such as on-demand video like YouTube. Our goal in this chapter is to understand why optical fiber permits such huge data rates. The answer to this question is not in the high speed of the light itself. In fact, light waves in fiber travel about 50% slower than do radio waves in air. The answer lies in the concept of ***bandwidth*** and the frequencies of the waves used in each case, as we shall see.

In Chapter 8, we discussed ***analog*** and ***digital*** communication. We treated the basics of analog radio, including the modulation of carrier waves to carry information. We also discussed ***frequency multiplexing***, which allows a single physical medium to carry many communication ***channels***. We discussed digital ***sampling*** of an analog signal to change it to a binary form suitable for transmission across a digital communication channel. Digital communication requires use of a chosen ***protocol***—a set of rules for interpreting a list of binary numbers.

We discussed the idea of the bandwidth of a communication channel, which is the range of frequencies allocated to each channel's broadcasting. For example, each AM station is permitted to use a small range (called a band) of radio frequencies covering about 10 kHz (e.g., 1275–1285 kHz), so its bandwidth is 10 kHz. If a channel has bandwidth equal to B, the shortest radio or light pulse that can be transmitted in that channel has time duration of about $1/B$. For example, a bandwidth of 10 kHz corresponds to a pulse duration of about 1/10 kHz = 10^{-3} seconds (sec), or 1 millisecond (msec).

In this chapter, we will learn about some of the optical hardware used to make the large bandwidth of light accessible for fiber-optic communication systems. We will see that using light pulses instead of radio signals offers a huge increase in data rate in digital systems, because the bandwidth of optical systems is far greater than in radio systems. The bandwidth of a medium is determined by its physical properties, so this leads us back to the physics of waves. In Chapter 13 we studied how light travels in glass optical fibers. The key concepts are ***refraction*** of light and ***total internal reflection***. This chapter brings together many concepts and discussions that were introduced in earlier chapters, and there are many references to those earlier chapters. Please return to these earlier sections and review them or read them for the first time. This is an opportunity to see the connections between the many topics we have discussed in this book.

15.2 OVERVIEW OF FIBER-OPTICAL COMMUNICATION SYSTEMS

Before discussing data transmission in fiber-optical systems, let us review communication systems in general. **Figure 15.1** shows the three main elements of any communication system:

- The ***transmitter***, which converts information to a physical form suitable for transmitting.

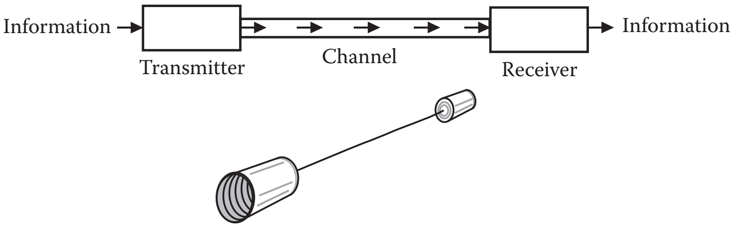

FIGURE 15.1 A communication system consists of a transmitter, a channel, and a receiver. A simple example is two tin cans and a taut string.

- The ***channel***, which is a physical medium that can carry energy in a form representing the information.
- The ***receiver***, which converts the energy received from the channel into a useful representation of the original information.

We discussed an example of this general scheme in Chapter 8, where we studied radio transmission systems—both analog and digital. In that case, the channel was the ***electromagnetic*** medium, air or vacuum (think of space communications). The transmitter converts data or audio information into physical radio waves, and the receiver converts these waves back into information, usually represented as voltages in an electronic circuit. We discussed the mathematical concept of ***information*** in Chapter 2, where we said that the amount of information in a signal or message equals the number of yes-no questions you would need to have answered to gain the information in the signal. Because yes-no questions have only two possible answers, the answer to a single yes-no question is a ***bit***, that is one binary digit, 0 or 1. Recall that one ***byte*** equals eight bits. In Chapter 8, we discussed the idea of sampling an analog signal to convert it to a list of binary numbers (also called bits). We also discussed modulation of a ***carrier wave***, by which we mean varying the amplitude of a wave to represent ones and zeros in the list of bits that represent the sampled signal. (You should review Sections 8.3 and 8.4.)

Since ancient times, light waves have been used for transmitting information over long distances. We learned in Chapter 7 that light waves are made of the same "stuff" as radio waves—electromagnetic fields. Oscillating electric charges create traveling waves of oscillating electric and magnetic fields. In vacuum, light waves travel with a speed $c = 3 \times 10^8$ m/sec, whereas in a dense medium light travels slower by a factor n called the ***refractive index***. That is, $c_n = c \div n$, as discussed in Chapter 13, Section 13.3. For example, for glass n equals about 1.5, so the speed of light in glass is 2×10^8 m/sec.

In an optical communication system, light pulses carrying data are transmitted inside *optical fibers*, which we discussed in Chapter 13, Section 13.11. The light pulses are created using ***lasers***, which we studied in Chapter 14. The elements of a basic optical communication system are shown in **Figure 15.2**. A list of bit values (ones and zeros) are sent into the transmitter in the form of voltage levels (high or low), where they control a *modulator*, which alters the power of a light beam produced by a laser. (Modulators are described below.) The laser produces a constant-power light beam, which experiences different amounts of attenuation as it passes through the modulator, depending on what bit value is being sent. The light emerging from the modulator is a series of pulses of high or low power. These pulses travel as far as 100 kilometers (km) by total internal reflection inside the core of the fiber until they reach the other end, where they are focused onto a light detector (a semiconductor photodetector), described

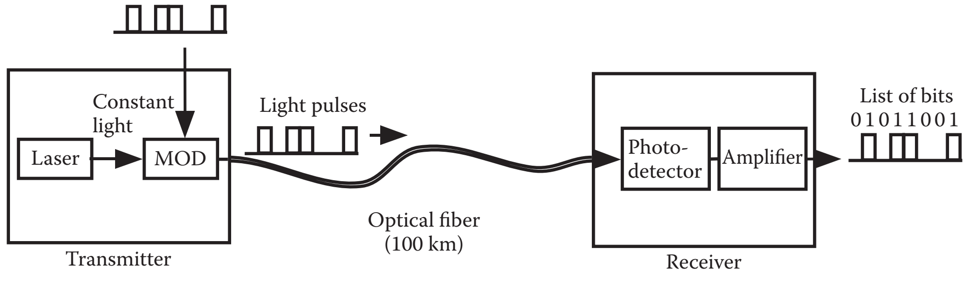

FIGURE 15.2 In a basic optical communication system, the transmitter contains a constant-power laser and a modulator, the channel is an optical fiber, and the receiver consists of a semiconductor photodetector and an electronic amplifier.

in Chapter 12 in Real-World Example 12.1. As explained there, the light entering the semiconductor crystal can elevate the energy of electrons in the crystal only if the light's frequency is high enough to cause the electron to jump from the lowest energy band to the next higher band. When this occurs, the crystal becomes electrically conducting, allowing a current to flow. A transistor amplifier increases the current of the signal to a level high enough for driving a computer memory or other device. In this way, the original list of bits can be transmitted over distances up to 100 km.

The practical distance limit of 100 km is set by the decrease of a light pulse's energy as it travels through the fiber, as discussed in Section 13.9. As we said there, for near-infrared light with wavelength equal to 1,500 nm, modern optical fiber transmits 95.5% of the light's initial power (or pulse energy) over a distance of 1 km. This means that after 100 km, the light power is decreased by a factor 0.01; that is, 1% of the initial light power transmits through 100 km. If we doubled the distance, then only 0.01% would be transmitted, which is not enough for the photodetector to detect reliably. As discussed in Section 14.8, this attenuation of the light can be compensated for by inserting laser amplifiers into the fiber every 100 km or so.

Let us estimate how many bits per second we can send using the basic system in Figure 15.2. Several factors limit this maximum data rate.

- Limits in the transmitter arise because of limitations on how fast the modulator can vary the laser power. Typical electronic systems (in 2008) can modulate a laser beam at a rate of up to 40 gigahertz (GHz). Therefore they can generate laser pulses representing binary data at a rate of 40×10^9 bits/sec. The time duration of each pulse equals

$$\textit{bit duration} = \frac{1}{40 \times 10^9 \text{ bits/sec}} = 25 \times 10^{-12} \text{ sec/bit} = 25 \text{ psec/bit}$$

This is a very brief time interval. For comparison, in the time it takes a housefly to flap its wings once (about 1 msec), the modulator can produce 40 million pulses!

- Limits in the fiber-optical channel arise because of broadening of the light pulses. When a short light pulse enters a fiber and travels a long distance, the pulse becomes stretched or broadened in duration. As discussed in Section 13.12, this is because of two effects. The first, ***mode dispersion***, refers to the varying times required for light to pass through a length of fiber when traveling in different directions (modes) within the fiber. The second—***material dispersion***—is caused by the same effect in glass that causes a beam of white light to spread (disperse) into a spectrum of different colors upon passing through a prism. Any short pulse of light is made up of a certain range of frequencies, called its spectral bandwidth, *B*. The duration of a pulse is given roughly by the inverse of its spectral bandwidth. That is:

$$\textit{pulse duration} = \frac{1}{\textit{bandwidth}} = \frac{1}{B}$$

For example, for a light pulse with a spectral range (bandwidth) equal to 10 GHz, the pulse duration equals 1 ÷ (10 GHz) = 10^{-10} sec, or 100 picoseconds (psec). (For another example, see Figure 8.23 in Chapter 8). A 100-psec light pulse contains a range of frequencies, and the different-frequency waves travel at slightly different speeds c_n. So, a 100-psec pulse, even if it travels in a single-mode fiber, will spread out slightly after traveling through a long fiber. This pulse broadening effect limits the number of pulses we can send during any fixed time interval. For example, if during transmission the pulses broaden to as long as 1 nanosecond (nsec; 10^{-9} sec) each, then we could not pack more than 10^9 such pulses into a 1-sec time interval; otherwise they would overlap and the bit values would become scrambled, as illustrated in Figure 13.25.

- Limits in the receiver occur because any photodetector has an upper speed at which it can operate reliably. As an example of such a response time, think of a factory assembly line where a conveyor belt moves a line of machine parts toward a worker (you). Your task is to pick each part up, perform an operation on it, and place it onto a different conveyor belt. Let us say that you can do this operation once in 3 sec. Your rate of operation completions is 0.33 Hz. As long as the parts come to you at a rate no greater than 0.33 Hz, you can process them just fine. But, if they come faster than 0.33 Hz, the parts get all jumbled together, and errors will occur. A photodetector has a certain response time, depending on how it is made. This is the time required for the detector to receive the light pulse, create a voltage pulse representing the power in the light pulse, and transmit this voltage to the next component in the electronic circuit. Very fast detectors can have a response time equal to 25 psec, corresponding to an operating rate of 40 GHz, or 40×10^9 pulses/sec. (Faster detectors exist, but they would strain the ability of the subsequent electronics to keep up.) Let us say, then, that 40 GHz is a reasonable rate to work with in practice.

If a basic fiber-optical system with a laser, a modulator, and a receiver can send about 40×10^9 pulses/sec, how can we best use this capability for communication? Consider sending telephone calls on such a system. Audio frequencies—the frequencies in speech and music—do not exceed about 20 kHz. A music compact disc (CD) is recorded using a sampling rate of 44 kHz, fast enough to be sure that no information is lost (as discussed in Chapter 8, In-Depth Look 8.1). This means that real-time sending ("streaming") of CD-quality music requires sending 44,000 pulses/sec through the fiber. This is only about one part in a million of the full capability of the fiber—40×10^9 pulses/sec. Therefore, a single fiber could carry 1 million CD-quality streaming signals simultaneously!

To see how this can be done, consider a simpler case of sending three CD signals on one fiber, as illustrated in **Figure 15.3**. Each CD player generates a stream of long voltage pulses, say 20 μsec each. In an electronic circuit called a ***multiplexer***, which is a part of the transmitter, these pulses are shortened to about 25 psec each and are interweaved as shown. The interweaving is done by delaying the streams from the signal sources by different amounts of time, then combining the streams, as shown. The pulses in the combined signal stream do not overlap in time because they are so short. They are then all sent together through the fiber in the form of optical pulses. At the receiver end of the fiber, this process is reversed. The short pulses are separated or demultiplexed, then stretched out in time to 20 μsec each, and sent to the separate users' computers or CD players. This procedure is called ***time multiplexing***.[1]

THINK AGAIN

When we say such a system is fast, we do not mean that the light travels particularly fast. We mean that the system itself has a short response time, so it can respond quickly.

The fact that such a fiber-based system can transmit data much faster (higher data rate) than metal-wire-based electronic systems or wireless radio systems is a consequence

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[1] Called time-division multiplexing (TDM) in the technical literature.

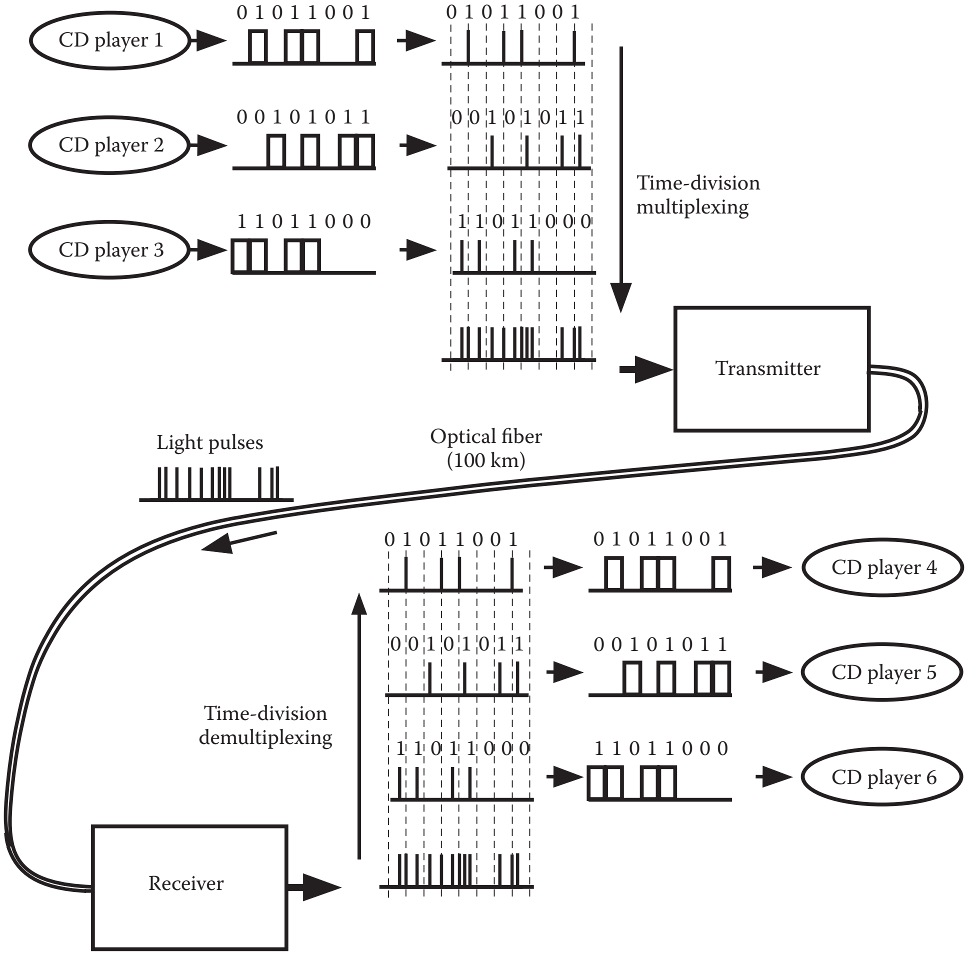

FIGURE 15.3 In a time-multiplexed optical communication system, slow (44 kHz) signals from three or more CD players are combined or multiplexed into a single faster stream (40 GHz) of shorter pulses, which are sent through the fiber. At the receiver, the shorter pulses are separated back into separate slower streams and sent to the individual users (CD players in the illustration).

of the physics of light waves in glass. It is not because of the fast speed of light itself. As we mentioned above, light actually travels slower in glass fiber than radio waves travel in air. Rather, it is because light waves have a much higher (carrier) frequency, about 10^{15} Hz, than the frequency of radio waves, approximately 10^6 to 10^9 Hz. According to our discussion above, the duration of a wave pulse is given roughly by the inverse of its spectral bandwidth. And, according to the Principle of Carrier Modulation discussed in Chapter 8, Section 8.4, we cannot modulate a carrier wave at a frequency higher than the frequency of the carrier without destroying the identity of that carrier wave. For this reason, a light wave, whose carrier frequency is much higher than that of a radio wave, can be modulated much faster than can a radio wave. This allows far more data pulses to be placed each second onto the light wave than can be put onto a radio wave. We can summarize these arguments by the following practical principle:

Principle of Single-Channel Data Rate: Because we cannot modulate a carrier wave at a frequency higher than the frequency of the carrier without destroying the identity of that carrier, a higher rate of transmitting data on a single channel can be achieved only by using a higher carrier frequency.