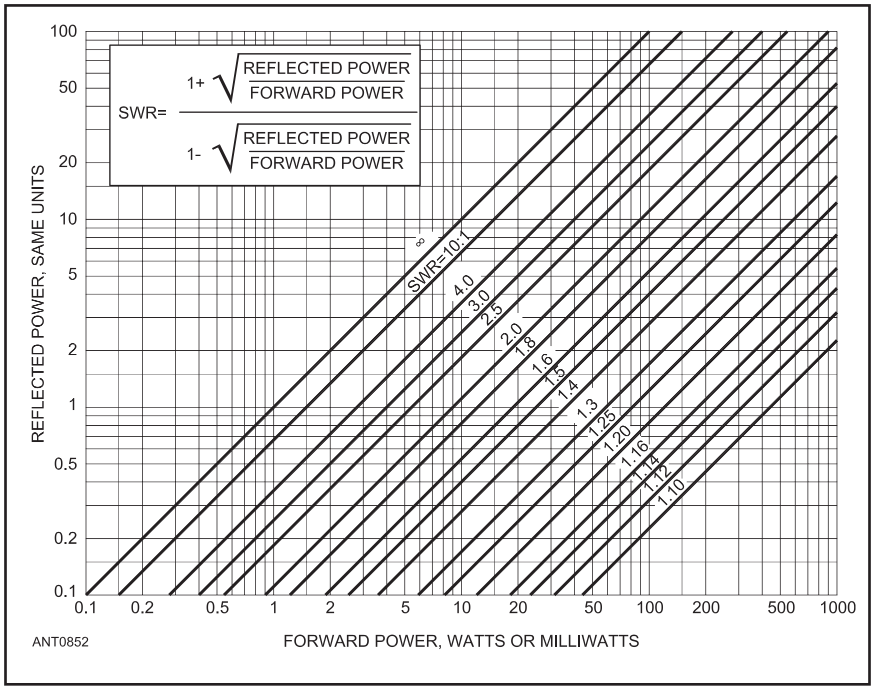


Figure 23.13 — SWR as a function of forward and reflected power.

Standing-Wave Ratio

The ratio of the maximum voltage (resulting from the interaction of incident and reflected voltages along the line) to the minimum voltage — that is, the ratio of E_{max} to E_{min} in Figure 23.12A, is defined as the *voltage standing-wave ratio* (VSWR) or simply *standing-wave ratio* (SWR).

$$SWR = \frac{E_{max}}{E_{min}} = \frac{I_{max}}{I_{min}} \quad \text{(Eq 9)}$$

The ratio of the maximum current to the minimum current is the same as the VSWR, so either current or voltage can be measured to determine the standing-wave ratio. The standing-wave ratio is an index of many of the properties of a mismatched line. It can be measured with fairly simple equipment, so it is a convenient quantity to use in making calculations on line performance.

The SWR is related to the magnitude of the complex reflection coefficient by

$$SWR = \frac{1+|\rho|}{1-|\rho|} \quad \text{(Eq 10)}$$

and conversely the reflection coefficient magnitude may be defined from a measurement of SWR as

$$|\rho| = \frac{SWR-1}{SWR+1} \quad \text{(Eq 11)}$$

We may also express the reflection coefficient in terms of forward and reflected power, quantities which can be easily measured using a directional RF wattmeter. The reflection coefficient may be computed as

$$\rho = \sqrt{\frac{P_r}{P_f}} \quad \text{(Eq 12)}$$

where

P_r = power in the reflected wave

P_f = power in the forward wave.

From Eq 11, SWR is related to the forward and reflected power by

$$SWR = \frac{1+|\rho|}{1-|\rho|} = \frac{1+\sqrt{P_r/P_f}}{1-\sqrt{P_r/P_f}} \quad \text{(Eq 13)}$$

Figure 23.13 converts Eq 13 into a convenient nomograph. In the simple case where the load contains no reactance, the SWR is numerically equal to the ratio between the load resistance R and the characteristic impedance of the line. When R is greater than Z_0,

$$SWR = \frac{R}{Z_0} \quad \text{(Eq 14)}$$

When R is less than Z_0,

$$SWR = \frac{Z_0}{R} \quad \text{(Eq 15)}$$

(The smaller quantity is always used in the denominator of the fraction so the ratio will be a number greater than 1).

SWR and Resonance

It is a common misunderstanding that for a transmission line connected to an antenna, minimum SWR occurs when the antenna is resonant. In a general sense, this is not true — minimum SWR occurs when the magnitude of the load's reflection coefficient, |r|, is at a minimum (see Eq 7). Viewing the load impedance on a Smith Chart as in **Figure 23.A**, the value of |r| is represented by the distance from the origin (center) to the point representing the load impedance. (The Smith Chart is explored in the PDF supplement, "The Smith Chart" on this book's CD-ROM.)

As the frequency changes, the impedance of an antenna changes. The example in Figure 23.A shows points A, B and C — three plausible load impedances for an antenna at different frequencies. Point O is the origin. The antenna is resonant at both A and C since the points are on the X=0 line through the middle of the chart. At point A the impedance is 0.2 + *j*0 or 10 Ω in a 50-Ω system and C represents 4.0 + *j*0 Ω or 200 Ω. The magnitude of ρ at A is 0.67 and the SWR = 5:1. The magnitude of ρ at C is 0.6 and the SWR = 4:1. Point B represents the normalized load impedance 0.8 + *j*0.8, which is 40 + *j*40 Ω in a 50-Ω system. The magnitude of ρ at B is 0.062 and the SWR = 1.13. Even though the load impedance at B is reactive (nonresonant) the SWR is lower than at either of the two resonant points at A and C.

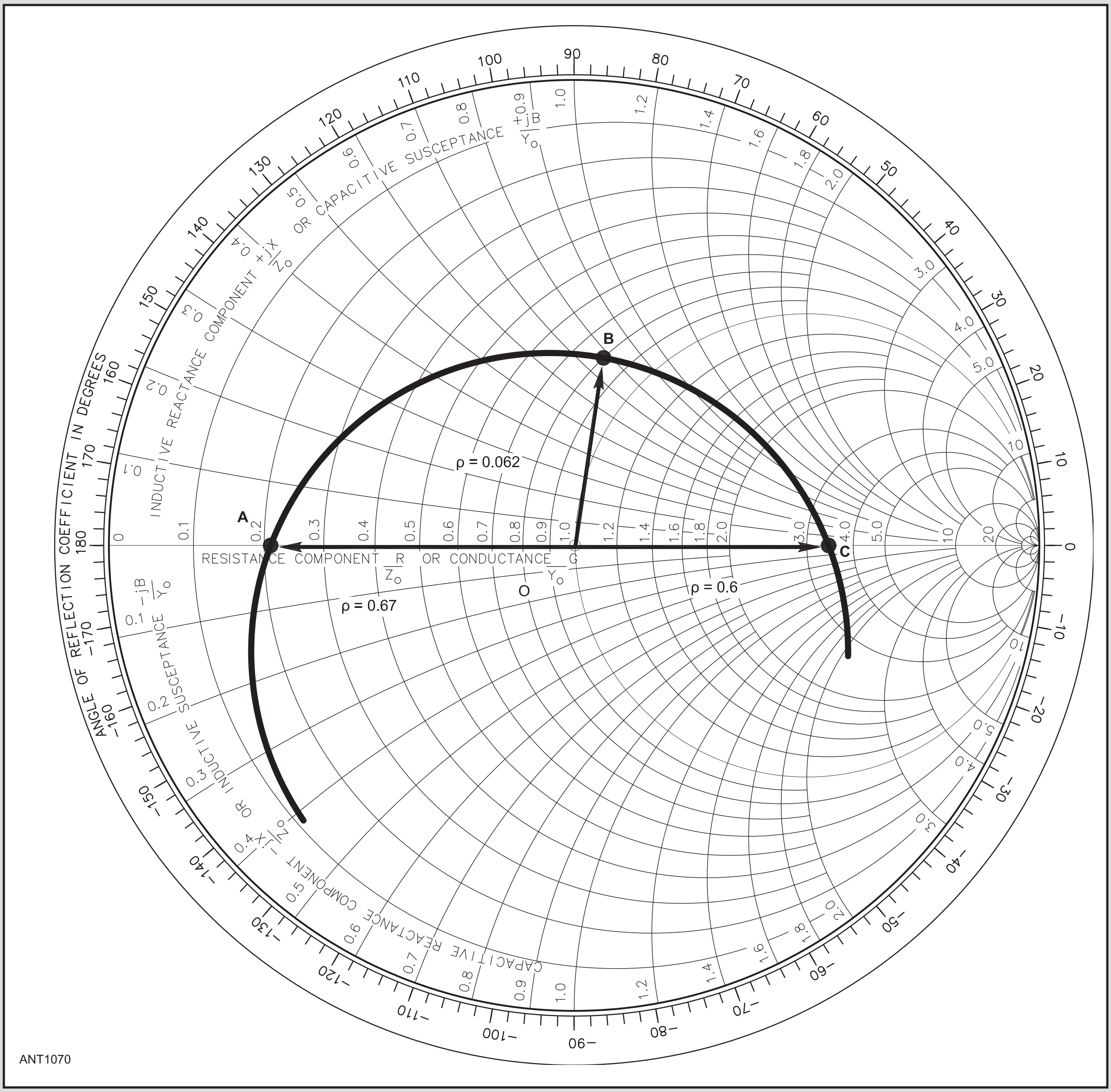


Figure 23.A — Load impedance viewed on a Smith Chart.

It is important to note that in a lossless transmission line, SWR does not change with length of the line or along the line. While the values of voltage and current do change along the line, the ratio of their maximum and minimum values does not. The value of SWR shown by typical amateur SWR measuring instruments may change with line length but that can result from a number of causes; inaccuracy of the voltage or current sensing circuits, common-mode current on the outside of a coaxial feed line shield, and signals from a nearby transmitter upsetting the voltage or current measurement being the most common reasons.

Flat Lines

As discussed earlier, all the power that is transferred along a transmission line is absorbed in the load if that load is a resistance value equal to the Z_0 of the line. In this case, the line is said to be *perfectly matched*. None of the power is reflected back toward the source. As a result, no standing waves of current or voltage will be developed along the line. For a line operating in this condition, the waveforms drawn in Figure 23.12A become straight lines, representing the voltage and current delivered by the source. The voltage along the line is constant, so the minimum value is the same as the maximum value. The voltage standing-wave ratio is therefore 1:1. Because a plot of the voltage standing wave is a straight line, the matched line is also said to be *flat*.

23.2.4 ADDITIONAL POWER LOSS DUE TO SWR

The power lost in a given line is least when the line is terminated in a resistance equal to its characteristic impedance, and as stated previously, that is called the *matched-line loss*. There is however an *additional loss* that increases with an increase in the SWR. (Modern transmitters will also reduce output power to protect the solid-state output devices from elevated SWR but this is not power lost in the feed line.)

Additional loss in the line occurs because the effective values of both current and voltage become greater on lines with standing waves. The increase in effective current raises the ohmic losses (I^2R) in the conductors, and the increase in effective voltage increases the losses in the dielectric (E^2/R). (The nature of feed line loss is discussed at length in *Reflections* by W2DU — see the Bibliography entries for M. W. Maxwell.)

The increased loss caused by an SWR greater than 1:1 may or may not be serious. If the SWR at the load is not greater than 2:1, the additional loss caused by the standing waves, as compared with the loss when the line is perfectly matched, does not amount to more than about ½ dB, even on very long lines. One-half dB is an undetectable change in signal strength. Therefore, it can be said that, from a practical standpoint in the HF bands, an SWR of 2:1 or less is every bit as good as a perfect match, so far as additional losses due to SWR are concerned.

As is illustrated by the examples of a 100-foot-long doublet and a 66-foot-long Inverted V at the beginning of the chapter on **Transmission Line System Techniques**, both non-resonant antennas that are in widespread use on HF, the impedance mismatch and SWR can be quite high. In such cases, losses in even modest lengths of feed line can be unacceptably high. (See the supplemental article "Multiband Operation with Open-wire Line" by George Cutsogeorge, W2VJN, on this book's CD-ROM.)

Above 30 MHz, in the VHF and especially the UHF range, where low receiver noise figures are essential for effective weak-signal work, matched-line losses for commonly available types of coax can be relatively high. This means that even a slight mismatch may become a concern regarding overall transmission line losses. At UHF one-half dB of additional loss may be considered intolerable!

The total loss in a line, including matched-line and the additional loss due to standing waves may be calculated from Eq 16 below for moderate levels of SWR (less than 20:1).

$$\text{Total Loss (dB)} = 10 \log \left(\frac{a^2 - |\rho|^2}{a\,(1 - |\rho|^2)} \right) \qquad \text{(Eq 16)}$$

where

$a = 10^{0.1\,ML}$ = matched-line loss ratio

ML = the matched-line loss in dB for the particular length of line

$|r|$ = the reflection coefficient at the load, calculated as in Eq 7

and reflected power is assumed to be re-reflected at the source.

Thus, the additional loss caused by the standing waves is calculated from:

$$\text{Additional Loss (dB)} = \text{Total Loss} - \text{ML} \qquad \text{(Eq 17)}$$

For example, RG-213 coax at 14.2 MHz is rated at 0.795 dB of matched-line loss per 100 feet. A 150-foot length of RG-213 would have an overall matched-line loss of

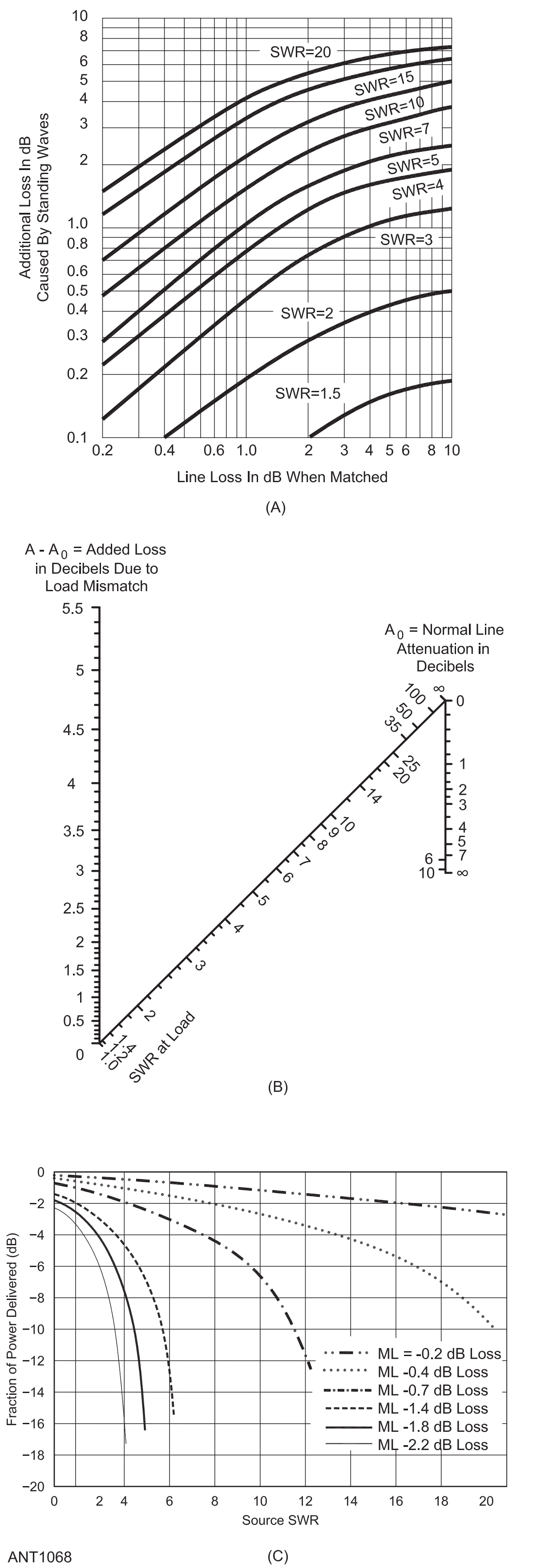
$$(0.795/100) \times 150 = 1.193 \text{ dB}$$

Thus, if the SWR at the load end of the RG-213 is 4:1,

$$\alpha = 10^{1.193/10} = 1.316$$

$$|\rho| = \frac{4-1}{4+1} = 0.600$$

Figure 23.14 — (A) Additional line loss due to standing waves (SWR, measured at the load). See Figure 23.24 for matched-line loss. To determine the total loss in dB, add the matched-line loss to the value from this graph. (B) Nomograph showing Added Loss in dB due to mismatch (SWR at Load) with a known line attenuation. Place a straightedge along the points representing load SWR and line attenuation. Read additional loss on the left-hand scale. (C) Fractional amount of the input power delivered to the load given source or input SWR and line attenuation. (Graph provided courtesy of Refined Audiometrics Laboratory, LLC by David McLain, N7AIG.)



and the total line loss

$$= 10 \log \left(\frac{1.316^2 - 0.600^2}{1.316\,(1 - 0.600^2)} \right) = 2.12 \text{ dB}$$

The additional loss due to the SWR of 4:1 is 2.12 – 1.19 = 0.93 dB. **Figure 23.14A** is a graph of additional loss versus SWR. Figure 23.14B is a nomograph equivalent to Figure 23.14A. Figure 23.14C is an alternative graph that shows the fraction of input power actually delivered to the load for a given source SWR and line Matched Loss (ML).

23.2.5 LINE VOLTAGES AND CURRENTS

It is often desirable to know the maximum voltages and currents that are developed in a line operating with standing waves. (We'll cover the determination of the exact voltages and currents along a transmission line later.) The voltage maximum may be calculated from Eq 18 below, and the other values determined from the result.

$$E_{max} = \sqrt{P \times Z_0 \times SWR} \qquad \text{(Eq 18)}$$

where

E_{max} = voltage maximum along the line in the presence of standing waves
P = power delivered by the source to the line input in watts
Z_0 = characteristic impedance of the line in ohms
SWR = SWR at the load

If 100 W of power is applied to a 600-Ω line with an SWR at the load of 10:1,

$$E_{max} = \sqrt{100 \times 600 \times 10} = 774.6 \text{ V}$$

From Eq 9, E_{min}, the minimum voltage along the line equals E_{max}/SWR = 774.6/10 = 77.5 V. The maximum current may be found by using Ohm's Law. $I_{max} = E_{max}/Z_0$ =774.6/600 = 1.29 A. The minimum current equals I_{max}/SWR = 1.29/10 = 0.129 A.

The voltage determined from Eq 18 is the RMS value — that is, the voltage that would be measured with an ordinary RF voltmeter. If voltage breakdown is a consideration, the value from Eq 18 should be converted to an *instantaneous peak voltage*. Do this by multiplying times $\sqrt{2}$ (assuming the RF waveform is a sine wave). Thus, the maximum instantaneous peak voltage in the above example is 774.6 × $\sqrt{2}$ = 1095.4 V.

Strictly speaking, the values obtained as above apply only near the load in the case of lines with appreciable losses. However, the resultant values are the maximum possible that can exist along the line, whether there are line losses or not. For this reason they are useful as a rule-of-thumb in determining whether or not a particular line can operate safely with a given SWR. Voltage ratings for various cable types are given in a later section.

Figure 23.15 shows the ratio of current or voltage at a loop, in the presence of standing waves, to the current or

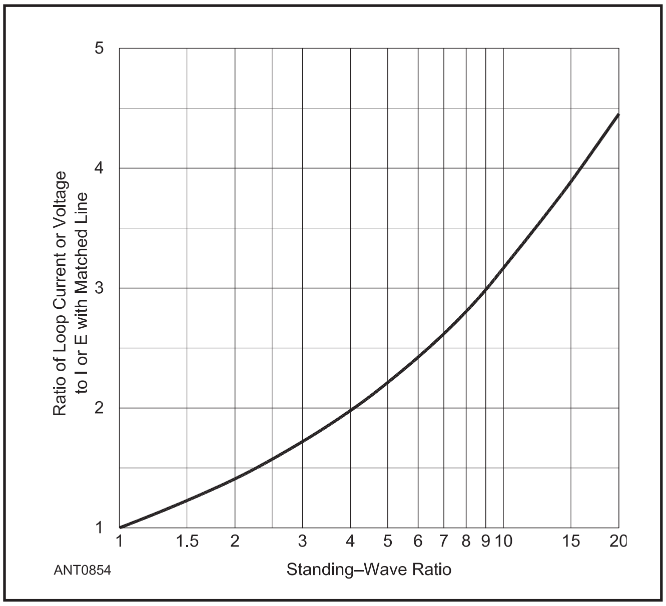


Figure 23.15 — Increase in maximum value of current or voltage on a line with standing waves, as referred to the current or voltage on a perfectly matched line, for the same power delivered to the load. Voltage and current at minimum points are given by the reciprocals of the values along the vertical axis. The curve is plotted from the relationship, current (or voltage) ratio = the square root of SWR.

voltage that would exist with the same power in a perfectly matched line. As with Eq 18 and related calculations, the curve literally applies only near the load.

23.2.6 INPUT IMPEDANCE

The effects of incident and reflected voltage and current along a mismatched transmission line can be difficult to envision, particularly when the load at the end of the transmission line is not purely resistive, and when the line is not perfectly lossless.

If we can put aside for a moment all the complexities of reflections, SWR and line losses, a transmission line can simply be considered to be an *impedance transformer*. A certain value of load impedance, consisting of a resistance and reactance, at the end of a particular transmission line is transformed into another value of impedance at the input of the line. The amount of transformation is determined by the electrical length of the line, its characteristic impedance, and by the losses inherent in the line. The input impedance of a real, lossy transmission line is computed using the following equation, called the *Transmission Line Equation*, which uses the hyperbolic cosine and sine functions.

$$Z_{in} = Z_0 \frac{Z_L \cosh(\gamma\ell) + Z_0 \sinh(\gamma\ell)}{Z_L \sinh(\gamma\ell) + Z_0 \cosh(\gamma\ell)} \qquad \text{(Eq 19)}$$

where

Z_{in} = complex impedance at input of line
Z_L = complex load impedance at end of line = $R_a \pm j\, X_a$
Z_0 = characteristic impedance of line = $R_0 - j\, X_0$
ℓ = physical length of line
γ = complex loss coefficient = $\alpha + j\,\beta$
α = matched-line loss attenuation constant, in nepers/unit length (1 neper = 8.686 dB; cables are rated in dB/100 ft)
β = phase constant of line in radians/unit length (related to physical length of line ℓ by the fact that 2π radians = one wavelength, and by Eq 2)

$$\beta = \frac{2\pi}{VF \times 983.6 / f(MHz)} \quad \text{for } \ell \text{ in feet}$$

VF = velocity factor

For example, assume that a half-wave dipole terminates a 50-foot long piece of RG-213 coax. This dipole is assumed to have an impedance of 43 + j 30 Ω at 7.15 MHz, and its velocity factor is 0.66. The matched-line loss at 7.15 MHz is 0.54 dB/100 feet, and the characteristic impedance Z_0 for this type of cable at this frequency is 50 – j 0.45 Ω. Using Eq 19, we compute the impedance at the input of the line as 65.8 + j 32.0 Ω.

Solving this equation manually is quite tedious, but it may be solved using a traditional paper Smith Chart or a computer program. (The PDF file "The Smith Chart" explains how to use the chart and is available on this book's CD-ROM.) *SimSmith* by AE6TY (**www.ae6ty.com/Smith_Charts.html**) is available for free download and there are several on-line calculators available if you search for "smith chart calculator" on the Internet. *TLW* (Transmission Line for Windows) is an ARRL program that performs this transformation, but without Smith Chart graphics. *TLW* is available from this book's CD-ROM.

One caution should be noted when using any of these computational tools to calculate the impedance at the input of a mismatched transmission line — the velocity factor of practical transmission lines can vary significantly between manufacturing runs of the same type of cable. For highest accuracy, you should measure the velocity factor of a particular length of cable before using it to compute the impedance at the end of the cable. See the chapter **Antenna and Transmission Line Measurements** for details on measurements of line characteristics.

Input SWR and Line Loss

If the line is not perfectly matched to the load the loss in the line reduces the amount of reflected power that returns to the source end of the line. This makes SWR appear lower at the source (transmitter) end of the line than it is at the load (antenna) end of the line. The longer the line or the higher the loss, the more power is dissipated as heat and the lower the input SWR. In fact, a long (many wavelengths) lossy transmission line can be used as a dummy load at VHF and higher frequencies.

A nomograph is given in **Figure 23.16** that relates load SWR, line attenuation, and load SWR. If you know any two of those three parameters, place a ruler between those two points and read the third from the intersection of the ruler with the scale for the unknown parameter.

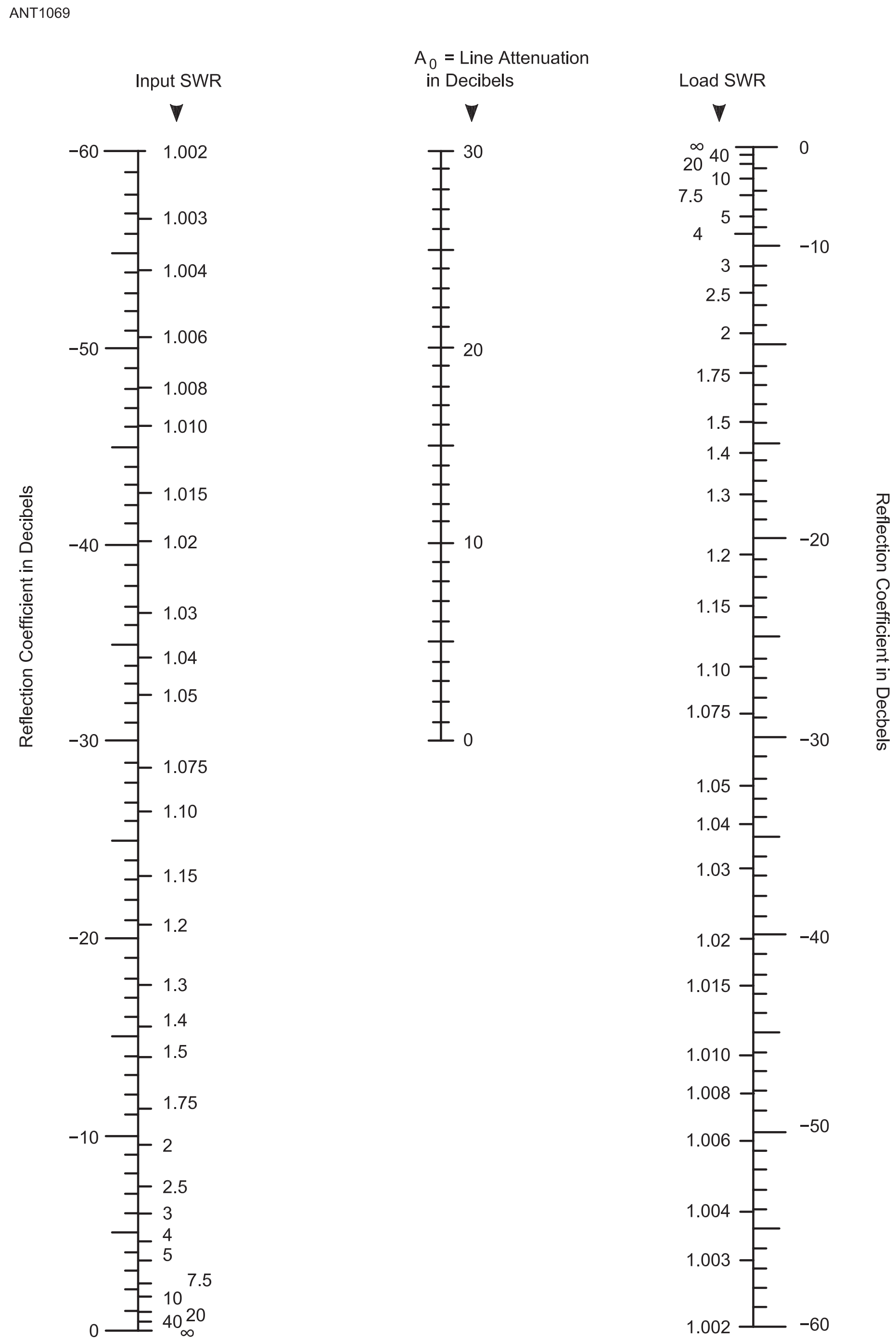


Figure 23.16 — Nomograph showing that load SWR, line attenuation or input SWR can be determined if two of the values are known. Place a straightedge between the two known values and read the value of the third where the straightedge crosses the scale for the third parameter.

Series and Parallel Equivalent Circuits

Once the series-form impedance $R_S \pm j\,X_S$ at the input of a particular line has been determined, either by measurement or by computation, you may wish to determine the equivalent parallel circuit $R_P \parallel \pm j\,X_P$, which is equivalent to the series form only at a single frequency. The equivalent parallel circuit is often useful when designing a matching circuit (such as an antenna tuner, for example) to transform the impedance at the input of the cable to another impedance. The following equations are used to make the transformation from series to parallel and from parallel to series. See **Figure 23.17**.

$$R_p = \frac{R_s^2 + X_s^2}{R_s} \qquad \text{(Eq 20A)}$$

$$X_p = \frac{R_s^2 + X_s^2}{X_s} \qquad \text{(Eq 20B)}$$

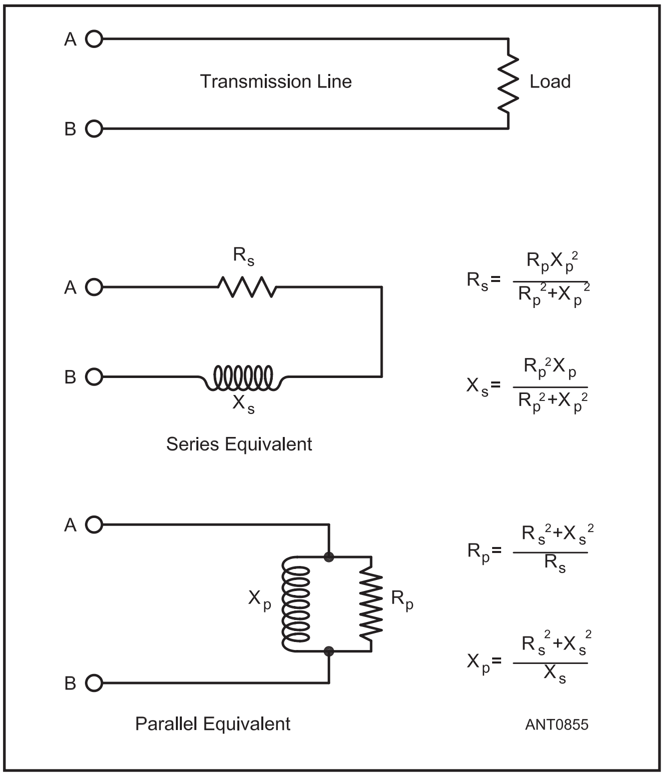


Figure 23.17 — Input impedance of a line terminated in a resistance. This impedance can be represented by either a resistance and reactance in series, or a resistance and reactance in parallel, at a single frequency. The relationships between the R and X values in the series and parallel equivalents are given by the equations shown. X may be either inductive or capacitive, depending on the line length, Z_0 and the load impedance, which need not be purely resistive.

and

$$R_s = \frac{R_p X_p^2}{R_p^2 + X_p^2} \quad \text{(Eq 21A)}$$

$$X_s = \frac{R_p^2 X_p}{R_p^2 + X_p^2} \quad \text{(Eq 21B)}$$

The individual values in the parallel circuit are not the same as those in the series circuit (although the overall result is the same, but only at one frequency), but are related to the series-circuit values by these equations. For example, let us continue the example in the section above, where the impedance at the input of the 50 feet of RG-213 at 7.15 MHz is $65.8 + j\,32.0\ \Omega$. The equivalent parallel circuit at 7.15 MHz is

$$R_p = \frac{65.8^2 + 32.1^2}{65.8} = 81.46\ \Omega$$

$$X_p = \frac{65.8^2 + 31.2^2}{31.2} = 169.97\ \Omega$$

If we were to put 100 W of power into this parallel equivalent circuit, the voltage across the parallel components would be

$$\text{Since } P = \frac{E^2}{R},\ E = \sqrt{P \times R} = \sqrt{100 \times 81.46} = 90.26\ \text{V}$$

Thus, the current through the inductive part of the parallel circuit would be

$$I = \frac{E}{X_p} = \frac{90.26}{169.97} = 0.53\ \text{A}$$

Highly Reactive Loads

When highly reactive loads are used with practical transmission lines, especially coax lines, the overall loss can reach staggering levels. For example, a popular multiband antenna is a 100-foot long center-fed dipole located some 50 feet over average ground. At 1.83 MHz, such an antenna will exhibit a feed-point impedance of $4.5 - j\ 1673\ \Omega$, according to the analysis program *EZNEC*. The high value of capacitive reactance indicates that the antenna is extremely short electrically — after all, a half-wave dipole at 1.83 MHz is almost 270 feet long, compared to this 100 foot long antenna. If an amateur attempts to feed such a multiband antenna directly with 100 feet of RG-213 50-Ω coaxial cable, the SWR at the antenna terminals would be (using the *TLW* program from the CD-ROM) 1740:1. An SWR of more than 1700 to one is a very high level of SWR indeed! At 1.83 MHz the *matched-line loss* of 100 feet of the RG-213 coax by itself is only 0.26 dB. However, the *total line loss* due to this extreme level of SWR is 26 dB.

This means that if 100 W is fed into the input of this line, the amount of power at the antenna is reduced to only 0.25 W. Admittedly this is an extreme case. It is more likely that an amateur would feed such a multiband antenna with open-wire *ladder* or *window* line than coaxial cable. The matched-line loss characteristics for 450-Ω window open-wire line are far better than coax, but the SWR at the end of this line is still 793:1, resulting in an overall loss of 8.9 dB. Even for low-loss open-wire line, the total loss is significant because of the extreme SWR.

This means that only about 13% of the power from the transmitter is getting to the antenna, and although this is not very desirable, it is a lot better than the losses in coax cable feeding the same antenna. However, at a transmitter power level of 1500 W, the maximum voltage in a typical antenna tuner used to match this line impedance is almost 9200V with the open-wire line, a level which will certainly cause arcing or burning inside. (As a small compensation for all the loss in coax under this extreme condition, so much power is lost that the voltages present in the antenna tuner are not excessive.) Keep in mind also that an antenna tuner can lose significant power in internal losses for very high impedance levels, even if it has sufficient range to match such impedances in the first place.

Clearly, it would be far better to use a longer antenna at this 160 meter frequency. Another alternative would be to resonate a short antenna with loading coils (at the antenna). Either strategy would help avoid excessive feed line loss, even with low-loss line.

23.2.7 SPECIAL CASES

Beside the primary purpose of transporting power from one point to another, transmission lines have properties that are useful in a variety of ways. One such special case is a line an exact multiple of λ/4 (90°) long. As shown earlier, such a line will have a purely resistive input impedance when the termination is a pure resistance. Also, short-circuited or open-circuited lines can be used in place of conventional inductors and capacitors since such lines have an input impedance that is substantially a pure reactance when the line losses are low. (An alternate way of explaining the interesting behavior of transmission lines — "My Feedline Tunes My Antenna!" by Byron Goodman, W1DX — is included on this book's CD-ROM. Originally published in 1956, this classic *QST* article is still useful today.)

The Half-Wavelength Line

When the line length is a multiple of 180° (that is, a multiple of λ/2), the input resistance is equal to the load resistance, regardless of the line Z_0. As a matter of fact, a line an exact multiple of λ/2 in length (disregarding line losses) simply repeats, at its input or sending end, whatever impedance exists at its output or receiving end. It does not matter whether the impedance at the receiving end is resistive, reactive, or a combination of both. Sections of line having such length can be added or removed without changing any of the operating conditions, at least when the losses in the line itself are negligible.

Impedance Transformation with Quarter-Wave Lines

The input impedance of a line an odd multiple of λ/4 long is

$$Z_i = \frac{Z_0^{\,2}}{Z_L} \qquad \text{(Eq 22)}$$

where Z_i is the input impedance and Z_L is the load impedance. If Z_L is a pure resistance, Z_i will also be a pure resistance. Rearranging this equation gives

$$Z_0 = \sqrt{Z_i Z_L} \qquad \text{(Eq 23)}$$

This means that if we have two values of impedance that we wish to "match," we can do so if we connect them together by a λ/4 transmission line having a characteristic impedance equal to the square root of their product.

A λ/4 line is, in effect, a transformer, and in fact is often referred to as a *quarter-wave transformer*. It is frequently used as such in antenna work when it is desired, for example, to transform the impedance of an antenna to a new value that will match a given transmission line. This subject is considered in greater detail in a later chapter.

Lines as Circuit Elements

Two types of non-resistive line terminations are quite useful — short and open circuits. The impedance of the short-circuit termination is $0 + j0$, and the impedance of the open-circuit termination is infinite. Such terminations are used in *stub matching* as described in the **Transmission Line System Techniques** chapter. Applications of line sections as circuit elements in connection with antenna and transmission-line systems are discussed in later chapters.

An open- or short-circuited line does not deliver any power to a load, and for that reason is not, strictly speaking a "transmission" line. However, the fact that a line of the proper length has inductive reactance makes it possible to substitute the line for a coil in an ordinary circuit. Likewise, another line of appropriate length having capacitive reactance can be substituted for a capacitor.

Sections of lines used as circuit elements are usually λ/4 or shorter. The desired type of reactance (inductive or capacitive) or the desired type of resonance (series or parallel) is obtained by shorting or opening the far end of the line. The circuit equivalents of various types of line sections are shown in **Figure 23.18**. Longer lengths of line are not necessary since any value of impedance available from a particular type of feed line is attainable in λ/4 or less.

When a line section is used as a reactance, the amount of reactance is determined by the characteristic impedance and the electrical length of the line. The type of reactance exhibited at the input terminals of a line of given length depends on whether it is open- or short-circuited at the far end.

The equivalent *lumped* value for any inductor or capacitor may be determined with the aid of the Smith Chart or Eq 19. Line losses may be taken into account if desired,

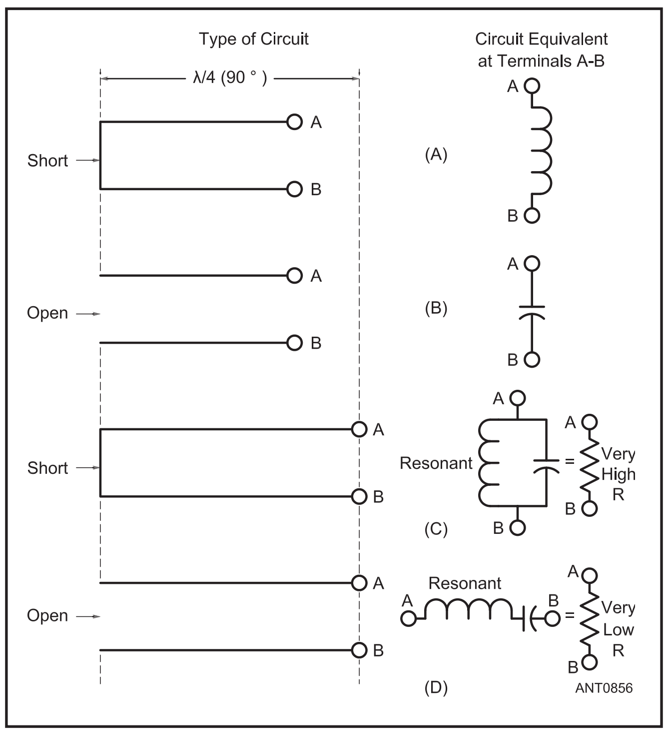


Figure 23.18 — Lumped-constant circuit equivalents of open- and short-circuited transmission lines.

as explained for Eq 19. In the case of a line having no losses, and to a close approximation when the losses are small, the inductive reactance of a short- circuited line less than λ/4 in length is

$$X_L \text{ in } \Omega = Z_0 \tan \ell \qquad \text{(Eq 24)}$$

where ℓ is the length of the line in electrical degrees and Z_0 is the characteristic impedance of the line.

The capacitive reactance of an open-circuited line less than λ/4 in length is

$$X_C \text{ in } \Omega = Z_0 \cot \ell \qquad \text{(Eq 25)}$$

Lengths of line that are exact multiples of λ/4 have the properties of resonant circuits. With an open-circuit termination, the input impedance of the line acts like a series-resonant circuit. With a short-circuit termination, the line input simulates a parallel-resonant circuit. The effective Q of such linear resonant circuits is very high if the line losses, both in resistance and by radiation, are kept down. This can be done without much difficulty, particularly in coaxial lines, if air insulation is used between the conductors. Air-insulated open-wire lines are likewise very good at frequencies for which the conductor spacing is very small in terms of wavelength.

23.2.8 VOLTAGE AND CURRENT ALONG A LINE

The voltage and current along a transmission line will vary in a predictable manner, whether that line is matched or mismatched at its load end. (The voltage and current along a matched line vary because of loss in the line.) Eq 26 below describes the voltage at point ℓ, while Eq 27 describes the current at point ℓ, each as a function of the voltage at the input of the line.

$$E_x = E_{in}\left(\cosh \gamma\ell - \frac{Z_0}{Z_{in}} \sinh \gamma\ell\right) \text{volts} \qquad \text{(Eq 26)}$$

$$I_x = \frac{E_{in}}{Z_{in}}\left(\cosh \gamma\ell - \frac{Z_{in}}{Z_0} \sinh \gamma\ell\right) \text{amperes} \qquad \text{(Eq 27)}$$

where γ = complex loss coefficient used in Eq 19, and cosh and sinh are the hyperbolic cosine and sine functions. The load end of the transmission line is, by definition, at a length of ℓ.

The power at the input and the output of a transmission line may be calculated using Eq 28 and Eq 29 below.

$$P_{in} = \left|E_{in}\right|^2 G_{in} \text{ watts} \qquad \text{(Eq 28)}$$

$$P_{load} = \left|E_{load}\right|^2 G_{load} \text{ watts} \qquad \text{(Eq 29)}$$

where G_{in} and G_{load} are the admittance at the input (the real part of $1/Z_{in}$) and the admittance at the load (the real part of $1/Z_{load}$) ends respectively of the line. Z_{in} is calculated using Eq 19 for a length of ℓ.

The power loss in the transmission line in dB is:

$$P_{loss} = 10 \log\left(\frac{P_{in}}{P_{load}}\right) \text{dB} \qquad \text{(Eq 30)}$$

23.3 FEED LINE CONSTRUCTION AND OPERATING CHARACTERISTICS

The two basic types of transmission lines, parallel conductor and coaxial, can be constructed in a variety of forms. Both types can be divided into two classes, (1) those in which the majority of the insulation between the conductors is air, where only the minimum of solid dielectric necessary for mechanical support is used, and (2) those in which the conductors are embedded in and separated by a solid dielectric. The first variety (air-insulated) has the lowest loss per unit length, because there is no power loss in dry air if the voltage between conductors is below the level at which corona forms. At the maximum power permitted in amateur transmitters, it is seldom necessary to consider corona unless the SWR on the line is very high.

Transmission lines in which the conductors are separated by a flexible dielectric have a number of advantages over the air-insulated type. They are less bulky, weigh less in comparable types and maintain more uniform spacing between conductors. They are also generally easier to install, and are neater in appearance. Both parallel conductor and coaxial lines are available with flexible insulation.

The chief disadvantage of such lines is that the power loss per unit length is greater than in air-insulated lines. Power is lost in heating of the dielectric, and if the heating is great enough (as it may be with high power and a high SWR) the line may break down mechanically and electrically.

23.3.1 AIR-INSULATED LINES

A typical construction technique used for parallel conductor or "two-wire" air-insulated transmission lines is shown in **Figure 23.19**. The two wires are supported a fixed distance apart by means of insulating rods called spacers. Spacers may be made from material such as Teflon, Plexiglas, phenolic, polystyrene, plastic clothespins or plastic hair curlers. Materials commonly used in high-quality spacers are isolantite or Steatite, Lucite and polystyrene. (Teflon is generally not used because of its higher cost.) The spacer length varies from 2 to 6 inches. Smaller spacings are desirable at higher frequencies (28 MHz and above) so radiation from the transmission line is minimized.

Spacers must be used at small enough intervals along

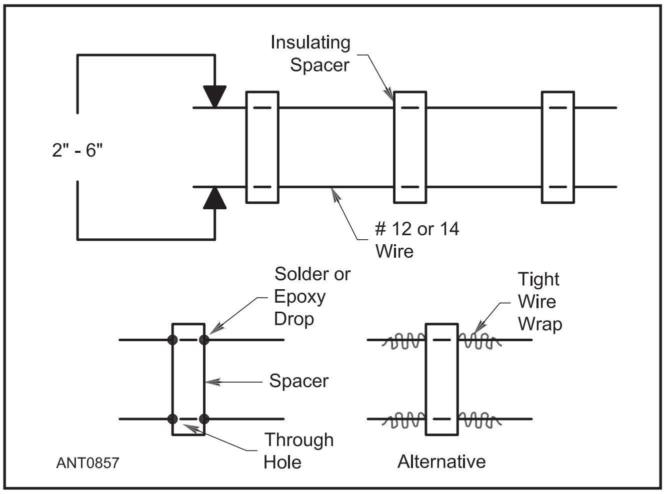


Figure 23.19 — Typical open-wire line construction. The spacers may be held in place by beads of solder or epoxy cement. Wire wraps can also be used, as shown.

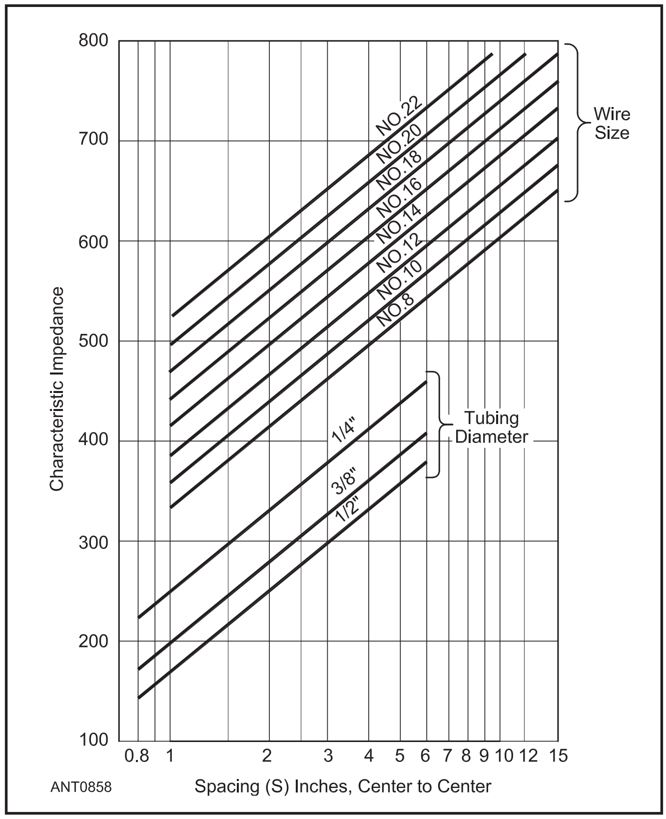


Figure 23.20 — Characteristic impedance as a function of conductor spacing and size for parallel conductor lines.

the line to keep the two wires from moving appreciably with respect to each other. For amateur purposes, lines using this construction ordinarily have #12 AWG or #14 AWG conductors, and the characteristic impedance is between 500 to 600 Ω. Although once used nearly exclusively, such homemade lines are enjoying a renaissance of sorts because of their high efficiency and low cost.

Where an air-insulated line with still lower characteristic impedance is needed, metal tubing from ¼ to ½-inch diameter is frequently used. With the larger conductor diameter and relatively close spacing, it is possible to build a line having a characteristic impedance as low as about 200 Ω. This construction technique is principally used for λ/4 matching transformers at the higher frequencies.

The characteristic impedance of an air-insulated parallel conductor line, neglecting the effect of the spacers, is given by

$$Z_0 = 120 \cosh^{-1}\left(\frac{S}{d}\right) = 276 \log\left[\frac{S}{d} + \sqrt{\left(\frac{D}{d}\right)^2 - 1}\right] \quad \text{(Eq 31A)}$$

where

Z_0 = characteristic impedance in ohms
S = center-to-center distance between conductors
d = outer diameter of conductor (in the same units as S)

An approximation that can be used when S >> d is:

$$Z_0 = 276 \log\left(\frac{2S}{d}\right) \quad \text{(Eq 31B)}$$

The error of the approximation becomes significant for S/d < 3. A useful identity for working with the $\cosh^{-1}$ or acosh function encountered in transmission line calculations is:

$$\cosh^{-1}(x) = \ln\left(x + \sqrt{x^2 - 1}\right)$$

The inverse hyperbolic cosine (cosh) is sometimes accessed on calculators by using the INV (inverse) key before COSH.

Impedances for common sizes of conductors over a range of spacings are given in **Figure 23.20**.

Four-Wire Lines

Another parallel conductor line that is useful in some applications is the four-wire line (**Figure 23.21C**). In cross section, the conductors of the four-wire line are at the corners of a square. Spacings are on the same order as those used in two-wire lines. The conductors at opposite corners of the square are connected to operate in parallel. This type of line has a lower characteristic impedance than the simple two-wire type. Also, because of the more symmetrical construction, it has better electrical balance to ground and other objects that are close to the line. The spacers for a four-wire line may be discs of insulating material, X-shaped members, etc.

Air-Insulated Coaxial Lines

In air-insulated coaxial lines (Figure 23.21D), a considerable proportion of the insulation between conductors may actually be a solid dielectric, because the separation between the inner and outer conductors must be constant. This is particularly likely to be true in small diameter lines. The inner conductor, usually a solid copper wire, is supported at the center of the copper tubing outer conductor by insulating beads or a helically wound strip of insulating material. The beads are usually are isolantite or Steatite, and the wire is generally crimped on each side of each bead to prevent

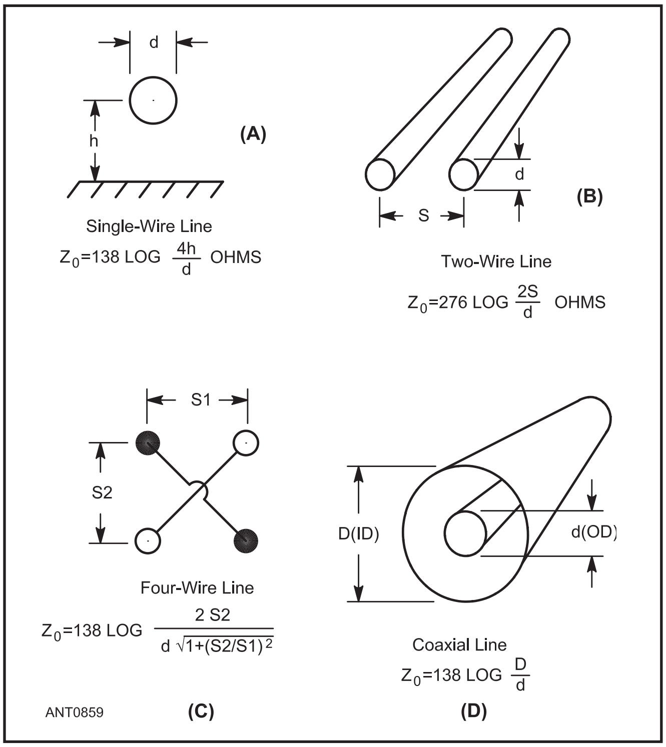


Figure 23.21 — Construction of air-insulated transmission lines.

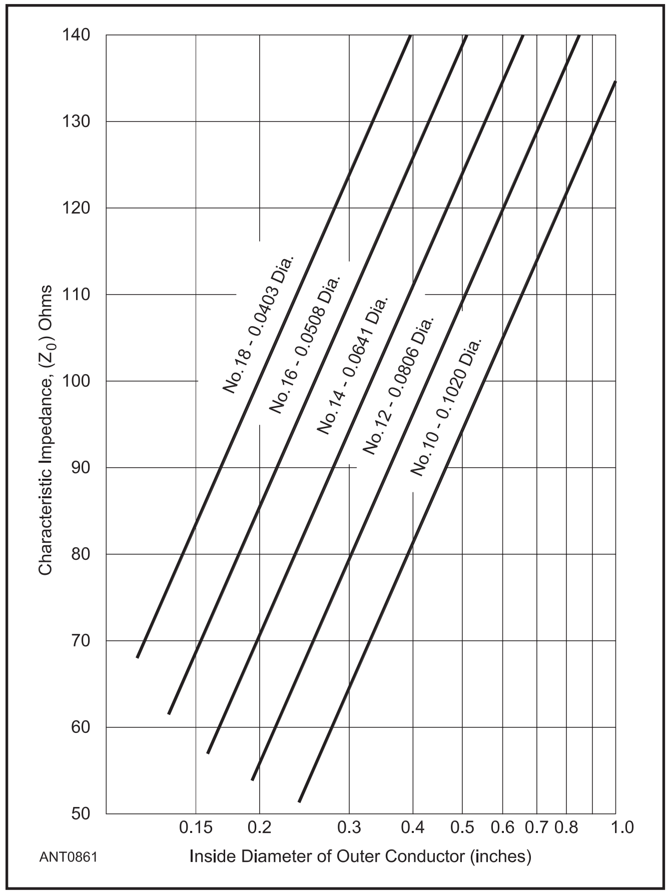


Figure 23.22 — Characteristic impedance of typical air insulated coaxial lines.

the beads from sliding. The material of which the beads are made, and the number of beads per unit length of line, will affect the characteristic impedance of the line. The greater the number of beads in a given length, the lower the characteristic impedance compared with the value obtained with air insulation only. Teflon is ordinarily used as a helically wound support for the center conductor. A tighter helical winding lowers the characteristic impedance.

The presence of the solid dielectric also increases the losses in the line. On the whole, however, a coaxial line of this type tends to have lower actual loss, at frequencies up to about 100 MHz, than any other line construction, provided the air inside the line can be kept dry. This usually means that air-tight seals must be used at the ends of the line and at every joint. The characteristic impedance of an air-insulated coaxial line is given by

$$Z_0 = 138 \log \frac{D}{d} \qquad \text{(Eq 32)}$$

where

Z_0 = characteristic impedance in ohms
D = inside diameter of outer conductor
d = outside diameter of inner conductor (in same units as D)

Values for typical conductor sizes are graphed in **Figure 23.22**. The equation and the graph for coaxial lines are approximately correct for lines in which bead spacers are used, provided the beads are not too closely spaced.

23.3.2 PARALLEL-CONDUCTOR LINES

The construction of a number of types of flexible line is shown in **Figure 23.23**. In the most common 300-Ω type (twin-lead), the conductors are stranded wire equivalent to #20 AWG in cross-sectional area, and are molded in the edges of a polyethylene ribbon about ½-inch wide that keeps the wires spaced a constant amount away from each other. The effective dielectric is partly solid and partly air, and the presence of the solid dielectric lowers the characteristic impedance of the line as compared with the same conductors in air. The resulting impedance is approximately 300 Ω.

Because part of the field between the conductors exists outside the solid dielectric, dirt and moisture on the surface of the ribbon tend to change the characteristic impedance of the line. The operation of the line is therefore affected by weather conditions. The effect will not be very serious in a line terminated in its characteristic impedance, but if there is a considerable mismatch, a small change in Z_0 may cause wide fluctuations of the input impedance. Weather effects can be minimized by cleaning the line occasionally and giving it a thin coating of a water repellent material such as silicone grease or car wax.

To overcome the effects of weather on the characteristic impedance and attenuation of ribbon type line, another type of twin-lead is made using an oval polyethylene tube with

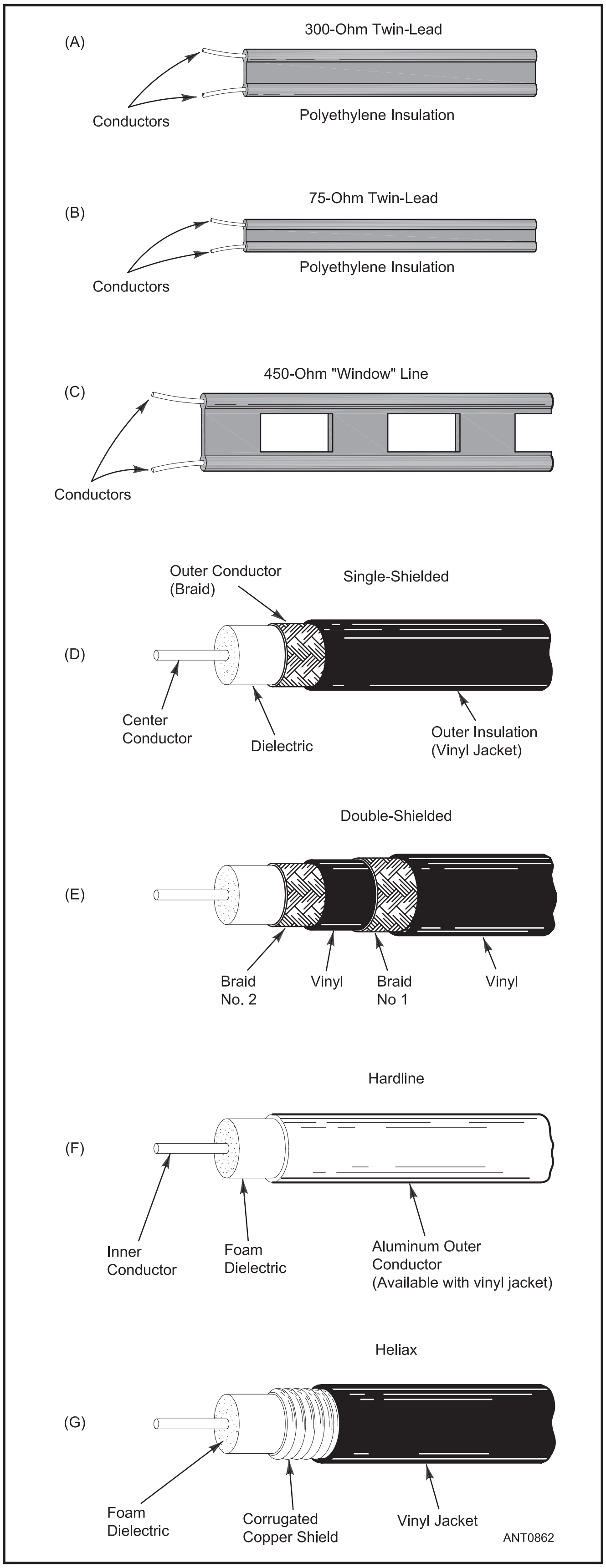


Figure 23.23 — Construction of flexible parallel conductor and coaxial lines with solid dielectric. A common variation of the double shielded design at E has the braids in continuous electrical contact.

an air core or a foamed dielectric core. The conductors are molded diametrically opposite each other in the walls. This increases the leakage path across the dielectric surface. Also, much of the electric field between the conductors is in the hollow (or foam-filled) center of the tube. This type of line is fairly impervious to weather effects. Care should be used when installing it, however, so any moisture that condenses on the inside with changes in temperature and humidity can drain out at the bottom end of the tube and not be trapped in one section. This type of line is made in two conductor sizes (with different tube diameters), one for receiving applications and the other for transmitting.

Transmitting type 75-Ω twin lead uses stranded conductors nearly equivalent to solid #12 AWG wire, with quite close spacing between conductors. Because of the close spacing, most of the field is confined to the solid dielectric, with very little existing in the surrounding air. This makes the 75-Ω line much less susceptible to weather effects than the 300-Ω ribbon type. The 75 Ω twinlead is becoming increasingly uncommon.

A third type of commercial parallel-line is so-called *window line*, illustrated in Figure 23.23C. This is a variation of twin-lead construction, except that *windows* are cut in the polyethylene insulation at regular intervals. This holds down on the weight of the line, and also breaks up the amount of surface area where dirt, dust and moisture can accumulate. Such window line is commonly available with a nominal characteristic impedance of 450 Ω, although 300-Ω line can be found also. A conductor spacing of about 1 inch is used in the 450-Ω line and ½ inch in the 300-Ω line. The conductor size is usually about #18 AWG. The impedances of such lines are somewhat lower than given by Figure 23.20 for the same conductor size and spacing, because of the effect of the dielectric constant of the spacer material used. The attenuation is quite low and lines of this type are entirely satisfactory for transmitting applications at amateur power levels.

23.3.3 COAXIAL CABLES

Coaxial cable is available in flexible and semi-flexible varieties. The fundamental design is the same in all types, as shown in Figure 23.23. The outer diameter varies from 0.06 inch to over 5 inches. Power handling capability and cable size are directly proportional, as larger dielectric thickness and larger conductor sizes can handle higher voltages and currents. Generally, losses decrease as cable diameter increases. The extent to which this is true is dependent on the properties of the insulating material.

Some coaxial cables have stranded wire center conductors while others use a solid copper conductor. Similarly, the outer conductor (shield) may be a single layer of copper braid, a double layer of braid (more effective shielding), solid aluminum (hardline and Heliax), aluminum foil or aluminized mylar, or a combination of these.

Voltage, Power and Loss Specifications

Selection of the correct coaxial cable for a particular application is not a casual matter. Not only is the attenuation

Table 23.1

Nominal Characteristics of Commonly Used Transmission Lines

RG or Type	*Part Number*	*Nom. Z_0 Ω*	*VF %*	*Cap. pF/ft*	*Cent. Cond. AWG*	*Diel. Type*	*Shield Type*	*Jacket Matl*	*OD inches*	*Max V (RMS)*	*Matched Loss (dB/100') 1 MHz*	*10*	*100*	*1000*
RG-6	Belden 1694A	75	82	16.2	#18 Solid BC	FPE	FC	P1	0.275	300	0.3	.7	1.8	5.9
RG-6	Belden 8215	75	66	20.5	#21 Solid CCS	PE	D	PE	0.332	2700	0.4	0.8	2.7	9.8
RG-8	Belden 7810A	50	86	23.0	#10 Solid BC	FPE	FC	PE	0.405	300	0.1	0.4	1.2	4.0
RG-8	TMS LMR400	50	85	23.9	#10 Solid CCA	FPE	FC	PE	0.405	600	0.1	0.4	1.3	4.1
RG-8	Belden 9913	50	84	24.6	#10 Solid BC	ASPE	FC	P1	0.405	300	0.1	0.4	1.3	4.5
RG-8	CXP1318FX	50	84	24.0	#10 Flex BC	FPE	FC	P2N	0.405	600	0.1	0.4	1.3	4.5
RG-8	Belden 9913F	50	83	24.6	#11 Flex BC	FPE	FC	P1	0.405	300	0.2	0.6	1.5	4.8
RG-8	Belden 9914	50	82	24.8	#10 Solid BC	FPE	FC	P1	0.405	300	0.2	0.5	1.5	4.8
RG-8	TMS LMR400UF	50	85	23.9	#10 Flex BC	FPE	FC	PE	0.405	600	0.1	0.4	1.4	4.9
RG-8	DRF-BF	50	84	24.5	#9.5 Flex BC	FPE	FC	PE	0.405	600	0.1	0.5	1.6	5.2
RG-8	WM CQ106	50	84	24.5	#9.5 Flex BC	FPE	FC	P2N	0.405	600	0.2	0.6	1.8	5.3
RG-8	CXP008	50	78	26.0	#13 Flex BC	FPE	S	P1	0.405	600	0.1	0.5	1.8	7.1
RG-8	Belden 8237	52	66	29.5	#13 Flex BC	PE	S	P1	0.405	3700	0.2	0.6	1.9	7.4
RG-8X	Belden 7808A	50	86	23.5	#15 Solid BC	FPE	FC	PE	0.240	300	0.2	0.7	2.3	7.4
RG-8X	TMS LMR240	50	84	24.2	#15 Solid BC	FPE	FC	PE	0.242	300	0.2	0.8	2.5	8.0
RG-8X	WM CQ118	50	82	25.0	#16 Flex BC	FPE	FC	P2N	0.242	300	0.3	0.9	2.8	8.4
RG-8X	TMS LMR240UF	50	84	24.2	#15 Flex BC	FPE	FC	PE	0.242	300	0.2	0.8	2.8	9.6
RG-8X	Belden 9258	50	82	24.8	#16 Flex BC	FPE	S	P1	0.242	300	0.3	0.9	3.2	11.2
RG-8X	CXP08XB	50	80	25.3	#16 Flex BC	FPE	S	P1	0.242	300	0.3	1.0	3.1	14.0
RG-9	Belden 8242	51	66	30.0	#13 Flex SPC	PE	SCBC	P2N	0.420	5000	0.2	0.6	2.1	8.2
RG-11	Belden 8213	75	84	16.1	#14 Solid BC	FPE	S	PE	0.405	300	0.1	0.4	1.3	5.2
RG-11	Belden 8238	75	66	20.5	#18 Flex TC	PE	S	P1	0.405	300	0.2	0.7	2.0	7.1
RG-58	Belden 7807A	50	85	23.7	#18 Solid BC	FPE	FC	PE	0.195	300	0.3	1.0	3.0	9.7
RG-58	TMS LMR200	50	83	24.5	#17 Solid BC	FPE	FC	PE	0.195	300	0.3	1.0	3.2	10.5
RG-58	WM CQ124	52	66	28.5	#20 Solid BC	PE	S	PE	0.195	1400	0.4	1.3	4.3	14.3
RG-58	Belden 8240	52	66	29.9	#20 Solid BC	PE	S	P1	0.193	1400	0.3	1.1	3.8	14.5
RG-58A	Belden 8219	53	73	26.5	#20 Flex TC	FPE	S	P1	0.195	300	0.4	1.3	4.5	18.1
RG-58C	Belden 8262	50	66	30.8	#20 Flex TC	PE	S	P2N	0.195	1400	0.4	1.4	4.9	21.5
RG-58A	Belden 8259	50	66	30.8	#20 Flex TC	PE	S	P1	0.192	1400	0.5	1.5	5.4	22.8
RG-59	Belden 1426A	75	83	16.3	#20 Solid BC	FPE	S	P1	0.242	300	0.3	0.9	2.6	8.5
RG-59	CXP 0815	75	82	16.2	#20 Solid BC	FPE	S	P1	0.232	300	0.5	0.9	2.2	9.1
RG-59	Belden 8212	75	78	17.3	#20 Solid CCS	FPE	S	P1	0.242	300	0.2	1.0	3.0	10.9
RG-59	Belden 8241	75	66	20.4	#23 Solid CCS	PE	S	P1	0.242	1700	0.6	1.1	3.4	12.0
RG-62A	Belden 9269	93	84	13.5	#22 Solid CCS	ASPE	S	P1	0.240	750	0.3	0.9	2.7	8.7
RG-62B	Belden 8255	93	84	13.5	#24 Flex CCS	ASPE	S	P2N	0.242	750	0.3	0.9	2.9	11.0
RG-63B	Belden 9857	125	84	9.7	#22 Solid CCS	ASPE	S	P2N	0.405	750	0.2	0.5	1.5	5.8
RG-83	WM165	35	66	44.0	#10 Solid BC	PE	S	P2	0.405	2000	0.23	0.8	2.8	9.6
RG-142	CXP 183242	50	69.5	29.4	#19 Solid SCCS	TFE	D	FEP	0.195	1900	0.3	1.1	3.8	12.8
RG-142B	Belden 83242	50	69.5	29.0	#19 Solid SCCS	TFE	D	TFE	0.195	1400	0.3	1.1	3.9	13.5
RG-174	Belden 7805R	50	73.5	26.2	#25 Solid BC	FPE	FC	P1	0.110	300	0.6	2.0	6.5	21.3
RG-174	Belden 8216	50	66	30.8	#26 Flex CCS	PE	S	P1	0.110	1100	0.8	2.5	8.6	33.7
RG-213	Belden 8267	50	66	30.8	#13 Flex BC	PE	S	P2N	0.405	3700	0.2	0.6	2.1	8.0
RG-213	CXP213	50	66	30.8	#13 Flex BC	PE	S	P2N	0.405	600	0.2	0.6	2.0	8.2
RG-214	Belden 8268	50	66	30.8	#13 Flex SPC	PE	D	P2N	0.425	3700	0.2	0.7	2.2	8.0
RG-216	Belden 9850	75	66	20.5	#18 Flex TC	PE	D	P2N	0.425	3700	0.2	0.7	2.0	7.1
RG-217	WM CQ217F	50	66	30.8	#10 Flex BC	PE	D	PE	0.545	7000	0.1	0.4	1.4	5.2
RG-217	M17/78-RG217	50	66	30.8	#10 Solid BC	PE	D	P2N	0.545	7000	0.1	0.4	1.4	5.2
RG-218	M17/79-RG218	50	66	29.5	#4.5 Solid BC	PE	S	P2N	0.870	11000	0.1	0.2	0.8	3.4
RG-223	Belden 9273	50	66	30.8	#19 Solid SPC	PE	D	P2N	0.212	1400	0.4	1.2	4.1	14.5
RG-303	Belden 84303	50	69.5	29.0	#18 Solid SCCS	TFE	S	TFE	0.170	1400	0.3	1.1	3.9	13.5

RG-8, RG-213 and Type Cables

The most common coax used for amateur applications is RG-8/U — a 50-Ω cable approximately 0.4 inch in diameter, with solid or foamed polyethylene center insulation, and capable of handling full legal power. A close second to RG-8/U is RG-213/U, also a 50-Ω cable and nearly identical. The two cable types are almost identical as seen in Table 23.1, but RG-213/U is slightly lossier than RG-8.

Many amateurs are unaware that RG-8/U is an obsolete military specification designation, meaning that the part number RG-8/U does not confer any particular level of quality or performance on the cable. RG-213/U, on the other hand, is a current military designation that can only be used for cables manufactured to the military specification for that cable, both for materials as well as manufacturing processes. This results in a more consistent product.

It is also common for manufacturers to add "type" after a military specification label, such as "RG-8 Type" or "RG-213 Type". This means that the cable has much the same performance characteristics as the "non-type" cable but is not guaranteed to meet that higher level of performance.

Should you decide to use RG-8/U or a "type" cable, read the specifications carefully. The *shield coverage* (the percentage of the center insulator covered by the copper braid shield) should be from 95 to 97% for a high-quality cable. You should not be able to easily see the center insulation through holes in the shield.

Another advantage of RG-213/U is that the jacket is made from non-contaminating PVC and many types of RG-213/U are rated for direct burial.

RG or Type	Part Number	Nom. Z_0 Ω	VF %	Cap. pF/ft	Cent. Cond. AWG	Diel. Type	Shield Type	Jacket Matl	OD inches	Max V (RMS)	Matched Loss (dB/100') 1 MHz	10	100	1000
RG-316	CXP TJ1316	50	69.5	29.4	#26 Flex BC	TFE	S	FEP	0.098	1200	1.2	2.7	8.0	26.1
RG-316	Belden 84316	50	69.5	29.0	#26 Flex SCCS	TFE	S	FEP	0.096	900	0.8	2.5	8.3	26.0
RG-393	M17/127-RG393	50	69.5	29.4	#12 Flex SPC	TFE	D	FEP	0.390	5000	0.2	0.5	1.7	6.1
RG-400	M17/128-RG400	50	69.5	29.4	#20 Flex SPC	TFE	D	FEP	0.195	1400	0.4	1.3	4.3	15.0
LMR500	TMS LMR500UF	50	85	23.9	#7 Flex BC	FPE	FC	PE	0.500	2500	0.1	0.4	1.2	4.0
LMR500	TMS LMR500	50	85	23.9	#7 Solid CCA	FPE	FC	PE	0.500	2500	0.1	0.3	0.9	3.3
LMR600	TMS LMR600	50	86	23.4	#5.5 Solid CCA	FPE	FC	PE	0.590	4000	0.1	0.2	0.8	2.7
LMR600	TMS LMR600UF	50	86	23.4	#5.5 Flex BC	FPE	FC	PE	0.590	4000	0.1	0.2	0.8	2.7
LMR1200	TMS LMR1200	50	88	23.1	#0 Copper Tube	FPE	FC	PE	1.200	4500	0.04	0.1	0.4	1.3
Hardline														
1/2"	CATV Hardline	50	81	25.0	#5.5 BC	FPE	SM	none	0.500	2500	0.05	0.2	0.8	3.2
1/2"	CATV Hardline	75	81	16.7	#11.5 BC	FPE	SM	none	0.500	2500	0.1	0.2	0.8	3.2
7/8"	CATV Hardline	50	81	25.0	#1 BC	FPE	SM	none	0.875	4000	0.03	0.1	0.6	2.9
7/8"	CATV Hardline	75	81	16.7	#5.5 BC	FPE	SM	none	0.875	4000	0.03	0.1	0.6	2.9
LDF4-50A	Heliax – ½"	50	88	25.9	#5 Solid BC	FPE	CC	PE	0.630	1400	0.02	0.2	0.6	2.4
LDF5-50A	Heliax – ⅞"	50	88	25.9	0.355" BC	FPE	CC	PE	1.090	2100	0.03	0.10	0.4	1.3
LDF6-50A	Heliax – 1¼"	50	88	25.9	0.516" BC	FPE	CC	PE	1.550	3200	0.02	0.08	0.3	1.1
Parallel Lines														
TV Twinlead (Belden 9085)		300	80	4.5	#22 Flex CCS	PE	none	P1	0.400	**	0.1	0.3	1.4	5.9
Twinlead (Belden 8225)		300	80	4.4	#20 Flex BC	PE	none	P1	0.400	8000	0.1	0.2	1.1	4.8
Generic Window Line		450	91	2.5	#18 Solid CCS	PE	none	P1	1.000	10000	0.02	0.08	0.3	1.1
WM CQ 554		440	91	2.7	#14 Flex CCS	PE	none	P1	1.000	10000	0.04	0.01	0.6	3.0
WM CQ 552		440	91	2.5	#16 Flex CCS	PE	none	P1	1.000	10000	0.05	0.2	0.6	2.6
WM CQ 553		450	91	2.5	#18 Flex CCS	PE	none	P1	1.000	10000	0.06	0.2	0.7	2.9
WM CQ 551		450	91	2.5	#18 Solid CCS	PE	none	P1	1.000	10000	0.05	0.02	0.6	2.8
Open-Wire Line		600	0.95-99***	1.7	#12 BC	none	none	none	**	12000	0.02	0.06	0.2	—

Approximate Power Handling Capability (1:1 SWR, 40°C Ambient):

	1.8 MHz	7	14	30	50	150	220	450	1 GHz
RG-58 Style	1350	700	500	350	250	150	120	100	50
RG-59 Style	2300	1100	800	550	400	250	200	130	90
RG-8X Style	1830	840	560	360	270	145	115	80	50
RG-8/213 Style	5900	3000	2000	1500	1000	600	500	350	250
RG-217 Style	20000	9200	6100	3900	2900	1500	1200	800	500
LDF4-50A	38000	18000	13000	8200	6200	3400	2800	1900	1200
LDF5-50A	67000	32000	22000	14000	11000	5900	4800	3200	2100
LMR500	18000	9200	6500	4400	3400	1900	1600	1100	700
LMR1200	52000	26000	19000	13000	10000	5500	4500	3000	2000

Legend:

**	Not Available or varies	N	Non-Contaminating
***	Varies with spacer material and spacing	P1	PVC, Class 1
ASPE	Air Spaced Polyethylene	P2	PVC, Class 2
BC	Bare Copper	PE	Polyethylene
CC	Corrugated Copper	S	Single Braided Shield
CCA	Copper Cover Aluminum	SC	Silver Coated Braid
CCS	Copper Covered Steel	SCCS	Silver Plated Copper Coated Steel
CXP	Cable X-Perts, Inc.	SM	Smooth Aluminum
D	Double Copper Braids	SPC	Silver Plated Copper
DRF	Davis RF	TC	Tinned Copper
FC	Foil + Tinned Copper Braid	TFE	Teflon®
FEP	Teflon ® Type IX	TMS	Times Microwave Systems
Flex	Flexible Stranded Wire	UF	Ultra Flex
FPE	Foamed Polyethylene	WM	Wireman
Heliax	Andrew Corp Heliax		

loss of significance, but breakdown and heating (voltage and power) also need to be considered. If a cable were lossless, the power handling capability would be limited only by the breakdown voltage. There are two types of power ratings: *peak power* and *average power*. The peak power rating is limited by a voltage breakdown between the inner and outer conductors and is independent of frequency. The average power rating is governed by the safe long-term operating temperature of the dielectric material and decreases as the frequency increases.

The power handling capability and loss characteristics of coaxial cable depend largely on the dielectric material between the conductors and the size of the conductors. The commonly used cables and many of their properties are listed in **Table 23.1**. The pertinent characteristics of unmarked coaxial cables can be determined from the equations in **Table 23.2**. The most common impedance values are 50, 75 and 95 Ω. However, impedances from 25 to 125 Ω are available in special types of manufactured line. The 25-Ω cable (miniature) is used extensively in magnetic-core broadband transformers.

In practical coaxial cables the copper and dielectric losses, rather than breakdown voltage, limit the maximum power than can be accommodated. If 1000 W is applied to a cable having a loss of 3 dB, only 500 W is delivered to the load. The remaining 500 W must be dissipated in the cable. The dielectric and outer jacket are good thermal insulators, which prevent the conductors from efficiently transferring the heat to free air. As a result the cable can heat up, softening the plastic insulation and allowing the geometry of

Table 23.2
Coaxial Cable Equations

$$C\ (\text{pF/foot}) = \frac{7.26\varepsilon}{\log(D/d)} \quad \text{(Eq A)}$$

$$L\ (\mu\text{H/foot}) = 0.14 \log \frac{D}{d} \quad \text{(Eq B)}$$

$$Z_0\ (\text{ohms}) = \sqrt{\frac{L}{C}} = \left(\frac{138}{\sqrt{\varepsilon}}\right)\left(\log \frac{D}{d}\right) \quad \text{(Eq C)}$$

$$\text{VF \% (velocity factor, ref. speed of light)} = \frac{100}{\sqrt{\varepsilon}} \quad \text{(Eq D)}$$

$$\text{Time delay (ns/foot)} = 1.016\sqrt{\varepsilon} \quad \text{(Eq E)}$$

$$f\ (\text{cutoff/GHz}) = \frac{7.50}{\sqrt{\varepsilon}\,(D+d)} \quad \text{(Eq F)}$$

$$\text{Reflection Coefficient} = |\rho| = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\text{SWR}-1}{\text{SWR}+1} \quad \text{(Eq G)}$$

$$\text{Return Loss (dB)} = -20 \log |\rho| \quad \text{(Eq H)}$$

$$\text{SWR} = \frac{1+|\rho|}{1-|\rho|} \quad \text{(Eq I)}$$

$$V\ \text{peak} = \frac{(1.15\ S\ d)(\log D/d)}{K} \quad \text{(Eq J)}$$

$$A = \frac{0.435}{Z_0 D}\left(\frac{D}{d}(K1+K2)\right)\sqrt{f} + 2.78\sqrt{\varepsilon}\,(PF)(f) \quad \text{(Eq K)}$$

where
- A = attenuation in dB/100 foot
- d = OD of inner conductor
- D = ID of outer conductor
- S = max voltage gradient of insulation in volts/mil
- ε = dielectric constant
- K = safety factor
- K1 = strand factor
- K2 = braid factor
- f = freq in MHz
- PF = power factor

Note: Obtain K1 and K2 data from manufacturer.

the conductors and the characteristic impedance to change or even short-circuit. Many amateur transmitter duty cycles are so low that substantial overload is permissible on current peaks so long as the SWR is relatively low, such as less than 2:1. **Figure 23.24** is a graph of the matched-line attenuation characteristics versus frequency for the most popular lines

A cable with a solid dielectric will handle higher power than a cable with a foam dielectric. RG-8/U with a solid dielectric will handle 5000 V maximum while the same cable with foam dielectric only has a 600 V rating. In addition, heating of the center conductor from cable loss can soften the center insulation. If the cable is heated while bent or wound into a coil, the center conductor can migrate through the insulation and change the cable's characteristic impedance or short to the outer shield. This is a particular problem for cables with foam insulation. When winding cables into a coil or bending them around corners, be sure that the bending radius is larger than the *minimum bending radius* specified for the cable.

As the operating frequency increases, the power-handling capability of a cable decreases because of increasing conductor loss (skin effect) and dielectric loss. RG-58 with foam dielectric has a breakdown rating of only 300 V, yet it can handle substantially more power than its ordinary solid dielectric counterpart because of the lower losses. Normally, the loss is inconsequential (except as it affects power handling capability) below 10 MHz in amateur applications. This is true unless extremely long runs of cable are used.

In general, full legal amateur power can be safely applied to inexpensive RG-58 coax in the bands below 10 MHz. RG-8 and similar cables can withstand full amateur power through the VHF spectrum, but connectors must be carefully chosen in these applications. Connector choice is discussed in a later section.

Excessive RF operating voltage in a coaxial cable can cause noise generation, dielectric damage and eventual breakdown between the conductors.

Deterioration

Deterioration of coaxial cable is most commonly caused by water or moisture infiltration which causes corrosion of the shield, dramatically increasing its losses. This usually occurs at the ends of cables where connectors are installed or the cable is separated into two conductors for attachment to an antenna.

Exposure of the inner insulating material to moisture and chemicals over time contaminates the center insulation and increases cable losses. Newer types of foam-dielectric cables are less prone to contamination than are older types of solid-polyethylene insulated cables.

Impregnated cables, such as Times Wire LMR-400-DB, are immune to water and chemical damage, and may be buried if desired. They also have a self-healing property that is valuable when rodents chew into the line. Cable loss should be checked at least every two years if the cable has been outdoors or buried. See the section on testing transmission lines.

The outer insulating jacket of the cable (usually PVC) is used solely as protection from dirt, moisture and chemicals. (The jacket's only electrical function is compressing the shield braid to keep the strands in good contact with each other.) If the jacket is breached, it generally leads to corrosion of the shield and contamination of the center insulation, again causing high losses.

The ultra-violet (UV) radiation in sunlight causes a chemical reaction in standard PVC jacket material that causes the plastic to break down into products that migrate from the

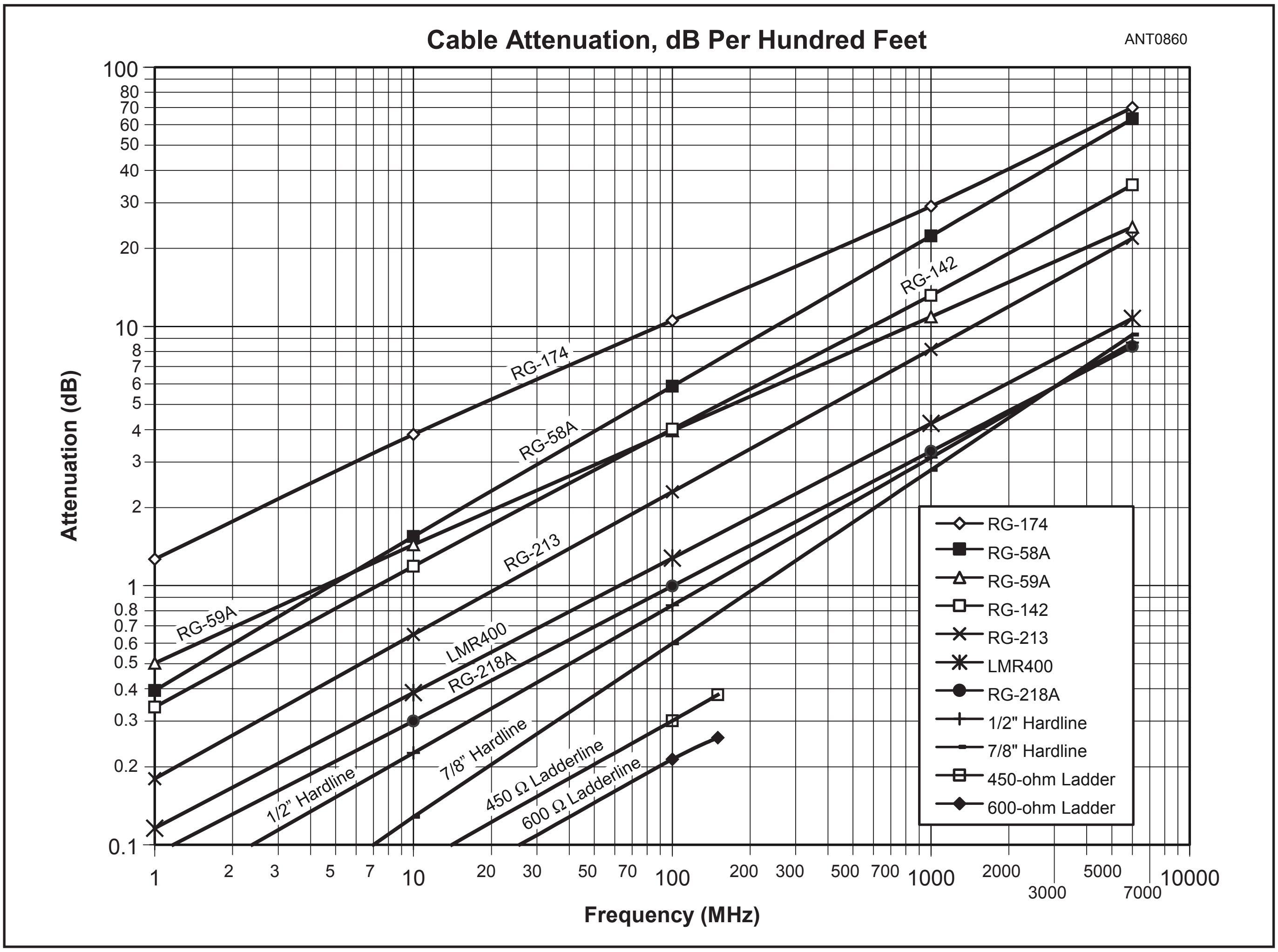


Figure 23.24 — **Nominal matched-line attenuation in decibels per 100 feet of various common transmission lines. Total attenuation is directly proportional to length. Attenuation will vary somewhat in actual cable samples, and generally increases with age in coaxial cables having a type 1 jacket. Cables grouped together in the above chart have approximately the same attenuation. Types having foam polyethylene dielectric have slightly lower loss than equivalent solid types, when not specifically shown above.**

jacket into the braid and center insulation, degrading the electrical properties of both. If your cable will be exposed to strong sunlight, use a cable with a non-contaminating jacket.

Cable Capacitance

The capacitance between the conductors of coaxial cable varies with the impedance and dielectric constant of the line. Therefore, the lower the impedance, the higher the capacitance per foot, because the conductor spacing is decreased. Capacitance also increases with dielectric constant.

Bending Radius

A normal amateur installation will create bends and turns in the feed line run. It is common to wind coax into a coil to form a common-mode RF choke or to store excess cable. Bending coax is acceptable as long as the *minimum bending radius* is not violated. A typical minimum bending radius is a multiple of the coax diameter. For example, a common minimum bending radius specification for RG-8 is 4 inches, which is a multiple of 8 (½ inch OD × 8). Coax with more rigid shield materials such as hardline or Heliax will have a larger bending radius.

If the cable will be subjected to regular flexing, such as if it is attached to a rotating antenna, use a cable with a stranded center conductor. When repeatedly bent or flexed, solid center conductors will develop *metal fatigue* and break.

Paralleled Lines

In order to obtain feed lines with intermediate or unusual characteristic impedances, identical lengths of line with Z_0 can be connected in parallel. The resulting characteristic impedance, $Z_{COMB} = Z_0 / N$, where N is the number of lines in parallel. For example, to create a section of line with $Z_0 = 37.5\ \Omega$, two sections of 75 Ω RG-11 or RG-59 can be connected in parallel to create a λ/4 matching section for a 25 Ω load. Paralleled cables have the same loss as a single cable

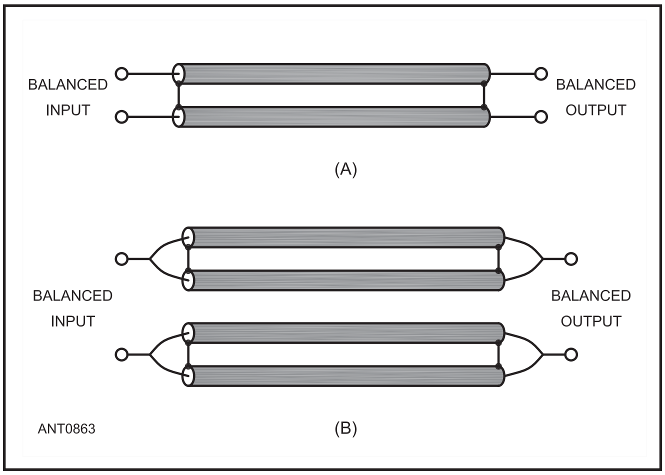


Figure 23.25 — Shielded balanced transmission lines utilizing standard small-size coaxial cable, such as RG-58 or RG-59. These balanced lines may be routed inside metal conduit or near large metal objects without adverse effects.

Waveguide and Microwave Cable

Rigid waveguide is used above 1 GHz and is uncommon below 10 GHz in amateur installations. Amateurs use special low-loss coaxial cables for short runs, along with special connectors such as the SMA family and others developed for consumer use in mobile networks and other microwave systems. The special techniques for working with these transmission lines at microwave frequencies are introduced in the chapter on **VHF and UHF Antenna Systems**.

Other useful references include the RSGB's *International Microwave Handbook* and the ARRL's *UHF/Microwave Experimenter's Manual*, which is out of print but available used. (See the Bibliography.) In addition, *QST*'s "Microwavelengths" column often contains information about working with transmission lines above 1 GHz.

would with an equal degree of mismatch.

Either coaxial or parallel-conductor lines may be combined in parallel. When using paralleled coaxial lines, if standard connectors and adaptors are not used and lines are spliced together, precautions must be taken to maintain shielding at the junctions or RF chokes must be placed on the line to block noise currents on the shield from entering the line and to prevent signals from inside the line escaping to flow on the outside of the shield. If parallel-conductor lines are combined they must be kept well apart (at least one line width) to avoid coupling between the lines.

Shielded Balanced Lines

Shielded balanced lines made from parallel coaxial cables have several advantages over open-wire lines. They can be buried and they can be routed through metal buildings or inside metal piping the same as for single coaxial lines. The outer surface of the shields can pick up noise and common-mode signals just as for single coaxial lines, as well.

The shields are connected together (see **Figure 23.25A**), and the two inner conductors constitute the balanced line. At the input, the coaxial shields should be connected to chassis ground; at the output (the antenna side), they are joined but left floating. (See the previous section's caution about blocking shield current at the open end of the cable.)

The characteristic impedance of a balanced shielded line is twice that of each single line — as if they were in series. Shielded balanced lines having impedances of 140 or 100 Ω can be constructed from two equal lengths of 70-Ω or 50-Ω cable (RG-59 or RG-58 would be satisfactory for amateur power levels). Paralleled RG-63 (125-Ω) cable would make a balanced transmission line more in accord with traditional 300-Ω twin-lead feed line (Z_0 = 250 Ω). Note that the losses for these shielded types of balanced lines will generally be higher than those for classic open-wire lines.

A high power, low-loss, low-impedance 70-Ω (or 50-Ω) balanced line can be constructed from four coaxial cables as in Figure 23.25B. The characteristic impedance of each pair of cables is one-half that of the single lines as described in the previous section. The net result is that the overall characteristic impedance is that of a single cable. Again, the shields are all connected together. The center conductors of the two sets of coaxial cables that are connected in parallel provide the balanced feed.

23.4 RF CONNECTORS

There are many different types of RF connectors for coaxial cable, but the three most common for amateur use are the UHF, Type N and BNC families. Type F connectors are becoming popular for use with receiving antennas and low-loss RG-6 coaxial cable. Type SMA connectors are commonly found on hand-held transceivers and microwave equipment. The type of connector used for a specific job depends on the size of the cable, the frequency of operation and the power levels involved.

If the connector is to be exposed to the weather, select a waterproof design such as Type N or take care to thoroughly waterproof the connector as discussed in the chapter **Building Antenna Systems and Towers.**

23.4.1 UHF CONNECTORS

The so-called UHF connector (the series name is not related to frequency) is found on most HF and some VHF equipment. PL-259 is another name for the UHF male, and the female is also known as the SO-239. These connectors are rated for full legal amateur power at HF and can be used through . They are poor for UHF work because they do not present a constant impedance, so the UHF label is a misnomer. PL-259 connectors are designed to fit RG-8 and RG-11 size cable (0.405-inch OD). Adapters are available for use with smaller RG-58, RG-59 and RG-8X size cable. UHF connectors are not weatherproof.

Figure 23.26 shows how to install the solder type of PL-259 on RG-8 cable. Proper preparation of the cable end is the key to success. Follow these simple steps. Measure back about ¾-inch from the cable end and slightly score the outer jacket around its circumference. With a sharp knife, cut through the outer jacket, through the braid, and through the dielectric — almost to the center conductor. Be careful not to score the center conductor. Cutting through all outer layers at once keeps the braid from separating. (Using a coax stripping tool with preset blade depth makes this and subsequent trimming steps much easier.)

Pull the severed outer jacket, braid and dielectric off the end of the cable as one piece. Inspect the area around the cut, looking for any strands of braid hanging loose and snip them off. There won't be any if your knife was sharp enough. Next, score the outer jacket about 5⁄16-inch back from the first cut. Cut through the jacket lightly; do not score the braid. This step takes practice. If you score the braid, start again. Remove the outer jacket.

Tin the exposed braid and center conductor, but apply the solder sparingly and avoid melting the dielectric. Slide the coupling ring onto the cable. Screw the connector body onto the cable. If you prepared the cable to the right dimensions, the center conductor will protrude through the center pin, the braid will show through the solder holes, and the body will actually thread onto the outer cable jacket. A very small amount of lubricant on the cable jacket will help the threading process.

Solder the braid through the solder holes. Solder through all four holes; poor connection to the braid is the most common form of PL-259 failure. A good connection between connector and braid is just as important as that between the center conductor and connector. Use a large soldering iron for this job. With practice, you'll learn how much heat to use. If you use too little heat, the solder will bead up, not really flowing onto the connector body. If you use too much heat, the dielectric will melt, letting the braid and center conductor touch. Most PL-259s are nickel plated, but silver-plated

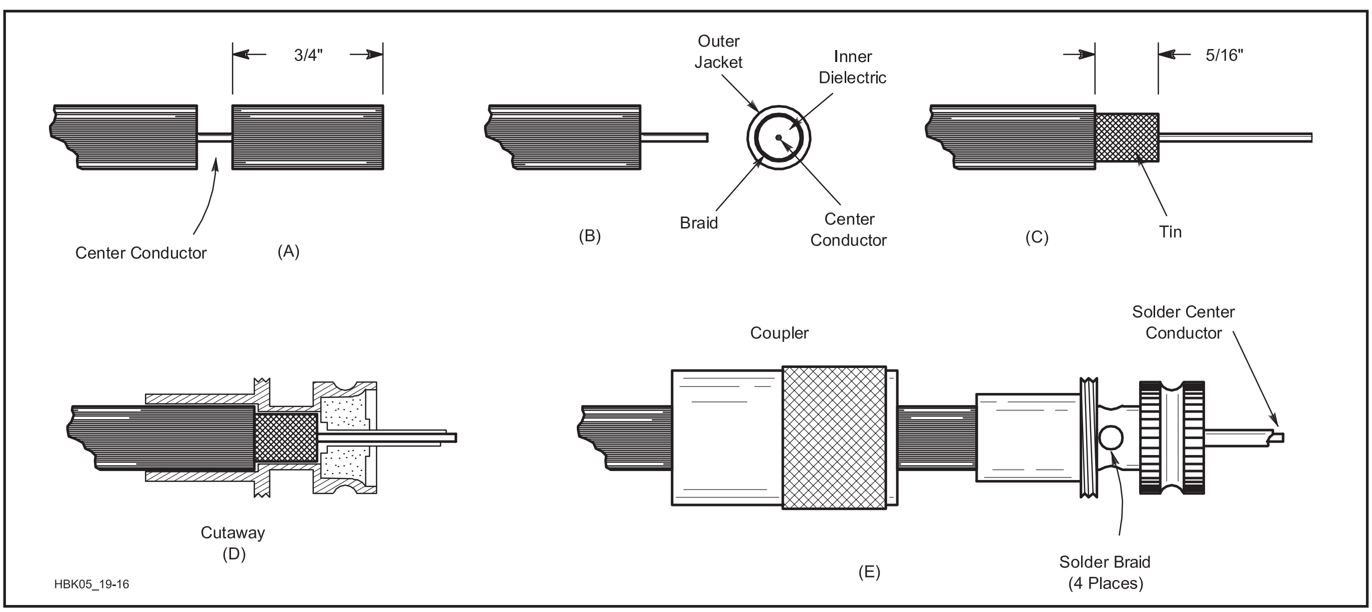
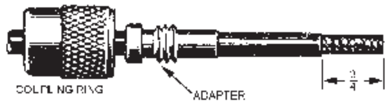
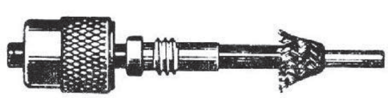


Figure 23.26 — The PL-259 plug of the UHF family of connectors is almost universal for amateur HF use and is popular for equipment operating in the VHF range. Steps A through E are described in detail in the text.

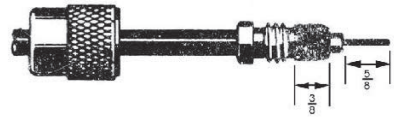
83-1SP (PL-259) Plug with adapters
(UG-176/U OR UG-175/U)



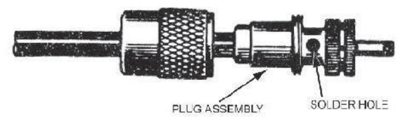
1. Cut end of cable even. Remove vinyl jacket 3/4" - don't nick braid. Slide coupling ring and adapter on cable.



2. Fan braid slightly and fold back over cable.



3. Position adapter to dimension shown. Press braid down over body of adapter and trim to 3/8". Bare 5/8" of conductor. Tin exposed center conductor.



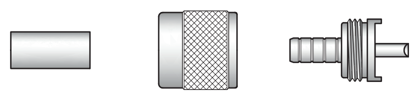
4. Screw the plug assembly on adapter. Solder braid to shell through solder holes. Solder conductor to contact sleeve.

5. Screw coupling ring on plug assembly.

HBK0460

Figure 23.27 — Installing PL-259 plugs on RG-58 or RG-59 cable requires the use of UG-175 or UG-176 reducing adapters, respectively. The adapter screws into the plug body using the threads of the connector to grip the jacket on larger cables. *(Courtesy Amphenol Electronic Components)*

UHF Connectors
Braid Crimp - Solder Center Contact



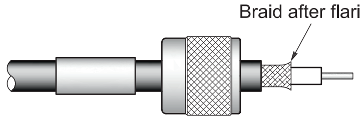
Amphenol	Cable RG-/U	Cable Attachment		Hex Crimp Data			Stripping Dims, inches (mm)		
		Outer	Inner	Cavity for Outer Ferrule	Die Set Tool 227-994	CTL Series Tool No.	a	b	c
83-58SP	58, 141	Crimp	Solder	0.213(5.4)	227-1221-11	CTL-1	1.14 (29.0)	0.780 (19.9)	0.250 (6.4)
83-58SP-1002	400	Crimp	Solder	0.213(5.4)	227-1221-11	CTL-1	1.14 (29.0)	0.780 (19.9)	0.250 (6.4)
83-59DCP-RFX	59	Crimp	Solder	0255(6.5)	227-1221-13	CTL-1	1.22 (30.9)	0.574 (22.6)	0.543 (13.8)
83-58SCP-RFX	58	Crimp	Solder	0.213(5.4)	227-1221-11	CTL-1	1.22 (30.9)	0.574 (22.6)	0.543 (13.8)
83-59SP	59	Crimp	Solder	0.255(6.5)	227-1221-13	CTL-1	1.22 (30.9)	0.574 (22.6)	0.543 (13.8)
83-8SP-RFX	8	Crimp	Solder	0.429(10.9)	227-1221-25	CTL-3	1.22 (30.9)	0.574 (22.6)	0.543 (13.8)

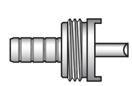
See www.AmphenolRF.com for assembly instructions for all other connectore types. These dimensions only apply to Amphenol connectors and may not be correct for other manufacturers.

Step 1

Step 1 Cut end of cable even. Strip cable to dimensions shown in table. All cuts are to be sharp and square. Do not nick braid, dielectric or center conductor. Tin center conductor avoiding excessive heat.

Step 2

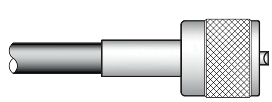




Body assembly

Step 2 Slide coupling nut and ferrule over cable jacket. Flair braid slightly as shown. Install cable into body assembly, so inner ferrule portion slides under braid, until braid butts shoulder. Slide outer ferrule over braid until it butts shoulder. Crimp ferrule with tool and die set indicated in table.

Step 3



Step 3 Soft solder center conductor to contact. Avoid heating contact excessively to prevent damaging insulator. Slide/screw coupling nut over body.

HBK0475

Figure 23.28 — Crimp-on UHF connectors are available for all sizes of popular coaxial cable and save considerable time over soldered connectors. The performance and reliability of these connectors is equivalent to soldered connectors, if crimped properly. *(Courtesy Amphenol Electronic Components)*

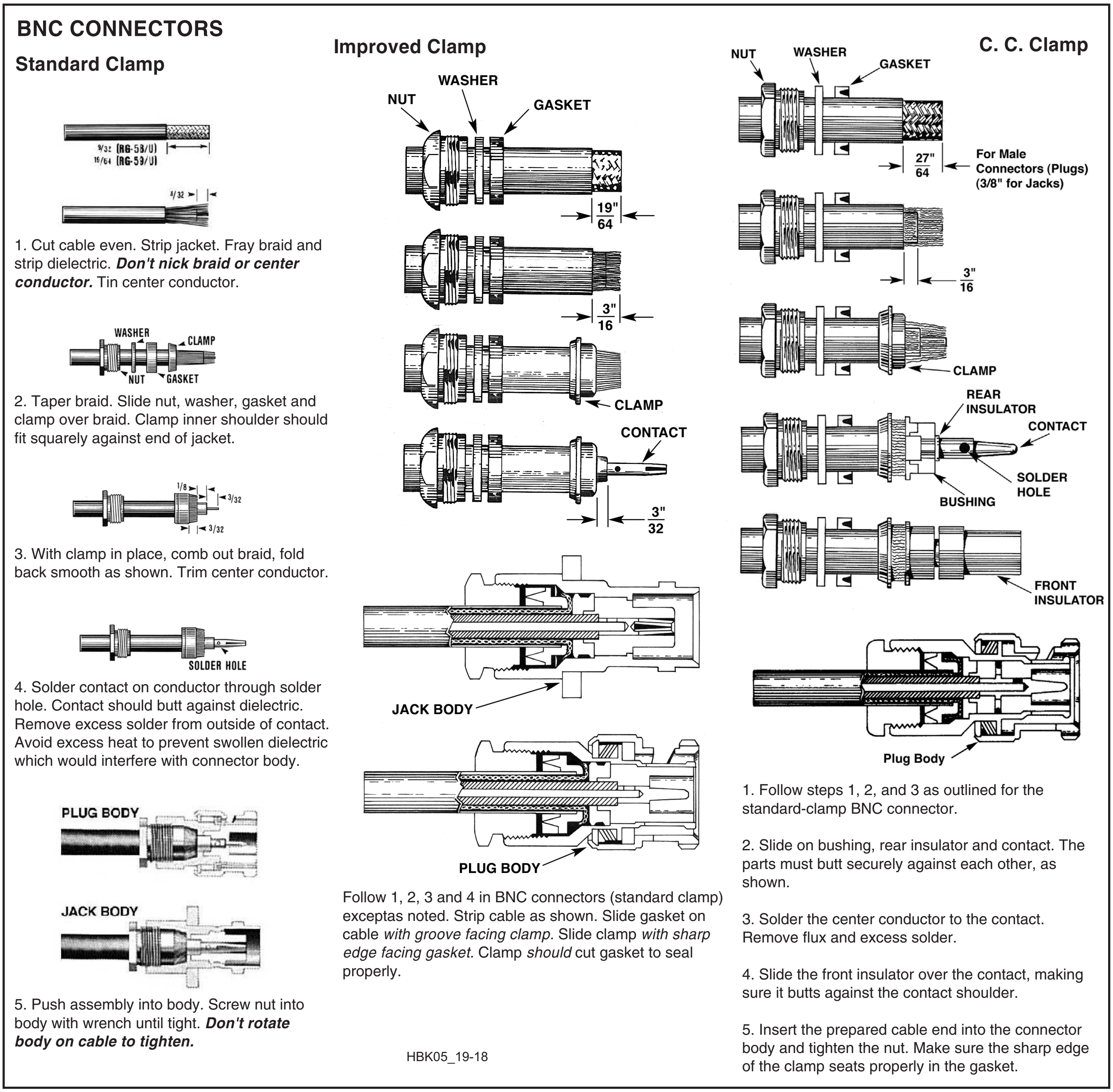


Figure 23.29 — BNC connectors are common on VHF and UHF equipment at low power levels. *(Courtesy Amphenol Electronic Components)*

connectors are much easier to solder and only slightly more expensive.

Solder the center conductor to the center pin. The solder should flow on the inside, not the outside, of the center pin. If you wait until the connector body cools off from soldering the braid, you'll have less trouble with the dielectric melting. Trim the center conductor to be even with the end of the center pin. Use a small file to round the end, removing any solder that built up on the outer surface of the center pin. Use a sharp knife, very fine sandpaper or steel wool to remove any solder flux from the outer surface of the center pin. Screw the coupling ring onto the body, and you're finished.

Figure 23.27 shows how to install a PL-259 connector on RG-58 or RG-59 cable. An adapter is used for the smaller cable with standard RG-8 size PL-259s. (UG-175 for RG-58 and UG-176 for RG-59) Prepare the cable as shown. Once the braid is prepared, screw the adapter into the PL-259 shell and finish the job as you would a PL-259 on RG-8 cable.

Figure 23.28 shows the instructions and dimensions for crimp-on UHF connectors that fit all common sizes of coaxial cable. While amateurs have been reluctant to adopt crimp-on connectors, the availability of good quality connectors and inexpensive crimping tools make crimp technology a good choice, even for connectors used outside. Soldering the center conductor after crimping in the connector tip is optional. UHF connectors are not waterproof and must be waterproofed whether soldered or crimped.

23.4.2 OTHER RF CONNECTORS

BNC Connectors

The BNC connectors illustrated in **Figure 23.29** are popular for low power levels at VHF and UHF. They accept RG-58 and RG-59 cable and are available for cable mounting in both male and female versions. Several different styles are available, so be sure to use the dimensions for the type you have. Follow the installation instructions carefully. If you prepare the cable to the wrong dimensions, the center pin will not seat properly with connectors of the opposite gender. Sharp scissors are a big help for trimming the braid evenly. Crimp-on BNC connectors are also available, with a large number of variations, including a twist-on version. A guide to installing these connectors is available on the CD-ROM accompanying this book.

Type N Connectors

The Type N connector, illustrated in **Figure 23.30**, is a must for high-power VHF and UHF operation. N connectors are available in male and female versions for cable mounting and are designed for RG-8 size cable. Unlike UHF connectors, they are designed to maintain a constant impedance at cable joints. Like BNC connectors, it is important to prepare the cable to the right dimensions. The center pin must be positioned correctly to mate with the center pin of connectors of the opposite gender. Use the right dimensions for the connector style you have. Crimp-on N connectors are also available, again with a large number of variations. A guide to installing these connectors is available on the CD-ROM accompanying this book.

Type F Connectors

Type F connectors, used primarily on cable TV connections, are also popular for receive-only antennas and can be used with RG-59 or the increasingly popular RG-6 cable available at low cost. Crimp-on is the only option for these connectors and **Figure 23.31** shows a general guide for installing them. The exact dimensions vary between connector styles and manufacturers — information on crimping is generally provided with the connectors. There are two styles of crimp — ferrule and compression. The ferrule crimp method is similar to that for UHF, BNC and N connectors in which a metal ring is compressed around the exposed coax shield. The compression crimp forces a bushing into the back of the connector, clamping the shield against the connector body. In all cases, the exposed center conductor of the cable — a solid wire — must end flush with the end of the connector. A center conductor that is too short may not make a good connection.

SMA Connectors

The SMA connector in **Figure 23.32** is the most common microwave connector. The cable center insulation is taken directly to the connector interface without air gaps. A standard SMA is rated for use to 12.4 GHz but high-quality connectors, properly installed, can be used to 24 GHz. For more information about SMA and other microwave connectors, see the Bibliography entry for Williams (the article is also available on this book's CD-ROM).

Hardline Connectors

Surplus hardline cable comes in various sizes (½, ⅝, ¾, 1 inch and so on) that are not compatible with standard RF connectors such as UHF or N. There have been dozens of inventive schemes published over the years that use plumbing hardware or other materials to fabricate an adaptor compatible with a standard connector. If you decide to make your own adapter, be cautious about using dissimilar metals and waterproof the connector carefully. Otherwise, use the recommended connectors from the manufacturer — these are often available as surplus on Internet websites.

Using RG-6 with RG-58 Crimp Connectors

RG-6 coaxial cable is readily and cheaply available as it is commonly used for domestic cable and satellite TV. Crimp-type BNC, N, PL-259 and others are readily obtainable for RG-58 cables. Crimp connectors for RG-6 other than Type F are becoming difficult to find. However RG-58 crimp connectors can be satisfactorily used on RG-6 and some other cables as described on the article by Garth Jenkinson, VK3BBK, on this book's CD-ROM.

23.4.3 CONNECTOR IDENTIFIER AND RANGE CHART

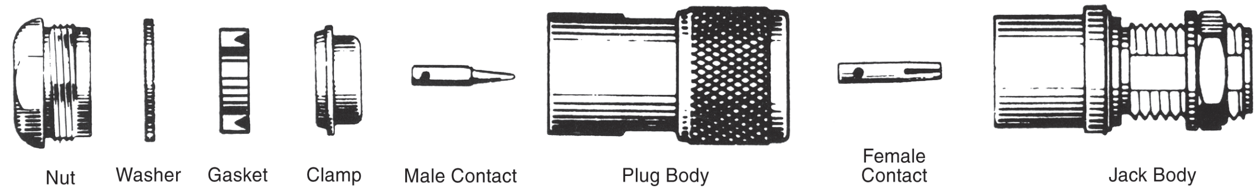
Figure 23.33 provides dimensions and side views to help identify the different types of connectors used for RF through microwave frequencies. Dimensions are provided in both imperial and metric units as appropriate. For mm-wave and microwave connectors, calipers or a micrometer may be required to provide an accurate measurement capable of distinguishing between similar connectors. These specifications are intended for connector identification only and should not be the sole dimensions used when laying out a circuit board or drilling a mounting hole. **Figure 23.34** shows the frequency ranges appropriate for popular connector types.

These figures and chart were provided by Pasternack (**www.pasternack.com**), a major distributor of coaxial connectors, cable, tools, and other RF materials and supplies.

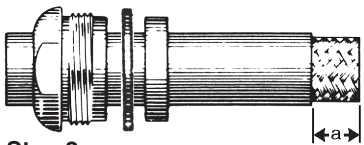
Type N assembly instructions

HBK05_19-19

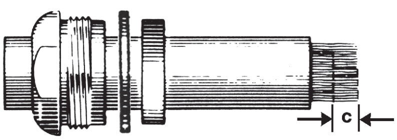
CLAMP TYPES



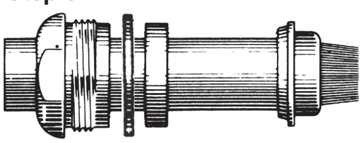
Step 1



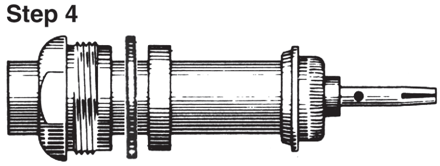
Step 2



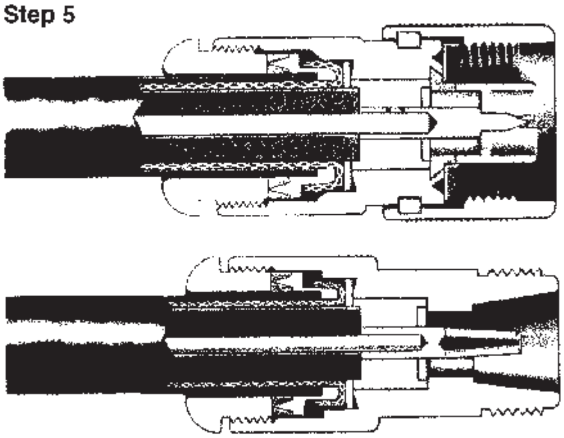
Step 3



Step 4



Step 5



Amphenol Number	Connector Type	Cable RG-/U	Strip Dims., inches (mm) a	Strip Dims., inches (mm) c
82-61	N Plug	8, 9, 144, 165, 213, 214, 216, 225	0.359(9.1)	0.234(6.0)
82-62	N Panel Jack	8, 9, 87A, 144, 165, 213, 214, 216, 225	0.312(7.9)	0.187(4.7)
82-63	N Jack		0.281(7.1)	0.156(4.0)
82-67	N Bulkhead Jack			
82-202	N Plug	8, 9, 144, 165, 213, 214, 216, 225	0.359(9.1)	0.234(6.0)
82-202-RFX	N Plug	8, 213, 214	0.315(8.0)	0.177(4.5)
82-202-1006	N Plug	Belden 9913	0.359(9.1)	0.234(6.0)
82-835	N Angle Plug	8, 9, 87A, 144, 165, 213, 214, 216, 225	0.281(7.1)	0.156(4.0)
18750	N Angle Plug	58, 141, 142	0.484(12.3)	0.234(5.9)
34025	N Plug		0.390(9.9)	0.203(5.2)
34525	N Plug	59, 62, 71, 140, 210	0.410(10.4)	0.230(5.8)
35025	N Jack	58, 141, 142	0.375(9.5)	0.187(4.7)
36500	N Jack	59, 62, 71, 140, 210	0.484(12.3)	0.200(5.1)

See www.AmphenolRF.com for assembly instructions for all other connector types. These dimensions only apply to Amphenol connectors and may not be correct for other manufacturers.

Step 1 Place nut, washer, and gasket, with "V" groove toward clamp, over cable and cut off jacket to dimension a.

Step 2 Comb out braid and fold out. Cut off cable dielectric to dim. c as shown.

Step 3 Pull braid wires forward and taper toward center conductor. Place clamp over braid and push back against cable jacket.

Step 4 Fold back braid wires as shown, trim braid to proper length and form over clamp as shown. Solder contact to center conductor.

Step 5 Insert cable and parts into connector body. Make sure sharp edge of clamp seats properly in gasket. Tighten nut.

Figure 23.30 — Type N connectors are required for high-power VHF and UHF operation. ***(Courtesy Amphenol Electronic Components)***

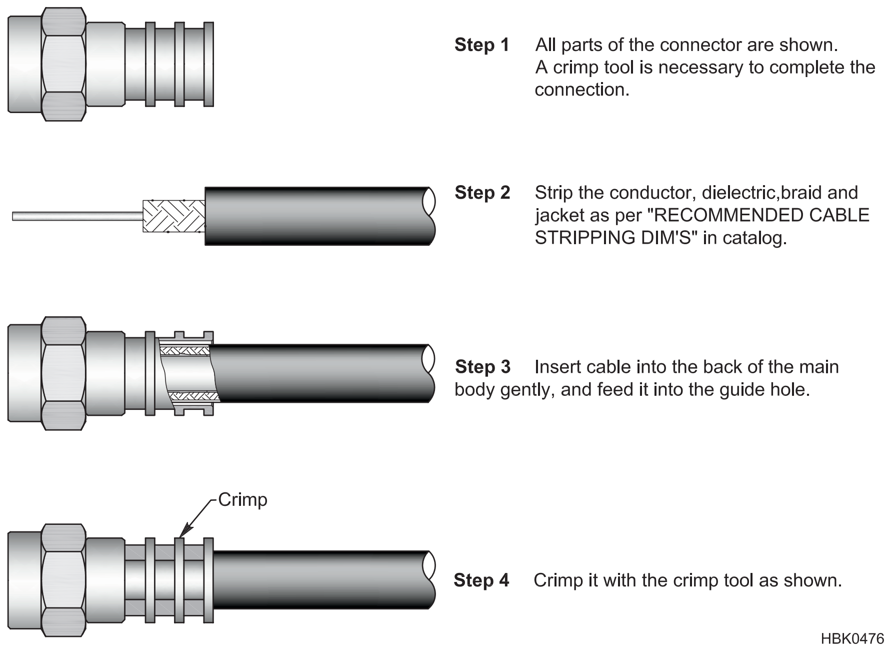


Figure 23.31 — Type F connectors, commonly used for cable TV connections, can be used for receive-only antennas with inexpensive RG-59 and RG-6 cable.

Figure 23.32 — A pair of SMA connectors, with male on the left and female on the right. SMA connectors are available in nickel, stainless steel, or gold finish.

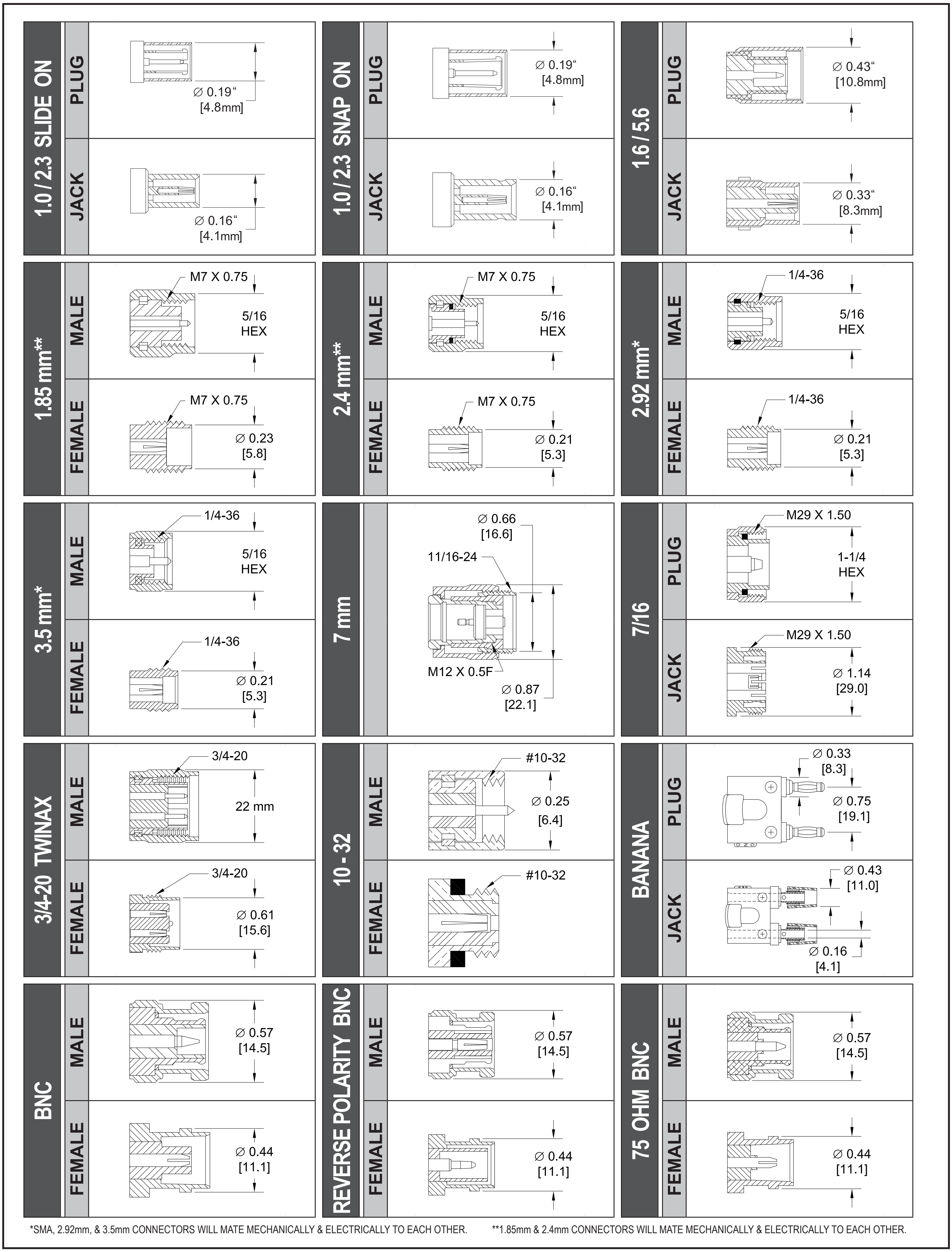
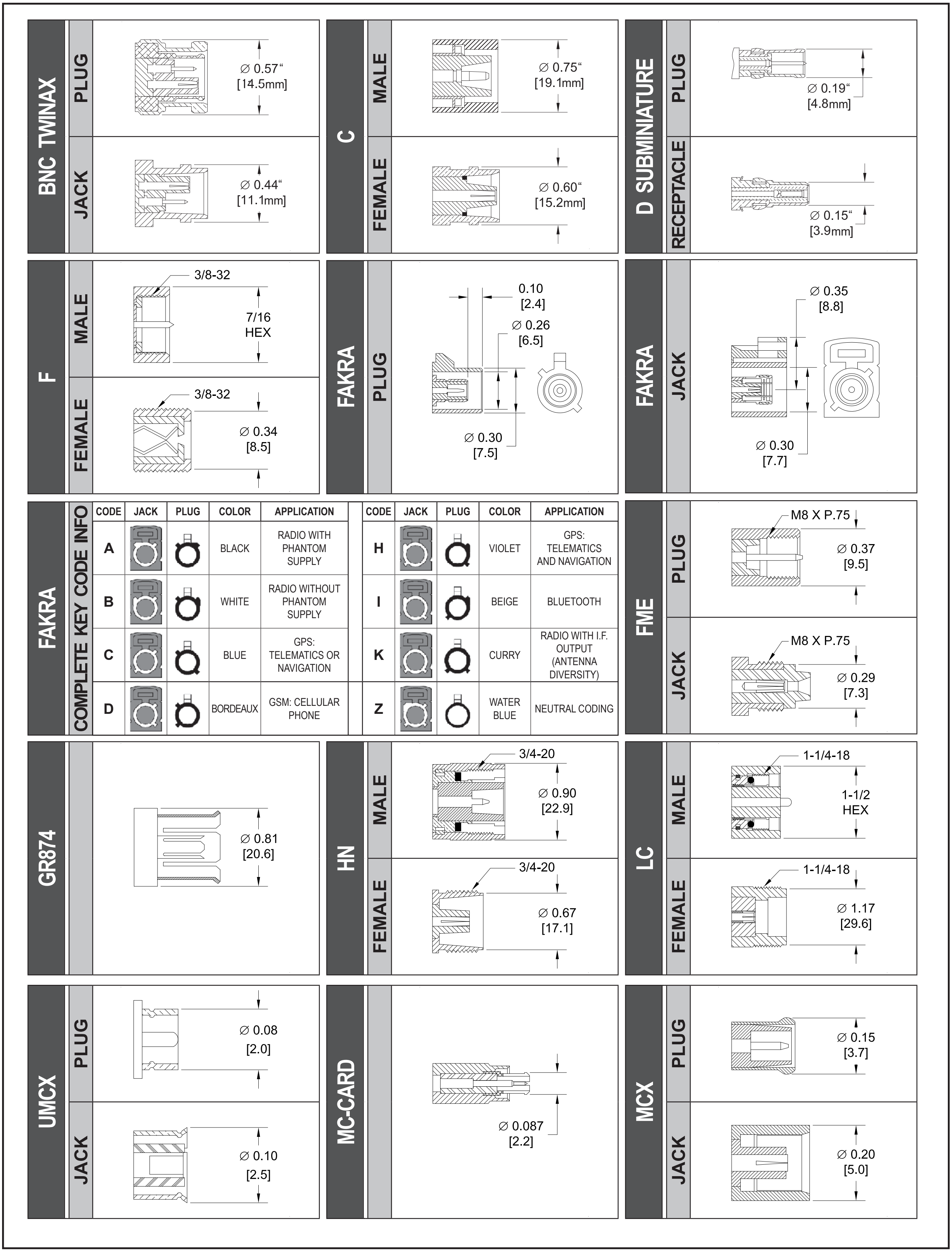


Figure 23.33A – Connector side views, set 1 of 4. (Courtesy of Pasternak)



CODE	JACK	PLUG	COLOR	APPLICATION	CODE	JACK	PLUG	COLOR	APPLICATION
A			BLACK	RADIO WITH PHANTOM SUPPLY	H			VIOLET	GPS: TELEMATICS AND NAVIGATION
B			WHITE	RADIO WITHOUT PHANTOM SUPPLY	I			BEIGE	BLUETOOTH
C			BLUE	GPS: TELEMATICS OR NAVIGATION	K			CURRY	RADIO WITH I.F. OUTPUT (ANTENNA DIVERSITY)
D			BORDEAUX	GSM: CELLULAR PHONE	Z			WATER BLUE	NEUTRAL CODING

Figure 23.33B – Connector side views, set 2 of 4. (Courtesy of Pasternak)

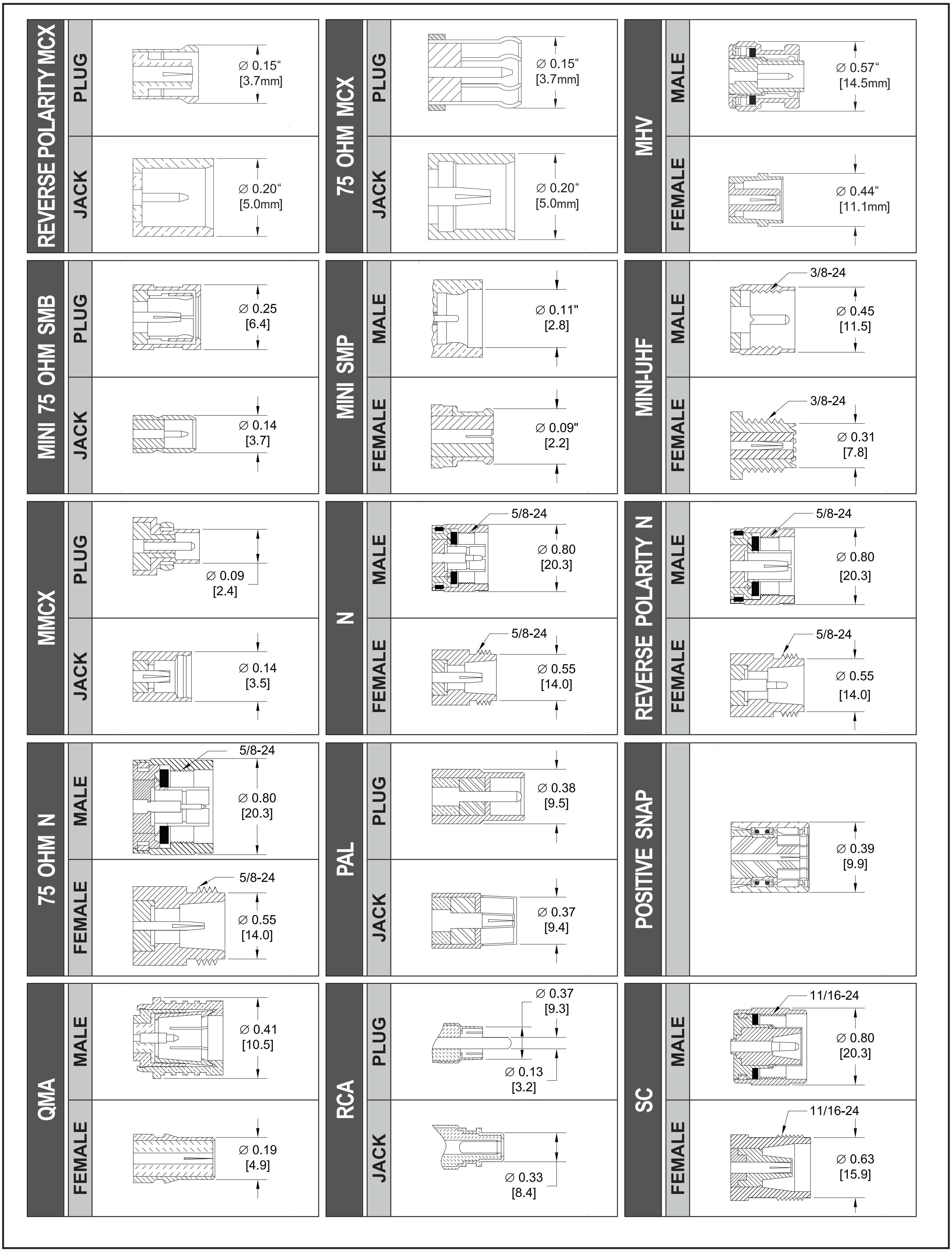


Figure 23.33C – Connector side views, set 3 of 4. (Courtesy of Pasternak)

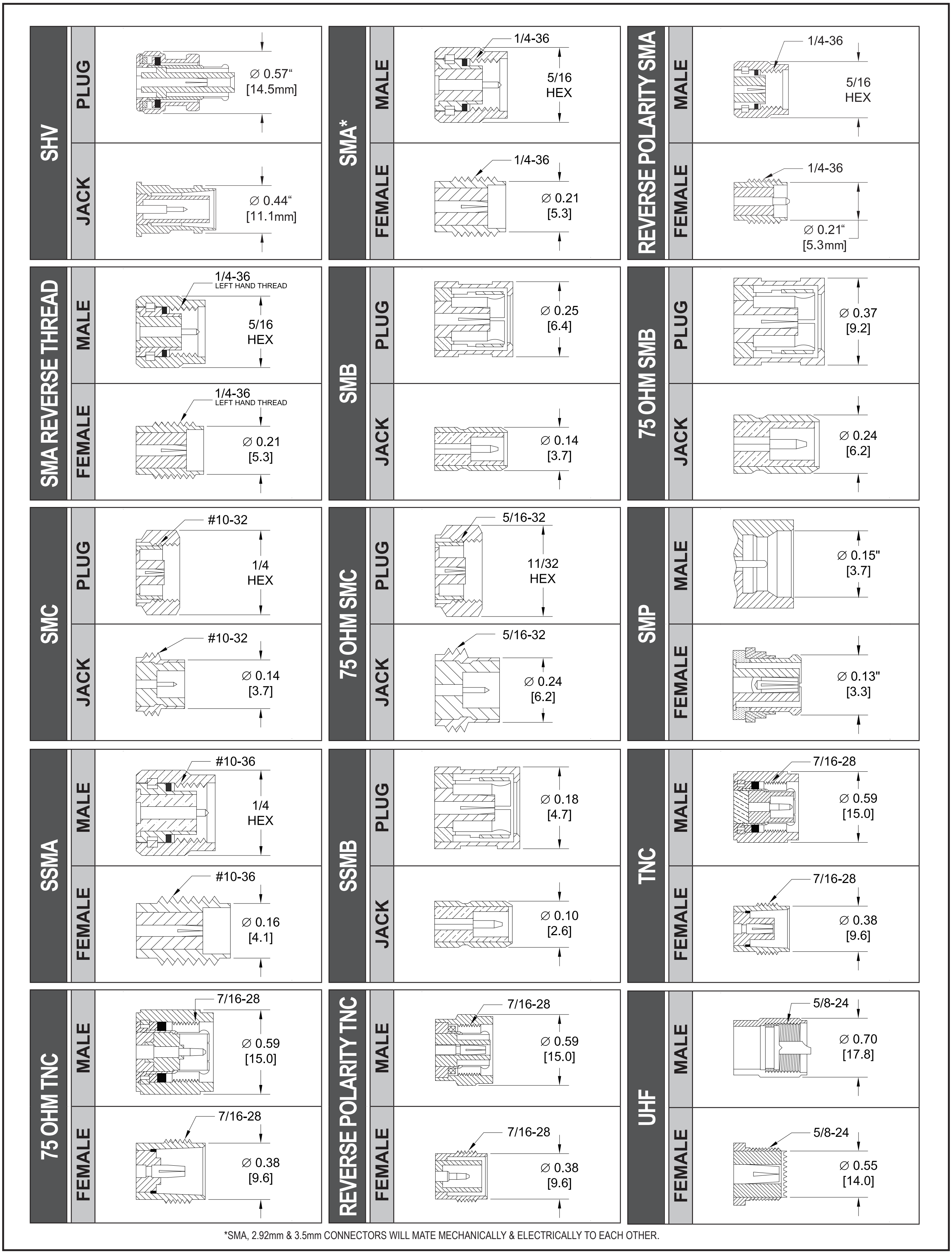
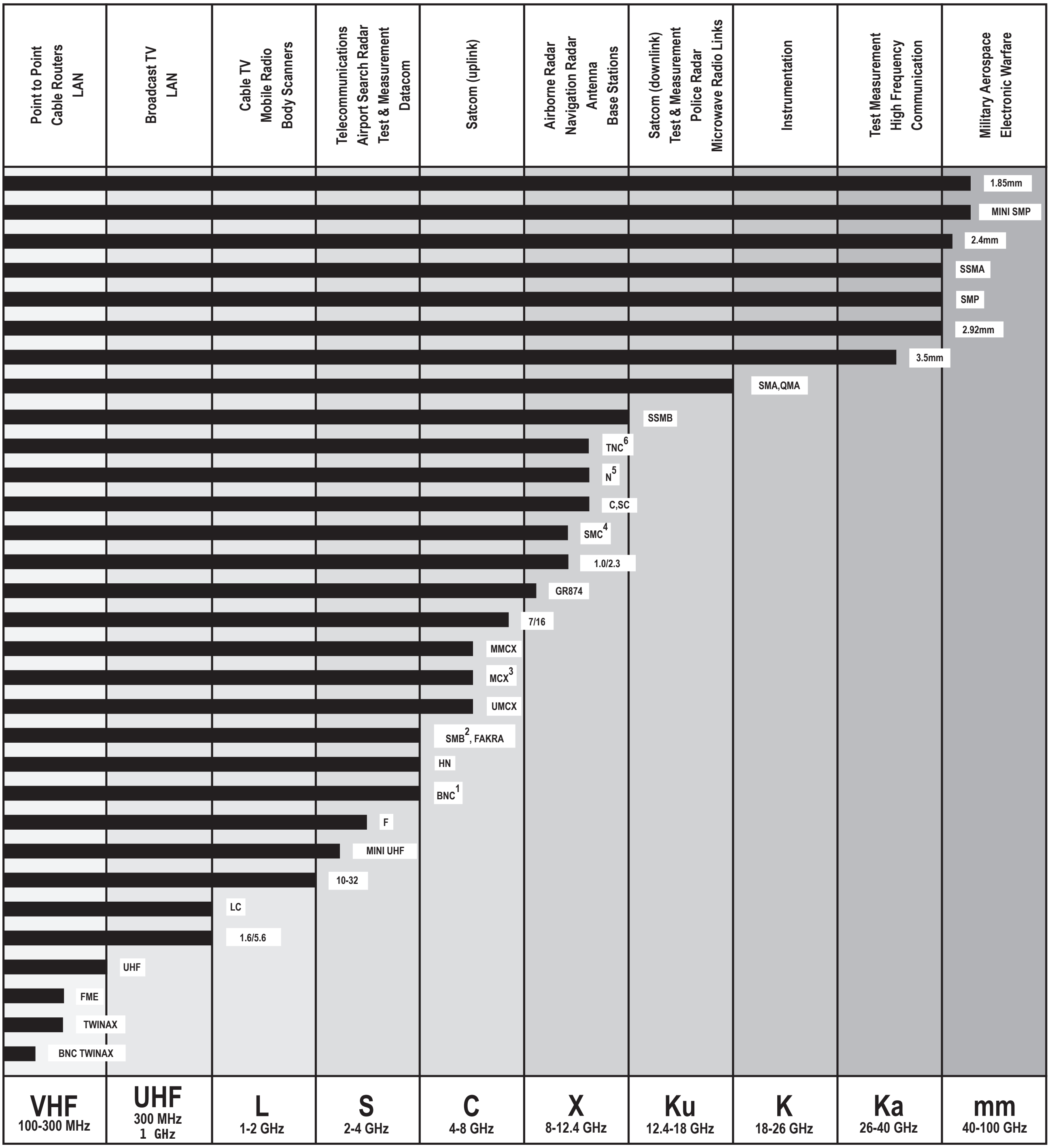


Figure 23.33D – Connector side views, set 4 of 4. (Courtesy of Pasternak)



Notes:

1: BNC-75 Ohm connectors operate up to 1 GHz
2: SMB-75 Ohm & Mini SMB-75 Ohm connectors operate up to 4 GHz
3: MCX-75 Ohm connectors operate up to 6 GHz
4: SMC-75 Ohm connectors operate up to 10 GHz
5: N-75 Ohm connectors operate up to 1.5 GHz
6: TNC-75 Ohm connectors operate up to 1 GHz

Figure 23.34 – Recommended frequency ranges by connector type. (Courtesy of Pasternak)

23.5 CHOOSING AND INSTALLING FEED LINES

23.5.1 COMPARING FEED LINES

The usual two primary considerations for choosing a feed line are loss at the frequency of use and cost. Starting with the impedance of the load attached to the feed line (usually an antenna feed point) determine the matched loss for types of feed line you are considering. **Table 23.3** and **Table 23.4**, published by Frank Donovan, W3LPL in 2008 give typical losses for various types of coaxial cable at frequencies in the amateur bands by using a calculator by VK1OD. (Most manufacturers specify losses at 1, 10, 100

Coaxial Feed Line Loss Calculators

Should you need exact loss calculations for a specific feed line, the loss may be found by using ARRL's *TLW* software available from this book's CD-ROM. A good on-line feed line loss calculator is provided by Times-Microwave at **www.timesmicrowave.com/calculator**. Another free calculator has been created by Dan McGuire, AC6LA, at **www.ac6la.com/tldetails1.html**.

Table 23.3
Cable Attenuation (dB per 100 feet)

MHz	*1.8*	*3.6*	*7.1*	*14.2*	*21.2*	*28.4*	*50.1*	*144*	*440*	*1296*
LDF7-50A	0.03	0.04	0.06	0.08	0.10	0.12	0.16	0.27	0.5	0.9
FHJ-7	0.03	0.05	0.07	0.10	0.12	0.15	0.20	0.37	0.8	1.7
LDF5-50A	0.04	0.06	0.09	0.14	0.17	0.19	0.26	0.45	0.8	1.5
FXA78-50J	0.06	0.08	0.13	0.17	0.23	0.27	0.39	0.77	1.4	2.8
3/4" CATV	0.06	0.08	0.13	0.17	0.23	0.26	0.38	0.62	1.7	3.0
LDF4-50A	0.09	0.13	0.17	0.25	0.31	0.36	0.48	0.84	1.4	2.5
RG-17	0.10	0.13	0.18	0.27	0.34	0.40	0.50	1.3	2.5	5.0
LMR-600	0.10	0.15	0.20	0.29	0.35	0.41	0.55	0.94	1.7	3.1
SLA12-50J	0.11	0.15	0.20	0.28	0.35	0.42	0.56	1.0	1.9	3.0
FXA12-50J	0.12	0.16	0.22	0.33	0.40	0.47	0.65	1.2	2.1	4.0
FXA38-50J	0.16	0.23	0.31	0.45	0.53	0.64	0.85	1.5	2.7	4.9
9913	0.16	0.23	0.31	0.45	0.53	0.64	0.92	1.6	2.7	5.0
LMR-400	0.16	0.23	0.32	0.46	0.56	0.65	0.87	1.5	2.7	4.7
RG-213	0.25	0.37	0.55	0.75	1.0	1.2	1.6	2.8	5.1	10.0
RG-8X	0.49	0.68	1.0	1.4	1.7	1.9	2.5	4.5	8.4	13.2
RG-58	0.56	0.82	1.2	1.7	2.0	2.4	3.2	5.6	10.5	20.0
RG-174	1.1	1.5	2.1	3.1	3.8	4.4	5.9	10.2	18.7	34.8

Table 23.4
Cable Attenuation (feet per dB)

MHz	*1.8*	*3.6*	*7.1*	*14.2*	*21.2*	*28.4*	*50.1*	*144*	*440*	*1296*
LDF7-50A	3333	2500	1666	1250	1000	833	625	370	200	110
FHJ-7	2775	2080	1390	1040	833	667	520	310	165	92
LDF5-50A	2108	1490	1064	750	611	526	393	227	125	69
FXA78-50J	1666	1250	769	588	435	370	256	130	71	36
3/4" CATV	1666	1250	769	588	435	385	275	161	59	33
LDF4-50A	1145	809	579	409	333	287	215	125	70	39
RG-17	1000	769	556	370	294	250	200	77	40	20
LMR-600	973	688	492	347	283	244	182	106	59	33
SLA12-50J	909	667	500	355	285	235	175	100	53	34
FXA12-50J	834	625	455	300	250	210	150	83	48	25
FXA38-50J	625	435	320	220	190	155	115	67	37	20
9913	625	435	320	220	190	155	110	62	37	20
LMR-400	613	436	310	219	179	154	115	67	38	21
RG-213	397	279	197	137	111	95	69	38	19	9
RG-8X	257	181	128	90	74	63	47	27	14	8
RG-58	179	122	83	59	50	42	30	18	9	5
RG-174	91	67	48	32	26	23	17	10	5	3

and 1000 MHz.) Table 23.4 specifies the length of line that will exhibit a loss of 1 dB.

To use Table 23.3, multiply the loss figure by the length of your feed line divided by 100 feet. For example, to find the loss of a 250-foot run of RG-213 at 28.4 MHz, multiply the table loss (1.2 dB) by 250/100 = 1.2 × 2.5 = 3.0 dB. Now use Equation 16 or one of the charts in Figure 23.14 to determine the total loss of the line at that frequency and SWR. If one of the cables is acceptable to you in performance and affordability, your job is done.

If you are operating with full power, you must also consider the peak voltage and power handling capability of the line. There may be other considerations in special circumstances. For example, operators who carry QRP equipment may elect to use RG-174 coax, even though it has high losses, because of its low weight.

For situations in which SWR is very high (such as for a nonresonant doublet used on multiple bands) or a very long run of feed line is required, open-wire line may be the best solution. Be sure to include the cost of impedance transformers in your system budget to connect the higher-impedance open-wire line to 50-Ω equipment and antennas.

If you are considering replacing a long run of cable with hardline or Heliax, **Table 23.5** should be helpful. This is a common situation for stations with antennas far from the transceiver and for VHF/UHF stations of any size. The cable lengths in the table are the lengths for which replacing them with Heliax would yield a 1-dB benefit. For example, replacing a 146-foot run of RG-213 with ½-inch Heliax would yield a 1 dB benefit on 10 meters. Similarly, an 85-foot run of Belden 9913 used on 2 meters could be replaced by ⅞-inch Heliax for a 1 dB benefit. The longer the cable run, the greater the benefit of replacing them with the lower loss of Heliax. (LDF4-50A and LDF5-50A are available at reasonable prices on auction websites, ham websites such as **www.eham.net** or **www.qrz.com**, and at hamfests.)

23.5.2 INSTALLING COAXIAL CABLE

One great advantage of flexible coaxial line is that it can be installed with almost no regard for its surroundings. It requires no insulation, can be run on or in the ground or in piping, can be bent around corners with a reasonable radius, and can be snaked through places such as the space between walls where it would be impractical to use other types of lines. In addition, coaxial lines are unaffected by proximity to other conductors and can be run inside metal conduit or attached to metal structures.

Coax must still be treated with care as described in the following paragraphs, especially when being pulled through a conduit. Cable grips should be used to spread the gripping force over a large area of the cable's surface and the amount of force should be limited to prevent distorting the cable's cross section.

Using Coax Braid

It is common to loosen and strip the shield braid from old coax and reuse it as a ground strap. Unfortunately, cable braid is not a very good RF conductor without its jacket! What makes braid work well in coaxial cable is the continuous pressure of the jacket that compresses the braid, keeps all of the strands in good contact, and protects it from water. This allows the braid to act as a continuous conducting surface.

When braid is removed from the cable, the jacket is no longer present to protect and compress the strands. This allows them to move away from each other and for the strand surfaces to corrode, greatly reducing the effectiveness of the braid at RF.

Used coax braid may be used for dc and low-frequency connections as long as it is protected from the weather but for a reliable RF connection use copper strap or heavy wire. Flat-weave tinned braid designed for unprotected use may be used as an RF conductor but never where it is exposed to water.

Coaxial cable inner conductor and center insulation can be used as a high-voltage wire to the rating of the coaxial cable as long as the insulation is not cracked or compromised in some other way.

Table 23.5
Advantage from Upgrading Feed Line

Feet Required For 1 dB Advantage If Replaced By LDF5-50A (7/8-inch Heliax)

MHz	*1.8*	*3.6*	*7.1*	*14.2*	*21.2*	*28.4*	*50.1*	*144*	*440*	*1296*
LDF4-50A	2500	1430	1250	910	715	625	475	279	158	90
RG-17	1666	1430	1110	770	560	475	420	120	60	30
FXA12-50J	1250	1000	770	525	435	355	255	120	75	40
9913	935	590	455	320	280	220	150	85	53	29

Feet Required For 1 dB Advantage If Replaced By LDF4-50A (1/2-inch Heliax)

MHz	*1.8*	*3.6*	*7.1*	*14.2*	*21.2*	*28.4*	*50.1*	*144*	*440*	*1296*
RG-17	-	-	-	-	-	-	-	220	90	40
FXA12-50J	-	-	2000	1250	1100	835	625	250	145	65
9913	1430	1000	715	500	455	345	235	135	75	40
RG-213	618	434	306	212	171	146	106	58	29	14

Jacket Protection

When installing coaxial cable, it is important to protect the cable jacket to prevent water from entering the cable at any point. First, handle the cable with care during storage and installation so that the jacket is not damaged. If damage to the jacket is noticed immediately and no water is allowed to enter the cable, limited amounts of damage can be repaired using the same technique for waterproofing splices made with RF connectors as described in the **Building Antenna Systems and Towers** chapter.

Secure the cable after it has been connected to the antenna so that the jacket is not abraded or chafed by motion due to wind or antenna rotation. Cables hanging vertically should be supported in such a way that any bending is gradual and with a radius comfortably above the minimum bending radius. Cable grips are available that clamp over a short length, spreading the pressure and avoiding damage to the jacket. If wire or plastic cable ties are used, do not over-tighten them so that the jacket is crimped.

An important part of jacket protection is the waterproofing of RF connectors. Exposed coaxial cable braid will act as a wick, drawing in moisture. To a lesser extent, cables with stranded center conductors or partially hollow center insulation will draw in moisture as well. Coaxial cable infiltrated by water or moisture, either in the braid or center conductor, rapidly becomes unusable due to loss. Coax with a discolored or tarnished shield is not repairable and should be discarded.

Burying Coax

There are several reasons why you might choose to bury coaxial cable feed lines. One is that buried cable is virtually free from storm and UV damage, and usually has lower maintenance costs than cable that is exposed to the weather. Another reason might be that underground cable interacts less with the radiation pattern of antennas, picks up less noise, and carries less common-mode RF on the outside of the shield. A buried cable will be aesthetically acceptable in almost all communities, as well.

Although any cable can be buried, a cable that is specifically designed for burial will have a longer life. *Direct-burial* cable has a high-density polyethylene jacket because it is both nonporous and will withstand a relatively high amount of compressive loads. In impregnated direct burial cables, an additional moisture barrier of polyethylene grease may be applied under the jacket; this allows the material to leak out, thus "healing" small jacket penetrations. These are referred to as "flooded" cables and the grease can make installing connectors more difficult. Neither RG-8/U or RG-213/U are automatically rated for direct burial — the cable vendor must specify the direct burial rating. The cable jacket is usually stamped with "Direct Burial" or the equivalent.

Here are some direct burial tips:

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

2) Bury the cable in sand or finely pulverized soil, free of 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 and lay the cable. Tamp in another six to eleven inches of sand above the cable. Place a creosoted or pressure-treated board in the trench above the sand prior to the final filling of the trench. This will provide some protection against damage that could be caused by digging or driving stakes.

3) When laying buried cable, leave some slack in the cable. A tightly stretched cable is more likely to be damaged as it is being covered with fill material.

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

5) It is important that burial is below the frost line to avoid damage by the expansion and contraction of the soil and water during freezing and thawing cycles.

Using Conduit

You may want to consider burying the coax in plastic pipe or electrical conduit. While plastic pipe provides a mechanical barrier, water incursion is practically guaranteed — water will either leak in directly or will condense from moisture in the air. Be careful to drill holes in the bottom of solid conduit at all low spots so that any moisture can drain out or use the perforated pipe that allows the water to drain out into the surrounding ground.

Whether the conduit is above or below ground, use large-radius sweeps to create bends instead of elbows. It is much easier to pull cable through the gradual bend of a sweep and pulling cables through too sharp a bend can damage it. Metal conduit and fittings frequently have sharp edges and burrs that will cut or even strip the jacket from coax being pulled over them. Before assembling each section, file off sharp or rough edges.

When choosing the size of the conduit, leave plenty of extra space — at least double the expected total diameter of your cable bundle. A 3 to 4 inch-diameter pipe is recommended. This greatly eases the pulling process and gives the cables plenty of room to move around connectors and joints in the conduit. Be sure to include a "fish rope" or "fish wire" with the final cable you pull so you can add or replace cables later.

If you also have rotator or other control cables, there may be local building codes that limit the number and type of cables that can share the same conduit.

23.5.3 INSTALLING PARALLEL-WIRE LINE

Open-Wire Line

In installing an open-wire line, care must be used to prevent it from being affected by moisture, snow and ice. If the line is home-made, only spacers that are impervious to moisture and are unaffected by sunlight and weather should be used on air-insulated lines. Ceramic spacers meet this requirement although they are somewhat heavy. The wider the line spacing, the longer the leakage path across the spacers, but this cannot be carried too far without running into line radiation, particularly at the higher frequencies. Six inches should be considered a maximum practical spacing for HF use.

The line should be kept away from other conductors, including downspouts, metal window frames, flashing, etc, by a distance of two or three times the line spacing. Conductors that are very close to the line will be coupled to it to some degree, and the effect is that of placing an additional load across the line at the point where the coupling occurs. Reflections take place from this coupled load, raising the SWR. The effect is at its worst when one wire is closer than the other to the external conductor. In such a case one wire carries a heavier load than the other, with the result that the line currents are no longer equal. The line then becomes unbalanced.

Twin-lead and Window Lines

Solid dielectric, two-wire lines have a relatively small external field because of the small spacing, and can be mounted within a few inches of other conductors without much danger of coupling between the line and such conductors. Standoff insulators are available for supporting lines of this type when run along walls or similar structures.

As with open-wire lines, avoid installing the line in such a way that snow, ice, or liquid water can build up on the line. This presents an additional dielectric to the conductors and can change the line impedance or create loss.

Mechanical Issues

Where a parallel-wire line must be anchored to a building or other structure, standoff insulators of a height comparable with the line spacing should be used if mounted in a spot that is open to the weather. Lead-in bushings for bringing the line into a building also should have a long leakage path.

When running any kind of parallel-wire line down the side of a tower or other conducting surface, balance can be preserved by twisting the line every few feet. This results in approximately equal coupling by each conductor. Twisting the line also reduces the tendency of the line to move in the wind.

Parallel-line also has more wind resistance than coaxial cable and tends to move quite a bit more. The continual flexing can cause the conductors to break at soldered or otherwise fixed joints. This is a particular problem for lines with solid conductors as is common with window line. Support the line where it is attached to an antenna with insulators designed to provide stress relief to parallel-wire lines. (See the **Antenna Materials and Construction** chapter.)

Sharp bends should be avoided in any type of parallel-wire line, because it causes a change in the characteristic impedance at that point. The result is that reflections take place from each bend. This is of less importance when the SWR is high than when an attempt is being made to match the load to the line Z_0. It may be impossible to get the SWR to the desired figure until bends in the line are made very gradual.

23.5.4 TESTING TRANSMISSION LINES

Coaxial cable loss should be checked at least every two years if the cable is installed outdoors or buried. (See earlier sections on losses and deterioration.) Testing of any type of line can be done using the technique illustrated in **Fig-ure 23.35**. If the measured loss in watts equates to more than 1 dB over the rated matched-line loss per 100 feet, the line should be replaced. The matched-line loss in dB can be determined from

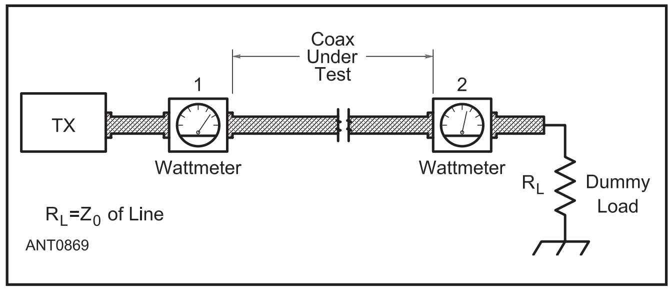


Figure 23.35 — Method for determining losses in transmission lines. The impedance of the dummy load must equal the Z_0 of the line for accurate results.

$$\text{dB} = 10 \log \frac{P_1}{P_2} \qquad \text{(Eq 33)}$$

where

P_1 is the power at the transmitter output

P_2 is the power measured at R_L of Figure 23.35.

Yet other methods of determining line losses may be used. If the line input impedances can be measured accurately with a short- and then an open-circuit termination, the electrical line length (determined by velocity factor) and the matched-line loss may be calculated for the frequency of measurement.

Determining line characteristics as just mentioned requires the use of a laboratory style of impedance bridge, or at least an impedance or noise bridge calibrated to a high degree of accuracy. But useful information about a transmission line can also be learned with just an SWR indicator, if it offers reliable readings at high SWR values.

A lossless line theoretically exhibits an infinite SWR when terminated in an open or a short circuit. A practical line will have losses, and therefore will limit the SWR at the line input to some finite value. Provided the signal source can operate safely into a severe mismatch, an SWR indicator can be used to determine the line loss. The instruments available to most amateurs lose accuracy at SWR values greater than about 5:1, so this method is useful principally as a go/no-go check on lines that are fairly long. For short, low-loss cables, only significant deterioration can be detected by the open-circuit SWR test.

First, either open or short circuit one end of the line. It makes no difference which termination is used, as the terminating SWR is theoretically infinite in either case. Then measure the SWR at the other end of the line. The matched-line loss for the frequency of measurement may then be determined from

$$\text{ML} = 10 \log \left(\frac{\text{SWR} + 1}{\text{SWR} - 1} \right) \qquad \text{(Eq 34)}$$

where SWR = the SWR value measured at the line input.

23.6 BIBLIOGRAPHY

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