Wire, Cable, AND Fiber Optics FOR VIDEO & AUDIO ENGINEERS

STEPHEN H. LAMPEN

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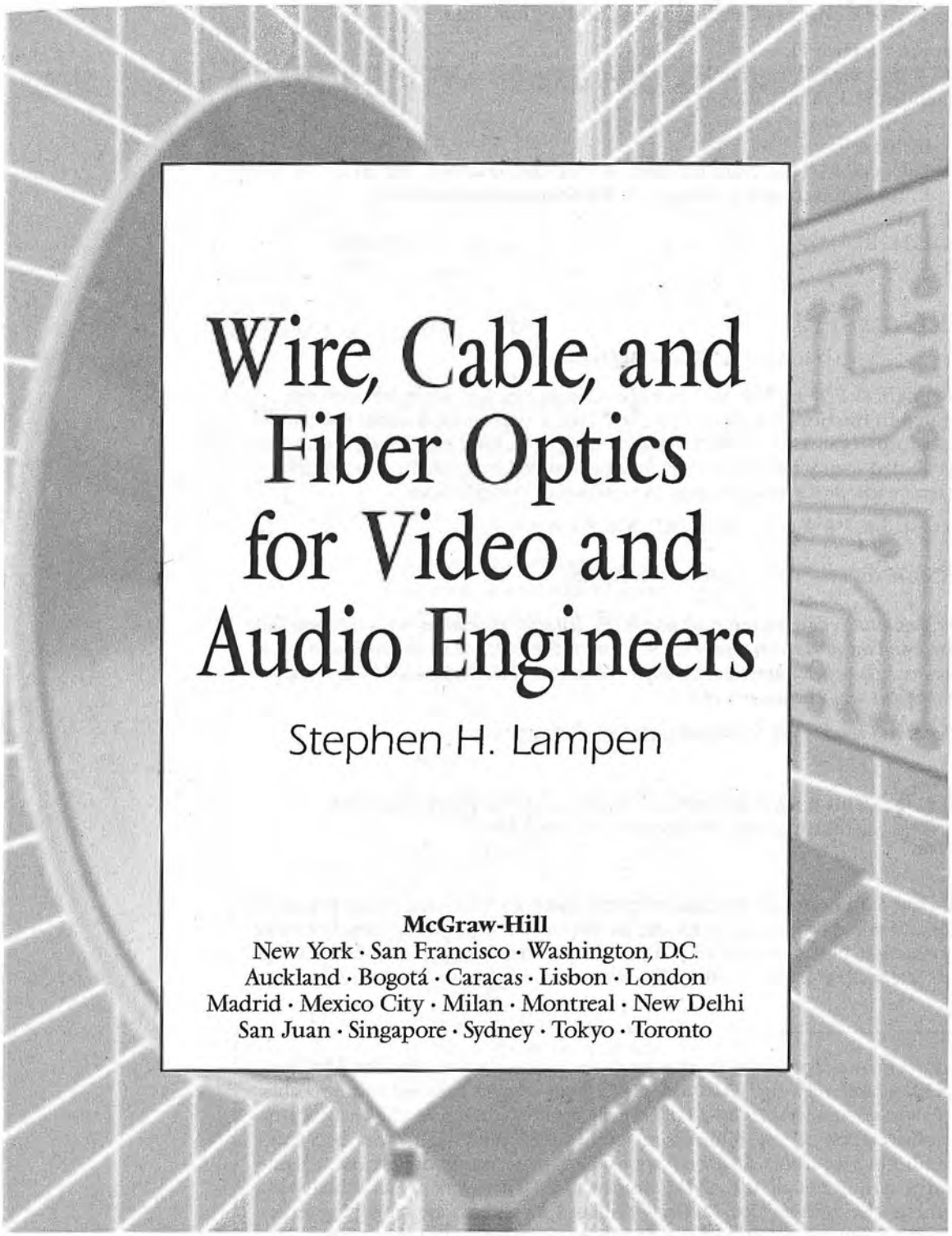

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Stephen H. Lampen

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Let's say you have a battery and a light bulb (Fig. 1-1). A battery uses chemicals to produce electricity. A light bulb turns electricity into heat and, most important, light. But how to connect these two together?

If you can conduct the electricity from the battery to the light bulb, you will have light. Since there is a "+" and a "—" terminal on the battery, and also two connections on the light bulb, if you attach the "+" to one terminal and the "—" to the other, the electricity made by the battery will flow through the filament in the bulb and it will light up (see "Notes and Comments" appendix, item 1).

If you use two pieces of straw to connect them, nothing will happen. If you try two pieces of string, even though the connections were perfect, nothing will happen. These do not conduct electricity. You need a *conductor*. If you make two thin wires out of metal, which is a conductor of electricity, and attach them to the battery and light bulb, they look like Fig. 1-2.

And the light bulb lights up! Turning it on and off is a different matter. You have to unplug the light bulb or the battery, or cut the wire. You have to add a *switch* (Fig. 1-3).

When the switch is open, no electricity will flow. When the switch is closed, it completes the circuit and the light bulb lights. Since usually you want to place the light bulb on the ceiling to light the room, it would be easier to run the wires together, as in Fig. 1-4.

Figure 1-1

A Battery

A Light Bulb

Figure 1-2

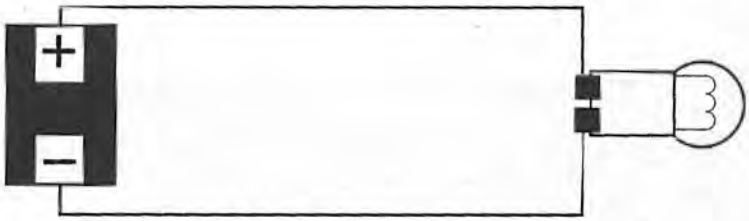


Figure 1-3

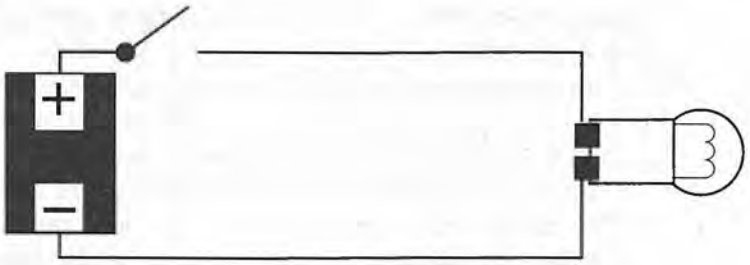


Figure 1-4

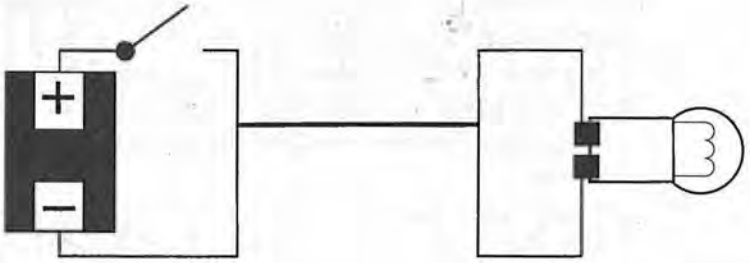
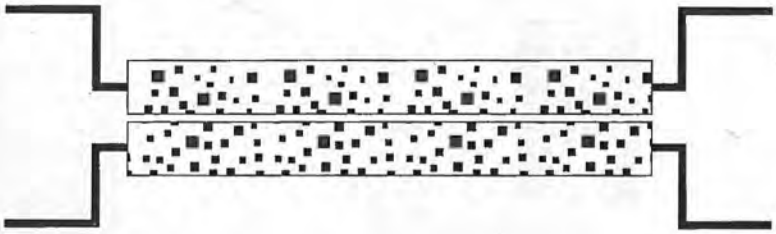


Figure 1-5



The light will not light, however, even with the switch closed. In fact, the wires will begin to get very, very hot. So you will turn off the circuit. You'll notice that the wires are touching each other. If you use bare wires, you must not let them touch; otherwise the electricity, which always takes the easiest path, will flow where they touch instead of through the light bulb (Fig. 1-6). In other words, the circuit is shorter than the one you tried to create. It's a *short circuit!* You must wrap each wire in a material that does not conduct electricity: an *insulator.*

These diagrams generally show bare wires, but they probably would be insulated except where the connections were made (Fig. 1-5).

You could make the wire *solid,* that is, one thick piece of metal. To increase flexibility, you could make it *stranded,* composed of many

smaller wires (Fig. 1-7). The diagrams show solid wires, but they just as easily could be stranded.

You could put a light bulb in the next room but keep the switch in your own room. If you turned the switch on and off, someone in the room with the light bulb would see it flashing and know that you were in the other room. You had *communicated* to the other person.

We could make a graph of what the light turning on and off might look like (Fig. 1-8). First off, then on, then off, then on, then off, and so on...

Now if you turned the switch on and off like Fig. 1-9, and if the person in the other room could read Morse code, he or she would know your flashing meant "S.O.S." or "HELP!"

In other words, the switch and light could be used to send messages from one place to another. A simple series of on-and-off could send information. The light could be in the next room, the next house, or the next town.

Figure 1-6

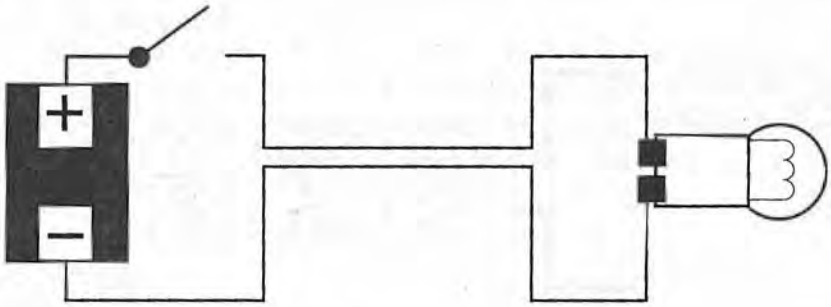


Figure 1-7

Figure 1-8

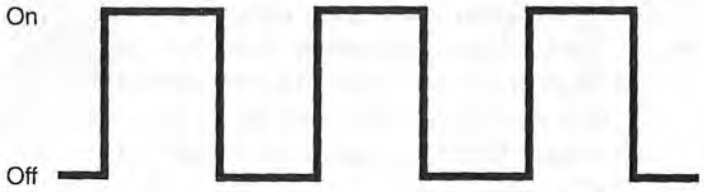


Figure 1-9

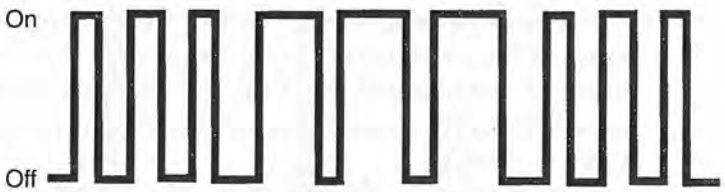
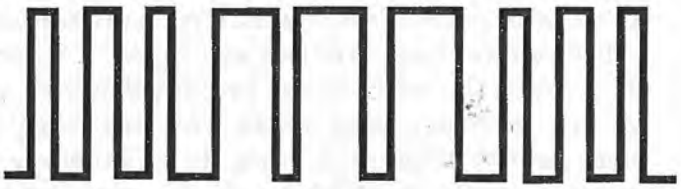


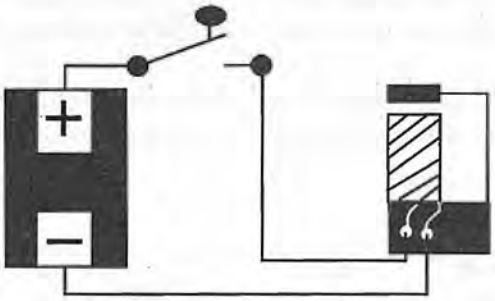
Figure 1-10



The Signal as it Leaves

The Signal at the Other End

Figure 1-11



All you need to get to the next town is enough electricity to overcome the *resistance* in the wire, which wants to turn the electricity into heat. Resistance can turn a good signal into an unusable signal (Fig. 1-10).

You could use a wire with less resistance (copper instead of steel, for example), but that would be more expensive. You could use thicker wire of the same type (more conductive area would mean less resistance), but that also would be expensive. You could use more electricity (higher voltage), but that would be dangerous. Or you could leave everything as it is and invent a more sensitive receiver. Historically, the sensitive receiver won out (Fig 1-11).

This chapter addresses some of the important electrical properties of cables that affect their performance, factors such as impedance, attenuation, and power- and voltage-handling capabilities. In addition, some of the ways these factors can interact are examined.

Impedance

Recall from Chap. 2 that impedance is the characteristic of a cable that works against the flow of electricity. In a twisted pair, impedance is calculated using the diameters of the two conductors in the construction, the distance between them, and the dielectric constant of the plastic used on the conductors.

In a coaxial cable, impedance is calculated using the diameter of the center conductor, the diameter of the shield, the distance between them, and the dielectric constant of the plastic used between. Large or small coaxial cable can be made with the same impedance by keeping the ratio of these factors the same.

Cables can be made in a number of common, "standard" impedances. Coaxial cable usually comes in 50, 75, and 93Ω impedances. Twisted-pair cable is most often seen in 100, 110, 124, and 150Ω flavors. No matter what the actual numbers, impedances are determined in the same general way (see Appendix A, "Notes and Comments," item 12).

Attenuation

All cables reduce the signal level as it passes down the cable. This is called *attenuation*. It can be caused by the resistance in the wire, the capacitance between conductors, impedance variations in the construction, inductance, and other factors. Attenuation is usually expressed as a loss of *x*-many dB (decibels) per unit length at a certain frequency. Thus cable X can be said to have lower loss at 50 MHz because it has an attenuation of 6 dB per 100 ft, while cable Y has 10 dB loss per 100 ft at the same frequency. Attenuation is also affected by the given impedance of a cable. In coaxial cable, a value of 77Ω gives the lowest attenuation. (See Fig. 3-1.)

Power Handling

With many types of cable, especially large-size coaxial cable, some users will wish to carry large amounts of power, such as the output of a transmitter or other radio-frequency amplification device. The efficiency of a cable's power handling (measured in watts) will be determined by the impedance chosen for that cable. The maximum power handling occurs around 30Ω (see Fig. 3-1 and Appendix A, item 11).

Voltage

Voltage is what drives a signal down the cable. With especially high voltages (above 600 volts), the dielectric material in coaxial cable can be critical to avoid arcing between the center conductor and shield. The ideal high-voltage point occurs at around 60Ω. (See Fig. 3-1.)

Contrasting Parameters

During the 1920s and 1930s, it was found that certain cable impedances worked best for the transfer of energy. For example, in video signals (which are generally high-frequency but low in power), the minimum attenuation occurs at 77Ω. Constraints of cable construction, such as using standard available gage sizes and standard mixtures of dielectrics, made a 75Ω cable easier to build.

In the case of transmission lines, which carry high frequencies and high power, the optimum power transfer occurs at 30Ω, but the maximum voltage rating occurs at 60Ω. Therefore, a 50Ω construction was the compromise solution. The actual mathematical mean is 51.5Ω, and you can still find some Mil-spec transmission cables of that impedance or higher (52 or 53Ω). They would be slightly better in voltage rating specifications than a straight 50Ω cable, although their power rating would be slightly less. To use them, transmitter and antenna would have to be tuned to that impedance, not 50Ω. (See Appendix A, "Notes and Comments," item 7.)

Attenuation curves (dB loss at a certain length for various frequencies) are commonly used to figure the loss of a cable. This information can be

Analog Audio

An *analog* is "a thing that is like something else." Analog signals are copies of other kinds of signals. For instance, Fig. 5-1 is a diagram that shows the compression and expansion of air pressure caused by a single tone from a sound-producing device such as a musical instrument or human voice.

The air pressure goes up and down, forced by the pressure from the musical instrument (such as a violin or guitar string), or from the vocal cords in the throat of a person speaking. If you looked at the eardrum of a person hearing the sound, its movement would be an analog or copy of that series of vibrations. In other words, the eardrum would be vibrating just like the original sound. Although the figure shows a wave every inch or so, this is just a representation. As mentioned in Chap. 2, acoustic (sound) waves are much shorter than electronic wavelengths at the same frequency. The acoustic wavelength at 20 kHz is 0.676 inch. The electronic wavelength of 20 kHz is over 9 miles!

If this sound were picked up by a microphone, the diaphragm in the microphone would also vibrate in an analog of the original sound. Coming out of the wires from that microphone, generated by the coil-and-magnet arrangement, would be the electronic analog of the original sound. Figure 5-2 is the analog audio signal.

Audio generally occupies the range from 20 Hz to 20 kHz. Compared to radio frequencies or data bandwidths, these are low-frequency signals. When signals get to much higher frequencies, and the wavelength gets shorter, eventually the spacing of the wires, the spacing of braid shields, the dimensions of the cable, and even the spacing of the pins in connectors, get closer to the wavelength and begin to have an effect on the signal.

Because analog audio cables are low-frequency constructions, and the wavelengths are very long, the impedance of the cable is of no conse-

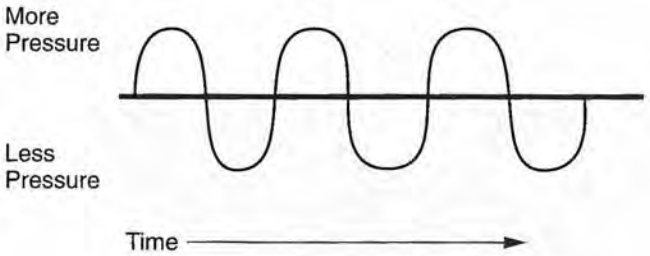


Figure 5-1

Figure 5-2

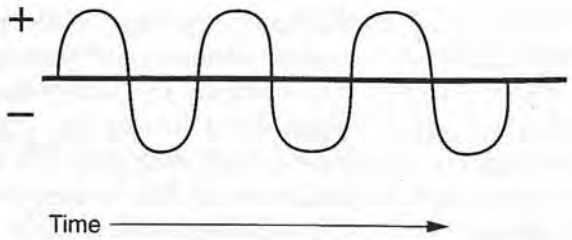


TABLE 5.1

Capacitance between conductors (pF/ft)	Highest frequency (kHz)			
	15	20	30	40
12	1474	1111	737	556
19	931	701	465	351
24	737	555	368	278
31	571	430	285	215
50	354	267	177	134

–3dB (half-power) length in feet

quence. The dimensions of the cable are very different from the wavelengths of the signals it carries. Impedance variation throughout a run of cable is equally unimportant. The only exception is the phone company, which often has lines that are miles long. They then must compensate for losses in the lines by adding filters and equalizers. But miles-long runs are almost unheard-of in a standard audio installation.

The capacitance of various dielectrics, however, can cause signal degradation at audio frequencies; this can be predicted and measured. Table 5.1 is a chart that shows the half-power point (3 dB loss) on a piece of cable, as determined by the highest frequency traveling down that cable, with common values of capacitance per foot and a standard 600Ω load impedance. A different load impedance would affect these distances. For a 1-dB loss, divide the length by 3.

You also should be aware that, if the cable is made unbalanced by attaching one of the twisted-pair wires to ground, the capacitance of the cable will be approximately doubled, because the shield has been added as a signal conductor. This greatly reduces performance over distance.

One other factor in distance is wire gage. While the industry standard is 22 AWG, many installers and designers are moving to 24 AWG because of the cost and size savings. There are two compromises in such a choice. The first compromise is ruggedness. Just because it is more wire, 22 AWG will last longer when moved, flexed, or abused. If it is used in an installation, however, such properties are of little consequence; the reduced size, weight, and cost of 24 AWG can have added benefit. The second compromise is an increase in resistance (Table 5.2).

Electrically a cable can be characterized as a series of resistors and parallel capacitors, bringing into play what is called an *R-C time constant.* The R-C time constant is what ultimately affects high-frequency performance and creates "roll off" of high frequencies. See more on R-C time constants in the "Digital Audio" section later in this chapter.

Because of the small size and reduced cost, foil shields are very common in all-analog, line-level audio applications. While foil shields lack the low-frequency effectiveness of braid shields, they are much easier to make, much cheaper, more flexible (although flex life is not as good), and much smaller in size than braid-shield cables. Multipair cables with

TABLE 5.2 **Resistance Per Thousand Feet (Ohms)**

AWG	Resistance (solid)	Resistance (stranded)
30	103.2	112
28	64.9	70.7
26	40.81	44.4
24	25.67	27.7
22	16.14	17.5
20	10.15	10.9
18	6.39	6.92
16	4.02	4.35
14	2.53	2.73
12	1.59	1.71
10	1	1.08

individually foil-shielded pairs (also called *snake cables*) sometimes include an overall shield for additional shielding protection.

Microphone Cables

In microphone-level applications (usually 50—60 dB below line level), losses, noise, and interference become more critical. For permanent, non-moving installation, the same foil pairs can be used. You must be more aware of the sources of interference, however, because foil shields are less effective at low frequencies.

Interference can be constant, such as from power wiring or high-voltage power lines, ballasts in fluorescent lighting, or permanent transmitters. Interference also can be transitory, such as from passing cars or devices with motors that cycle on and off (such as refrigerators or air conditioning). Still other sources can be completely random: ship radar, CB, cellular phones, 2-way radio, or other moving transmitter sources. Avoid running microphone lines near or parallel to anything that may generate an electromagnetic field. In many cases, solid-steel conduit can be a major help in reducing induced noise in microphone lines.

Microphone or "mic" cables are usually made for flexibility, flex life, and low handling noise, and not necessarily for performance. The best dielectric materials are somewhat inflexible, so most microphone cables use rubber, neoprene, PVC, or similar materials. While mic cables are excellent from the microphone to the connector in the wall or stage box, they are not intended for long runs. Run foil pairs (either single or snake) from that point.

Flexibility and flex life also can be affected by the metals used, the strandings used, and the plastics used to jacket them.

While copper is generally used, cadmium bronze is physically stronger and has much better flex life. Cadmium, however, is toxic when vaporized and is difficult to work. Copper alloys now being developed approach the strength and flex life of cadmium bronze, without the cadmium but at added cost.

All other things being equal, the higher the strand count, the greater the flex life. Thus, microphone cable designs with each conductor having 19 strands, 40 strands, or even 105 strands are readily available, each with increased flex life.

Microphone jacket materials include rubber and its artificial cousins (EPDM, neoprene, Hypalon). They are very rugged and have good flexibility. PVC, especially some of the new matte finish versions, can come very close in flexibility, though not in ruggedness. Other materials, such as polyethylene or Teflon, can be very rugged but are poor in the flexibility department. Since flexibility is of major importance in microphone cable, these last materials are rarely used.

Quad Microphone Cables Quad or "star-quad" microphone cables (Fig. 5-3) are four-conductor microphone constructions that have very low noise and hum pickup. The four conductors are wound together in a spiral. To get the added noise rejection, join the wires that are across from each other into a single pair. Usually these are color-coded to aid in identifying which to combine.

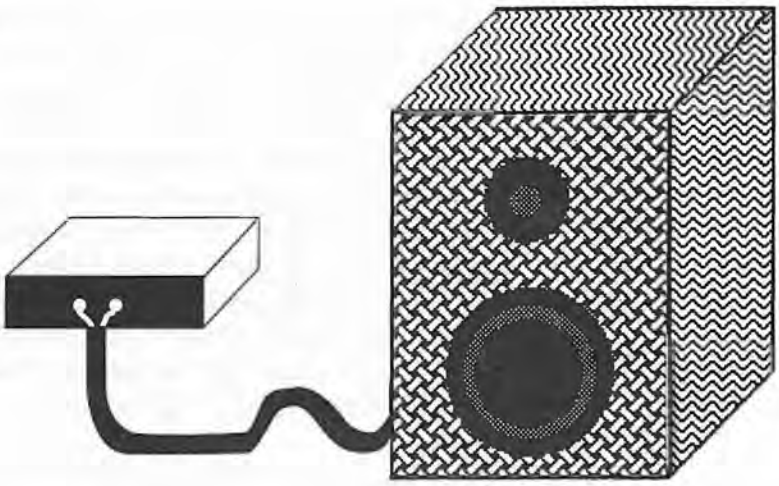
Using Fig. 5-3 as a guide, after stripping off the jacket and separating the braid, strip and combine first the two black wires and then the two white wires. The resulting pair is a balanced line. This produces common mode rejection at each pin, as well as noise rejection from the balanced line configuration itself. Hum reduction can be as great as 30 dB improvement over standard microphone cable.

Speaker Cable

When audio began to become important, radio manufacturers had a problem. Tubes were used to amplify the signal, and the output impedance of a tube is very high (thousands of ohms). Building a speaker to match that output impedance (for maximum power transfer) would

Figure 5-3

Figure 5-4



require a large, heavy coil of wire in the speaker, a technically difficult and expensive problem. The solution was to insert a transformer between the amplifier and the speaker, which reduced the high-impedance output to 4, 8, or 16Ω. This meant that only a few turns of wire in the coil of the speaker would match that impedance.

As long as the speaker was inside the radio and the distance from the amplifier portion of the radio to the speaker was just a few inches or feet, it worked well. When hi-fi began to arrive, engineers realized that speaker performance could be improved if the radio (or, more correctly, the amplifier in the radio) and its speaker were in separate boxes. Then the wire to the speaker might run many feet, and the resistance of the wire would be a major factor in using up the amplifier's power (Fig. 5-4).

Because the output impedance of an amplifier is low (4 to 16Ω), the current (amperage) must be high in order to get a given amount of power to the speaker. The lower the resistance of the cable, the more power gets to the speaker (see Appendix A, "Notes and Comments," item 11). It is now fashionable in hi-fi circles to use very large-gage wire to keep the power loss in the wire to a minimum.

The demand for exotic, low-resistance speaker cables has spawned an entire industry. Whether the exotic constructions and materials make a difference, or are worth the extra cost, is still a topic of discussion. But large-gage wire is certainly better than small gage-wire at transferring power from a low-impedance output amplifier to a speaker.

Table 5.3 shows the percentage losses to expect, and distances you can go, at 4 or 8Ω load impedances.

There is a second concern with speaker wiring, called *damping factor*. This is the ratio between the output impedance of the amplifier and the impedance of the speaker. Damping factor can change over frequency. As the frequency gets higher, the damping factor will get smaller.

The actual output impedance of modern amplifiers is very low, and therefore the damping factor is very high. Cutting-edge amplifiers can have a damping factor as high as 20,000 at low frequencies, dropping to 2000 or so at 1 kHz. This allows the energy to be transferred almost entirely to the speaker. Because the vast majority of energy is in the low frequencies, you might think that only the low frequencies are affected, but this is not so.

Much music contains very sharp spikes or fast transitions, such as percussion instruments or piano music. These are, by definition, high frequencies. Indeed, some of these transients and harmonics of music go beyond the range of human hearing, yet many listeners claim they can hear the difference when these ultrasonic signals are missing.

If you could see these sound waves, or their electrical analogs, you would see a very sharp transition from low to high level. This is also

TABLE 5.3

Distance in Feet at 11% Loss (0.5 dB)							
	24 AWG	22 AWG	20 AWG	18 AWG	16 AWG	14 AWG	12 AWG
4Ω	10	15	25	40	40	90	140
8Ω	20	35	50	85	115	185	285
Distance in Feet at 21% Loss (1 dB)							
	24 AWG	22 AWG	20 AWG	18 AWG	16 AWG	14 AWG	12 AWG
4Ω	25	35	50	90	125	195	305
8Ω	45	70	105	190	250	395	610
Distance in Feet at 50% Loss (3 dB)							
	24 AWG	22 AWG	20 AWG	18 AWG	16 AWG	14 AWG	12 AWG
4Ω	85	135	195	340	470	740	1150
8Ω	170	275	390	685	935	1480	2285

distances you can

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level. This is also

G	12 AWG
	140
	285
G	12 AWG
	305
	610
G	12 AWG
	1150
	2285

called *rise time*. When a waveform with a very fast rise time appears, a poor damping factor will have the effect of smoothing over that spike and therefore affecting the ability of the speaker to reproduce it. The resistance of the wire reduces the damping factor, so the lower the resistance of the wire, the better chance the speaker will have at reproducing such details. Here again, larger wire is better than smaller wire.

You should be aware that very few speakers have linear impedance over the range of audio frequencies. That is, it is rare that they are the same impedance at all frequencies. This is especially true where multiple drivers (woofers, midranges, tweeters) are used to reproduce the entire range of frequencies. Passive circuits are included, whose purpose is to divide the frequencies among the speaker elements. These are called *crossovers*.

Often during the transition between speakers, the apparent impedance can fall from 8Ω to only 2—3Ω. Some amplifiers cannot drive these low impedances without distortion. It takes four times the current to drive a 2Ω load as it does an 8Ω load. In such cases, added resistance in the wire actually can improve speaker performance by providing a greater load.

Distributed Loudspeaker Systems

Impedances of 4 or 8Ω are most common in amplifier outputs. Manufacturers of commercial amplifiers might also supply an output transformer with a number of secondaries, say one marked 8Ω and another marked "70-volt."

The actual impedance of a 70-volt output transformer depends upon the wattage of the amplifier. A 25-watt, 70-volt amplifier has an actual output impedance of 196Ω. There are less common 25- and 100-volt systems. You can go much, much farther with these systems on smaller, cheaper wire than with 4 or 8Ω output impedances. This is because the resistance of the wire becomes only a tiny fraction of the output impedance of the amplifier. Increasing the impedance of the amplifier reduces the amount of current running on the wire. Since this is critical to loss on the wire, increasing the impedance increases the voltage and reduces the loss, so smaller-gage wire can be used (see Appendix A, "Notes and Comments," item 11).

Actual speakers are still 4 or 8Ω, however, so when the wire is connected to each speaker, there must first be a small transformer to

reconvert from 70-volt to 4 or 8Ω. Because of this transformation/retransformation process, the quality of the eventual audio can depend to a great degree on the quality of the transformers. Low-frequency response (below 100 Hz) is lost first. It contains much of the electrical energy, so transformers must be extremely well-made to pass these low frequencies. Because the speakers in distributed systems are most often small, cheap speakers with no baffle or box behind them, the loss of low-frequency reproduction is usually accepted.

Distributed systems are used extensively where quality is not the primary consideration, such as in public address, background music, or paging systems. Dozens, even hundreds, of speakers can be run off one amplifier, and virtually any kind of wire can be used. In background music or paging, the speakers are most often mounted in ceiling tiles or hung on walls. Any kind of speaker could theoretically be wired up to a distributed system. The quality of the original program material (such as background music) is often equally low, however, so putting in high-quality speakers or high-quality transformers will not improve anything.

Another advantage of 70-volt systems is the transformer on the speaker, which comes with various connections (called *taps*) that allow the power fed to that speaker to be controlled. Some speakers can be louder, some medium volume, and some softer, and they will maintain that ratio among them no matter what the setting of the master volume control. This is often desirable where the volume should be high in noisy locations and low in quiet locations.

The main wiring consideration is often the fire rating of the cable. Most speaker systems are in drop ceilings, which normally require plenum-rated cable.

Table 5.4 shows the distance you can run in a 70-volt system at three levels of loss and seven wire gage sizes.

If you want excellent reproduction and cannot accept the compromises of a distributed system, there is one other way to run long lines with speakers. That way is not to run them! Put the amplifiers next to the speaker and run line-level audio down foil-shielded pairs to those amplifiers. They may have to be modified to accept a balanced-line input, but the distance it can run, and the resultant quality, will be excellent. Systems such as this are built into stadiums and auditoriums. Often the remote amplifiers turn on and off with the control console and other equipment at the control point.

TABLE 5.4

Distance (ft) at 11% Loss (0.5 dB)						
24 AWG	22 AWG	20 AWG	18 AWG	16 AWG	14 AWG	12 AWG
520	820	1170	2070	2840	4490	6920
Distance (ft) at 21% Loss (1 dB)						
24 AWG	22 AWG	20 AWG	18 AWG	16 AWG	14 AWG	12 AWG
1120	1770	2520	4450	6100	9650	14,890
Distance (ft) at 50% Loss (3 dB)						
24 AWG	22 AWG	20 AWG	18 AWG	16 AWG	14 AWG	12 AWG
4210	6650	9500	16,720	22,950	36,300	56,000

Digital Audio

The recent move by manufacturers into digital audio has caused a lot of confusion among audio professionals. Some of this confusion is due to the fact that digital audio is partly digital and partly audio. It is digital in that you are converting analog signals into digital data at one of a number of data rates. This conversion produces a high-data-rate signal, where before you had a relatively low-frequency analog signal.

In digital audio, analog rules no longer apply. The signal is now data and must be treated as data. For instance, the cable must have a specific impedance. Cable capacitance is now a critical number. Wire twisting, wiring spacing, dielectric compounds, and shielding style are now more important.

The Audio Engineering Society (AES) and European Broadcast Union (EBU) have set up specifications for digital audio cable. By the time a one- or two-channel analog signal is converted to digital data, there are some significant data rates to be handled. The AES/EBU specifications are:

- 110Ω ±20 percent
- 3.072 Mbps data rate (one or two channels)

The two-channel version is the same cable as the one-channel version. Thus a one-channel cable is also a two-channel cable, and a 12-pair digital audio snake can be a 12- or 24-channel digital audio snake.

The AES/EBU specification mentions an impedance of 110Ω but does not actually give a tolerance. However, ±20% can be extrapolated from the data on equipment within the specifications.

There are three ways to make digital audio cable: immobilize the twisted pairs, use solid pairs, or convert to coax.

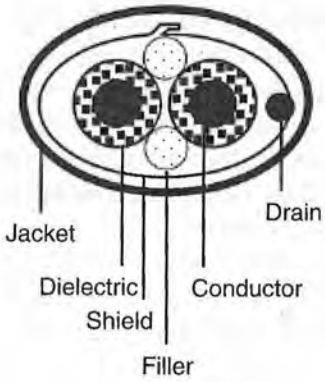
Immobilization Take a standard twisted pair cable, use a better dielectric, and then pack the construction with "fillers" (Fig. 5-5). Immobilization keeps the wires at a predictable distance (and therefore a predictable impedance), regardless of the flexing of the cable. Naturally, fillers will add cost and size to the cable. Immobilization also improves the *capacitance unbalance*, which is variations in capacitance over the length of the cable.

Immobilization can also be accomplished by bonding, gluing, or extruding the twisted pair together during the manufacturing process. These constructions have excellent impedance tolerance and low capacitance unbalance.

Solid wires Solid wires can be twisted together with a fair amount of accuracy. They have poor flexibility and flex life, however, and should be considered only for permanent installations.

Digital audio on coax AES/EBU-spec digital audio also can run on coaxial cable through the use of a transformer called a *balun*, which converts from a **bal**anced line (twisted-pair) to an **un**balanced (coax). Because impedance tolerance is so much tighter on coax, you can go up to 500 meters.

Figure 5-5



Many of the advantages of twisted pairs are lost, however: balanced lines, common-mode noise rejection, cross-talk rejection, and independent shielding. In addition, two transformers (baluns) must be bought for every channel to be converted, one for each end of the cable! These two transformers easily can cost $40 and up per pair.

If an installation is digital audio and video, it can be cost-effective to put everything on the same coax as the video. Simply buy more coax to do the digital audio, and use the same strippers, crimpers, and connectors. In addition, the labor cost saving of making up a crimp-crimp BNC connector, versus soldering an XLR, might just make the cost of baluns a wash.

SP-DIF and SDIF Digital Audio

SP-DIF and SDIF are two other digital audio standards. SP-DIF (Sony/Phillips Digital Interface) is based on coaxial cables and BNC connectors. SDIF (Sony Digital Interface) is a consumer system based on RCA connectors.

With SDIF, very short lengths (under 1 meter) probably can be run with standard, hi-fi RCA hookup cables. For greater lengths, true 75Ω coaxial cable is recommended. It should be noted that RCA connectors are not any specified impedance, much less 75Ω, but at short distances (with most likely only two connectors in the path), they have a minor effect on the digital signal.

Jitter

Digital signals are sequences of ones and zeros, looking much like the square wave shown in Fig. 5-6.

As cable length increases, the square wave becomes less and less square. Impedance imperfections (structural return loss) reflect some of the signal back to the source, a phenomenon measured as *VSWR*, or *voltage standing wave ratio.*

Capacitance tends to make the edges of each square ragged (see Appendix A, item 13). The point is that, in a system transmitting a digital signal down a cable, the resultant square wave does not look very square, making it difficult to establish exactly where 0—1 and 1—0 transitions are. This is a timing error and is known as *jitter.*