

## PART II The MEDIUM

### Chapter 4 Wired Communications

The oldest medium for electrical communications is the wire, so we shall start with that.

#### Wire Communications

When you use a wire connection to send a signal from one place to another, you generally need a minimum of two wires to do it. That's because the wire will need to carry some current (even though that current may be tiny), and you need a complete circuit for the current to flow.

So is it possible to communicate with just one wire? The answer is yes... sort of.

When the very first telegraph systems started reaching out across America, the entire process of making and installing wires was in its infancy. To save money and time, these systems (as well as the first telephone systems many years later) used just one wire, as shown in Fig. 4-1. At each end was a telegraph set, consisting of a telegraph *key* and a *sounder*. The key was just a switch that could be pushed by the operator to send *Morse code* messages by closing and opening the circuit. The sounder was an electromagnet with a moving metal arm which clicked — made a sound — as the electric current and resulting magnetic field made it move back and forth. The two telegraph sets made a large series circuit, with a battery at one end.

The series connection was made through just one wire, stretched across the wilderness on telephone poles, and later topped with small glass insulators. The other conductor in the circuit was the ground (or earth, as they call it in England.) Although the earth is not a very good conductor, there is enough water as well as various impurities to allow it to conduct electricity. Even a bad wire can have a low resistance if it is thick enough, and the earth certainly has a large cross-section.

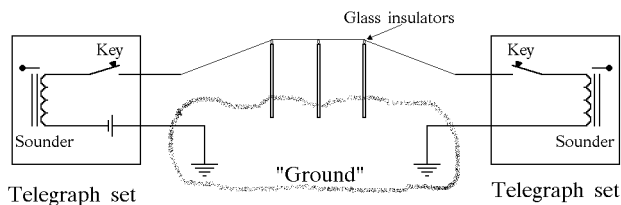


Fig. 4-1. An early telegraph system

The system worked fairly well with telegraphy, and even worked with telephone circuits. But it was soon discovered that telephone communications worked better when the ground connection was replaced by a second wire. Not only is the earth not a perfect conductor, but there are often other currents flowing in the earth, which introduce additional voltages into the series circuit and interfere with the signal. A prime example is lightning, which can induce huge currents and voltages in the earth. Less obvious are voltages induced from high-voltage power lines and ground currents due to other electrical problems (these, of course, were not a major problem in the early days of the telephone.)

Even with two wires, however, a problem still remains: the pickup of noise from other sources, and *crosstalk* — signals leaking through from other nearby telephone lines. The pickup of noise and crosstalk is a problem even in shorter wires, and there are essentially four ways of attacking the problem: increase the signal level, use low impedance connections, add shielding, and provide noise cancellation. Let's examine these alternatives.

#### (a) Increase the desired signal level

Increasing the voltage level of the desired signal will increase the signal-to-noise ratio — the ratio of the desired signal voltage to the noise voltage, also abbreviated SNR. But ... if the noise comes in the form of crosstalk from other nearby lines (whose signal level has also been raised) then the SNR is not really affected. This is therefore not good enough to solve a telephone problem.

#### (b) Use low impedance connections

In Fig. 4-2, we see a source with an internal resistance  $R_{out}$  sending some desired signal to a load resistance  $R_{load}$ . We show the desired signal as dc, but that doesn't matter. At the same time, we have some external noise signal  $V_n$  positioned nearby, and some coupling impedance (or resistance)  $R_c$  which exists between the noise signal at the top, and the desired signal below it. We now want to calculate how much of the

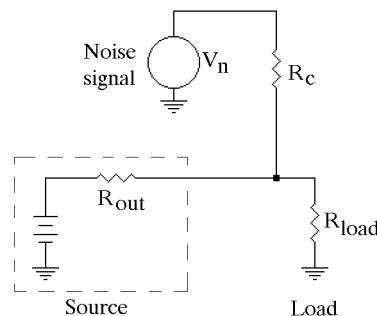


Fig. 4-2. Noise coupling into a circuit

noise voltage  $V_n$  gets to the load resistor  $R_{load}$ . We can ignore the desired signal from the battery, and just consider the three resistors as making up a voltage divider;  $R_{out}$  and  $R_{load}$  are in parallel, and  $R_c$  feeds them. The voltage across the load is therefore

$$V_{load} = V_n \times \frac{(R_{out} \parallel R_{load})}{R_c + (R_{out} \parallel R_{load})}$$

If either  $R_{out}$  or  $R_{load}$ , or both, are very small compared with  $R_c$ , then the denominator in the fraction is fairly large, but the numerator is very small.  $V_{load}$  is therefore also small.

$R_c$ , the resistance (or more commonly, the impedance) which represents the coupling from the noise source to the desired circuit is typically quite large, because there is usually no direct connection from the noise source to the desired circuit; the two might just be two wires close to each other within a cable. If either the source or load in the desired circuit has a much lower resistance, then the amount of noise signal coupled to it will be small.

It is therefore possible to use low-impedance circuits to send a signal from one place to another without excessive noise pickup. But the distance is limited because of wire resistance. In a telephone circuit, for instance, the resistance of the wire could easily be several thousand ohms; when this is inserted into the circuit between the source and the load, the amount of signal reaching the load drops drastically.

### (c) Use Shielded wire

Another way to prevent a cable from picking up noise is to shield it. For example, all the audio cable commonly used between phonographs, tape recorders, and other home hi-fi components (except speakers) is normally shielded wire, such as that shown in Fig. 4-3.

The shield serves three purposes: it prevents outside interference from getting to the inner wire (which carries the actual signal), it prevents the signal from leaking out and affecting other nearby circuits, and it also serves as the second or ground wire, needed to complete the circuit so current can flow.

Shielded wire is used for many purposes, from carrying audio signals to carrying radio frequency (RF) or

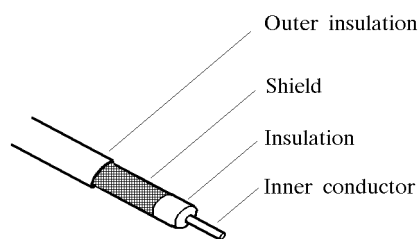


Fig. 4-3. Construction of a shielded wire

microwave signals; in the latter case, it is often called *coax* or *coaxial cable*, rather than shielded wire, but the principle is the same. Fig. 4-4 shows several popular connectors for audio (the RCA phono plug and the phone plug — notice the *o* at the end of phono, and the *e* at the end of phone) and for radio-frequency signals (the PL-255 RF connector and the BNC connector.)

When properly used, shielded or coax wire does have the advantage of not picking up or releasing stray signals. But it is expensive — to use it for just a single telephone conversation over any long distance would be exorbitantly expensive.

Like all cables, shielded cable also has a loss. For example, it quite often happens that the signal coming out of such a cable is only half as strong as what went in (or even weaker.) In RF applications, much of this loss is caused by the inner insulator; hence many high-quality cables use air (or even an inert gas) as the insulator, with just a thin spiral-wound strip of insulator to separate the shield from the inner conductor. This increases the cost even more.

A second problem, especially in audio applications, is that the shield is so close to the center conductor that there is appreciable capacitance between the two. This tends to short out higher frequencies, so that the cable does not carry high-frequency signals as well as low-frequency ones. In audio applications, this kind of cable is seldom used in lengths over several hundred feet.

A third problem exists in long-distance audio circuits due to the presence of the grounded shield. Audio equipment often has three-wire AC plugs, which ground the cabinet of the equipment through the AC power system. When two pieces of equipment are located some distance apart, these grounds are not directly connected together, and so the cabinets of these two devices may be at a slightly different voltage. When a shielded wire is run between the two, the shield is a second connection between the two cabinets; because of the slight voltage differences, a small 60-Hz AC current flows through the shield and causes a voltage drop. Even though this voltage drop may be just a tiny fraction of a

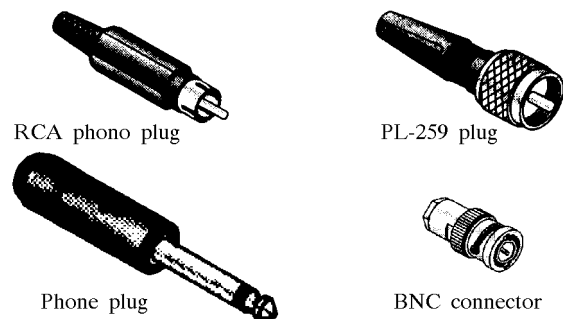


Fig. 4-4. Several connectors for shielded wire

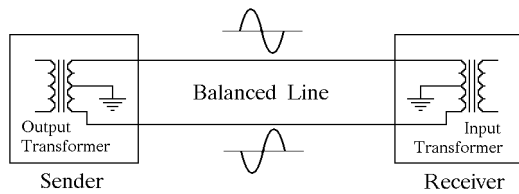


Fig. 4-5. A balanced audio line

volt, this may be significant compared with the audio voltage in the cable. This voltage along the shield is then added to the audio signal in the cable, and appears as a hum signal.

This isn't much of a problem in a home hi-fi installation, since most home hi-fi components are close together and are usually plugged into the same outlet. But it is a major problem in recording and broadcast studios, where signals may have to travel from room to room, or even from one side of town to the other.

The result of all this is that shielded cable is seldom used today for runs longer than a few hundred feet. Telephone companies did use coax cable for inter-city runs years ago, but no more. Cable TV companies still use coax cable in large quantities, but even there coax is being replaced by optical fibers for the long runs.

#### (d) Balanced Lines for Noise Cancellation

Recording and broadcast studios solve many of their wire problems by using balanced line, which may be shielded as well, but where shielding is often not even needed.

Fig. 4-5 shows how a balanced line was used before the days of modern solid-state equipment. With vacuum tubes, the connections to and from balanced lines were usually done with transformers. A center-tapped output transformer would feed the line, and another center-tapped transformer would take the signal from the line. Neither of the two wires in the line was grounded; instead, the ground (if used) was connected to the center taps of the two transformers.

As Fig. 4-5 shows, the signals on the two wires are exact opposites of each other — whenever one wire goes plus, the other goes minus by the exact same amount. You can think of this as a seesaw — whenever one end of the seesaw goes up, the other end goes down by the same amount, and the center (where the hinge is — the physicists call it the fulcrum) never moves up or down. We call this type of line a *balanced* line because the voltages on the two wires are exactly equal (but opposite), so they cancel themselves out. (The shielded or coax line, on the other hand, has the signal on the inside lead only, and is therefore called *unbalanced*.)

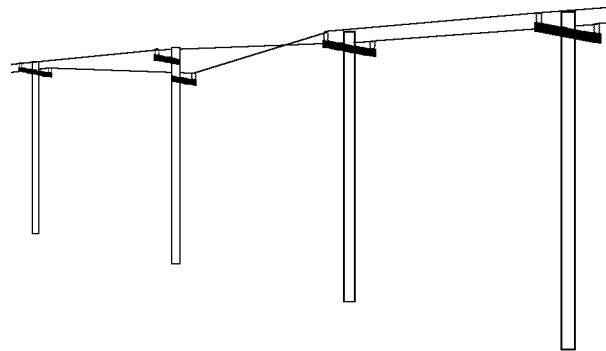


Fig. 4-6. An old twisted-pair telephone line

The output transformer on the left thus puts out equal but opposite voltages on the two wires. The input transformer on the right is wired directly across the two wires, and thus sees only the voltage difference between the two wires. Any voltage that is common to both wires will not appear across the transformer, and will thus be ignored.

Now suppose that there is some external source of electrical noise, which is picked up by the two wires. If the two wires are close enough to each other, they will pick up the same amount of noise. But if both wires pick up the same noise, this doesn't change the voltage *difference* between them, which means that the input transformer in the receiver doesn't see that noise at all. Shielding is therefore not always needed to keep noise and interference out of a balanced line.

The trick, of course, is to make sure that both wires pick up the noise or interference in exactly the same way. To make sure that this happens, the two wires are usually twisted together, which gives this type of line the name *twisted pair*. (In fact, one of the favorite buzzwords in modern local area networks is UTP, which simply means unshielded twisted pair.) Sometimes it's interesting to look at some old telephone poles out in the country (or along an old railroad track) and see how they arranged the twisted pair in the old days — see Fig. 4-6.

There are, of course, some cases where shielding is used in addition to the balanced line. Although the use of a two-wire balanced system cancels out noise and hum, it is not perfect. If the signal is small enough, the noise and hum might still be significant. Thus the low-level microphone cables in recording and broadcast studios are always both shielded and balanced. (Microphone cables in home-type equipment are generally shielded but unbalanced. That's because home-type microphones usually have short cables, whereas professional mikes might be used with very long cables.)

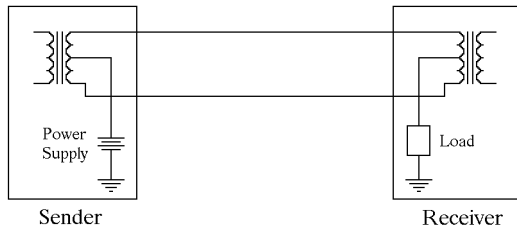


Fig. 4-7. “Simplex” or “phantom” power connection

## DETOUR

Fig. 4-7 shows an interesting and useful variation on a balanced line, which shows how to make the balanced line do two jobs. In addition to carrying a balanced signal, it also carries power from the sender to the receiver.

Instead of the centertaps of the two transformers being grounded, as they were in Fig. 4-5, the sender’s centertap connects to a power supply. One side of the power supply is grounded, while the other side sends power, through the transformer, to both of the balanced wires. At the receiver end, the load connects from its input transformer to ground.

The receiver’s signal transformer only looks for the difference between the two wires, whereas the power supply feeds both lines equally. The transformer does not therefore see the power, and receives only the signal. The load, on the other hand, ignores the signal and receives only the power, since the signals on the two wires cancel.

This type of connection is called either a *simplex* or a *phantom* connection. (“Simplex” is the same word, but has a different meaning from its normal use in communications.) The phantom power signal is usually DC, but could also be AC; it can also be used in either direction. The scheme is used in a number of places:

- Condenser microphones in professional recording studios need DC power for their internal amplifiers. The same microphone cable that carries audio from the mike to the console carries DC power back to the microphone.
- Radio stations that use a single balanced line to send audio from a remote location such as a high school gym back to the studio, sometimes use a simplex connection to send a “talk-back” audio

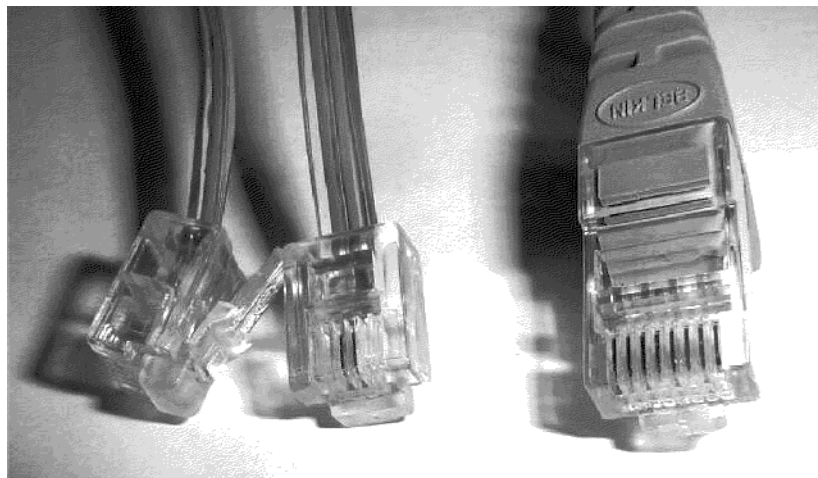


Fig. 4-8. RJ-11 and RJ-45 balanced connectors

channel from the studio back to the remote site. In this way the technician in the studio can give instructions to the announcer at the remote location.

- T-1 digital lines (which will be discussed in Chapter 17) use a similar (though slightly different) scheme to provide power to equipment which may be out on a telephone pole or in a manhole, far from a normal power plug.

## END OF DETOUR

Many different connectors are used for balanced lines; Fig. 4-8 shows two that are common today. Both are known as USOC RJ-type connectors — USOC is the *Uniform Service Order Code*, a set of interface standards commonly used by telephone companies.

On the left are two views of an RJ-11 plug, which is commonly used to connect a telephone to its wall plug. It is also sometimes called a 6-position RJ connector, since it has space for six connections, although usually only two or four are used.

On the right is an RJ-45 connector, sometimes called an 8-position RJ connector since it has room for eight pins. It is often used for Ethernet local area networks, but variations are also used elsewhere.

## Characteristic Impedance

Think for a moment about how an ohmmeter works. Inside every ohmmeter is a small battery. When you connect the ohmmeter across a resistor, the meter connects that battery across the resistor. Current starts to flow through the resistor, the meter measures how much

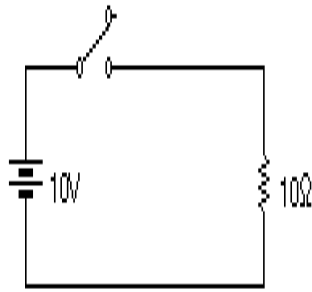


Fig. 4-9. A simple series circuit

current there is, and computes the resistance from Ohm's law:

$$\text{resistance} = \frac{\text{voltage across resistor}}{\text{current through it}}$$

In a digital meter, that division is done by a small computer circuit; in an analog meter, the scale calibration does the job. Either way, however, the meter indicates the apparent resistance.

Now, imagine that you have an infinitely long length of some cable, such as the flat twin-lead cable used for TV antennas, and you connect the ohmmeter between the two wires at your end. What will you measure?

Connecting the ohmmeter to the end of your cable connects its battery across the two wires. The ohmmeter of course doesn't know whether there is an inch, a foot, or a mile of wire there, so it sends some current out its test leads, hoping eventually to reach a resistor at the end. Normally, the current would reach a resistor after going through just a few feet of wire, and settle down to whatever current Ohm's law wants; the meter would then show the resistance. In this case, however, that test current just keeps going forever (at almost the speed of light), searching for a resistor that isn't there. The ohmmeter, however, doesn't know that this test current never reached a resistor; it happily measures the current and voltage, and displays a value of resistance anyway.

The amount of current that flows depends on the kind of cable. Actually, its resistance has fairly little to do with it; it's the capacitance between the two wires, and the inductance of the wires, that mainly determine how much current flows down the cable. The resistance the meter measures therefore depends on the type of cable; we call it  $Z_0$ , or the *characteristic impedance* of the cable.

While we can perform this experiment in theory (the Germans call this a *Gedanken Experiment* or Thought Experiment), we cannot really do it with a meter because we cannot get an infinitely long length of cable. But the characteristic impedance can be measured in other ways with shorter cables, as long as we measure

the voltage and current fast enough that the current doesn't have enough time to reach the end.

Different cables have different characteristic impedances, depending on their construction and dimensions — the TV twin-lead is 300 ohms, the coaxial cable used for cable TV or TV antennas is 75 ohms, while the coax generally used for transmitting antennas is 50 ohms. And the twisted-pair cable generally used for audio and telephone circuits would measure 600 ohms.

## Reflections

Now look at Figure 4-9. Here we see a simple circuit, consisting of a 10-volt battery, a switch, and a 10-ohm resistor, all connected in series. Right now, the switch is shown open, and so there is no current. Once we close the switch, current starts to flow. The value is given by Ohm's Law as  $I = V/R$ ; this works out to 10 volts / 10 ohms, or 1 ampere.

But let's complicate the issue a bit by making the wires between the switch and the resistor 186,000 miles long. Let's assume that the wire has no resistance, but it does have a characteristic impedance  $Z_0$  of perhaps 100 ohms. What is the current just after we close the switch?

Since it takes light one second to travel the distance from the resistor to the switch and battery, even if the battery had a high-power telescope so it could "see" the resistor at the far end, it could still not know precisely what is at the end of the wire at the instant the switch closes — it could only see what was there one second earlier. So, as before, the current it sends out depends not on the resistor, but on the characteristic impedance of the line. The current is therefore

$$I = \frac{10 \text{ volts}}{100 \text{ ohms}} = 0.1 \text{ ampere}$$

So, if we had a voltmeter and ammeter connected at the switch, we could see 10 volts and 0.1 ampere entering the line as soon as the switch closes. One half second later, that voltage and current reach the middle of the line; one second later they finally reach the resistor.

The problem is that 10 volts and 0.1 ampere are all wrong for a 10-ohm resistor. By Ohm's law, if there is 10 volts, there should be 1 ampere instead of 0.1 ampere; if, on the other hand, there is only 0.1 ampere, then there should be only 1 volt, not 10.

So imagine that the resistor can talk to the wire. It looks at the voltage and current it's getting, and says "No, no, no -- something is wrong -- there is too little current and too much voltage. Suppose we compromise — you increase the current, and I decrease the voltage, Ohm's Law will be satisfied, and we'll both be happy."

But to make a fair compromise, both parties should give in by equal amounts. That is, if the wire provides  $x$  percent more current, the resistor should drop the voltage by the same  $x$  percent. In this case (we will see why in a moment) both compromise by 81.8 percent. That is, the wire increases the current from 0.1 to 0.1818 amperes (an 81.8% increase), while the resistor drops the voltage from 10 to 1.818 volts (an 81.8% decrease). These two values now satisfy Ohm's Law, since

$$\frac{1.818 \text{ volts}}{0.1818 \text{ amperes}} = 10 \text{ ohms}$$

This situation, however, leads to a new problem. The resistor is happy because the voltage is now less than 10 volts while the current is more than the original 0.1 ampere. But a short distance back from the resistor, the line voltage and current are still 10 volts and 0.1 amperes. But this can't be! In a parallel circuit, the voltage must be the same everywhere, while in a series circuit, the current should be the same everywhere. And so the 81.8% drop in the voltage, and the 81.8% increase in the current, must start to travel back along the line, eventually making the voltage and current the same everywhere along the wire.

One way to look at this is to think of an outgoing signal (10 volts and 0.1 amperes) traveling from the battery to the resistor, and a second, returning signal, traveling back from the resistor toward the battery. The returning signal is (in this case) 81.8% of the outgoing signal. The polarity of this *reflected signal* is such that the current adds to the outgoing current (making it larger), while the reflected voltage subtracts from the outgoing voltage to make it smaller, thus changing the total voltage and current along the wire. We say that part of the outgoing voltage and current have been reflected from the load, and travel back along the line.

The reflection will eventually reach the battery, which will look at the lower voltage, and do everything it can to boost it back to the required 10 volts. In the process, it will send out a burst of more voltage and current (but still the wrong values). These will go back to the resistor, cause yet another reflection, and so on. "Eventually" the voltage and current will stabilize at the 10 volts and 1 ampere that DC circuit theory says we should have, but this will take a number of reflections back and forth. How long this process takes depends on the length of the wire between the battery and resistor. With 186,000 miles of wire, this process takes seconds; with just a few feet of wire on a lab bench, the process might take just a few nanoseconds —short enough that you might never notice the delay unless you had extremely fast test equipment. Which explains why the DC circuits courses ignore the entire process!

In the above example, we said that the voltage would drop by 81.8%, while the current would increase by the same 81.8%. This number (expressed as the number 0.818, rather than a percentage) is found from the *reflection coefficient*, represented by the capital greek letter Gamma ( $\Gamma$ ):

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

where  $Z_L$  is the value of the load resistor (10 ohms in this case), while  $Z_o$  is the characteristic impedance (which is 100 ohms in our example.) So in this example the reflection coefficient is

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{10 - 100}{10 + 100} = \frac{-90}{110} = -0.818$$

The reflection coefficient describes how much of the outgoing voltage (10 volts) is reflected from the load resistance. The minus sign tells us that the reflection will be the opposite polarity of the outgoing voltage; since the outgoing voltage was +10 volts, the reflected voltage is negative. The reflection will thus be -8.18 volts (10 volts times -0.818) and the voltage across the resistor will then be  $10 - 8.18 = 1.82$  volts.

The outgoing voltage is sometimes called the *forward voltage* or *incident voltage*, so

$$V_{forward} = V_{incident} = 10 \text{ volts}$$

In the same way, the *reflected voltage* is sometimes called the *reverse voltage*, so

$$V_{reverse} = V_{reflected} = -8.18 \text{ volts}$$

Knowing how much voltage will actually reflect is nice, of course, but it's more interesting to look at three special cases:

Case 1: There is no load resistor at the end of the cable at all — the output is open. In this case,  $Z_L$  is infinite, and the equation becomes

$$\Gamma = \frac{\infty - Z_o}{\infty + Z_o} = \frac{\infty - 100}{\infty + 100} = \frac{\infty}{\infty} = +1$$

That's because the  $\infty$  on the top and bottom are so big that we might as well ignore the  $Z_o$ . (Mathematicians will generally not be happy with this calculation, but the answer is right so we'll ignore their concerns.) So, with the output open, the reflection coefficient is +1, and 100% of the outgoing signal is reflected (with the same polarity).

Case 2: If, on the other hand, the end of the cable is shorted, then  $Z_L$  is zero, and the equation becomes

$$\Gamma = \frac{0 - Z_o}{0 + Z_o} = \frac{0 - 100}{0 + 100} = \frac{-100}{+100} = -1$$

In this case, the reflection coefficient is  $-1$ , and so 100% of the outgoing voltage is again reflected, but this time the polarity changes (because of the minus sign.) That makes sense, since the voltage at a short circuit must be zero; the only way to get this is if the outgoing voltage and the returning voltage exactly cancel each other out.

Case 3: Suppose, on the other hand, that the load resistance  $Z_L$  is exactly equal to  $Z_o$ ? In that case, the equation becomes

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{100 - 100}{100 + 100} = \frac{0}{+200} = 0$$

Since the numerator of the equation becomes zero, the reflection coefficient is therefore also zero, and nothing is reflected at all.

So we see that the only way to get no reflection is to load the end of the line with a resistance exactly equal to the characteristic impedance of the line itself.

Let's see how reflections in cables can cause problems.

### Reflections in digital circuits

Fig. 4-10 shows a simple test circuit which we can try in the lab. At the left we have a pulse generator; the pulse generator acts sort of like a battery and switch, except that it closes the switch only for a very short time (less than a microsecond) and then immediately opens it again. In other words, it connects a voltage to the line for a tiny instant, and then immediately disconnects it. The pulse generator feeds a length of transmission line (100 feet of RG-58 coax cable makes a good lab experiment), whose far end is shown open. A fast oscilloscope is connected across the pulse generator to show us the signal.

Fig. 4-11 shows the result. The fairly sharp pulse at the left is the signal coming out of the pulse generator. It appears as a narrow pulse, on for just a very short time. The slightly smaller pulse at the right is what comes back from the end of the line — this is the reflection. It is slightly smaller, because there is about a 10% loss of voltage in going down the cable and back (this is, after all, a practical cable, not a theoretical, loss-free one.)

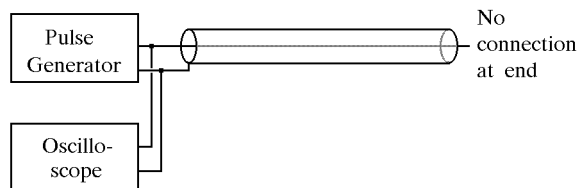


Fig. 4-10. Experiment to show reflections

Note also that the returning pulse is slightly wider and not nearly as nice and square. This is caused by the various parts of the pulse traveling down the cable at slightly different speeds, which results in the pulse spreading slightly.

From this picture, we could calculate the signal loss in the cable; much more interesting, though, is to calculate how fast the signal travels. In this picture, the scope sweep was set to  $0.05 \mu\text{sec}$  per division; since the spacing between the two pulses is about 6 divisions, the delay between the outgoing and returning pulses is about  $0.3 \mu\text{sec}$ . In that time, the pulse travelled 200 feet (100 feet from the generator to the end, and another 100 feet to return.) The signal velocity is therefore

$$\text{velocity} = \frac{\text{distance}}{\text{time}} = \frac{200 \text{ feet}}{0.3 \mu\text{sec}} = 6.67 \times 10^8 \text{ feet/sec}$$

Since there are 5280 feet in a mile, this works out to about 126,000 miles per second. Note that this is slower than the speed of light, which is usually given as 186,000 miles per second; this latter figure is only true for light in a vacuum, not for light in air, glass, or other materials.

In our electrical case, the speed of the signal in the cable is about 68% of the speed of light; we call this fraction the *velocity factor* of the cable, and usually write it as 0.68 rather than 68%. (Remember that our measurement is only an approximation; the actual published velocity factor for RG-58 cable is slightly less, but the delay time is hard for us to read from the scope, and so 0.68 is about as close as we're going to get.)

The velocity factor is thus

$$\text{velocity factor} = \frac{\text{actual speed}}{\text{speed of light}}$$

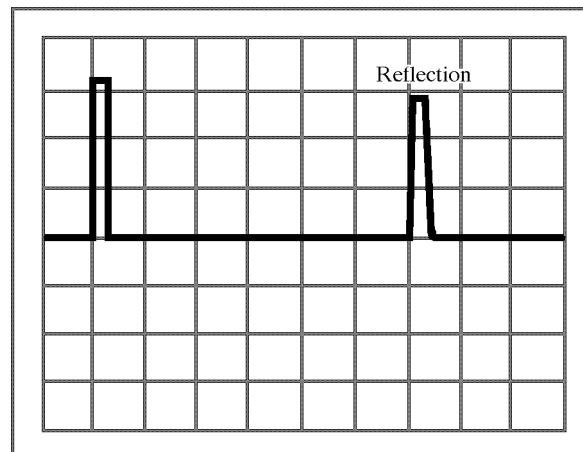


Fig. 4-11. Reflection from an open-ended cable

Now imagine that the pulse in Fig. 4-11 is just one of many pulses being sent in a cable, perhaps as part of a computer local area network. If the end of the cable is open, then the pulses reflected from the end will get mixed in with the outgoing pulses, and cause major errors in the system. So reflections can be a big problem in digital systems.

Fig. 4-11 dealt with a line whose far end was open. If the far end had been shorted, there would still be a reflection, but the reflected signal would be negative instead of positive.

From our previous discussion, we can now see that the only way to prevent reflections is to make sure that the end of the cable is properly terminated — we must place a resistor at the end of the line, and make sure that its resistance is equal to the characteristic impedance of the line. If the resistance is slightly off, there will be a reflection, but it might not be large enough to matter. In general, a resistance larger than the characteristic impedance will provide a positive voltage reflection; a resistance smaller than the characteristic impedance will provide a negative reflection. Thus the cables in local area networks are always connected to a load resistor at the end; sometimes the resistor will be inside the computer interface card, other times it may be mounted externally, but it will always be somewhere. And since the signals in these cables can travel in either direction, there will be a termination resistor at each end of every cable.

Incidentally, putting a proper load resistor at the end of the cable is not enough — *how* you connect it is important too. If that resistor is right at the end of the cable, with short leads, all is fine. But Fig. 4-12 shows what happens if that resistor is connected with long clip-leads. There is still a small reflection; in fact, there are now *two* small reflections. At point A is a small positive reflection, caused by the clip-leads. The two clip-leads

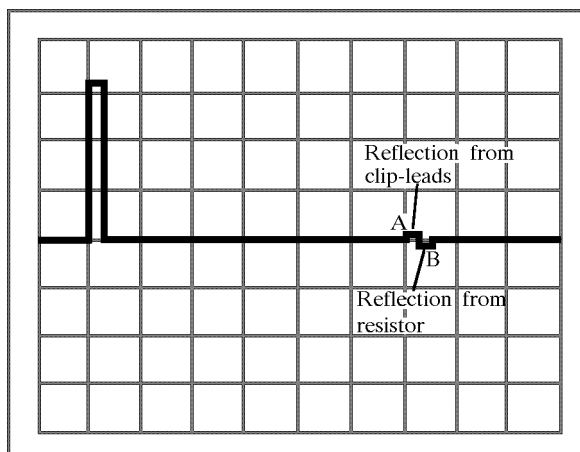


Fig. 4-12. Reflection from a bad connection

make a small transmission line, but its characteristic impedance is higher than that of the coax cable. So we get a positive reflection at this point. A foot later, the termination resistor has a lower resistance than the clip-lead impedance, and so we get a small negative reflection at point B. This points out that this type of test, called *time-domain reflectometry* (or TDR) because it measures the reflections and the time they occur, lets us analyze the locations of shorts and opens, as well as the locations of bad connections. Commercial TDR instruments are thus very useful for finding problems in buried or hidden cables.

### Reflections in analog circuits

Analog signals can be reflected from the ends of cables just as digital ones can. For example, consider the antenna lead from a TV antenna to the TV set. To prevent reflections, the characteristic impedance of the cable usually matches both the impedance of the antenna, and the impedance of the TV set's antenna input. Since there are two kinds of common antenna leads in use — the flat “twin-lead” cable which has a  $Z_o$  of 300 ohms, and the round TV coax with a  $Z_o$  of 75 ohms — many TV sets have two separate inputs as well. TV antennas usually have a 300-ohm connection, but we often use a 75-to-300-ohm matching transformer to match it to 75-ohm coax cable. (There's a second reason too — the 300-ohm twin-lead is a balanced lead, whereas the coax is unbalanced, so slightly different connections are needed.)

Why the careful impedance matching? Because reflections can cause delays. If some of a received TV signal went directly to the TV set, while a small portion of it was reflected from the set back to the antenna, and then reflected a second time from the antenna back to the set, the TV set would get a weak signal shortly after the main, strong one. This would cause a ghost image to appear to the right of the main image. (If you get ghosts in your TV image, don't immediately blame the antenna installation. Ghosts are also often caused by reflections from nearby buildings, hills, or other large objects.)

But there is a second way to look at reflections of analog signals. For this discussion, we will need the concept of a wavelength, so...



Imagine a raft floating in the middle of a lake, as shown in Fig. 4-13. Some giant is pushing the raft up and down at the rate of  $f$  cycles per second. This causes circular waves to travel outward from the raft to the edges of the lake; let's suppose that these waves travel outward at a velocity  $v$ .

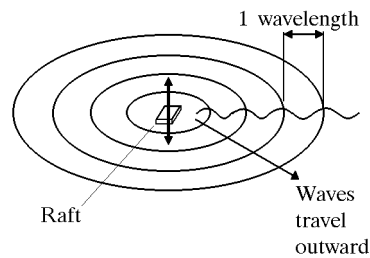


Fig. 4-13. The meaning of a wavelength

If the frequency of the waves is  $f$  cycles per second, the time between waves is  $1/f$  seconds. During that time, a wave moves outward

$$\text{Distance} = \text{Velocity} \times \text{time} = v \times \frac{1}{f} = \frac{v}{f}$$

This quantity is called the *wavelength*, and its symbol is the lower case Greek letter lambda:

$$\lambda = \frac{\text{velocity}}{\text{frequency}}$$

The wavelength is therefore the distance that a wave signal would travel in the time it takes to do one cycle.



Let's now change the test circuit of Fig. 4-10, by substituting a sine-wave generator instead of the pulse generator; this gives us Fig. 4-14. Let us now temporarily modify that generator so it sends out exactly one cycle of a wave. The reflection will then also be one cycle of a sine wave, as shown in Fig. 4-15. Since the line is open-circuited, the reflection coefficient  $\Gamma$  is +1, so the reflected signal looks the same as the outgoing signal. Let us temporarily assume that the line has either no loss or very low loss, so that the reflected signal is the same size as the outgoing signal, again as shown in Fig. 4-15.

Depending on the length of the line, that reflection could arrive at the oscilloscope (which is at the beginning of the line, right next to the signal generator) at various times. So let's examine a few special cases.

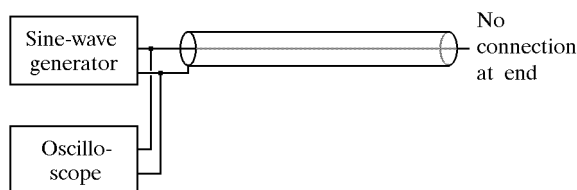


Fig. 4-14. Reflection of an analog signal

Case 1. Suppose that the line is exactly one-quarter of a wavelength long, and its far end is open-circuited. We earlier defined a wavelength as the distance a signal travels in the time of one cycle. For the velocity, of course, we now have to take the velocity in the cable, and we have already learned that this velocity is smaller than the speed of light in a vacuum; it is the speed of light times the velocity factor for the particular cable.

Let's put some numbers on this. Suppose we use an RG-58 cable with a velocity factor of about 0.65, and a frequency of 1.6 MHz. One wavelength is then

$$\lambda = \frac{186,000 \text{ miles per second} \times 0.65}{1,600,000 \text{ Hz}} = 0.0756 \text{ mile}$$

which is about 399 feet. A quarter-wavelength is then about 100 feet.

So let's take 100 feet of RG-58 cable, leave the far end open-circuited, and send a 1.6 MHz signal into it. The signal will take exactly one quarter of a cycle to travel down to the end. Since the end is open, the reflection coefficient  $\Gamma$  is +1, and so the signal is completely reflected. It now takes a quarter of a cycle to travel back to the beginning of the line, arriving exactly one-half of a cycle after it started. Assuming a low-loss line, the signal coming back will be almost exactly the same size as the outgoing signal.

The only problem is that the returning signal is now exactly one-half of a cycle behind the outgoing signal. In other words, the positive half-cycle of the sine wave arrives just as the signal generator is producing the negative half-cycle. And so the forward and reflected cycles, rather than being separated as shown in Fig. 4-15, overlap. In fact, the positive and negative half-cycles exactly cancel, producing 0 volts at the input into the line. The oscilloscope will see nothing.

Let us now extend this a bit by running the signal generator continuously, rather than just outputting one

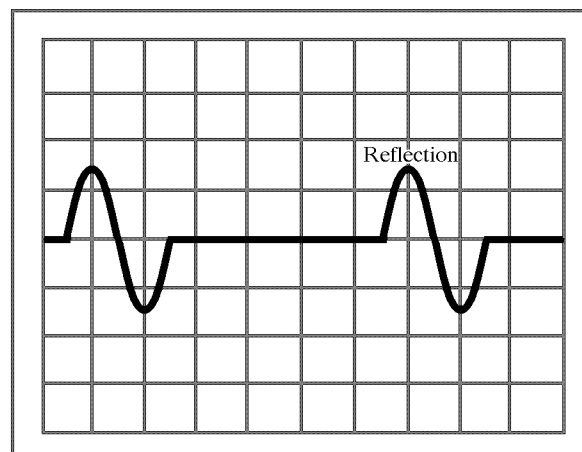


Fig. 4-15. A sine-wave being reflected

cycle. Now *every* outgoing half-cycle will be met by a returning half-cycle that is exactly 180 degrees out of phase with it. Hence the outgoing signal will be continuously cancelled out by a returning signal. And the scope still sees nothing!

Let's think about this for a moment. The signal generator in Fig. 4-14 is generating a voltage (we didn't specify how big) but the actual voltage measured by the scope at the input into the line is 0 volts. How can that be? The only possible explanation is that the transmission line behaves like a short circuit. There is current, but no voltage.

We can summarize this as follows: *A quarter-wavelength transmission line which is open-circuited at the far end behaves like a short circuit at its input.* It may be a bit hard to believe, but it is true. You can prove it on a lab bench with fairly simple equipment.

One more thing — the generator, thinking it is feeding a short circuit, is outputting more than its normal current, trying to overcome that short. So the input to the line is a point of zero voltage, but higher than normal current. It would probably be a good idea to place a resistor in series with the generator lead just to avoid damaging it, but this is usually not necessary in the lab.

Case 2. Let's now take a similar case, but instead of leaving the far end of the line open-circuited, let's short it and see what happens as the positive half-cycle part of a sine wave leaves the signal generator.

The signal takes a quarter of a cycle to reach the short. Because the reflection coefficient  $\Gamma$  at a short is equal to  $-1$ , the positive half of the sine-wave is completely reflected, but the minus sign means that it becomes negative rather than remaining positive. This signal now takes another quarter of a cycle to arrive back at the signal generator, arriving exactly a half of a cycle after it left.

Let's stand back and think about this for a moment. The positive half of a cycle left the generator, was inverted into a negative reflection, and returns just as the generator is outputting the following negative half of the cycle. The generator is now trying to output a negative voltage, but there is already a negative voltage on the line. So the generator doesn't really have to do anything to make the voltage negative. Hence it does not output any current. How can that be? The only possible explanation is that the transmission line behaves like an open circuit. There is a voltage, but no current.

We can summarize this as follows: *A quarter-wavelength transmission line which is short-circuited at the far end behaves like an open circuit at its input.* This, too, may be a bit hard to believe,

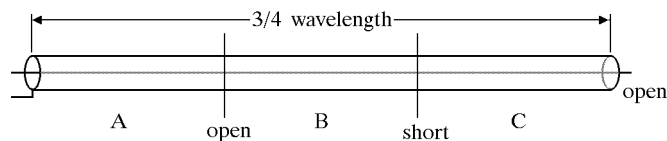


Fig. 4-16. A 3/4-wavelength cable

but it is true. Given the right test equipment, you can prove it for yourself.

We can extend this idea to other lengths of cables. For example, the cable in Fig. 4-16 is 3/4 wavelength long. What do we see if we look into the input?

Let's imagine that the line is split into the three parts labelled A, B, and C in Fig. 4-16, each part one-quarter of a wavelength. Since the right end of part C is open, the left end of it looks like a short. Part B therefore sees a short at the right, so its left end looks open. Finally, part A sees an open at its right end, so its left end looks like a short. So a 3/4-wavelength line which is open at the far end looks like a short at its input.

We can extend this reasoning to any line whose length is some multiple of a quarter-wavelength, and which is either shorted or open at its end. But what about other lines?

### More complicated cases

In most cases, transmission lines will not be an exact multiple of a quarter-wavelength, and they will not have an exact short or open at their end. What then?

The mathematical analysis of such cases is fairly difficult, and most professionals will use a special kind of graph called a Smith Chart to figure out what happens. But even without the Smith Chart, we can still get a general idea of what is going on. So let's consider the case in Fig. 4-17, where we see a transmitter feeding a 75-ohm load (such as an antenna) through a 50-ohm transmission line that is 1.68 wavelengths long.

Because the load resistance is not equal to the line's characteristic impedance, there will be a reflection. The reflection coefficient is

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{75 - 50}{75 + 50} = \frac{25}{125} = 0.2$$

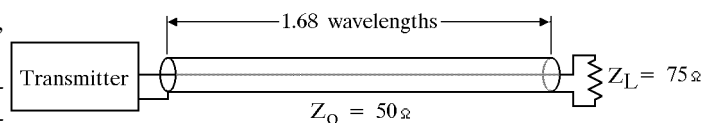


Fig. 4-17. A more complicated example

so 20% of the outgoing voltage is reflected back to the transmitter. Let's assume that the transmitter is putting out 10 volts of radio frequency (RF) signal; the reflected voltage is then 2 volts. This is obviously not good, because the load is not getting as much power as it should.

As the reflected signal goes back to the transmitter, there will be points along the cable where the reflected voltage will add to the outgoing voltage, giving us more than 10 volts. This voltage is called  $V_{\max}$ , and is equal to

$$V_{\max} = V_{\text{forward}} + V_{\text{reflected}}$$

In our example, this voltage is  $10 + 2 = 12$  volts.

At the same time, there will be other places along the line where the two voltages are opposite, and so they subtract to give

$$V_{\min} = V_{\text{forward}} - V_{\text{reflected}}$$

In our example, this voltage is  $10 - 2 = 8$  volts.

Ideally, if the load was perfectly matched to the line, there would be no reflected voltage, and so  $V_{\max}$  and  $V_{\min}$  would be equal — the voltage would be the same 10 volts everywhere, and there would be no maximum or minimum. But that seldom happens exactly.

The presence of maxima and minima means that we can take measurements along the line, and find these points of maximum and minimum. This is not particularly practical with coax cable, but it can be done with open-wire balanced lines, where you can easily get to the wires to take voltage readings between them. It is also sometimes done with microwaves; microwave signals (i.e., signals with a very high frequency on the order of GigaHertz) are usually carried in waveguides (more on these later.) It is possible to cut a slot into a waveguide and insert a small probe to take voltage readings inside it. This can be used to measure the VSWR, but it can also be used to find the frequency. Because the distance from a maximum to a minimum point is a quarter-wavelength (and the distance between two minima is therefore a half-wavelength), this can be used to measure the wavelength of a signal. If you know the speed of the signal in the waveguide, you can then calculate the frequency.

We say that these minima and maxima indicate the presence of *standing waves* along the line, and then define a *standing wave ratio* (also called a *voltage standing wave ratio* because we measure the voltage), abbreviated as SWR or VSWR:

$$\text{VSWR} = \frac{V_{\max}}{V_{\min}} = \frac{V_{\text{forward}} + V_{\text{reflected}}}{V_{\text{forward}} - V_{\text{reflected}}}$$

In our case, this is  $12/8$  or 1.5.

In the best case, if  $V_{\max}$  and  $V_{\min}$  were equal, the VSWR would be 1; many people read this as "1 to 1" or 1:1.

In the worst case, when *everything* is reflected,  $V_{\text{forward}} - V_{\text{reflected}} = 0$  and the denominator is zero, so the VSWR is infinite. So measuring the VSWR is a common way of checking whether an antenna is well matched to the transmitter and its feedline. (It is not a perfect measure, because a resistor load equal to the transmission line's characteristic impedance would produce no reflections, yet obviously radiate no signal into the air either!)

## Measuring VSWR

Although we can calculate the VSWR once we know the load impedance, at high frequencies (such as radio frequencies) it is much easier to measure it directly; hence VSWR is often used at RF frequencies, but quite seldom at low frequencies, such as for audio signals.

The two most common instruments used are an inexpensive SWR bridge, and a much more expensive (and more accurate) device called a through-line wattmeter. The Bird Thru-Line meter is the most common brand name of the latter. Both of these work on pretty much the same principle; Fig. 4-18 shows how the SWR bridge works.

The meter has a metal trough running from one end of the case to the other, with the transmitter and antenna connectors at opposite ends of the case. Running through the trough are the three wires labelled A, B, and C in Fig. 4-18.

Wire A carries the signal from the transmitter to the antenna. Wires B and C are close to it, but not touching; they are called *sense wires*.

Let's look at wire B first. Because B is right next to A, there is a small capacitance between the two. This causes wire B to pick up a small amount of signal from A. But as current goes through wire A to the antenna, it also generates a small magnetic field. Wire B is in that field, and therefore picks up a small amount of signal

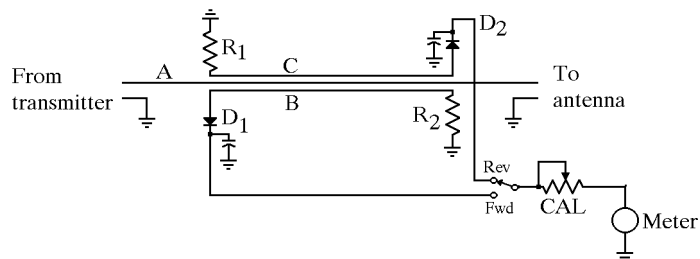


Fig. 4-18. The sensor portion of an SWR bridge

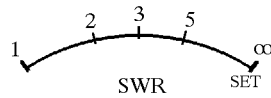


Fig. 4-19. An SWR bridge's meter scale

from the magnetic field as well. The polarity of the signal picked up through the capacitance does not depend much on which way the signal is going, but the polarity of the inductively coupled signal does. For an outgoing signal from the transmitter to the antenna, the two voltages add, whereas for the reflected signal, they cancel. Diode D<sub>1</sub> therefore gets a signal proportional to the outgoing or forward signal, but ignores the voltage from the reflected signal. In the same way, diode D<sub>2</sub> gets a signal proportional to the reflected signal. The two voltages are then rectified and filtered by the two diodes and capacitors, and fed through the FWD-REV switch to the meter.

The secret to the measurement is in the meter's scale calibration, shown in Fig. 4-19. To use the meter, we first connect it to the transmitter, set the FWD-REV switch to the FWD or Forward position, and turn on the transmitter. Then we set the CALibrate control so that the meter reads full-scale; there is usually a small SET mark at the right end of the scale. Regardless of how much power or voltage the transmitter is sending out, this calibrates the SWR Bridge to that level.

The next step is to switch the FWD-REV switch to the REVERSE setting (without touching the CALibrate control). If all of the power is reflected from the antenna, indicating an infinite VSWR, the reverse voltage is the same as the forward voltage, and thus the meter will read full-scale. So the full-scale end of the scale reads ∞. If, on the other hand, the antenna is a perfect match, then the reverse voltage is zero and the VSWR is 1; hence the left end of the scale reads 1.

At the midpoint, the reverse voltage is exactly half of the forward or outgoing voltage. For example, if the outgoing signal is 10 volts and the reverse is 5 volts, the VSWR is then

$$\text{VSWR} = \frac{V_{\max}}{V_{\min}} = \frac{10 + 5}{10 - 5} = \frac{15}{5} = 3$$

so the midpoint reads 3. Other points along the scale are similarly marked to read the VSWR. Since VSWR above 3 is generally considered quite bad, the right half of the scale is usually colored red.

The typical SWR Bridge costs \$20-30, and covers a fairly limited frequency range. For more accurate measurements, many professionals use the Bird ThruLine Wattmeter. This meter works on the same principle, but instead of having two separate sensing wires, two di-

odes, and a switch to select them, there is one sensing wire and its diode, mounted in a rotating assembly called a *slug*. The slug has a printed arrow on it, and you rotate it to measure the forward or reverse voltage. The meter is calibrated in watts, rather than in VSWR. Because the reading depends on frequency and power, Bird makes several dozen different slugs for various power and frequency ranges. This makes the power readings quite accurate, but the disadvantage is that you have to calculate your own VSWR from the forward and reverse power readings. (In practice, many technicians take the easy way. If the forward power is "big" and the reverse power is "small", then they are happy!)

### One application — a waveguide

The idea that a line shorted at one end can appear open at the other, and vice versa, has some interesting applications. Consider microwaves, for instance.

Microwaves are radio waves that have a very high frequency, typically more than several GigaHertz. This also means that they have a very small (micro) wavelength. For example, a signal at 10 GHz has a wavelength of about 1¼ inches. At these frequencies, signals travel only on the surface of wires, not inside them; this is the so-called *skin effect*. A much more severe problem is that most insulators do not work very well at these frequencies — they are too lossy. So it is difficult to build a cable to carry them any great distance.

But suppose you used a pair of uninsulated wires (A and B in Fig. 4-20) held up by a wire loop, as shown at the left of the figure. If the wire loop was exactly ¼ wavelength long, then its top would appear open even though the bottom is shorted. In other words, a perfect insulator made of metal!

In practice, this is a tad tough to fabricate. But since you could place these wire loops as close together as you wanted, there is no reason why they cannot be made into the continuous trough shown as C in Fig. 4-20. To prevent rain water from collecting inside, we place another identical trough (D) above it, giving us a rectangular pipe called a *waveguide*. The signal simply travels along the inside edge of the pipe, roughly in the middle

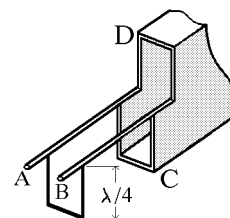


Fig. 4-20. Development of a waveguide

of the long side, which is now  $\frac{1}{2}$  wavelength long ( $\frac{1}{4}$  wavelength from the middle toward each end.)

The frequency at which the long side of the waveguide is exactly a half-wavelength long is called the *critical frequency*. Frequencies lower than the critical frequency can't make it through the waveguide because the distance from the midpoint to the edge is too small — they get shorted out by the edge of the loop. But frequencies *above* the critical frequency can make it through, simply by travelling a bit closer to the edge.

Most waveguides are fairly small. But if you've ever driven through a long tunnel, you've been inside a large waveguide. You may have noticed that your AM radio goes dead almost as soon as you enter the tunnel, whereas your FM radio only gradually fades out as you go in. The reason is that the typical tunnel is too small to let AM broadcast signals through. Since the typical AM station has a wavelength of 600 feet or more, the tunnel would need to be more than 300 feet (a half wavelength) in diameter to let the signal in. So AM signals simply don't make it into the tunnel. FM broadcast station frequencies, on the other hand, have a wavelength of about 10 feet, so even the smallest tunnel will let them through.

Tunnels don't really make good waveguides, though, because they are not made of a good conductor. Underwater tunnels are made from short sections of steel pipes, with waterproofing compound joining them to prevent leaks. This waterproofing insulates the sections from each other, so FM signals, though they get part way into the tunnel, cannot really travel all the way through. Still, it makes an interesting example.

The idea of radio waves getting through holes is similar. For example, if you wanted to shield a room to prevent radio waves from getting in or out, you could completely encase it in a solid sheet of copper. But this isn't necessary — you can use copper sheet with holes in it, as long as the holes are substantially smaller than  $\frac{1}{2}$  wavelength. Likewise, the metal sheet covering the window in a microwave oven door has holes that we can see through. But the holes are much smaller than the microwave wavelength, and so the microwave energy cannot get through.

## Transformers for impedance matching

Quite often you need to match one impedance (for example, a 75-ohm cable) to another (such as a 300-ohm antenna.) This particular case is a common one with TV antennas; many TV antennas are designed for 300-ohm twin-lead, but used with 75-ohm coax cable.

In this example, there is more than just impedance matching at stake. Coax cable is unbalanced (the signal travels on the inner wire, while the outer shield should

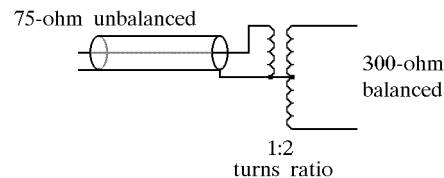


Fig. 4-21. A typical TV matching transformer (balun)

be at ground potential), whereas most TV antennas are balanced (both connections carry the signal, but out of phase with each other.) Such transformers are also often called *baluns*, because they connect between a *balanced* and an *unbalanced* device.

Matching transformers are readily available just for this purpose. The ones for TV use are cheap because only low power is involved; the ones for transmitting applications must handle the full transmitter power and so they are bigger and more expensive.

Fig. 4-21 shows the wiring of a typical TV balun transformer designed to match 75-ohm coax to a 300-ohm balanced antenna. The transformer consists of two wire windings, wound near or over each other. Since the impedance ratio of the two windings of a transformer is the square of the turns ratio (the ratio of the number of turns on the primary and secondary), for a 300-to-75 ohm impedance match (a ratio of 4-to-1), we need a turns ratio of 2-to-1. So the 300-ohm side of the transformer has twice as many turns as the 75-ohm side.

The matching transformer in Fig. 4-21 has the advantage of being usable over a wide range of frequencies. But if you only need to match at one specific frequency, you can use a length of transmission line instead.

We've now learned that a  $\frac{1}{4}$ -wavelength cable can change a short into an open, or vice versa. But there's more to it than that. If the characteristic impedance of the cable is  $Z_o$  and the load on its output is  $Z_{load}$ , then the impedance  $Z_{in}$  you see looking into the cable is

$$Z_{in} = \frac{Z_o^2}{Z_{load}}$$

Notice that this makes sense: if  $Z_{load}$  is an open (infinite impedance), then  $Z_{in}$  is a short (zero impedance.) If  $Z_{load}$  is a short (zero impedance), then  $Z_{in}$  is an open (infinite impedance.) And if  $Z_{load}$  is equal to  $Z_o$ , then  $Z_{in}$  is also  $Z_o$ . So far so good.

But we can take this equation and rewrite it as

$$Z_o^2 = Z_{load} \times Z_{in}$$

$$Z_o = \sqrt{Z_{load} \times Z_{in}}$$

So if we want to connect a load  $Z_{load}$  of 300 ohms to a 75-ohm input  $Z_{in}$ , all we have to do is connect a  $\frac{1}{4}$ -wavelength line between them whose characteristic impedance is

$$Z_o = \sqrt{Z_{load} \times Z_{in}} = \sqrt{300 \times 75} = 150 \text{ ohms}$$

With the 300-ohm load on a  $\frac{1}{4}$ -wave section of line having a 150-ohm characteristic impedance, the input into the line will look like 75 ohms, a perfect match.

There are two catches, of course — this will only work at the one frequency that the line is cut for, and you cannot mix a balanced line with an unbalanced line. So this is totally unusable for the typical TV application. But it is perfectly suited for those single-frequency applications in communications.

### Last thoughts

There is one other idea that should be covered, but that didn't somehow fit into any of the previous sections. In a balanced transmission line (such as the 300-ohm twin lead used in TV antennas), it's obvious that the signal travels along both conductors. But many people believe that in coax the entire signal travels only along the inside conductor, and the shield is there only for the ride, so to speak — to keep outside signals out, and inside signals in. Not so.

If you place a load, such as a resistor, at the end of a line, the only way to get a current to flow in the resistor is to have both ends of it connected to *something*. Whatever current flows into the resistor from the center conductor must flow out the other end, and into the shield. So the shield takes an active part in the process. This will be an important concept when we talk about antennas. An antenna cannot connect just to the center conductor of the coax, because then the current has nowhere to go. There must be a solid connection from the coax shield to some active part of the antenna so that current can return along the shield; if not, then some of the current will flow along the outside of the coax shield, which makes the coax cable part of the antenna — not necessarily desirable.

### Cable loss

Most of our previous discussion has assumed that there was no loss in a cable; that's not true. There is always a loss, though we can often ignore it for short cables — and even when we can't ignore it, there are times when we can't do anything about it, so we often ignore it anyway.

The actual loss in a cable depends on three things — the type of cable, its length, and the frequency of the

signal sent through it. A slight complication is that some of the more common cable types come in several different variations — for example, RG-58 cable comes as plain RG-58, RG-58A, RG-58B, RG-58C, and foam RG-58 — and often users (and even salesmen) don't pay much attention to the difference.

The following table shows the loss (in dB per 100 feet) of several typical transmission lines: RG-174 (a very small 50-ohm coax cable with a diameter of 0.1 inch), RG-58 (a 53-ohm coax with a diameter of about 0.2 inch), RG-8 (a 52-ohm coax with a 0.4 inch diameter), and  $\frac{7}{8}$ -inch hardline (a coaxial cable with a stiff aluminum jacket, intended for commercial applications).

	Loss at 10 MHz	Loss at 100 MHz
RG-174	3.8 dB	12 dB
RG-58	1.2 dB	3.8 dB
RG-8	0.68 dB	2.5 dB
$\frac{7}{8}$ " Hardline	0.13 dB	0.55 dB

There may not be much difference in a one- or two-foot length, but obviously the difference can be huge in long lengths, such as might be used to feed a signal to an antenna on a tall tower. Note also how the loss increases drastically at high frequencies; the loss at even higher frequencies is even worse. This explains why microwave antennas usually put part of the receiver right at the antenna — that minimizes the cable loss at microwave frequencies.

### Summary

Our treatment of transmission lines has been a very brief, simplified one. There's a lot more to this subject. For one thing, even though we've used the symbol  $Z$  in our calculations to keep things general (and to use the same symbols as most other books and articles), we've ignored the fact that these are really impedances — we've made believe that all the  $Z$ 's have been pure resistances. That makes things simple, but is not exactly realistic. But at this point we will use the standard excuse you'll find in many books: "More advanced treatment is beyond the scope of this book."