CHAPTER

3

# Fundamentals of Communications

## About This Chapter

Communications is the most important application of fiber optics. Optical fibers serve as low-cost, flexible "pipes" that carry signals in environments ranging from climate-controlled office buildings to the ocean bottom. They span distances ranging from a few meters inside an automobile to nearly 10,000 kilometers across the Pacific ocean. They carry signals at speeds up to trillions of bits per second and form the backbone of the global telecommunications network.

To understand these uses of optical fibers, you need to understand the basic concepts behind modern communications. This chapter explains how communications systems function, the types of signals they transmit, the types of services they offer, and how the communications industry works. This chapter also shows you how fiber optics fit in with other communications equipment in the global network.

## Communications Concepts

Communications is the process of conveying information, and the word is used in two distinct senses. One is communication through the use of the written or spoken word by writers, public speakers, broadcasters, and public relations specialists. The other is *telecommunications*, which is sending information over a distance using technology. In this book, I discuss the use of fiber optics in telecommunications, although I usually simply say "communications."

Telecommunications sends signals over a distance by fiber, wire, or radio waves.

Many different technologies are used in modern telecommunications. Electrical signals travel through plain copper wires and coaxial cables, also made of copper. Radio and microwave signals travel through the air from antennas on the ground, in aircraft, or in satellites. Beams of light travel through the air or through optical fibers. To learn about these technologies, we'll quickly examine the history of communications.

## A Short History of Communications

The earliest long-distance communications were made by signal fires that relayed simple information. The ancient Greeks relayed news of the fall of Troy by lighting fires on a series of mountain peaks. During the American Revolution, patriots watched the belfry of Boston's Old North Church for signal lamps. These lamps would reveal the path of British troops leaving Boston to seize weapons stored in Concord. Such signals could be seen for miles, but the people sending them had to arrange the signals' meaning in advance. So the patriots knew that one lamp meant the British were leaving Boston by crossing a narrow neck of land leading west; two lamps meant the British were leaving by boat. (Paul Revere was already on his way; the lanterns were used to warn others in case Revere was caught.) The message was vital to the revolution, but it was also simple. The two lanterns conveyed only two bits of information: that the British were coming and that they were crossing the water.

The optical telegraph relayed messages from hilltop to hilltop 200 years ago.

A written letter or a human messenger could carry more information but took time to travel, on foot or by horse. The first system that we might call telecommunications was a series of hilltop towers built in the 1790s by French engineer Claude Chappe. Each tower was in sight of the next and had an operator to relay messages by moving a set of wooden arms. The operator in each tower looked through a telescope to read the message coded by the positions of the arms in the previous tower, recorded the message, then relayed it to the next tower by moving the arms of his own tower. This process continued on down the line to others, as shown in Figure 3.1. Other countries soon adopted Chappe's *optical telegraph*, and it remained in use for decades until it was replaced by Samuel Morse's *electrical telegraph*.

The electrical telegraph sends signals through wires as a series of short and long electrical pulses. Known as Morse code, "dots" and "dashes" represent letters. Each dot or dash is a bit of information. Like the optical telegraph, the electrical telegraph requires operators to relay signals; but wires can carry signals further between operators, and transmission isn't interrupted by darkness or bad weather. Because of these advantages, the electrical telegraph spread across the continents and, in 1866, across the Atlantic. Telegraph wires formed a network running between major cities. Telegraphers received signals and either delivered them locally or relayed them to more distant stations. People did not have home telegraphs; but the stock ticker, a special-purpose telegraph that printed information on stock trades, was available in the stockbrokers' offices.

Multiplexing allowed telegraph lines to carry two or more signals at once.

The first telegraph lines could carry only one message at a time, but inventors soon discovered ways to make them carry two or more signals at once, a process called *multiplexing*. Alexander Graham Bell was trying to invent a new type of multiplexer when he realized that his invention could be used to carry voice. Instead of sending dots and dashes through the wire, Bell modulated an electrical signal that reproduced a speaker's voice. He called his invention the *telephone*. (Bell also invented a device he called the "*photophone*," which modulated the brightness of a beam of light sent through the air, but it never proved practical.)

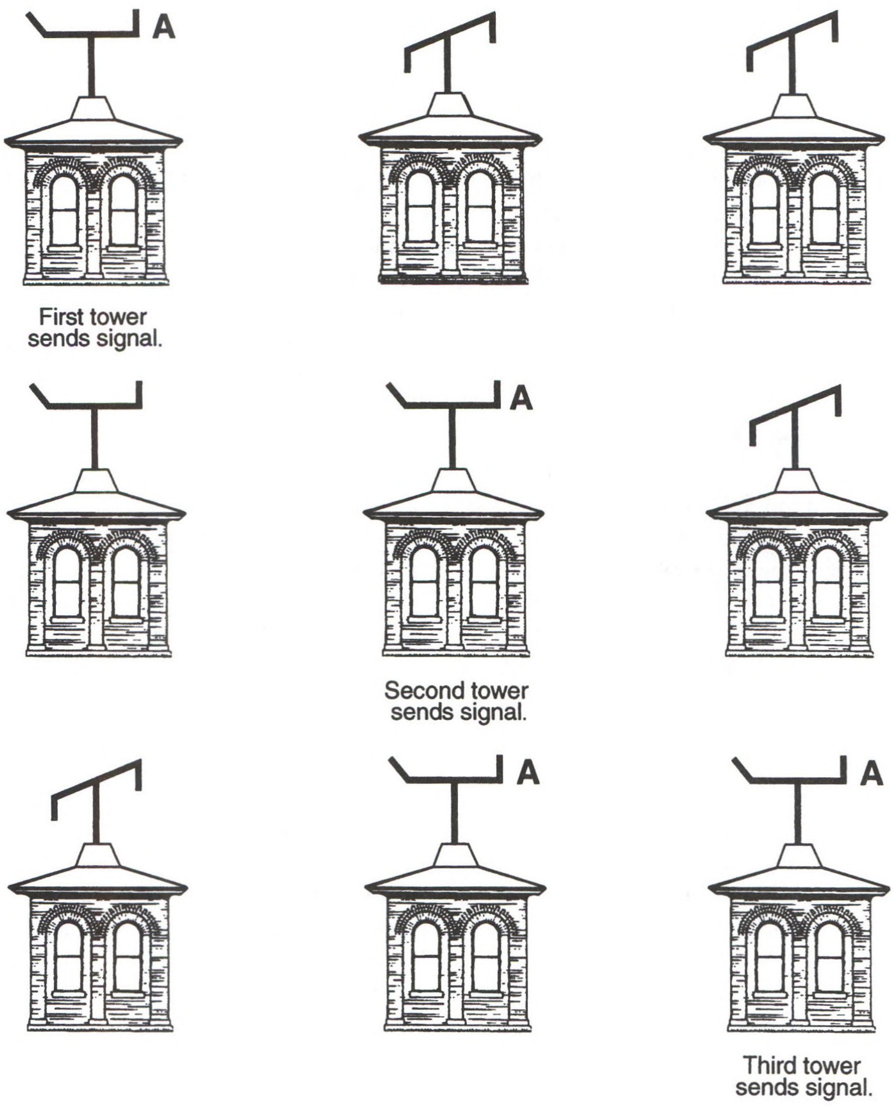



**FIGURE 3.1**
*Relaying messages by moving the arms on an optical telegraph.*

Although many telegraph companies saw no future in the telephone, it soon spread to homes and offices. By the 1890s, dense thickets of telephone wires stretched between poles in downtown areas. The early telephone network differed from the telegraph network because voice signals could not travel as far through wires as the dots and dashes of the telegraph. The telephone worked locally; the telegraph could send signals long distances. Operators and mechanical devices could regenerate telegraph signals when they became weakened by distance; but telephone signals could not be amplified until vacuum tube circuits were developed. Only in 1915 could telephone calls reach across North America, and not until 1956 did a submarine cable carry telephone conversations under the Atlantic—90 years after the first transatlantic telegraph cable.

Radio communications followed. Guglielmo Marconi showed that radio waves could transmit telegraph signals by a mile in 1896 and steadily increased the distance in the following years. Radio's advantage was that it required no wires, and the British Admiralty saw its potential for communicating with ships at sea. Ships in trouble could transmit pleas for help (most famously the Titanic). Radio telephones followed and in the 1920s became the first way to send voices across the Atlantic. Radio broadcasting began about the same time.

Radio moved to higher frequencies as electronics improved.

Radio communications began at low frequencies, but improvements in electronic technology opened up higher frequencies. Higher frequencies can carry more information, as we'll see later. Low frequencies of tens or hundreds of kilohertz are fine for voices, but television pictures carry more information and require higher frequencies. Television signals are broadcast at frequencies of tens or hundreds of megahertz, a thousand times higher than the band used for audio-only radio.

High-frequency radio signals and microwaves, which are really higher-frequency radio waves, can multiplex voice or video signals, just as electrical telegraph could carry multiple messages. This led telephone networks to use chains of high-frequency radio and microwave towers to relay signals tens of kilometers, repeating signals in an electronic version of Chappe's optical telegraph. By 1970, satellites were relaying voice and video signals around the world and the telecommunications network had become global. That made it possible to make telephone calls around the world, although the rates were dollars per minute or more. Long-distance calls within the United States cost less, but could still add up to budget-busting bills.

Then fiber-optic communications arrived. When the American long-distance market was opened to competition in the early 1980s, telephone companies built their new national high-capacity backbone lines with optical fiber. The ever-increasing capacity of fiber now far exceeds that of any other telecommunications medium.

The demand for transmission capacity has increased steadily.

This brief history of communications carries a few important lessons. The demand for transmission capacity has increased steadily. Engineers have turned to new technologies to provide more capacity and to send signals over longer distances. Transmission capacity has always been a key limitation. Distance and connectivity are also important. People have friends and family scattered around the world; businesses need to contact people in far-flung places. It's no longer enough to have phones at home and at work; people want mobile phones in their pockets so they can be reached at anytime and anywhere. Let's look at the key concepts of capacity and connectivity.

## Transmission Capacity and Bandwidth

Bandwidth traditionally has been in short supply.

Transmission *capacity* or *bandwidth* tells us how much information a system can carry. Bandwidth has traditionally been in short supply, so communications systems are designed to make the most of it by various means. Depending on what's being transmitted, bandwidth can be measured in various ways, and that requires more explanation.

The telephone is a familiar example that illustrates the principles of transmission capacity. A corded phone is linked to the telephone network by a pair of copper wires, which normally can carry a voice signal several miles. Higher frequencies suffer greater attenuation

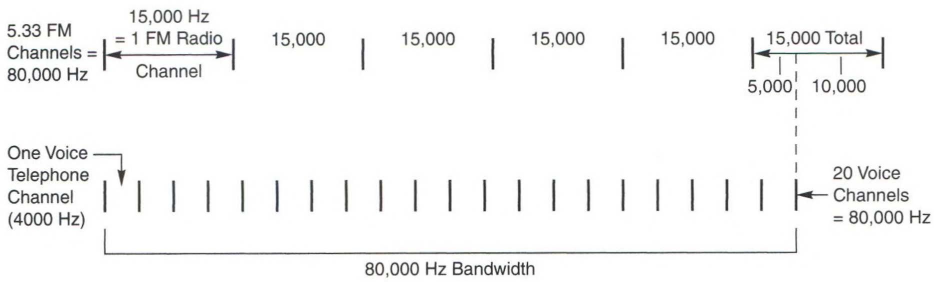



**FIGURE 3.2**
*80,000 hertz of bandwidth can carry twenty 4-kHz voice channels, or 5.33 FM radio channels.*

than lower frequencies, so phone lines carry frequencies of only 300 to 4000 hertz, much less than the human ear's nominal range of 20 to 20,000 hertz. The high end of this band is reserved for control signals, so the actual bandwidth is about 300 to 3400 hertz. This is enough for intelligible conversation, but not for high-fidelity reproduction. The telephone industry settled on this limit long ago, which means that the nominal bandwidth of a phone line is 4000 hertz. In contrast, FM radio has a bandwidth of 15,000 hertz per channel, which gives it much better fidelity.

Frequency range is one way to measure bandwidth for analog signals, such as voice and music, which vary continuously. Bandwidth also can be measured by the number of standard channels that can fit in the band. For example, a system that can transmit 80,000 hertz, as shown in Figure 3.2, can carry 20 telephone voice channels or 5.33 FM radio channels. In this case, each channel is a distinct signal.

Analog bandwidth is measured in frequency range or number of channels.

For digital transmission, bandwidth is the number of bits per second passing through the system. (Be aware that computer data storage is measured in *bytes* rather than in bits; one byte contains eight data bits, and may contain extra bits for error correction.) Digital bandwidth also can be measured as the number of standard channels transmitted. For example, a standard analog telephone voice channel can be converted to a digital signal carrying 64,000 bits per second. A digital signal carrying 20 digitized standard voice channels has a nominal line rate of 1,280,000 bits per second or 1.28 megabits per second.

You will note that the digitized bandwidth seems to be higher than the corresponding analog bandwidth. The numbers indeed are larger, but comparing digital and analog capacity is not as simple as comparing the numbers, as you'll see when you learn about analog and digital signals later in this chapter.

## Multiplexing

The builders of electrical telegraphs realized that it costs less to build one high-capacity system that could carry many signals than build several separate systems with lower capacity. This technique, called *multiplexing*, can be used for any type of signal as long as the bandwidth is available. Modern telecommunications systems typically multiplex signals together in three different ways: by frequency, by wavelength, or by time.

Multiplexing combines many signals into one higher-speed signal.

- *Frequency-division multiplexing* is the transmission of signals at different frequencies of which radio and television broadcasts are good examples. Each area broadcaster broadcasts signals at a specific frequency or band. Stations are set at standard frequencies, such as 89.7 MHz for an FM radio station or 204 to 210 MHz assigned to channel 12 on the U.S. television dial. Other broadcasters in the region are assigned other frequencies. You tune your radio or television receiver to select one of these frequencies, but all of them are transmitted through the air simultaneously. (For broadcasting, a buffer is usually kept in reserve between adjacent channels, so neither channel 11 nor channel 13 would operate in the same area as channel 12.) Broadcast signals go through the air, but frequency-division multiplexing also works through cable. In fact, frequency-division multiplexing is standard in cable television, where certain frequency bands are reserved for specific video channels, although the frequencies may not match those on the broadcast dial.

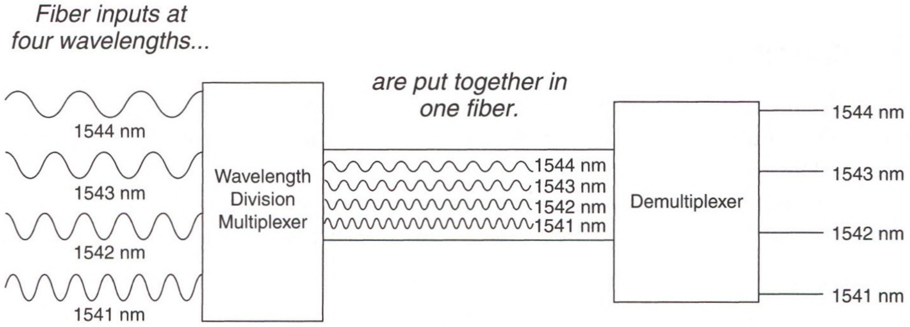
- *Wavelength-division multiplexing* is the optical counterpart of frequency-division multiplexing. Separate signals modulate light sources emitting at different wavelengths, just as separate signals modulate radio transmitters broadcasting at different frequencies. Each separate wavelength is an *optical channel.* Light from the separate sources is combined and transmitted through a single optical fiber. Then the wavelengths are separated again, or *demultiplexed,* at the other end, as shown in Figure 3.3. As with frequency-division multiplexing, the wavelengths can be packed closely together, but the signals must not overlap.

Time-division multiplexing works only for digital signals.

- *Time-division multiplexing* combines streams of bits from two or more sources to produce a single stream of bits at a faster rate, as shown in Figure 3.4. For example, four signals at 10 million bits (megabits) per second can be combined to generate one 40-Mbit/s signal. Figure 3.4 shows data bits being interleaved, with one bit from stream A followed by one from stream B, then one from stream C, one from stream D, and finally the next bit from stream A. As you will learn later, other variations on time-division multiplexing may arrange the incoming data bits differently, such as in blocks called *packets.* Note that time-division multiplexing is designed specifically to work with digital signals made of strings of incoming bits.

Note that although demultiplexing may seem to be merely the opposite of multiplexing, separating the combined signals often is a more complex and demanding task than

**FIGURE 3.3** *Wavelength-division multiplexing combines signals in one fiber.*



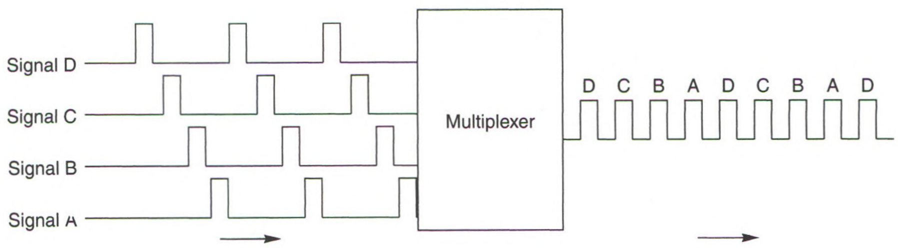



**FIGURE 3.4**
*Time-division multiplexing combines several slow signals into one faster signal.*

multiplexing. Imperfect demultiplexing leaves you with too little of the desired channel, or too many undesired channels scrambling your signal.

## Terminology

In introducing the broad area of communications, we have covered a lot of ground and introduced some terms that have specific meanings in the field. Telecommunications is full of confusing buzzwords, so let's pause to review and explain some important terms before going on to cover the field in more detail.

*Information* is what is communicated. It may be a very simple message confirming receipt of some anticipated message, conveyed by lighting a signal fire. Or it can be a huge and complex message, such as digital files that contain an entire book, an album of music, or a motion picture. Even if the "information" contains something this is not at all informative, such as your least favorite television program; it still counts as information.

A *signal* transmits that information. Signals may take many forms, such as acoustic, electronic, or optical. They may be converted from one form to another, and still contain the same information. For example, when you make a long-distance telephone call, your telephone converts the sound waves from your mouth into an electrical signal. This electrical signal is converted into an optical signal at a telephone switching office, then back to an electronic form at another telephone switching office, and finally back into sound waves at the other person's telephone. Signals are coded in various formats so they can be understood by both the sender and the receiver, as you'll learn in the next section.

A *system* is a collection of equipment that performs a task, such as transmitting a signal. It's also a vague word that can elude precise definition. Systems can contain other systems, sometimes called *subsystems*, and can range in scale from gigantic to tiny. We often speak of the telephone system as one entity that includes all telephone equipment, but it also includes switching systems that direct phone calls to their proper destinations.

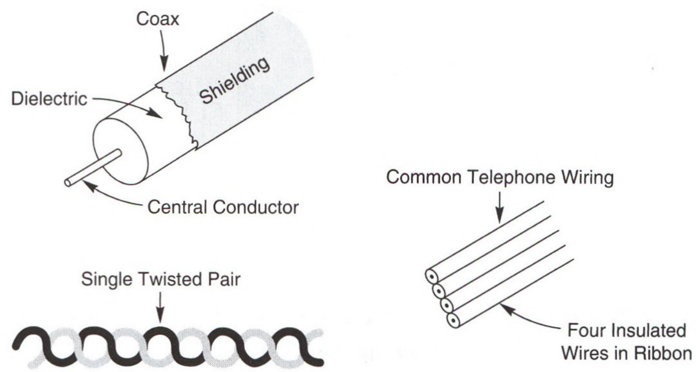
*Solution* is a meaningless marketing buzzword. It often functionally means "system," or "something that someone gets paid for selling you."

A *channel* is a distinct signal. An example is the signal from a television station that you select on your dial or remote control. A multiplexed signal may carry many channels. An *optical channel* is a signal carried on one wavelength; a single fiber may carry many optical channels.

Radio waves have frequencies from 10 kHz to 100 GHz.

*Radio* from a telecommunications standpoint describes frequencies of the electromagnetic spectrum from about 10 kilohertz to 100 gigahertz. Different parts of that spectrum are used for different purposes. Radio waves broadcast both sound (often called simply "radio")

**FIGURE 3.5**
*Types of copper cables.*




Microwaves have frequencies of 1 to 100 GHz.

"Copper" is the generic term for all metal cables.

and video (television). The radio spectrum is divided into many bands, which carry various services; these bands vary from region to region.

*Microwaves* are high-frequency radio waves ranging from about 1 to 100 GHz, corresponding to wavelengths of 30 centimeters to 3 millimeters. Waves at the upper end of the microwave range and higher sometimes are called *millimeter waves,* because their wavelengths are measured in millimeters. "Microwaves" is an old name, given at a time when radio wavelengths less than a meter were considered short.

*Wireless* literally means "without wires." In practice, it means sending signals through the air, without a physical connection, to a fixed or mobile terminal such as a cellular telephone or pager. Signals sent by radio waves, microwaves, and visible or infrared light through the air are examples of wireless communications.

*Coaxial cable* is a metal clad cable with a central wire running along its axis. The central wire is surrounded by a nonconductive material called a *dielectric* (usually plastic) and covered by a metal shield, as shown in Figure 3.5. The central wire carries current, and the shield confines the electromagnetic field generated by the current and blocks external electromagnetic fields that could induce noise. Often called *coax,* coaxial cable transmits radio and low-frequency microwave signals. Coax is commonly used for cable television and video signals.

*Twisted pair* is—strictly speaking—a pair of thin insulated copper wires wound around each other in a helical pattern. Twisted pair is the nominal standard for telephone wiring in homes and offices. However, a closer look reveals that telephone wires are often flat strips containing four parallel wires, as shown in Figure 3.5. Only two wires are needed to carry signals for a single phone line. High-performance versions of twisted pair, such as *Category 5 cable,* can carry higher-frequency signals.

*Copper* is the generic term for metal cables, including twisted pair and coax, because most metal cables are made of copper.

# Signals and Formats

Telecommunications signals and their formats are crucial elements in any communications system. The sender and receiver of any message must agree on a format that both can understand. This is true for both one-way communications, like television broadcasts, and two-way communications, like telephone calls. The transmitter must generate the signal in a format that the receiver can convert to a usable form.

As mentioned earlier, signals can be generated, transmitted, and received in different ways, including sound waves, electrical currents, electronic voltages, and light. We'll start with some very general ideas about telecommunications signals and formats, then consider some specific points important for fiber optics.

## Carriers and Modulation

To understand the basic structure of a telecommunications signal, let's start with a very simple example: an AM radio station. AM stands for *amplitude modulation,* which describes its operation. The radio station is licensed to operate at a specific frequency in a certain location. A radio-frequency oscillator at the station generates a single pure wave that oscillates at the exact frequency specified by the license, such as 980 kHz in the AM band. This pure wave is called the *carrier* because it carries the signal; but it is not a signal because it's only a pure tone that carries no special information.

A telecommunications signal is a modulated carrier wave.

The input is a signal, which may be an announcer's voice or a piece of music. The sound waves are converted to an electronic signal, which varies in intensity with the volume of the sound wave at any instant. That is, the electrical intensity is proportional to the acoustic intensity. The electronic signal is at the same frequency as the original sound. This is called a *baseband* signal, meaning that the input signal is at its intended frequency.

This baseband signal modulates the amplitude of the carrier wave. For clarity, Figure 3.6 shows a very simple case, where the modulation simply switches the carrier wave on and off, as if sending Morse code. This is the modulated transmitter output. For a real radio station, this would produce an irregular wave that varies with the sound intensity at any instant.

The carrier wave has a higher frequency than the baseband signal.

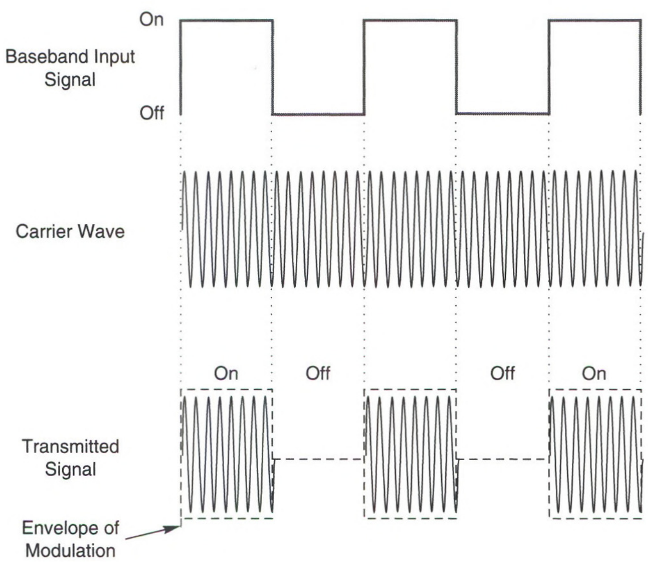



**FIGURE 3.6**
*Input signal modulates a carrier wave.*

Note that the radio carrier frequency is much higher than the highest frequency in the baseband input signal. AM radio stations broadcast at frequencies of 540 to 1700 kHz, well above the 5-kHz upper limit on the baseband audio-frequency signal. This is a common feature in the modulation of carrier frequencies to generate telecommunications signals. The transmitter modulates the carrier with the input audio signal. The receiver *demodulates* the received radio signal, effectively removing the carrier frequency to recover the baseband audio signal.

Another important point is that the transmitter and receiver have to agree on the same format to transmit a signal properly. For a radio station, one part of that format is the carrier frequency. Tune your radio to 680 kHz, and you won't hear a radio station broadcasting at 570 kHz or 890 kHz.

The type of modulation also is critical. AM radio modulates the intensity of the carrier frequency. FM radio uses *frequency modulation,* which modulates the frequency of the carrier signal rather than its intensity. That approach gives a much cleaner signal, as you can easily tell if you compare the sound quality of AM and FM stations. However, you can't decode AM radio with an FM tuner.

Amplitude modulation is standard in fiber-optic systems.

The same principles apply in fiber optics. Light waves are the carriers, and their frequencies are much higher than the frequencies of the signals they transmit. Amplitude modulation is standard in commercial fiber-optic systems.

## Analog and Digital Communications

Digital signals transmit a series of bits. Analog signals vary continuously.

Communications signals come in two basic types, *analog* and *digital,* as shown in Figure 3.7. The level of an analog signal varies continuously, making it an analog of the variations of the original input. A digital signal transmits a series of bits; if the input signal was analog, the bits represent how that input signal varies. Virtually all practical digital signals are binary codes, which are at either a high level ("on" or "one") or a low level ("off" or "zero"), as shown in Figure 3.7.

Analog and digital formats each have advantages. The older analog technology is more readily compatible with our senses and much existing equipment. Our ears, for example, detect continuous variations in sound level, not merely the presence or absence of sound; likewise our eyes detect levels of brightness, not merely the presence or absence of light.

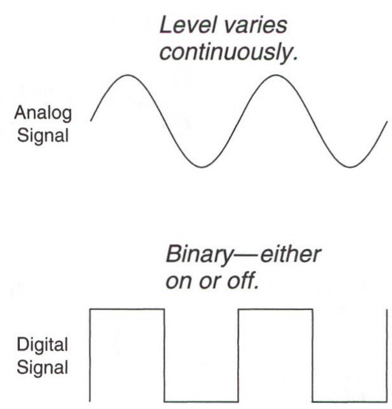



**FIGURE 3.7**
*Analog and digital signals.*

Both audio and video communications traditionally have been in analog format. The wires that serve corded telephones deliver continuously varying analog electronic signals to a standard telephone handset, which converts the incoming electronic signals to continuously varying sound waves. Traditional analog television sets likewise receive analog signals, which they decode to display pictures on the screen.

Digital signals, on the other hand, are easier to process with electronics and optics: It is much simpler and cheaper to produce circuits that detect whether a signal is at a high or low point (on or off) than it is to produce one that can accurately replicate a continuously varying signal. Digital signals also are much less vulnerable to noise and distortion. For an analog device, the output must increase linearly with respect to the input to accurately reproduce an input signal; and once noise gets into an analog signal, it's very hard to remove. In contrast, digital signals don't have to be reproduced accurately; all you need is to be able to tell the ones from the zeroes. It's like the difference between seeing a person across the street clearly enough to identify them (analog), and merely recognizing that someone is across the street (digital).

Digital signals are easy to process with electronics and optics.

These advantages are leading engineers to shift increasingly to digital transmission. Recorded music is largely digital, with CDs having replaced phonograph records and audiocassette tapes. Most cellular telephones rely on digital transmission, and the new high-definition television signals are digital. Cable television transmission is a mixture of digital and analog signals. All this technology is possible because signals can readily be converted between analog and digital formats. For example, the telephone network includes circuits that convert the analog electrical signals that replicate your voice to digital form, and other circuits that convert those digital signals back to analog form so you can understand them.

The idea of analog-to-digital conversion is simple, as shown in Figure 3.8. A conversion circuit samples an analog signal at regular intervals, measuring its amplitude at that instant. In the telephone system, the samples are taken 8000 times per second, twice the highest frequency (4000 Hz) that must be reproduced. Each measurement is assigned to one of a number of possible slots that represent different amplitude levels. The amplitude in today's phone systems is described by an eight-bit code, so there are a total of 256

Analog telephone signals are digitized at 64,000 bits per second.

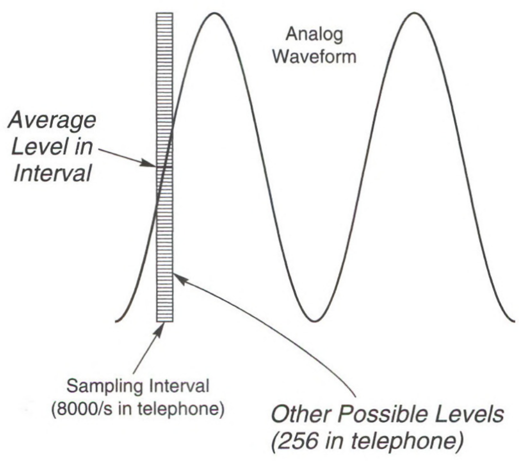



**FIGURE 3.8**
*Digitization of an analog signal.*

possible signal levels. This produces 64,000 bits per second. (Older telephone systems used a seven-bit code for signal amplitude, which gives 128 signal levels and produces 56,000 bits per second.)

Digital-to-analog conversion is straightforward. The circuit sets the signal amplitude at the level measured for each sampling interval, essentially building the analog waveform interval by interval.

Comparing the analog bandwidth of 4000 Hz to the digital bandwidth of 64,000 bits per second suggests another potential disadvantage of digital transmission. Accurate digital reproduction of an analog signal requires sampling at a rate faster than the highest frequency in the analog system. In addition, each sample requires several bits of data, so digital systems seem to require a higher overhead. It isn't that bad in reality, because there is no precise equivalence between analog and digital capacity requirements. Digital systems can tolerate limited bandwidth much better than analog systems because they only need to detect the presence of a pulse, not reproduce its shape accurately. In many cases, the bandwidth needed to carry a digitized version of an analog signal is comparable to the bandwidth needed by the original analog signal.

Fiber optics work well for digital transmission, and initially were mainly used in digital systems. The light sources used with fiber-optic systems are vulnerable to nonlinearities that can distort analog signals at high frequencies, but engineers have succeeded in making highly linear analog fiber systems, which are mainly used to distribute cable television signals.

## Electronic and Optical Signals

At first glance, conversion of signals between optical and electronic formats seems automatic. An electronic signal goes into a transmitter, and an optical signal emerges from the attached optical fiber. Conversely, an optical input to a receiver produces an electronic output. However, the process isn't quite that simple.

Optical signals are the number of photons. Electrical signals are the current or voltage.

In optical devices, the signal is the number of photons, which corresponds to the flow of current. A laser is switched on by increasing the current passing through it; a detector produces a current proportional to the number of photons reaching it.

Electronic signals can be represented in two ways: as a *voltage*, or electrical potential, and as a *current*, or the number of electrons flowing through a circuit. Voltage and current are related, but in practice one or the other is considered the signal, depending on the circuit elements used. Simple circuits can convert a voltage variation to a current variation. Most electronic circuits in optical systems use voltage signals, which must be converted to current variations to drive the optical system. This conversion is not difficult, but you should realize the signals are not exactly equivalent.

# Connectivity

Pipes and switches can represent a communications system.

Communications systems provide *connectivity* by transmitting signals from place to place. A critical job of any communications system is to get the signals to the right place. To understand how this is done, we'll divide the parts of a communications system into two basic categories: pipes and switches.

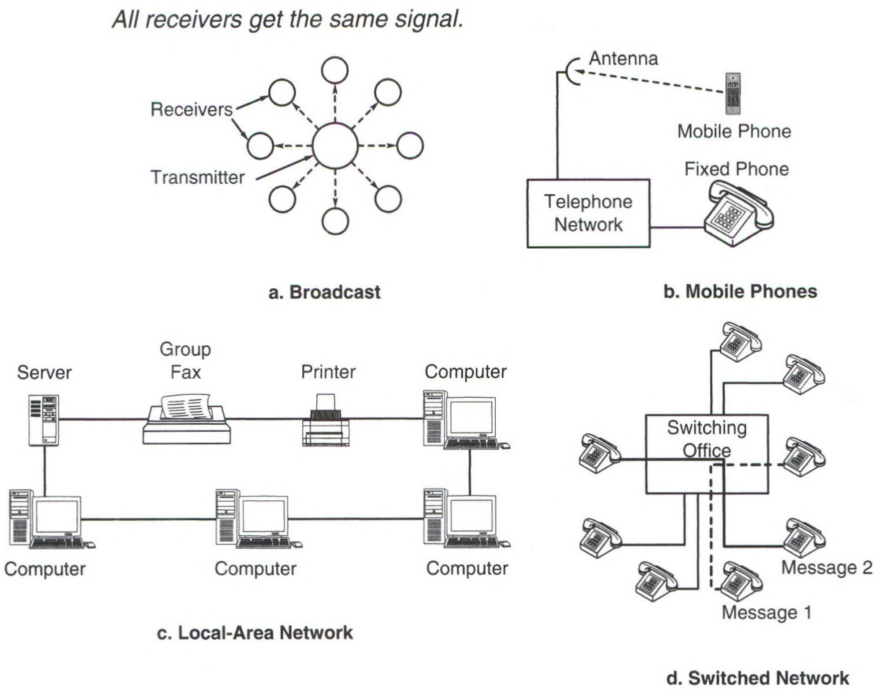



**FIGURE 3.9**
*Some representative communications systems.*

As you saw in Figure 1.6, pipes transmit signals from one point to another. A point-to-point link, such as the one between your personal computer and its keyboard, is an example of a pipe. Switches direct signals arriving from one point to other points; the telephone system, for example, contains many switches to direct calls locally, nationally, or globally. With enough pipes and switches, a communications system can make all the connections you need.

The pipes and switches view of communications is obviously an oversimplification, but it can be useful for understanding the basic designs of communications systems. We'll consider three basic approaches to connectivity: broadcasting, switching, and networking. These approaches are shown in Figure 3.9.

## Broadcasting

A broadcast system sends the same signal to everyone who receives it. In its usual simple form, broadcast transmission is one-way, from the signal source to many individuals. Local radio and television stations are good examples. Their transmitters radiate signals from a main antenna that can be picked up by receivers throughout the local area. Satellite television works the same way; a satellite broadcasts microwaves, which home receivers detect and decode. Broadcasting may not reach everyone within range, because some people don't have antennas, televisions, or satellite television service.

Broadcasting sends the same signal to all points.

Broadcasting doesn't have to be through the air. Cable television systems broadcast signals through a network of optical fibers and coaxial cables. Most subscribers receive the same signals; but premium channels are broadcast in a scrambled form that can be decoded only by using special equipment. Cable television systems set aside certain channels for two-way service. These channels enable them to provide telephone and broadband data service, and allow customers to order special services, such as pay-per-view programs.

Signals transmitted through the air are not broadcast if only one person or receiver can receive them. For example, cellular telephone conversations are transmitted through the air by local towers, but only the person with the proper cell phone can decode signals directed to that phone. Other phones and antennas working in the same frequency range can pick up the signals, but cannot decode them.

## Switched Systems

A switched system makes temporary connections between points.

A *switched system* makes temporary connections between terminals so they can exchange information. The telephone system is a familiar example. An old-fashioned telephone switchboard made *physical connections* between phones when the operator plugged wires into the jacks. Today, electronic switches in a telephone company switching office perform the same function for local phone calls, completing a circuit that links your telephone to the phone you are calling. These switches also route long-distance calls through a network of other switches that direct them to their destinations.

When these switches make a connection, they dedicate transmission capacity between the two phones for as long as they stay on the line. For a local call, the connection goes through phone wires from your home to the local switching office, then from the switching office through wires to the other caller's phone. For a long-distance call, the switches reserve a *voice channel*, providing room for one phone call on a multiplexed line that carries many separate conversations on multiple voice channels. Once the call is complete, the line is released and can be used for other calls.

The key aspects of a switched system are the following: They make temporary connections, dedicate transmission capacity between a pair of nodes or terminals, and make connections between any pair of terminals attached to the switch. Our example used wired telephones, but cell phones work the same way, except that the signals are transmitted through the air rather than over wires.

## Networking

Networked computers are interconnected so they can communicate with each other.

The word *network* has many meanings. One of these is a specific architecture for connecting computer terminals. A computer network consists of many terminals connected so they can send signals to one another. These connections are always "on," so each terminal can send messages to any other terminal at any time. The signal that carries the message may pass through many terminals, but it is addressed specifically to one terminal, so other terminals cannot read it. (For our purposes, we assume that system security can't be breached.) The permanent connections are like streets on which delivery trucks travel to deliver parcels to your home.

An office *local-area network* (LAN) is a good example of this type of network, as shown in Figure 3.10. A message from one terminal to another may go through the whole network,

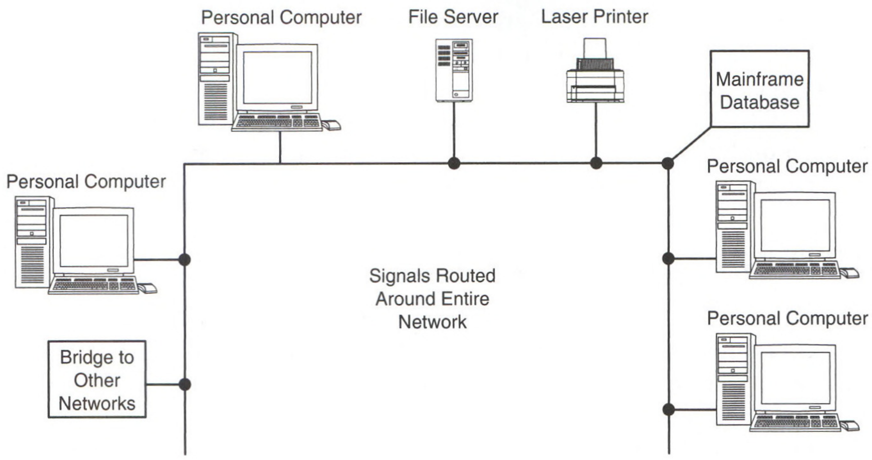



**FIGURE 3.10** *An office local-area network (LAN).*

but the only terminal that receives the message is the one to which it's addressed. The results look superficially like the switched telephone system, but the details differ considerably, as you will see later. Note, for example, that the networking approach does not set aside any transmission capacity to send a particular signal.

Networking lies at the heart of packet switching, which directs messages by a process called *routing*. As you will learn later, routing differs greatly from the type of switching described previously.

# Transmission Media and Switching Technologies

So far, we've largely ignored the media used for pipes and switches. In a general context, the nature of the pipes doesn't matter a lot. Telephone calls made over wired phones and cell phones serve the same purpose, even though they are transmitted and directed in different ways. An office local-area network can be implemented over wires, fiber-optic cables, or wireless links. Cable television does differ significantly from over-the-air broadcast television because it allows two-way transmission, but the differences are largely due to the switches.

Switching technology matters more because it can constrain the system performance. In the early days of the telephone system, switching was done mechanically. Now most switching is done electronically. Electronic switches operate in two different ways: by setting the path that signals will follow (as in making a telephone connection), or by reading the address transmitted with a data message and directing that message to the proper address.

Switching technology can constrain performance.

During the bubble, prospects for optical switching created a concept called *optical networking*. The idea was overpromoted, but included an important concept that shouldn't be lost. Because fiber optics have the highest capacity of any current transmission medium, they form the high-capacity core of the modern telecommunications network—the communications equivalent of superhighways in our network of roads and highways. Optically switched signals could remain in optical form throughout the high-capacity fiber-optic core of the network. Keeping the signals in optical form would allow them to remain organized in the same way they are arranged for optical transmission, with separate signals carried on different wavelengths in the same fiber. Interest in optical networking evaporated when the bubble ended, but may revive as Internet traffic continues to increase.

# Communications Services

So far we've talked about communications from a general standpoint. Now let's look at specific types of communications services. We won't try to cover everything. Rather, we will concentrate on the types of services most likely to reach modern homes and businesses: voice, video, and data. The three were originally quite distinct services, but have come to converge as different networks offer the same services.

## Telephony

Voice communications, the oldest of the services, is traditionally defined as *telephony* and delivered to subscribers through copper wires. The telephone system is a switched network that offers global connectivity, so you can call any continent from your phone. You can loosely divide the telephone system into a hierarchy of subsystems, shown in simplified form in Figure 3.11.

Home phones are part of the local loop and connect to a local switching office.

Your home or business phone is part of the base of the phone network, variously called the *subscriber loop*, the *local loop*, or the *access network*. These links run from individual

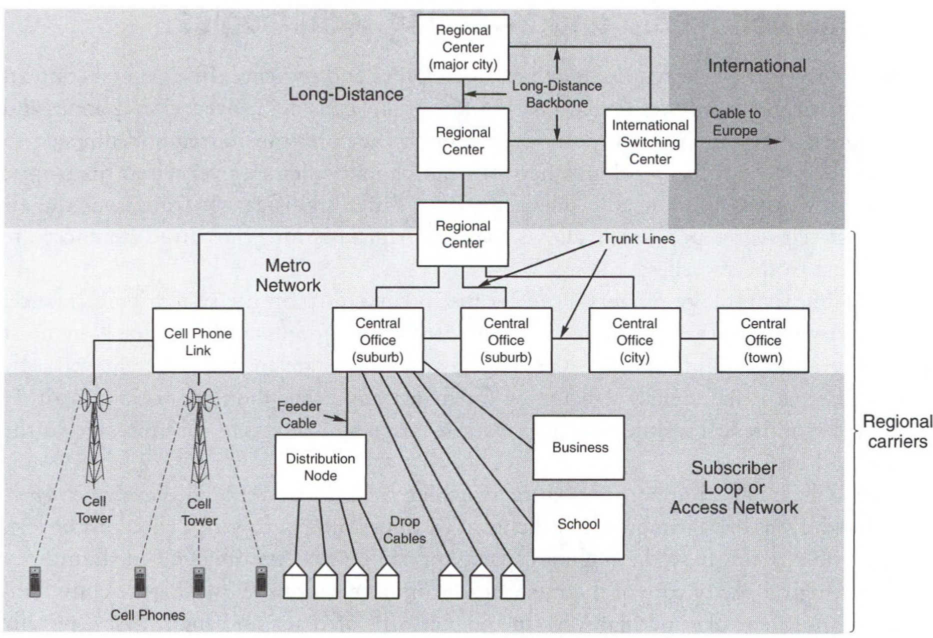



**FIGURE 3.11** *Elements of the telephone network.*

telephones to local telephone switching offices (called *central offices* in the industry). A typical central office serves thousands of homes either directly or through feeder cables that carry signals to neighborhood distribution nodes. Central offices multiplex calls directed outside their local areas on *trunk lines*, which run between central offices, connecting cities, towns, and suburbs in the area. Together with other links between telephone company facilities and large organizations, trunk lines form the *regional* or *metro network* that carries telephone traffic in the area. The access and metro networks—or subscriber loop and regional networks—are the realm of *regional carriers* or *local exchange carriers* that provide services within a region. The best known of these carriers are the *regional Bell operating companies* (RBOCs), sometimes called ILECs for Incumbent Local Exchange Carriers: Bell South, SBC, Verizon, and Qwest. Their smaller competitors, called *competitive local exchange carriers* (CLECs), offer regional telephone services, usually over the phone lines installed by the incumbents. You'll learn more about regional phone networks in Chapter 24 and about local phone networks in Chapter 25.

Many local phone systems also offer broadband Internet access via *digital subscriber line* (DSL). Unlike basic phone service, DSL is always on, so you don't have to dial in as you do with a conventional modem. However, DSL transmission distances are limited, so the service is not available to homes far from the central office.

Long-distance service is a separate business, but is now offered by most of the regional carriers as well as companies that specialize in long-distance service, such as AT&T and MCI. Local and regional service areas are distinguished on the basis of area codes that existed when the original seven Bell operating companies split from AT&T in 1984, so the maps of these areas may look strange today. Long-distance carriers pick up signals at regional nodes and transport them around the country via long-distance backbone systems. These backbone systems, in turn, connect with international systems such as submarine cables running to Europe, Asia, and South America. Although you see only one long-distance carrier on your phone bill, in reality calls may pass through multiple carriers to reach their destination. You'll learn more about the global telephone network in Chapter 23.

Cellular phones, pagers, and satellite phones link to this global telecommunications system. In a sense, the mobile services are like regional phone carriers that distribute signals locally through the air on radio waves rather than through cables. However, they generally provide their own long-distance service, which may be billed at the same rate as local service.

Fiber-optic cables are used throughout the backbone and regional networks, and run to many of the local distribution nodes and cell phone towers shown in Figure 3.11. Large organizations, such as universities and big office buildings, often have direct fiber-optic connections. With a few exceptions, copper lines run from regional distribution nodes to homes and small businesses.

Optical fibers are the backbone of the global telecommunications network.

## Cable Television and Video

Cable-television networks now offer telephone service and broadband Internet access in competition with the telephone network. Superficially cable lines resemble telephone lines in that they distribute signals from a central facility (called a *head-end*) to neighborhood nodes and individual homes. However, the network designs differ significantly, reflecting the origins of cable TV.

Cable TV systems now offer telephone and broadband Internet access.

Sometimes called *CATV* (for Community Antenna TV), cable TV systems originally distributed signals in areas outside the reach of standard broadcast television. A single tall antenna picked up distant broadcasts, and the system distributed the same signal to all subscribers. (It beat having everyone install their own antenna to pick up distant stations.) Cable later offered additional channels from distant "super stations" and from special services distributed by satellite links. Today virtually all cable systems offer two-way services, but their internal architecture differs from that of local telephone systems.

Video signals require much more bandwidth than sound signals, so cable TV systems use coaxial cable to connect to homes. The coax runs from neighborhood distribution nodes, attached via fiber-optic cables to the cable head-ends, which distribute signals in the community. As in the original cable systems, the basic design distributes the same signals to all subscribers in broadcast style. Premium services are transmitted in a coded form that requires special decoders.

Modern cable systems have refined this design by setting aside channels that provide services in addition to broadcast-style video. These channels carry special services to and from individual neighborhood nodes, which distribute them to homes in a networked model. For example, cable modem service is really multiple subscribers sharing the capacity of one cable channel, which functions as a local-area network serving those homes. As in an office network, each subscriber sees only messages addressed to them, not the other data traveling on the network. Cable systems use similar technology to offer telephone service.

Cable TV systems now offer a combination of analog and digital services on separate channels. Digital signals typically are offered at premium rates with the analog services in the basic package. Special cable boxes are needed to receive the digital video signals.

You will learn more about cable TV systems in Chapter 27.

## Data Communications and the Internet

Data communications include local-area networks and the Internet.

Most people think that all data communications goes over the Internet, but that is an illusion arising from the use of personal computers in homes and offices. There are two types of personal links to the Internet: *dial-up* connections made by home modems over ordinary phone lines to companies that provide Internet service, or *broadband* connections using DSL or cable modems. Small businesses also may use these same types of service, but larger businesses use special higher-speed services. Most organizations have internal *local-area networks* (LANs), such as the one shown in Figure 3.10, to transfer data among their own computers, and they use these local-area networks to link to the Internet. (Even home offices may have LANs to link computers to each other, a printer, and a cable modem or DSL.)

Local-area networks typically run within a building or within a campus of buildings that houses a large organization. As you will learn in Chapter 26, small LANs may be linked together to form larger wide-area networks that serve the whole organization. Individual personal computers typically connect over short lengths of special high-quality copper cable made for data transmission; Category 5 cables are widely used. Wireless connections also are possible. Fibers run to individual devices only if they require very high-speed connections; are far from the main network; or are in an environment where copper wires don't work well, such as where heavy machinery generates strong electromagnetic noise.

Backbone wide-area networks that serve large buildings, or links between corporate networks and remote sites or the Internet, typically use fibers. The longer the link and the higher the speed, the more likely fibers are to be used.

Fibers also provide the backbone of the Internet, which functions like the long-distance telephone network. The hardware is essentially the same as that used for long-distance telephone traffic, but the data-transmission protocols are different. You'll learn more about data transmission standards in Chapters 20 and 26.

## Convergence

Voice, video, and data services have evolved considerably during the past decades. Modern versions of these systems strongly resemble each other and can provide similar services, an effect the industry calls *convergence.* The similarities are both more and less than they seem, and deserve a brief explanation.

Voice, video, and data services are converging, and can be offered over one network.

Both voice and data are transmitted over digital backbone systems, but the hardware and protocols differ in detail. The traditional telephone network is optimized for voice traffic with a separate voice channel reserved for each telephone call. The Internet is optimized for data traffic without fixed channels for separate data streams. Telephone lines have long carried digital data and now data lines can carry voice signals, a scheme called *VoIP* for *Voice over Internet Protocol.* Advocates claim VoIP will replace ordinary phone lines, but it sometimes sounds like a bad cell-phone connection.

Connectivity is essential for both telephone and Internet traffic. You don't want a voice line or an e-mail address that can't connect to the rest of the world's phones and e-mail addresses. Somewhere along the line all voice and data signals must be identified and directed to the right place. Connectivity is not as essential for video, and video feeds to cable TV networks typically are via satellite links, which transmit encoded signals picked up by antennas on the ground. Depending on costs, the video signals may be distributed through fiber in a metropolitan area, but usually they are not transmitted long distances through fiber on the ground.

The distinctions among the various long-distance telecommunications networks are more organizational than physical. In reality, one fiber-optic cable may contain fibers carrying different signals for different organizations. For example, a single fiber might carry telephone traffic at one wavelength and Internet traffic on another. Companies may trade capacity on their cables with other organizations that have excess capacity on different routes.

## Other Communications Services

Voice, video, and Internet data are the three major services of the telecommunications world, but you should be aware of other communications services that fill specific market niches.

- *Broadband fixed wireless* services use microwave antennas to provide broadband service in regions where companies think it would be too expensive to install cables. The idea has been around for a while, but has never caught on widely.
- *Data transmission inside vehicles* is becoming more important as the number of control systems increases. Sometimes fiber is used for vehicle systems because of its

broad bandwidth and immunity to electromagnetic interference. Fibers are used in ships, some aircraft, the International Space Station, and some high-end automobiles, as described in Chapter 28.

- *Closed circuit video* transmission is needed for surveillance, monitoring, and broadcasting of sports events. Fibers have high bandwidth, are lightweight, and suffer little interference, so they often are used in these applications.

# The Business of Telecommunications

Understanding telecommunications technology requires learning a little about the business of telecommunications. Telecommunications is a complex industry that involves different companies offering different goods and services. Business considerations have shaped the present network.

## A Very Short History of the Telecommunications Business

Telephone service was considered a natural monopoly.

Private companies started the telephone industry in the late 1800s, but government agencies became involved as the telephone became a vital service. Governments considered telephone service to be a "natural monopoly" because they felt it only made sense to build a single telephone system to serve all homes and businesses. Through most of the twentieth century, most telephone service outside the United States was run by government post, telephone, and telegraph agencies. In the United States, private telephone service was heavily regulated by state and federal agencies, and most of the nation's cities were served by a single giant company, AT&T.

This began to change in the late 1970s, as other companies began to offer long-distance service. In 1984, AT&T spun off seven regional operating companies, three of which have since disappeared in mergers. Overseas, telephone agencies were separated from post offices and privatized. Cellular telephone networks emerged in the same period, and now handle a large share of telephone traffic. Cellular service is competitive, with multiple companies offering service across the United States.

The trend in the cable industry is also toward consolidation. Cable TV began as small companies scattered around the country, but is now dominated by a handful of *Multiple System Operators* (MSOs) such as Comcast and Time-Warner. Internet services now are offered by telephone and cable companies, and by other companies including Microsoft, AOL, and Earthlink.

The telecommunications bubble pumped a tremendous amount of money into the industry, which companies used to expand and to buy other companies, often at greatly inflated prices. New companies tried to build "overlay" networks that provided services in competition with existing phone and cable systems, but only a few of them survived the collapse of the bubble. Most of the local "competition" that remains today is based on regulations that require phone companies to lease their transmission lines to other companies that want to provide phone service. Cable companies aren't required to lease their lines, but sometimes allow other companies to offer broadband service over their cables.

## THINGS TO THINK ABOUT

### Regulations

Telecommunications has always been a regulated industry. Although the changes of recent years have been called "deregulation," it might be better to call them "changes in regulation." Governments used to set the prices that carriers could charge. Now they write rules that require carriers to lease their lines to competitors at specified prices and under certain conditions. These regulations assure the public access to essential services at reasonable cost and protect the public from crooks and fools. (The crooks and fools made their presence evident during the bubble years when WorldCom faked its accounts and Enron tried to create a market for bandwidth trading. Most of us consider access to at least basic telephone service at honest prices to be essential in today's society.)

What regulations are proper? Does the Federal Communications Commission (FCC) act in the public interest, as its charter specifies? Or do corporate lawyers and lobbyists who contribute generously to political campaigns shape its regulations? FCC policies can't help but shape the future of the telecommunications industry. Are Congress and the FCC too concerned with promoting corporate profits and issues like preventing copying of digital music and video? These are questions that deserve serious debate.

## Types of Businesses

The telecommunications industry includes distinct types of companies that earn money in different ways. The most important types include the following:

- *Carriers* transmit information over lines that they own or rent. Local and long-distance telephone companies are both carriers, and some companies provide both services. Cable TV systems also function as carriers. They sell transmission service as well as access to networks.
- *Carriers' carriers* lease capacity on transmission lines they built to carriers and other companies who need service. They don't retail to individuals or small businesses. They are wholesalers that provide service to other companies.
- *Internet Service Providers* (ISPs) provide Internet access, and related services such as Web hosting and e-mail. They range from giant corporations to small independent companies, and usually are retailers of services.
- *Equipment manufacturers* make hardware and software that they sell to companies and individuals. Their products range from expensive hardware for long-distance networks to desktop cables and modems.
- *Contractors and installers* install hardware for carriers. Many specialize in construction.

# What Have You Learned?

1. Telecommunications sends signals over a distance through such media as optical fibers, copper wires, and radio waves.

2. The optical telegraph was the first form of telecommunications 200 years ago. The electrical telegraph made it obsolete. Telephones followed, then broadcast radio and television.
3. Improvements in electronic technology allowed operation at increasingly higher radio frequencies, which offered more bandwidth for signal transmission.
4. The demand for transmission capacity has increased steadily, and bandwidth has traditionally been in short supply.
5. Analog bandwidth is measured by the frequency range. Digital bandwidth is measured in bits per second.
6. Multiplexing combines many signals into one higher-speed signal. The important types are frequency-division multiplexing, wavelength-division multiplexing, and time-division multiplexing. Time-division multiplexing works only for digital signals.
7. Copper is a general term that includes twisted pair and coaxial cables.
8. Telecommunications systems transmit signals by modulating a carrier wave with a baseband signal. The baseband signal is at a lower frequency than the carrier.
9. Fiber-optic systems use amplitude modulation.
10. Analog signals vary continuously. Digital signals transmit a series of bits. Analog signals can be digitized, then converted back to analog format. Analog telephone signals are digitized at 64,000 bits per second.
11. Electrical signals are current or voltage. Optical signals are the number of photons.
12. A communications system can be viewed as an array of pipes and switches. The pipes carry signals, and the switches direct them.
13. Broadcast communications directs the same signal to many points.
14. A switched system makes temporary connections between terminals. The telephone system is an example.
15. Networking interconnects computers permanently so they can send messages to each other. Each message carries a label so only one computer receives it.
16. The telephone system includes the local loop, which connects subscribers, local switching offices, regional or metro networks, and a long-distance backbone system. Optical fibers provide the backbone.
17. Cable TV systems resemble telephone systems locally. They offer television and broadband Internet access as well as video.
18. Data communications includes local-area networks and the Internet.
19. Convergence is the merging of voice, video, and data services so they can be offered over one network.
20. Telephone service was considered to be a natural monopoly and was run by government agencies or heavily regulated private monopolies. Most countries' telephone networks are now private and regulated differently.

# What's Next?

Now you have a general idea how fiber optics and telecommunications work. The rest of the book will present more details about the technology. Chapters 4 through 7 cover optical fibers and their important features.

# Further Reading

Roger L. Freeman, *Fundamentals of Telecommunications* (Wiley InterScience, 1999)

Gil Held, *Voice and Data Internetworking* (McGraw-Hill, 2000)

Anton A. Huurdeman, *The Worldwide History of Telecommunications* (Wiley InterScience, 2003)

Gary M. Miller, *Modern Electronic Communication* (Prentice Hall, 1999)

Tom Standage, *The Victorian Internet* (Berkeley Books, 1998)

# Questions to Think About

1. How does using a higher-frequency carrier affect the amount of information that can be transmitted?
2. Why does multiplexed transmission of a combined signal cost less than separate transmission of each signal?
3. Computer networks, mobile telephones, and broadcast systems all distribute signals to many terminals. How do these systems differ?
4. Why is frequency-division multiplexing equivalent to wavelength-division multiplexing?
5. The bandwidth of digitized signals measured in bits per second is much higher than the bandwidth of the original analog signal measured in hertz. For example, the analog bandwidth of a phone line is 4000 Hz, but the digitized signal is 64,000 bits per second. Why are these two bandwidths usually equivalent in practice?
6. Why was telephone service considered to be a natural monopoly?
7. Data transmission rates to personal computers have increased from 1200 bits per second with a dial-up modem in 1985 to about 400,000 bits per second with a cable modem or DSL in 2000. If bandwidth keeps increasing at the present rate, how fast will transmission be in 2015?

# Chapter Quiz

1. Which came first?
    a. electrical telegraph
    b. optical telegraph

c. telephone
d. wireless radio transmission

**2.** Which of the following statements are true for analog signals?
a. They vary continuously in intensity.
b. They are transmitted in parts of the telephone network.
c. They are compatible with human senses.
d. They can be processed electronically.
e. All of the above

**3.** Which of the following statements are true for digital signals?
a. They can encode analog signals.
b. They are transmitted in parts of the telephone network.
c. They can be processed electronically.
d. They are used in computer systems.
e. All of the above

**4.** You digitize a 10-kHz signal by sampling it at twice the highest frequency (i.e., 20,000 times a second) and encoding the intensity in 8 bits. What is the resulting data rate?
a. 20 kbit/s
b. 64 kbit/s
c. 144 kbit/s
d. 160 kbit/s
e. 288 kbit/s

**5.** What part of the telephone network is connected directly to your home telephone if you get your telephone service from a local telephone company?
a. subscriber loop
b. feeder cable
c. trunk line
d. backbone system

**6.** What part of the telephone network carries the highest-speed signals?
a. subscriber loop
b. feeder cable
c. trunk line
d. backbone system

**7.** Time-division multiplexing of eight signals at 150 Mbit/s each produces
a. eight optical channels each carrying 150 Mbit/s.
b. one channel carrying 120 Mbit/s.
c. one channel carrying 1.2 Gbit/s.
d. eight signals at 150 MHz.

**8.** What are the "pipes" used to broadcast television signals from a station on the ground?

a. air

b. optical fibers

c. coaxial cables

d. twisted pair

**9.** The carrier signal modulated to produce one optical channel in a fiber-optic system is

a. a single wavelength of light generated in the transmitter.

b. a radio-frequency signal supplied electronically to the transmitter.

c. an acoustic vibration in the optical fiber.

d. a combination of wavelengths generated by several light sources.

**10.** Who offers DSL and what service does it normally provide?

a. Television broadcasters offer it for Internet access.

b. Cable television carriers offer it for Internet access.

c. Telephone carriers offer it for Internet access.

d. Cable television carriers offer it for telephone service.

e. Internet service providers offer it for telephone service.

**11.** What is the only important telecommunications system that uses fiber to transmit analog signals?

a. local telephone service

b. long-distance telephone systems

c. Internet backbone systems

d. cable TV systems

e. none

**12.** What U.S. government agency regulates telecommunications?

a. Federal regulations have been abolished.

b. Department of Homeland Security

c. Department of Commerce

d. Federal Communications Commission

e. International Telecommunications Union