In this chapter we examine the technologies of communication links: optical links, copper lines, and radio waves. Some understanding of these systems is part of a basic technological literacy and helps one to appreciate the characteristics of networks. For readers not interested in details, we summarize the key ideas and results in Section 7.1. The subsequent sections are more detailed and may be skimmed by non-electrical engineering majors. Sections 7.2, 7.3, and 7.4 examine optical links, copper lines, and radio links, respectively. Each section starts with an overview of the technology.

The complements provide more details about some aspects of implementations and of communication theory. These complements can be read independently of one another.

In the first section we explain how links transport bits and the characteristics of the links having the most impact on their performance.

### 7.1 Communication Links and Their Characteristics

In this book we consider only communication links that use electromagnetic waves. We ignore acoustic links even though they are useful in some specialized applications.

#### 7.1.1 Digital Link

A digital link is illustrated in Figure 7.1. The link delivers bits by first converting them into signals that propagate through a channel. The receiver converts the signals back into bits. Seen as a network element, the link is characterized by its bit rate, bit error rate, and distance.

The signals propagate through the medium as electromagnetic waves. These waves may be guided by an optical fiber, a pair of wires, or a cable, or the waves may propagate in free space as radio waves or as optical waves.

The graphs in Figure 7.2 show the maximum length as a function of the bit rate for communication links built with a coaxial cable, a wire pair, and three types of optical fiber:
FIGURE 7.1
Digital link. The main components of a digital communication link are a modulator, the channel, and a demodulator. The figure also sketches the signals.

FIGURE 7.2
Achievable distance as a function of the bit rate for optical links, wire pairs, and cable. (The graphs are approximate.)
the choice between cable modem and high-speed modem over telephone lines depends on a number of factors. Although cable has a larger bit rate than a wire pair, the cable of the CATV plant is shared by up to a few hundred users whereas the telephone line is not shared. A shared channel requires a MAC protocol and security, and is more prone to interference.

We now examine the propagation of the electromagnetic waves and the limitations on the transmission rate and distance of links. These sections explain how the graphs in Figure 7.2 are obtained.

We then discuss the conversion of bits into signals (called modulation). In particular, we discuss the tradeoff between the range of frequencies that the signals occupy and the bit error rate. This tradeoff is important because applications differ in the scarcity of the frequencies and in the susceptibility to errors.

### 7.1.2 Frequency and Propagation

We consider links where electromagnetic waves transport the bits. Two qualities of electromagnetic waves make them suitable for transporting information in a network. First, they propagate, enabling them to move from one place to another, as from a transmitter to a receiver. Second, they contain energy that can be used to carry messages. We know, from quantum mechanics, that this energy should be viewed as being carried by photons. One can think of a photon as a minute burst of electromagnetic energy. An electromagnetic wave is a stream of photons. The energy of a single photon is so minuscule that an ordinary lightbulb emits about $10^{20}$ photons every second. In this section we look at the propagation of electromagnetic waves to see how they transport bits between the nodes of a network. We explain that electromagnetic waves are guided by using their different propagation properties in different media. Waves are modified, distorted, and weakened during their propagation. The telecommunications engineer takes these modifications into account when designing the transmission equipment. We discuss how the wave modifications limit the rate at which a link can transmit messages reliably.

The propagation of electromagnetic waves is described by the equations postulated in 1863 by James Clark Maxwell, an ingenious Scottish physicist and mathematician. Maxwell understood that the phenomenon of propagation is caused by the interactions of an oscillating electrical field and an oscillating magnetic field "pushing" one another through empty space or some other medium. These ideas developed from Michael Faraday's work. Faraday had shown earlier that a changing magnetic field generates an electrical field; this effect is at work in a car alternator. Maxwell argued that in an electromagnetic wave a changing magnetic field induces a changing electrical field, which in turn generates a changing magnetic field, and so on, thus causing the wave to propagate. The left part of Figure 7.3 illustrates the interaction of the varying electrical field $E$ and magnetic field $M$.

Light is a familiar example of propagating electromagnetic waves. Radio waves are electromagnetic waves, too, but they differ from light waves by their frequency, which is lower by a few orders of magnitude. The frequency is the number of oscillations of the electric and magnetic fields in one second. Frequency is measured in hertz; one hertz is written as 1 Hz, and it corresponds to one full oscillation per second. (See the center part of Figure 7.3.) Thus, the electric and magnetic fields of an electromagnetic wave with a frequency of $10^8$ Hz make $10^8$ oscillations per second. In the case of visible light, different frequencies are perceived by the eyes and the brain as different colors. The
**FIGURE 7.3**

Electromagnetic waves: Their propagation (left), frequency (center), and typical frequency ranges (right).

![Diagram of electromagnetic waves and frequency ranges]

**Frequency ranges:**
- Twisted pairs: 0–a few 100 kHz
- Coaxial cable: a few 100 kHz–1 GHz
- Waveguide: 1 GHz–a few hundred GHz
- Optical fiber: 100 THz (10^{14} Hz)
- AM radio: 1 MHz
- VHF TV: 20 MHz–80 MHz
- FM radio: 88 MHz–108 MHz
- UHF TV: 300 MHz–600 MHz
- Cellular phones: 850 MHz, 1.2 GHz, ...
- Satellite: 1 GHz–100 GHz

The *propagation speed* of an electromagnetic wave in a vacuum or in air is approximately equal to \( c = 3 \times 10^8 \) meters per second. Thus, light from the moon, which is about 400,000 km from Earth, reaches us in slightly more than 1 second.

Frequencies of typical electromagnetic waves are between 88 MHz (1 MHz = 1 megahertz = 10^6 Hz) and 110 MHz for FM stations, from 30 MHz to 300 MHz for TV stations. Satellites transmit microwaves (above 1 GHz = 1 gigahertz = 10^9 Hz). Visible light covers the frequencies from \( 4 \times 10^{14} \) Hz (red light) to \( 7 \times 10^{14} \) Hz (blue light). See the right part of Figure 7.3 for typical ranges of frequencies transported by cables and wires and used in various applications.

An electromagnetic wave can be described by its *wavelength* instead of by its frequency. The wavelength is defined as the speed of propagation in a vacuum \( (c) \) divided by the frequency. For instance, the wavelength of red light is the speed of light \( (c) \) divided by the frequency \( (4 \times 10^{14} \) Hz) and is, therefore, equal to 0.75 \( \mu m \). \( \mu m = 1 \) micrometer = \( 10^{-6} m \). Thus, the wavelength of visible light ranges from about 0.43 \( \mu m \) for blue light to 0.7 \( \mu m \) for red light. The wavelengths 0.8 \( \mu m \), 1.3 \( \mu m \), and 1.5 \( \mu m \) are in the *infrared range*; i.e., they correspond to frequencies less than that of red light; those are typical wavelengths in optical fiber communication links.

Communication networks transmit information over electromagnetic waves that propagate in air, with radios, or in vacuum, with satellites. Communication networks also use transmission media that guide the propagation of electromagnetic waves, such as optical fibers and copper lines and cables. The electrons in the wires or the cable of a copper line interact with the electromagnetic wave and guide it.

After having discussed the general propagation of electromagnetic waves, we examine the sources of limitations to the transmission of bits by electromagnetic waves.

### 7.1.3 Limitations

There are four basic phenomena that limit the rate and distance of bit transmissions by electromagnetic waves: attenuation, distortion, dispersion, and noise. We examine each of these phenomena, illustrated in Figure 7.4, and describe the limitations they introduce.
**Attenuation**

Attenuation is the loss of energy of the wave as it propagates. When a wave propagates in a fiber or a transmission line, some of its energy is absorbed and converted into heat. Attenuation is illustrated in the left part of Figure 7.4. An electromagnetic wave that propagates in a vacuum or in the air spreads out as a cone or as a sphere. Consequently, the energy of the wave per unit area decreases as the wave propagates. Accordingly, when the wave reaches an antenna or an optical detector, that device captures an energy that has decreased with the propagation distance. Electromagnetic waves may also be reflected, refracted, or absorbed by physical objects in their path. The absorption is called shadowing because of the analogy with visible light. The antenna may capture the superposition of electromagnetic waves sent by the same transmitter that have been reflected or diffracted differently. Such superposition modifies the power the antenna receives.

After propagating over some distance, the guided or unguided electromagnetic wave does not have enough power for a receiver to detect it reliably. Thus, attenuation limits the usable propagation distance. The maximum usable distance depends on the rate at which the propagation reduces the power and on the amount of power that the wave can lose before becoming too weak for the receiver. The attenuation in a transmission line or fiber depends on the frequency of the electromagnetic wave. The attenuation in radio transmissions depends on the shadowing and reflections.

**Distortion**

We call a superposition of electromagnetic waves a signal. Remarkably, a signal with a single frequency keeps its frequency as it propagates, although the propagation attenuates and delays the signal. When a signal is composed of multiple frequencies, its propagation in a transmission link or fiber attenuates and delays differently the different frequencies. As a result, the shape of the received signal differs from that of the transmitted signal. Communication engineers call this shape modification distortion. Figure 7.4 illustrates the distortion of a signal. When it leaves the transmitter, the amplitude of the signal alternates between two opposite values. After transmitting through a cable, this amplitude has a more complicated shape. Cable or wire pair transmission links use a device called an equalizer to compensate for these different attenuations at different frequencies. The equalizer amplifies differently the various frequencies to make up for the different attenuations.
Dispersion
A burst of electromagnetic energy that a transmitter sends in wires, a cable, or an optical fiber spreads as it propagates. Communication engineers call this phenomenon dispersion. Consequently, bursts sent in rapid succession tend to merge as they propagate and become harder to distinguish. Figure 7.4 sketches the spreading out of bursts as they propagate. If the bursts correspond to bits, these bits become difficult to detect after some distance, all the more so when the bursts are close together. Thus, dispersion limits the usable propagation distance to a maximum value that depends on the size of the bursts the transmitter sent, i.e., on the bit rate. We explain in Section 7.2 that dispersion limits the product $R \times L$ of the bit rate $R$ times the distance $L$. The limit on $R \times L$ depends on how fast bursts spread as determined by the physics of the transmission medium.

Noise
A fourth phenomenon affects the transmission of bits: noise. Noise is an unpredictable variation in the signal that reaches the receiver. The physical causes of noise include the thermal agitation of electrons in conductors, uncertainty in the number of photons that a light source generates, and electromagnetic waves that sources other than the transmitter produce and the receiver picks up. Figure 7.4 illustrates the noise that corrupts a received signal.

Without noise it would be possible to transmit bits arbitrarily fast, at least as fast as the circuits can operate. To appreciate this fact, consider a transmission line, say a 1-km-long telephone line. Assume that when one applies a voltage of $V$ volts across one end of the line, after a fixed time, say 1 ms, the voltage across the other end of the line stabilizes to the value $\alpha \times V$. Here, $\alpha$ captures the attenuation. If there were no noise, one could determine $\alpha$ by selecting $V = 1$ and measuring $\alpha \times V$. Thereafter, one could transmit an arbitrarily long string of bits $b_1b_2\ldots b_n$ by selecting $V = b_12^{-1} + b_22^{-2} + b_32^{-3} + \ldots + b_n2^{-n}$. The receiver would then measure $\alpha V$, calculate $V$ by dividing by the known value of $\alpha$, and recover the bits $b_1b_2\ldots b_n$ by writing out the binary expansion of $V$. Using this procedure, we could transmit $n$ bits in two milliseconds: one millisecond to measure $\alpha$ and the other to send the bits. Since $n$ was arbitrary, this argument shows that it would be possible to transmit bits arbitrarily fast over a noiseless transmission line.

The noise prevents us from measuring the voltage $V$ accurately and therefore limits the number of bits in this binary expansion that can be recovered reliably. It seems therefore plausible that the larger the noise, the fewer the number of bits we could transmit in a given time. Accordingly, we suspect that the transmission rate decreases if the line is more noisy.

Also, if we can vary the voltage $V$ faster, then we can send bits faster. The speed at which we can change the voltage and hope that these variations are reflected accurately (except for the noise) at the other end of the line is limited by the bandwidth of the transmission line. This bandwidth specifies the range of frequencies that the line can transmit. (See Figure 7.3 for typical values.)

The above arguments indicate that the rate at which one can transmit bits over a transmission line increases with the bandwidth of the line and decreases with the noise.

In 1948, Claude Shannon made these intuitive arguments precise. He explained that noise introduces a fundamental limit on the rate at which a communication channel can transmit bits reliably. Communication engineers call this limit the capacity of the channel.
For instance, if the capacity of a channel is equal to 30 kbps, then it is possible to design a transmitter and a receiver that transmit 29,999 bits per second over the channel with an error rate smaller than $10^{-9}$, i.e., with fewer than 1 bit out of $10^9$ being incorrectly received. Such a channel cannot transmit reliably faster than 30,000 bps. We explain the main concepts of Shannon’s theory in Section 7.5.

A good transmission link makes few errors. For instance, the bit error rate of a typical optical fiber link is $10^{-12}$. Such a link corrupts 1 bit out of $10^{12}$ bits, on average. If the transmission rate of the link is 155 Mbps, then one incorrect bit arrives every $10^{12}/155 \times 10^6$ s, i.e., about every 2 hours, on average.

Copper lines (wire pairs and coaxial cables) have larger bit error rates: $10^{-7}$ is typical. A transmission link that sends packets of $N$ bits each with a bit error rate equal to BER corrupts some fraction of the packets. That fraction is the packet error rate PER of the link. Assume that the bit errors are independent (see Appendix A). The packet error rate PER is the probability that the $N$ bits of one packet are not all received correctly and is equal to

$$\text{PER} = 1 - (1 - \text{BER})^N.$$

You can verify that

$$\text{PER} \approx N \times \text{BER} \quad \text{if} \quad N \times \text{BER} \ll 1.$$

For instance, if $N = 10^5$ and $\text{BER} = 10^{-7}$, then $\text{PER} \approx 10^{-2}$.

Whereas the bit error rate of a coaxial cable or optical fiber link can be made very small, the situation is very different in wireless links. In those communication links, the bit error rate can be as large as $10^{-3}$. Moreover, the error rate fluctuates widely over time. The wireless receiver may find itself in a region where the power it receives is too low to recover the bits successfully. This effect that reduces the signal power is called fading. Fading is caused by the superposition of different reflected fractions of the transmitted electromagnetic wave that annihluate one another and by the shadowing that objects in the propagation path produce.

We can now revisit Figure 7.2 and explain it in the light of the preceding discussion. The attenuation limits the usable length. The maximum usable length imposed by the attenuation is indicated in Figure 7.2 by a horizontal line for optical fiber links. For a coaxial cable, the attenuation increases rapidly with the frequency and, consequently, with the bit rate. There is a practical limit to the power of an electronic transmitter. As a result, the maximum length of a cable link decreases rapidly with the bit rate, as shown on the figure.

In a fiber link, the dispersion limits the product $R \times L$ of the bit rate times the length. This limitation corresponds to a limit on $\log (R \times L) = \log (R) + \log (L)$. Thus, the dispersion limit translates into a line with slope $-1$ in the figure since its axes have logarithmic scales. That dispersion limit is smallest for step-index fibers and largest for single-mode fibers, as we explain in the next section. As a result, the dispersion limits for these three types of fibers correspond to three distinct graphs, as the figure shows.

We have examined the four fundamental sources of limitations of transmission links. Next we explore the practical methods that the links use to transmit the bits. That is, we discuss the conversion between bits and signals.
7.1.4 Converting between Bits and Signals

The transmitter converts bits into signals. This conversion is called modulation. The receiver performs the reverse conversion: the demodulation from signals to bits. This conversion takes place in a modem (for modulator-demodulator) when the channel is a transmission line. When the transmission is optical or over radio waves, the conversions are made by a transmitter and a receiver.

Modulation schemes differ in their bit error rate and the range of frequencies in the signal they produce. As a rule, modulation schemes that occupy a smaller range of frequencies have a larger bit error rate. Thus, different modulation schemes are appropriate in different situations, depending on the scarcity of the frequencies and the noise level.

We describe a few representative modulation procedures for transmitting a group of bits. We indicate the technologies that use each method: copper lines (L) such as wire pairs and coaxial cables, optical fibers (F), and radio links (R).

**Asynchronous Baseband Transmission (L)**

Figure 7.5 illustrates the operations of an asynchronous baseband transmission system over a copper line. The transmitter and the receiver each have a clock with approximately the same rate $R$ (Hz). The transmitter first groups the bits into short words of $K$ bits. (For instance, $K = 8$.) Initially, the transmitter sets the voltage at its end of the transmission line to 0 volt. To send the first word, the transmitter, using its clock, sets the voltage successively to $V$ volts during $T = 1/R$ seconds for each bit 0 in the word and to $-V$ volts for each bit 1. (For instance, $V = 5$.) Engineers call this representation of bits bipolar modulation. The transmitter then resets the voltage to 0 volt for at least some short duration before continuing with the subsequent words.

**Figure 7.5**

Asynchronous transmission over a transmission line. The transmitter and receiver have clocks with approximately the same frequency. The receiver starts its timing when the first bit arrives. The difference in clock rates might cause the receiver to operate incorrectly.
The receiver detects that a word is arriving when it notices that the line voltage jumps away from its initial zero value. At that time, the receiver starts its clock and uses it to determine when it should measure the line voltage to recover the successive bits. The receiver then gets ready to receive another word: it waits until the line voltage once again jumps away from zero.

Communication engineers call this method asynchronous baseband transmission. Asynchronous refers to the fact that the transmitter and receiver are not synchronized to each other. Transmissions of words of \( K \) bits can occur at arbitrary times. Baseband means that the fluctuations of the transmitted signal follow the changes of the successive bits and do not occur at higher frequencies.

The timing of the asynchronous transmission method limits the size \( K \) of the words and the bit rate \( R \) to small values. Indeed, since the receiver and transmitter clocks never have exactly the same rate, the timing of the receiver becomes less accurate as it keeps on measuring bits. Figure 7.5 shows that a small difference in the clock rates makes the receiver operate incorrectly if the bit string is too long.

The serial line (RS-232-C) between your computer and modem or printer uses this transmission method. (See Section 7.9 for details.)

**Asynchronous Optical Transmission (F)**

Some optical links use a procedure similar to asynchronous baseband transmission. The transmitter sends words of \( K \) bits by switching the light source ON for each bit 1 and OFF for each bit 0, in each case for \( T \) seconds. This procedure is called ON-OFF keying (OOK). The transmitter adds a leading 1 to each word. The receiver uses this start bit to detect the arrival of a word.

The infrared remote control of your TV set uses this transmission procedure.

**Asynchronous Broadband Transmission (L, R)**

This method groups bits into words and times the bits as in the previous methods. When using frequency shift keying (FSK), the transmitter sends a 0 by transmitting a sine wave of frequency \( f_0 \) and a 1 by transmitting a sine wave of frequency \( f_1 \), each during \( T \) seconds. With binary phase shift keying (BPSK), the transmitter sends a 0 by transmitting a sine wave of frequency \( f_0 \) and a 1 by transmitting a sine wave of the same frequency but whose phase differs by 180°. (See Figure 7.6.)

The communication engineer selects frequencies \( f_0 \) and \( f_1 \) that the transmission line transmits well. For instance, a telephone line is designed to transmit the frequencies between 300 Hz and 4000 Hz, which cover the main range of the human voice. A suitable choice for such a line is \( f_0 = 1070 \) Hz and \( f_1 = 1270 \) Hz.

Assume that a modem is sending a bit stream with rate 150 bits per seconds using BPSK with a frequency \( f_0 = 600 \) Hz. The resulting signal is a sequence of sine wave bursts with frequency \( f_0 \) and phases that vary as the bits being transmitted alternate between 0 and 180°. This signal is shown in Figure 7.7. The energy density diagram in the right part of Figure 7.7 shows how much energy the signal contains at the various frequencies. That is, if one filters the signal so that only the frequencies between \( f \) Hz and \( f + 1 \) Hz are retained (as we do in audio with a graphic analyzer), then the energy of the filtered signal is proportional to the energy density of the signal at the frequency \( f \).
FIGURE 7.6
FSK and BPSK. To transmit bits using FSK, the transmitter sends a short sine wave burst per bit. The frequency of the burst depends on the bit 0 or 1 being transmitted. Using BPSK, the sine wave bursts have the same frequency for bits 0 and 1 but their phases are different.

The energy of that signal covers a range of frequencies around $f_0$. In this example, one can show that most of the energy in the signal is in the range [525 Hz, 675 Hz]. Thus, the width of this range of frequencies, called the bandwidth of the signal is equal to 150 Hz. We conclude that, for this specific modulation scheme BPSK, the bandwidth in hertz is approximately equal to the bit rate in bits per second.

Other modulation schemes use a bandwidth in hertz that is some small multiple (typically between 0.15 and 0.5) of the bit rate in bits per second. The smaller the multiple, the more susceptible the signal is to be degraded by noise. That is, robustness against noise is achieved at the cost of some bandwidth. The precise tradeoff between bandwidth and noise robustness is characterized by rate distortion theory, which falls beyond the scope of this text.

Radio links use procedures similar to BPSK and FSK, but with higher frequencies. An antenna radiates and receives electromagnetic waves effectively if the length of the antenna is comparable to the wavelength of the electromagnetic wave. The wavelength of

![Diagram of FSK and BPSK](image-url)
an electromagnetic wave with frequency $f$ Hz is equal to $c/f$, where $c = 3 \times 10^8$ m/s. Thus, a 1-foot antenna is suitable for frequencies around 1 GHz and would therefore be appropriate for $f_1$ and $f_0$ around that frequency.

We explain other modulation schemes in Section 7.3.

**Synchronous Baseband Transmission (L)**

Synchronous transmissions use a different timing mechanism than asynchronous methods. To keep the receiver synchronized to the incoming bits, even after thousands of bits, the synchronous methods use a *self-synchronizing code*, i.e., a code that contains the timing information in addition to the transmitted bits.

The Manchester code is a self-synchronizing code that many copper lines use. This code represents a bit 1 by setting the line voltage high for $T/2$ seconds and low for the following $T/2$ seconds. The code represents a bit 0 by reversing the order of the two values. (See Figure 7.8.)

When the transmitter sends a sequence of bits using the Manchester code, the line voltage makes a transition in every epoch of $T$ seconds. The receiver uses these transitions to remain synchronized to the incoming bits. Specifically, the receiver uses a phase-locked loop, as we explain in Appendix C. To start the synchronization, the transmitter sends a set of extra bits, called a *synchronization preamble*, before the bits to be transmitted. An example of a synchronization preamble is 0101010101111. If the receiver gets synchronized during the preamble, then it can determine the beginning of the bits by detecting the last bit of the preamble. Most local area networks, including Ethernet at 10 Mbps and token ring, use the Manchester code.

By introducing one extra transition for every bit, the Manchester code doubles the frequencies in the signal. When used at a high transmission rate, say 100 Mbps, over a twisted pair of wires, these higher frequencies make the line radiate an unacceptable level of power in the FM band. This unacceptable radiation power is why 100-Mbps Ethernets and FDDI (fiber distributed data interface) networks use other self-synchronizing codes over twisted wire pairs: MLT-3 and NRZI. Figure 7.8 illustrates those codes.

The NRZI (non-return to zero with inversion) signal makes a transition for every bit 1. When using this signal, the transmitter needs to make sure that the bit stream contains enough 1s. Since the transmission line must work for arbitrary bit strings, including those that contain few 1s, NRZI is used together with a *line code* that inserts 1s in the original bit stream at the transmitter and removes them at the receiver. The 4B/5B code that we explain on the next page (in the section on synchronous optical transmissions) is an example of codes that insert the needed 1s.

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**FIGURE 7.8**

*Some widely used self-synchronizing baseband modulation schemes.*
The MLT-3 (multilevel-ternary) signal transmits 0s as 0 volt and 1s alternatively as \(+V\) and \(-V\). As for NRZI, this scheme requires a line code that inserts 1s.

You will note that these codes generate a signal that changes less rapidly than the Manchester code. To achieve the 100-Mbps transmission rate over twisted pairs, Ethernet and FDDI use two or three twisted pairs in parallel.

**Synchronous Broadband Transmission (L, R)**

Synchronous broadband transmissions use the modulation methods we described for asynchronous broadband transmission. The sine waves contain the timing information, so these signals are self-synchronizing.

**Synchronous Optical Transmission (F)**

A synchronous transmission over an optical fiber also uses a self-synchronizing code. Some optical links use the Manchester code to produce the voltage that drives the light source.

To limit the rate of transitions of the optical signal, high-bit-rate optical links use another self-synchronizing code. One such code, called 4B/5B, first groups the bits to be transmitted into words of 4 bits. The code then represents each of the 16 possible 4-bit words by a 5-bit word. The sixteen 5-bit words of the 4B/5B code are selected to contain enough transitions between 0s and 1s. The transmitter then sends the successive 5-bit words using OOK. The resulting light signal contains enough transitions to keep the receiver synchronized. A link may keep on sending a reserved 5-bit word, called the *idle symbol*, to indicate the absence of data bits and to keep the receiver clock synchronized.

The optical links of FDDI use the 4B/5B encoding. Other links use a similar code called 6B/8B.

In the next sections, we describe how optical, radio, and wired communication links work. That description helps us to understand the characteristics of the links.

### 7.2 Optical Links

FDDI uses optical links to connect computers separated by more than 100 m. Some Ethernet connections are over optical links. High speed (e.g., 155 Mbps) and long (≥ 100 m) links of ATM networks are optical. Finally, all long-distance telephone links are optical. Some systems use free-space infrared transmissions to set up wireless local area networks or to communicate between a camcorder and a TV set or between computer devices such as a computer, printer, keyboard, and mouse. In this section we focus on links with optical fibers.

#### 7.2.1 Overview

A guided optical link consists of a transmitter equipped with an optical source, an optical fiber, and an optical detector attached to a receiver. The transmitter converts the bits into an optical signal, for instance using OOK as we explained in the previous section. The optical signal propagates in the fiber and hits the detector. The detector and the receiver convert the optical signal back into bits. We discuss the characteristics and sources of limitations of optical links.
End-to-End Characteristics
Optical fiber communication links transmit at a very large bit rate over a long distance. Some links can transmit at rates larger than 10 Gbps over more than 100 km. Moreover, bit streams that transmitters send using different colors of light can coexist in the same fiber. The bit error rate of these links can be kept below $10^{-12}$. The cost per km and per Mbps of these links is much lower than with any other technology. Optical fiber links make the modern high-performance communication networks possible.

The large bit rate and long distances are possible because of the small dispersion and low attenuation in optical fibers. We examine those phenomena next.

Dispersion Limit
We explain why dispersion limits the product $R \times L$ of the bit rate $R$ times the usable length $L$ of fiber. Imagine a pulse of light that propagates in a fiber. The laws of propagation imply that different fractions of the energy in that pulse travel at different speeds along the fiber. Let us say that the slowest fraction of the energy takes $D$ seconds more to cover 1 km of fiber than the fastest fraction of that energy. If the pulse travels across $L$ km of fiber, then the slowest fraction of energy reaches the end $D \times L$ seconds later than the fastest fraction. Consequently, if the transmitter injects a pulse with a duration of $T$ seconds, then that pulse has a duration of $T + D \times L$ seconds after $L$ km of fiber.

Consider now a sequence of bits 1010101010101 · · · modulated by OOK into a light wave. Say that the bits are sent at rate $R$ bps, so that each bit 1 corresponds to a pulse with duration $T = 1/R$ seconds and each 0 to the absence of light, also for $T$ seconds. After $L$ km of fiber, the pulses that represent the 1s have a duration equal to $T + D \times L$. Accordingly, the gaps between these pulses are equal to $T - D \times L$ after $L$ km. The bit stream is difficult to detect if these gaps are a small fraction of $T$, say if they are less than $0.50 \times T$. Thus, the maximum value of $L$ is such that $D \times L \leq T/2 = 1/2R$. We can rewrite this condition as $R \times L \leq 1/2D$. Recapitulating our discussion, we have found that dispersion imposes the limit

$$R \times L \leq \frac{1}{2D}.$$  \hspace{1cm} (7.1)

Recall that, in this expression, $D$ is the difference in travel times of the slowest and fastest fractions of the energy of the light after 1 km of fiber. We call $D$ the dispersion rate of the fiber. The value of $D$ depends on the type of fiber, as we explain later.

Three Types of Fiber
An optical fiber is a long cylinder made of plastic or glass. Three types of fibers are used in networks: step index, graded index, and single mode. These three fibers are sketched in Figure 7.9.

Note the different shapes of the rays of light in the fibers. As we explain in the next section, these different shapes result in different values of the dispersion rate $D$ of these fibers. Consequently, these fibers have different dispersion limits, as we saw in (7.1). The limits are as follows:

$$R \times L \leq \begin{cases} 
10 \text{ Mbps} \times \text{ km} \text{ for a step-index fiber} \\
1 \text{ Gbps} \times \text{ km} \text{ for a graded-index fiber} \\
200 \text{ Gbps} \times \text{ km} \text{ for a single-mode fiber}
\end{cases} \hspace{1cm} (7.2)$$
We should note that some single-mode fibers are specially designed to have an even smaller dispersion rate. These _dispersion-compensated fibers_ achieve a dispersion limit that can exceed 1000 Gbps × km.

Figure 7.10 shows the attenuation of an all-glass fiber as a function of the wavelength. An attenuation of _A_ dB/km means that the power _P(L)_ after _L_ km is equal to the power _P(0)_ injected in the fiber multiplied by a factor _10^{-(AL)/10}_. That is,

\[
P(L) = P(0) \times 10^{-\frac{AL}{10}} \quad \text{and} \quad 10 \log_{10} \left( \frac{P(0)}{P(L)} \right) = AL \text{ dB.}
\]

Consequently, the attenuation after _L_ km is equal to _A_ × _L_ dB, or _A_ dB/km.

Note two ranges—or windows—of wavelengths where the attenuation is particularly low. These windows cover about 0.1 μm, one around 1.3 μm and the other around 1.55 μm. The attenuation in these windows is about 0.4 dB/km and 0.2 dB/km, respectively. These

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**Figure 7.9**

_Three types of fiber: step index, graded index (GRIN), and single mode (SMF)._  

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**Figure 7.10**

_Attenuation in an all-glass fiber._
windows cover a range of frequencies with a width equal to a few terahertz. (1 terahertz = \(10^{12}\) Hz.) An optical fiber has a bandwidth so large that it could transmit simultaneously all the telephone conversations that happen at any given time in the world. However, the rates of optical links are limited by dispersion and by the maximum rate of optical transmitters and receivers.

The propagation speed in these fibers is \(c/\eta\) where \(c = 3 \times 10^8\) m/s and \(\eta \approx 1.5\) is the refractive index of the fiber. Thus, the propagation speed is approximately \(2 \times 10^8\) m/s, which corresponds to a propagation time equal to 5 \(\mu\)s per kilometer of fiber.

### 7.2.2 Propagation in Fibers

We explain how light propagates in step-index, GRIN, and single-mode fibers. Our discussion helps us understand the result in (7.2). We discuss the three fiber types separately, starting with the step-index fiber.

#### Step-Index Fiber

A step-index optical fiber is a cylindrical core of glass or plastic with refractive index \(\eta\) that is surrounded by a tube of glass or plastic with a slightly smaller refractive index \(\nu\). (See Figure 7.9.)

In a step-index fiber, rays that make an angle larger than some critical angle \(\theta\) with the axis of the fiber gets refracted into the outer material and escape the fiber. The critical angle \(\theta\) is such that \(\cos \theta = \nu/\eta\). The other rays propagate through a series of total reflections, as shown in Figure 7.9. Different angles of propagation are called modes and, accordingly, the step-index fiber is called a multimode fiber. Depending on their angle, rays of different modes cover different distances for each kilometer of fiber that they go through. All these rays travel at velocity \(c/\eta\) in the core with refractive index \(\eta\). The different distances that different modes cover result in different travel times, which corresponds to some dispersion rate \(D\), as we explained above in “Dispersion Limit.”

To calculate \(D\), note that rays parallel to the axis of the fiber have a travel time equal to \(T_1 = 1/(c/\eta) = \eta/c\) per kilometer of fiber. Rays with the maximum reflected angle \(\theta\) cover the maximum distance equal to \(1/\cos \theta\) km to go through 1 km of fiber. The travel time of these rays is then \(T_2 = T_1/\cos \theta = T_1 \times (\eta/\nu)\). Hence, \(D = T_2 - T_1 = (\nu/c)(\eta/\nu - 1)\).

For a typical fiber, \(\nu = 0.99 \times \eta\). Thus, \(D \approx (\nu/c)(\eta/\nu - 1) = (\eta - \nu)/c\). Using (7.1) we then find that the dispersion limit is given by

\[
R \times L \leq \frac{c}{2(\eta - \nu)}.
\]

With \(\eta - \nu = 0.01\), this bound gives the first result indicated in (7.2).

#### GRIN Fiber

In addition to the step-index fibers, communication systems also use graded-index (GRIN) fibers. The refractive index of the core of a GRIN fiber decreases with the distance from the fiber axis. In such a fiber, the rays are subject to continuous refractions and propagate along oscillatory paths as illustrated in Figure 7.9. Thus, a GRIN fiber is also a multimode fiber. The modes are different oscillating paths.

The rays that travel longer distances go through regions of the fiber where the refraction index is smaller and, therefore, where the propagation speed is larger. Thus, remarkably,
longer distances are compensated by larger average speeds. As a result, the propagation
time of the longer rays is similar to that of rays which travel closer to the center of the fiber.
As a consequence, the modal dispersion of GRIN fibers is substantially smaller than it is in
step-index fibers. The analysis of GRIN fibers shows that (7.3) becomes

\[ R \times L \leq \frac{2c\eta_1}{(\eta_1 - \eta_2)^2} \]  

for GRIN fibers. (7.4)

In this expression, \( \eta_1 \) is the refractive index at the center of the fiber and \( \eta_2 \) is the refractive
index at the periphery of the fiber. Typical values give \( R \times L \leq 1 \text{ Gbps} \times \text{km} \), i.e., \( 10^9 \text{ bps} \times \text{km} \).

**Single-Mode Fibers**

We learned that multiple modes limit the transmission rate in a fiber. The GRIN fibers
reduce but do not eliminate the modal dispersion. Is it possible to construct a fiber having a
single transmission mode? The answer is yes.

If the radius of the core of a step-index fiber is small enough (about 8 \( \mu \text{m} \)), then
only one mode can propagate. The reason is that the successive reflections of a ray inter-
terfere with each other and such interference destroys some modes. This phenomenon
is somewhat similar to the phenomenon which makes a pipe organ vibrate only at spe-
cific frequencies. The analysis of the solutions of Maxwell’s equations shows that only
a finite set of modes propagates along the fiber, instead of the continuum of angles from
0 to \( \theta \) that Figure 7.9 deceptively suggests. When the radius is small enough, only
the mode that is parallel to the fiber exists and such a fiber is called a single-mode fiber.
Because single-mode fibers have no multimodal pulse spreading, they have a small dispersion
rate \( D \).

Note, however, that all fibers—including single-mode fibers—are subject to material
dispersion. This dispersion is caused by the differences of the refractive index at different
wavelengths, which results in different velocities of different wavelengths. A light source
emits light that covers some frequency band characterized by a spectral width. The spectral
width \( \sigma \) of a light source is the width of the interval of frequencies where the power of light
is at least equal to half its peak value. Using this definition, one can show that the material
dispersion imposes a limit given by

\[ R \times L \leq \frac{1}{4\Phi \sigma} \]  

(7.5)

where

\[ \Phi = \frac{d^2\eta(\lambda_0)}{d\lambda^2} \]  

(7.6)

is the second derivative of the refractive index with respect to the wavelength, evaluated at
\( \lambda_0 \), the average of the wavelength of the source. The value of \( \Phi \) is \( 10^{-12} \text{ s/km} \times \text{nm} \) for a
silica fiber at \( \lambda_0 = 1.3 \text{ \( \mu \)m} \). The value of \( \sigma \) is about 1 nm for a GaAsP laser and about 3
nm for a laser diode. (GaAsP designates a specific semiconductor crystalline alloy.) We discuss
laser diodes and other transmitters below. These values correspond to the limits
\[ R \times L \leq 250 \text{ Gbps} \times \text{km} \text{ and } R \times L \leq 80 \text{ Gbps} \times \text{km} \text{, respectively.} \]

We now turn our attention to the light sources.
7.2.3 Light Sources

Optical links use two types of light source: light-emitting diodes (LEDs) and laser diodes (LDs). The main characteristics of these sources are the intensity and wavelengths of the light they produce and the maximum rate at which they can be modulated. A laser diode can be modulated faster than an LED and has a smaller spectral width. A smaller spectral width produces a smaller dispersion and enables many LDs to share the 100-nm window around 1.55 μm of an optical fiber.

An LED is a PN semiconductor junction. An LED connected to a constant current source produces a light beam with an intensity proportional to the current. The physical phenomenon at work is that a fixed fraction of the injected electrons induce electron-hole recombinations; when such a recombination occurs, the energy lost by the electron is emitted as a photon. Typical LEDs generate a few milliwatts [1 milliwatt (mW) = 10⁻³ watt] of optical power when about 50 mA (1 mA = 10⁻³ ampere) are injected. If the injected current changes rapidly, then the optical power emitted by the diode drops with the rate of change. Physically, the electron-hole pairs take some time to recombine and they cannot do so efficiently if the current changes too fast. This effect limits the frequency at which one can modulate, i.e., modify, the intensity of the light beam. This frequency limit is indicated by the cutoff frequency at which the power is reduced to 70 percent of its peak value. Typical values of the cutoff frequency of LEDs range from 1 kHz to 100 MHz.

LEDs can be used for transmitting strings of bits by OOK or analog signals that take a continuous set of possible values. LEDs are used in consumer electronic devices ranging from remote controls to wireless headphones; in those applications, the LEDs emit infrared light. Infrared LEDs are also used in local area communication networks. LEDs that emit visible light are also used as inexpensive and long-lasting indicators.

Essentially, a laser diode (LD) is a PN junction in an optical cavity. That is, the junction is terminated by two parallel semireflecting faces A and B; the distance between the faces is some multiple of half a wavelength generated by electron-hole recombinations. The junction is forward-biased and emits photons. Some photons "hit" free electrons that then recombine and emit coherent photons, by stimulated emission. That is, when an incident photon leads an electron to lose an amount of energy equal to that of the photon, then a second photon is emitted with the same frequency and phase as the first photon. These stimulated emissions form a chain reaction. Some of the emitted light waves are attenuated by out-of-phase interference with reflections from the faces A and B. That is, the interference with the reflections acts as a filter which attenuates light waves unless they have a specific phase and wavelength. The chain reaction is self-sustaining if the gain due to stimulated emissions is larger than the loss due to the imperfect reflections (and to absorption). This self-sustaining reaction occurs when enough electron-hole pairs recombine in the junction and, therefore, when the forward bias is sufficient.

The cutoff frequency of an LD is a few orders of magnitude larger than that of an LED. Some LDs can be modulated at up to 11 Gbps. LDs are temperature-sensitive. The optical power for a given value of the injected current depends significantly on the temperature because heat increases the generation of free electrons and free holes. This dependency can be controlled with sophisticated circuitry that monitors the LD temperature and adjusts the injected current correspondingly. LDs are used in compact disc players and in long-distance optical communication systems.
7.2.4 Light Detectors

The receiver of an optical link contains a light detector that converts the light into an electrical signal. The light detector is followed by a preamplifier that amplifies the weak current that comes out of the detector. The output of the preamplifier enters a circuit that measures the amount of current that the light detector produces during the successive bit durations. This circuit contains the PLL that we discussed earlier.

The light detector is a PN junction, a PIN diode, or an APD (avalanche photo-diode). The main characteristics of a light detector are the range of wavelengths it responds to, its quantum efficiency, and the rate of variation of intensity of light it can track. The quantum efficiency is the fraction of incident photons that the light detector converts into electrons.

A PN photodiode is a reverse-biased PN junction. The reverse bias increases the electrical field in the junction and prevents charges from moving across it. When the junction is illuminated, some photons are absorbed by electrons in the p region close to the junction; these electrons become free when the energy of the photons is adequate. The freed electrons are pushed across the junction by the large electrical field and have a good chance of making it through the device and of contributing an external current. Thus, a PN photodiode acts as a light-dependent current source.

The rate at which the PN-photodiode detects bits depends on how fast it can follow variations in the intensity of light. The long travel time of freed electrons across the device limits that rate to about 1 MHz.

The second type of optical receiver is the PIN diode, the most commonly used photodetector in communication networks. The PIN diode has three layers which are, respectively, p-doped, intrinsic (i.e., not doped), and n-doped, hence the name PIN. The intrinsic layer is large; since it is not doped, its resistivity is high. As a result, when the diode is reverse-biased, there is a large electrical field across the intrinsic region. Most photons are absorbed in the intrinsic region and free charges that race across the device. This fast travel results in a rate of detection that can be as high as 20 GHz.

The third type of optical detector is the avalanche photodiode. An APD is a PIN diode with a very large junction electrical field. The operating mechanism is roughly that the reverse bias of the diode is so large that freed charges race through the diode so fast that they free additional charges through “impacts.” This effect results in an avalanche that makes the APD much more sensitive than a PIN diode: a single photon may, through the avalanche effect, free as many as 100 charges.

7.2.5 Free-Space Infrared

Infrared communication is also used in free space. Applications include connecting a computer to a peripheral such as a printer or a keyboard and interconnecting computers.

IrDA, the Infra-Red Data Association, is an independent industry association formed in June 1993 with the objective of defining standards for low-cost infrared interconnections. The standards defined so far are for the transmission rates 2400 bps, 115.2 kbps, 1.152 Mbps, and 4 Mbps.

- The IrDA transmitters use the wavelength 0.86 μm with a 1-meter range. The bit encoding is OOK at the low bit rates and pulse position modulation (PPM) at 4 Mbps. PPM encodes a group of bits by adjusting the timing of a pulse of light. For instance, PPM4
groups the bits 2 by 2 and transmits the bits by sending the pulse in one of four time slots that make up a frame. PPM achieves a lower BER than OOK at large bit rates because the transmitter can use a larger peak value of the light intensity—which is then easier to detect—for a given average emitted power.

### 7.3 Copper Lines

In this section we explore copper lines such as wire pairs and coaxial cables. The telephone network uses twisted pairs for the subscriber loop between the customer telephone set and the local telephone switch. When the telephone company wires an office building for telephones, it usually installs redundant twisted pairs in anticipation of future needs. Consequently, most office buildings have unused twisted pairs already installed. These spare twisted pairs can be used for wiring local area networks, thereby eliminating the need for a costly dedicated wiring of the building.

#### 7.3.1 Overview

Copper lines guide electromagnetic waves through the interaction of a varying electrical field and magnetic field that are produced by and also induce varying currents in the wires.

A transmission line is characterized by the range of frequencies—the bandwidth—that it can transmit with a low attenuation. The attenuation in a transmission line increases with the frequency because electrons, being charged particles, repulse each other. At high frequencies, the electrons are pushed at the periphery of the conducting material that makes up the transmission line. Consequently, the effective section of conductor that the current goes through is very small and the apparent resistivity of the transmission line is high.

A wire pair radiates electromagnetic fields when traversed by a varying current. Conversely, an external electromagnetic field induces a varying current in a wire pair. These effects produce crosstalk between adjacent pairs: a signal in one pair leaks into the other pair. The radiation may also disturb the operations of radio receivers or of other electronic equipment. To prevent such disturbances, the Federal Communication Commission regulates the acceptable level of radiation at different frequencies. The FCC limitations force the communication engineers who design transmitters for wire pairs to employ clever encoding and modulation methods that limit the amount of energy of the signal that the transmitter injects into the twisted pairs at different frequencies.

The radiation of a wire pair is reduced by twisting the pair. Indeed, the fields generated by two successive loops of a twisted pair are of opposite signs and tend to cancel one another. Similarly, a twisted pair is less sensitive to crosstalk than an untwisted wire pair. In practical terms, a single twisted pair can transmit at up to about 50 Mbps over 100 m and up to 4 Mbps over 1500 m.

A coaxial cable, because of its shield that surrounds the center conductor, radiates and picks up very little energy. The coaxial cable has a larger bandwidth than a twisted pair (about 400 MHz over 2 km). With an efficient modulation scheme—using 0.5 Hz/bps—the coaxial cable (or "coax") can transport about 800 Mbps over 2 km. This rate is enough for 500 digital TV channels compressed at 1.5 Mbps each.
7.3.2 Modulation

The following scheme, called quadrature phase shift keying (QPSK), produces a signal that covers a smaller range of frequencies than PSK and FSK and is used by high-speed telephone and cable modems. The transmitter groups the bits 3 by 3. For each of the 8 possible groups of 3 bits, the transmitter selects a pair of numbers \((a_n, b_n)\) equally spaced on the unit circle, as shown in Figure 7.11. The transmitter then sends the signal \(a_n \cos(2\pi f_0 t) + b_n \sin(2\pi f_0 t)\) for \(T\) seconds. The figure shows the signals that correspond to the 3-bit words 000, 001, 011. For instance, to transmit the three bits 011, the transmitter transmits the signal \(-0.7 \cos(2\pi f_0 t) + 0.7 \sin(2\pi f_0 t)\) for \(T\) seconds. Figure 7.12 shows the signal the transmitter sends to transmit the bit string 000'001'011'000.

The coefficients of \(\cos(2\pi f_0 t)\) and \(\sin(2\pi f_0 t)\) change only once every 3 bits. This rate is the symbol rate of the modulation scheme; a symbol represents 3 bits in this example. By analogy with our discussion of BPSK, one can expect the bandwidth of the signal to be approximately equal to the symbol rate.

Instead of using 8 points \((a_n, b_n)\) on the circle, we could choose \(2^k\) points anywhere on and inside the circle. Each of these coefficients is then associated with word of \(k\) bits. This modulation method is called quadrature amplitude modulation (QAM). With this choice, the symbol rate is equal to the bit rate divided by \(k\), say \(R/k\). The signal bandwidth is then approximately equal to \(R/k\) Hz.

**Figure 7.11**
QPSK. The transmitter groups the bits 3 by 3. To transmit a 3-bit group, the transmitter sends
\[
a_n \cos(2\pi f_0 t) + b_n \sin(2\pi f_0 t)
\]
for \(T\) seconds, where the coefficients \((a_n, b_n)\) correspond to the group.

**Figure 7.12**
Transmission of a bit string using QPSK.
\[
a(t) \cos(2\pi f_0 t) + b(t) \sin(2\pi f_0 t)
\]
To detect a BPSK, QPSK, or a QAM signal, the receiver measures the coefficients $a$ and $b$ to recover the symbol $(a, b)$ and the group of bits that are encoded by this symbol. By choosing $k$ larger, the bandwidth $R/k$ gets smaller. However, the points $(a_n, b_n)$ that represent the groups of bits become closer to one another as $k$ increases, and this closeness makes it more difficult for the receiver to guess the correct value. This discussion shows that there is a tradeoff between the bandwidth of the signal and the sensitivity to noise. Thus, if a transmission line has little noise but can only transmit a narrow range of frequencies, then QAM with a large $k$ is the suitable choice. Conversely, if the line is noisy but transmits a wide range of frequencies, then BPSK is a better choice.

Fast modems use additional methods to further increase their spectral efficiency. Two such methods, called minimum shift keying (MSK) and Gaussian minimum shift keying (GMSK), replace the sharp transitions of the coefficient of the sine wave of BPSK by smoother transitions. That is, instead of changing from $+\sin(2\pi f_0 t)$ when transmitting a bit 1 to $-\sin(2\pi f_0 t)$ when transmitting a bit 0, MSK and GMSK change the coefficient of the sine wave from +1 to -1 gradually. This smoother change reduces the bandwidth of the signal.

**Multiplexing**

A transmission link with bandwidth $[f_0, f_1]$ can transmit different signals that cover nonoverlapping ranges of frequencies in the range $[f_0, f_1]$. The receiver can select one of the signal by filtering out the others. Thus, a coaxial cable with bandwidth [300 MHz, 1 GHz] can transmit 70 TV programs with 6-MHz-wide spectra and a number of digital signals using QPSK. Some cable TV companies are implementing such systems to offer telephone services, access to the Internet, and video on demand.

Telephone companies are also using broadband transmission methods to deliver high-speed data services in addition to the regular telephone service on a regular copper subscriber loop. This combination—called ADSL for asymmetric digital subscriber loop—competes with the cable TV solutions. (See Section 7.10.)

A wireless cable—with its oxymoronic name—replaces a coaxial cable by radio transmitters to provide community antenna TV (CATV). When the transmitter covers only a small radius, the wireless cable also provides a return channel from the subscribers' premises. That return channel is used for telephone service or for control messages of a video-on-demand service.

**Modems**

Wired and wireless modems (modulator-demodulators) use the transmission method described above, sometime using slightly different modulations to encode the bits. Here are a few representative modems:

- **9.6 kbps (V.32):** This modem uses QAM with a 32-point constellation.
- **14.4 kbps (V.32 bis):** This modem uses QAM with a 64-point constellation.
- **28.8 kbps and 33.6 (V.34):** This modem uses QAM with a 960-point constellation at 28.8 kbps and a 1664-point constellation at 33.6 kbps. The modem adjusts both the symbol rate and the carrier frequency.
- **56 kbps:** This modem provides an asymmetric service (56 kbps downstream and 30 kbps upstream). (See the next page for some details.)
Compression MNP5 and V.42 bis: To reduce the number of bits they must transmit, some modems first compress the bit stream before transmitting it and decompress it at the destination. The MNP5 compression uses run length encoding: Instead of sending a string of $K$ zeros, the modem sends the number $K$. Since the number $K$ can be encoded with approximately $\log_2 K$ bits, this compression scheme can be very effective when $K$ tends to be large. V.42 bis uses the Lempel-Ziv compression algorithm that we explain in Chapter 8.

Cable modems: Fast modems can take advantage of the large bandwidth of coaxial cables to transmit data very fast on a CATV network. These modems typically use a modulation scheme such as QPSK with a fast rate of signal changes.

56-kbps Modems. These recent modems use an approach different from QAM. To understand this approach, let us examine how bits are sent by the central office of the telephone company to the subscriber. When the central office gets a bit stream to deliver to the subscriber, it assumes the successive bytes $v_n$ are analog voice samples $s_n$ that were first compressed as $\mu(s_n)$ before being quantized (digitized) as $\nu_n$. The function $\mu(\cdot)$ is a function that compresses large values that are rare. This compression results in smaller quantization errors for the frequent small-valued samples and reduces the quantization noise in the digitized samples $v_n$.

Accordingly, the line interface electronics in the central office decompresses the samples by computing $\mu^{-1}(v_n)$. The electronics then produces an analog signal $s(t) = \sum_n g(t - n\tau)\mu^{-1}(v_n)$ where $g(\cdot)$ interpolates between the values $\mu^{-1}(v_n)$ placed every $\tau = 125 \mu s$.

When the bytes $v_n$ are data, the demodulator in the 56-kbps modem must recover these bytes from $s(t)$. The optimal decoder for these bytes must be designed by assuming that the noise in the channel is Gaussian. Remarkably, this approach doubles the effective rate of the modem over the rate that can be achieved by using QAM. The magic happens because this approach exploits the precise shape of the compression.

As the above description shows, this approach works only if there is a single analog-to-digital conversion in the link. Thus, you can use the 56-kbps modem to download data from a remote server that is attached to the network with an ISDN line or another digital service. This modem does not work (at 56 kbps) if the server itself is sending the data over a voiceband modem.

7.3.3 CATV and Video-on-Demand Systems

The cable television system evolved in four major steps. Initially, the transmission was analog over a tree-like coaxial cable plant. Amplifiers compensate the loss of power due to the attenuation of the signal as it propagates. Since amplifiers also amplify the noise, the noise limits the range of the distribution system. For the NTSC (National Television System Committee) standard, different TV channels are modulated in different frequency bands that are 4.5-MHz wide.

The second step is the replacement of sections between the CATV head-end station and segments of the coaxial cable by optical fibers. This hybrid fiber–coax plant has an improved signal quality because fibers have a smaller attenuation than coaxial cable. The cost of the optical links is shared by the users attached to the same coaxial cable segment.
Chapter 7  Physical Layer

The third step is the digital transmission of compressed video. The compression uses the MPEG1 standard at 1.5 Mbps. The decompression is performed by the user's set-top box. With a suitable QPSK modulation of the 1.5-Mbps bit stream, a TV channel then occupies only 600 kHz instead of 4.5 MHz. Consequently, the coaxial cable can carry about 500 TV channels. If 500 users are attached to the same coaxial segment, each can have a dedicated channel.

The fourth step is the two-way transmission of control messages between the users' equipment and the CATV station. This transmission is packetized and takes place on dedicated frequency bands. Amplifiers in the upstream direction, from the users to the CATV station, are needed to transmit the messages. With this fourth step, the users can request video programs or pieces of information. Thus, 500 users can each request different video programs from the CATV station. The upstream channels can also be used to provide local access to the Internet or to other service providers. The IEEE 802.14 is defining standards for transmission and multiple access over cables.

7.4 Radio Links

Radio links are used when mobility is required or to avoid the cost of setting up a wired link.

7.4.1 Overview

An antenna radiates and receives an electromagnetic wave efficiently if its length is about half the wavelength of the electromagnetic wave. Thus, to radiate an electromagnetic wave at 10 kHz, the antenna should have a length close to half of $3 \times 10^5$ km/s/10^4 Hz = 30 km, which is not practical. If the frequency of the wave is 100 MHz, then the length required is about 1.5 m, which is the length of the antenna of an FM receiver. For a frequency of 1 GHz, the length becomes 0.15 m, which is the size of a direct satellite broadcasting TV antenna.

If the signal to be transmitted has a low frequency, such as a music program with a frequency range from 0 to 10 kHz, then the transmitter first modifies the frequencies in the signal before sending it to the antenna. To perform this modification, the transmitter generates a sine wave at a high frequency $f_0$ Hz—called the carrier—and it uses the signal to be transmitted to modify the amplitude, the frequency, or the phase of that carrier. This operation—called modulation—produces a signal with a frequency close to $f_0$ whose amplitude, frequency, or phase variations represent the signal to be transmitted. The antenna has a length suitable for transmitting the carrier. When the receiver gets the modulated carrier, it converts the variations in frequency or amplitude or phase into the transmitted signal.

By using carriers at slightly different frequencies, the transmitter can send different signals on the same antenna. These modulated carriers have different frequencies and the receiver can select which one it listens to. For instance, all the broadcast radio and TV programs share the air waves and the radio or TV set can select which one it receives. Thus, modulation serves two purposes: (1) modifying the frequency of the signal to make the antenna efficient and (2) separating different signals in frequency.
7.4.2 Propagation

The analysis of propagation shows that the power per unit area first decays with the square of the distance and then decays with its fourth power. Detailed measurements reveal that reflections on buildings, vegetation, and other objects make the actual power decay less regular than the theory predicts. Computer programs enable communication engineers to model the environment where the radio operates and to predict the strength of the electromagnetic wave as a function of the location. Such computer tools are useful to plan the location of transmitters. However, the only sure way of determining the actual range of coverage of an antenna is to measure the power of the signal received at various locations.

7.4.3 Cellular Networks

Cellular networks are widely used to provide mobile telephone services. These systems started in the 1970s with analog transmissions where voice was frequency-modulated to provide a number of telephone channels. The region is divided into cells, and cells that are far enough apart can use the same set of frequencies. Thus, if seven cells repeat periodically to cover the area, each using a different set of $N$ frequencies, then $7N$ frequencies are used for the whole area. The density of active users that the system can accommodate is then equal to $N/S$ users per square kilometer where $S$ is the surface area of one cell.

These analog systems are progressively being complemented or replaced with digital systems. Digital systems take advantage of voice compression to reduce the range of frequencies that a voice channel occupies. In addition, digital transmission can be made more robust to noise.

One key mechanism of a digital cellular system is the sharing of the frequency band allocated by the regulating agencies to the system. One method uses frequency-division multiple access (FDMA) combined with time-division multiple access (TDMA). When this method is used, the frequency band is first divided into a set of channels. Each channel is then decomposed into a number of voice circuits by time division. That is, a channel transports a bit stream that is arranged into frames and each frame is divided into $K$ slots. The slots are allocated to the different voice circuits. In another method, code-division multiple access (CDMA), the signals of the different users all occupy the complete frequency band. However, these signals are obtained by multiplying the users bit streams by distinct pseudorandom sequences that take the values $+1$ and $-1$ and change rapidly. To recover the bit stream of a particular user, the receiver multiplies the signal it receives by the pseudorandom sequence that characterizes that user. The signals of other users, when multiplied by this particular sequence, appear to the receiver as a fast-changing noise that can be averaged out.

7.5 Complement 1: Shannon Capacity

The capacity can be calculated from the characteristics of the link—such as the attenuation and delay at different frequencies—and of the noise. Shannon showed that the capacity of
the byte interleaving of different digital streams. Given the importance of this technology, we describe the architecture of SONET and its framing structure.

### 7.7.1 SONET Architecture

Figure 7.14 shows SONET. This network consists of switches, multiplexers, and regenerators connected by optical fibers. This network provides bit ways between users. SONET bit ways are used to transport telephone calls. The bit ways are also used to connect Internet routers or ATM switches.

In SONET terminology, the link that the network makes available to users is a path. The path carries user bits between two access points. The access points may be attached to ATM switches, to Internet routers, or to telephone switches. The path packages the user bits in frames called *synchronous payload envelopes* (SPEs). Each SPE contains a path overhead field that the access points use to monitor the connection. Thus, an SPE has two parts: the path *overhead* and the *payload* that contains the user bits. The user bits may encode telephone conversations, video or audio signals, or ATM cells.

The path itself is transported across a set of *lines* between its source and its destination. A line is the transmission facility that transports bits between two multiplexers. A line transports line frames that consist of some overhead monitoring information plus the line payload bits. The line payload bits transport SPEs. Thus, we may think of a line as a conveyor belt that carries SPEs.

Finally, a line may consist of a number of *sections*. A section is the part of a line between devices where a light-to-electronics conversion occurs. These devices include multiplexers and also regenerators that clean up and amplify the signals. A section transports section frames that contain some overhead information plus the section payload bits which transport line frames. The transmission itself occurs on optical fibers.

**FIGURE 7.14**

*SONET: The figure shows the three-layer hierarchy of the synchronous optical network: sections make up lines that make up paths.*

![SONET Architecture Diagram](image)
7.7.2 Frames

Figure 7.15 sketches the frames that SONET transports on its paths, lines, and sections. We illustrate the frames transported by lines at 155 Mbps. The frame, transmitted row by row, contains $9 \times 270$ bytes and it repeats 8000 times per second. The total bit rate is therefore equal to $8 \times 9 \times 270 \times 8000 = 155.52$ Mbps. The first factor (8) in the product converts bytes into bits. Out of the $9 \times 270 = 2430$ bytes of the frame, $4 \times 9 = 36$ are section overhead bytes, $5 \times 9 = 45$ bytes are LINE overhead bytes, and $1 \times 9 = 9$ bytes are the path overhead bytes. Thus, the user data rate is equal to $8 \times 260 \times 9 \times 8000 = 149.76$ Mbps.

We stated that all the transmitters in SONET are synchronized to a common clock. Now imagine that you are using a SONET path to carry a video signal or packets generated by your workstation or telephone signals produced by non-SONET equipment. To prevent the need to synchronize your equipment with the rest of the network, SONET enables SPEs to float with respect to the line frames. This floating is illustrated in Figure 7.15. That is, the SPEs can start at arbitrary times within a line frame. A special pointer in the line overhead indicates where the SPE starts. The receiver uses that pointer to locate and recover the SPE. Moreover, when not synchronized, the user may generate bits slightly faster or more slowly than the line bit rate. If the user rate is slightly larger, then the SPE payload overflows periodically. When an overflow occurs, SONET places the extra user bits in a specific field within the line overhead. Conversely, if the user rate is slower, then the SPE payload underflows whenever there are not enough user bits to fill it up. A specific field in the line overhead indicates the underflow and specifies the number of empty bytes inside the SPE payload.

**FIGURE 7.15**

*SONET frame over 155 Mbps. The frame is read from left to right and from top to bottom. OH represents overhead.*

![SONET Frame Diagram](image)
The SONET and SDH standards specify the meaning of the overhead bytes shown in Figure 7.16. Some of these bytes are error detection codes. Some section overhead bytes identify the constituting signals that are multiplexed. The SDH and SONET standards—probably needlessly—differ in the meaning of the overhead bytes, which complicates the interfacing of these two standards.

The 155-Mbps signal that we described is called STS-3, for synchronous transmission signal of level 3. An STS-1 signal at 51.84 Mbps was standardized in the United States but not in Europe. That signal is well suited for transporting the 45-Mbps DS-3 signals that the non-SONET telephone equipment carries.

Different SONET signals are multiplexed by byte interleaving. Thus, four STS-3 signals get combined to form a STS-12 signal. The rate of STS-12 is exactly 4 times that of STS-3, i.e., 622.08 Mbps.

### 7.8 Complement 4: Power Budget in Optical Link

In this section we explain how to calculate the power flow through an optical link. The objective is to find out how long the link can be, given the characteristics of its components. Figure 7.17 shows the link. We specify the power of light that a source produces in watts
or in dBm. By definition, a power of $P_T$ milliwatts corresponds to

$$10 \log_{10} \left( \frac{P_T \text{ mW}}{1 \text{ mW}} \right) \text{ dBm}.$$ 

For instance, a power of $1 \mu W = 10^{-6}$ watt is equal to $-30$ dBm, since $10 \log_{10}(10^{-6}/10^{-2}) = 10 \log_{10}(10^{-3}) = 10 \times (-3) = -30$.

The receiver sensitivity [$P_R$ watts or $P_R$(dBm)] is the power the receiver must receive to detect the bits with a bit error rate equal to $10^{-12}$. Consequently, the propagation along the fiber can reduce the power of the light by a fraction $P_T/P_R$, i.e., by

$$10 \log_{10} \frac{P_T}{P_R} = 10 \log_{10} \frac{P_T}{1 \text{ mW}} - 10 \log_{10} \frac{P_R}{1 \text{ mW}}$$

$$= 10 \log_{10} \frac{P_T}{1 \text{ mW}} - 10 \log_{10} \frac{P_R}{1 \text{ mW}}$$

$$= P_T(\text{dBm}) - P_R(\text{dBm}).$$

This last expression is the attenuation in decibels that is acceptable before the received power falls below the sensitivity of the receiver.

The attenuation in the fiber is $A$ dB/km. Consequently, the maximum length of the fiber, as determined by the attenuation, is

$$L_{\text{att}} = \frac{P_T(\text{dBm}) - P_R(\text{dBm})}{A \text{ dB/km}}.$$ 

In practice we must also take into account the power loss caused by couplers that attach the source and detector to the fiber and by splices that join fiber segments together. These losses are a few hundredth of a decibel per device. Finally, we should keep a safety margin for the loss of sensitivity caused by noise in the preamplifier and the source detector.

Thus, a more accurate determination of the maximum length of the fiber uses the following formula:

$$L_{\text{att}} = \frac{P_T(\text{dBm}) - P_R(\text{dBm}) - 0.05 \times N - 6}{A \text{ dB/km}}. \quad (7.8)$$

In this expression, $N$ is the number of couplers and splices, 0.05 is the loss per coupler or splice, and 6 is the safety margin for noise. The above formula is called the power budget formula for the link.
Once we have determined the maximum length from the attenuation using (7.8), we must take into account the limitations due to the dispersion. These limitations are expressed in (7.2).

We illustrate these calculations on one example: a single-mode fiber at 500 Mbps. The wavelength is 1.55 μm and we use a glass fiber with an attenuation of 0.2 dB/km. The source is a laser diode with a transmitted power of 10 mW and the receiver sensitivity is equal to −50 dBm. We want to calculate the maximum length of the link. To use the power budget formula (7.8) we first convert the transmitted power into dBm: $P_T$ (dBm) = $10 \log_{10}(10 \text{ mW})/(1 \text{ mW}) = 10$ dBm. We need one coupler at the source and one at the detector. The number of splices is the number of fiber segments minus one. The number of fiber segments depends on the total length and on the length of each segment, say 10 km. Assume that we need $K$ segments, i.e., $K + 1$ splices and couplers. We find

$$L_{att} = \frac{10 - (-50) - 0.05(K + 1) - 6}{0.2} \approx 270 - \frac{K}{4} \text{ km.}$$

Next we use the dispersion limit (7.2). For the single-mode fiber we find that $R \times L \leq 200$ Gbps/km. Since $R = 500$ Mbps, we conclude that $L \leq L_{disol} = 400$ km. Thus, the attenuation limits the usable length to about 264 km whereas the dispersion limits the length to 400 km. We conclude that the maximum length of the fiber is 264 km. Using a dispersion-compensated fiber would not increase the usable length at 500 Mbps.

### 7.9 Complement 5: RS-232-C

The connection between a printer and a computer, a computer and a terminal, or a computer and a modem often conforms to the Electronics Industries Association's (EIA) standard RS-232-C (recommended standard 232-C). That standard is commonly known as the serial line interface. A very similar version of this standard is recommended by the ITU under the name V.24. These standards specify the connectors, the assignment of connector contacts (pins) to the various signals, and the sequence of operations involved in a transmission.

The RS-232-C standard is intended for transmission at up to 38,400 bps over short distances (typically less than 15 meters). RS-232-C uses asynchronous baseband transmission (see Section 7.1) with bipolar modulation.

The RS-232-C connectors have 9 or 25 pins. (See Figure 7.18.) A typical connection uses only four to nine connection wires, which are not twisted. The pins are assigned to

**Figure 7.18**

RS-232-C serial line with its connector and the signals.
ground, data signals (send and receive), and to control signals. The main control signals are request to send, clear to send, and some timing signals. The pin assignments depend on the device type: either DTE (data terminal equipment, such as a terminal or a computer) or DCE (data circuit-terminating equipment, such as a modem or a printer).

RS-232-C is suitable only for short connections since a current may flow between the two grounds of the two connected devices. Such a ground current induces a voltage drop which modifies the voltage differential between the signal and the ground wires. If the connection is too long, then the voltage drop may be so large that bits are received incorrectly. In addition, a large loop formed by the signal and the ground wires may be subjected to electromagnetic interference that might also introduce errors in the transmission.

A typical full-duplex transmission from a DTE (a computer, for example) to a DCE (a printer, for example) using RS-232-C proceeds as follows:

- **DTE to DCE**: The DTE sends data on line 2; it can do so when wire 6 (data set ready) indicates a 0 (i.e., a positive value). Thus, the DCE can stop the transmission by the DTE by dropping the voltage value on the DSR line so as to indicate a 1. If line 5 (clear to send) is connected, the DTE can transmit only when it is positive (this is the case for many computers).

- **DCE to DTE**: The DCE sends data on line 3; it can do so when line 20 indicates a 0.
  If line 4 is connected, the DCE can transmit only when it is positive.

Two additional wires are usually used when the DCE is a modem: CD (carrier detect) and RI (ring indication). CD signals that the carrier is present and RI that the modem is being called by a remote device.

One notices a form of *handshaking* between the two devices. Handshaking is the name given to a procedure for agreeing on the terms of an information exchange. In RS-232-C, the handshaking is a coordination between the DCE and the DTE to make sure that the transmission starts only when the destination is ready to receive the data.

Computer devices that communicate using asynchronous transmissions contain an integrated circuit called a UART (*universal asynchronous receiver and transmitter*). When transmitting, the UART frames the information bits between a start bit and a parity bit (if one is used) and it transmits the bits one after the other at the rate specified by a clock. The UART performs the reverse operations when the device receives bits.

### 7.10 Complement 6: ADSL

In this section we examine a recent major development in the transmission technology over existing telephone lines. This development is motivated by the market for high-speed access to the Internet for residential customers and by a possible demand for video-on-demand applications. Business users also demand access to a remote LAN. It is estimated that by 1998 about 50 percent of the U.S. households will have a PC and that 85 percent of them will use a modem.

Asymmetric digital subscriber line (ADSL) is a high-speed digital transmission technology developed for the existing telephone twisted pair lines. ADSL transmits at a rate from 500 kbps to 8 Mbps downstream (from the central office of the telephone operator) and from 64 kbps to 1 Mbps upstream over one pair of copper wires. ADSL can provide
FIGURE 7.19
Frequencies in ADSL signals.

<table>
<thead>
<tr>
<th>0–4 kHz</th>
<th>100 kHz–1 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>POTS</td>
<td>downstream</td>
</tr>
<tr>
<td>25–100 kHz</td>
<td>upstream</td>
</tr>
</tbody>
</table>

standard telephone service ("plain old telephone service," or POTS) concurrently with the data service.

The actual rates that can be achieved depend on the length and quality of the copper line. On a clean line it is possible to transmit at 2 Mbps over 5.5 km if the diameter of the wire is 0.5 mm and over 4.6 km if it is 0.4 mm. The higher rate of 6 Mbps is possible only over 3 to 4 km. The frequency ranges of the different services are sketched in Figure 7.19.

Two competing modulation techniques have been developed for ADSL: carrierless amplitude/phase modulation (CAP) and discrete multitone (DMT). CAP is a form of QAM. DMT divides the spectrum into 4-kHz bands and transmits independently in the different bands. DMT allocates power to the different channels depending on the noise power and transmission loss in each band. Each channel sends QAM pulses that can represent up to 11 bits of data while the poorer channels carry fewer bits and can even be shut down entirely. This method enables DMT to avoid noisy parts of the spectrum.

ADSL uses error correction codes. Most existing implementations use Reed-Solomon and trellis codes (see Chapter 6). These codes are effective at correcting bursts of errors that last as long as 500 μs. Such bursts are commonly caused by electrical appliances.

ADSL is not compatible with the current digital subscriber line technologies that multiplex telephone signals to a remote electronics box which demultiplexes them for the local users.

A few network-level models are being studied for ADSL services. One model runs ATM over ADSL between the central office and the subscriber. In this model, the central office uses an ATM/IP gateway. Another model uses Ethernet on the subscriber line and an Ethernet switch attached to the IP router in the central office. The ATM model may offer more flexibility for integrating various quality of services such as constant bit rate for video applications and bursty IP traffic.

A large number of companies manufacture ADSL equipment, and field trials took place in 1997. Some telephone companies have announced plans for large scale deployments. Providing ADSL service on a large scale requires deploying a high-throughput data network to serve the subscribers.

Summary

The objective of this chapter is to explain the digital transmission of information.

- Information is transmitted as electromagnetic waves whose propagation is described by Maxwell’s equations. Guided propagation is subject to dispersion, attenuation, and noise, which limit the rate and distance of a transmission line.