# TELECOMMUNICATIONS FOR MANAGEMENT

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## CHAPTER 4

# TRANSMISSION SYSTEMS

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## 4.1 INTRODUCTION

When Agamemnon returned victorious from the Trojan War with his mistress Cassandra in tow, large mountaintop fires transmitted the news from Troy to Mycenae. This warning gave his queen, Clytemnestra, and her lover time to plot his murder. And in 490 B.C. an unknown courier ran the 26.4 miles from Marathon to Athens to signal the Athenians' victory over the Persians, thereby delivering a message and creating a media event. Somewhat more recently, the lantern lights on the Old North Church signaled to Paul Revere that the British were coming, and off he rode to warn the Minutemen.

By the 1800s, the Russians had extended semaphore telegraphy—then consisting of blades arranged on mountaintops—1200 miles, from Leningrad to the Prussian frontier. Each arrangement of the blades was confirmed for accuracy and sent back by the next station to avoid signaling errors, a very slow process. A Parisian, Charles Havas, gained considerable advantage over his journalistic competitors by using homing pigeons to deliver news from London in 7 hours. Although the homing pigeons in today's *Andy Capp* cartoon reflect his laziness, they've been most efficiently used to transmit battlefield information since the Roman era and helped Havas start the forerunner of the worldwide French press agency, Agence France Presse.

The legendary pony express was able to deliver information from St. Joseph's, Missouri, to San Francisco in 8 days if the riders escaped the Indians.

This exciting adventure in transmission by human and pony lasted only 19 months, until October 1861, when the Pacific Telegraph Company completed *its* transmission route. This is probably one of our earliest examples of the productivity of electrical communications technology; both riders and ponies were laid off!

Transmission systems have been with us throughout history. Indeed, there is no "history" before the ability to transmit knowledge of the past. These systems all have their own advantages and disadvantages, uses, and symbolic import; McLuhan's dictum that the medium is the message holds for both old and new transmission systems. Receiving a telegram nowadays in the United States has more emotional impact than receiving a telephone call. In some places in Europe, the reverse is true.

The purpose of this chapter is to discuss transmission systems. But we will emphasize electromagnetic, typically point-to-point, and instantaneous communications. Thus, we will not consider mass media such as books and newspapers or radio and television in the popular sense. It is often difficult to separate the "system" from the media used because in modern transmissions the arriving content often travels through many channels and at many rates, which can differ each time the message is transmitted and retransmitted.

First we will consider several of the basic terms of transmission that were introduced in Chapter 2, including noise, bandwidth, frequency, and analog and digital transmission. This discussion is followed by an explanation of modulation and multiplexing techniques for both digital and analog transmission. After an overview of networks and switching techniques, we will briefly introduce the major transmission systems. Finally, we will compare various attributes of these systems.

## 4.2 BASIC TRANSMISSION FACTORS

### 4.2.1 Noise

The time required for any electrical operation such as turning a current on or off is proportional to certain physical characteristics of the cable or wire. When a voltage is impressed on the wire at one end, it does not immediately appear at the other; it increases from 0 to the maximum value as the capacity of the wire or cable is charged up.

If the voltage at the transmitting end is impressed and taken away in too short a time, a very small or hardly noticeable voltage change will appear at the receiver. The signal may not be *detectable.* No signal is detected unless it is larger than a certain *threshold.* The threshold is determined both by the sensitivity of the receiving apparatus and by the magnitude of the spurious fluctuations—*noise* —which always occur on any communications channel. If it is less than the noise at the receiving end, the signal will pass undetected. Many of the major developments in communications technology over the past 30 years, including the satellite and the microprocessor, have focused on how to insure that the information sent is accurately received and, of course, economically transmitted.

One way to reduce the cost of transmission is to increase the speed of transmission. But two factors limit the speed of communications:

**1** There is always noise in the communication channel. The received signal must be a certain degree larger than the spurious fluctuations owing to noise. Noise is caused by *distortion* (in the transmission system), *interference* (from extraneous but similar signals), and *random fluctuations.*

**2** The received signal is always *attenuated;* that is, the received signal is always less than the transmitted signal. If the signal is attenuated too much it will not be detected through the noise.

A quantity which has been found to be very useful is a function of the logarithm of the signal power $S$ divided by the noise power $N$. This quantity is usually measured in decibels as

$$\text{Signal-to-noise ratio} = 10 \log_{10} S/N$$

A signal-to-noise ratio of 10 dB means that the signal power is 10 times the noise power. A signal-to-noise ratio of 20 dB means that the signal power is 100 times the noise power. A ratio of −3 dB means that the signal power is half the noise power.

### 4.2.2 Bandwidth and Frequency

Bandwidth is an extremely important characteristic of a signal because the cost of its transmission is fundamentally dependent on its bandwidth. Generally speaking, higher bandwidth signals cost more to transmit. More information sent in a shorter time period requires greater bandwidth. Thus, both bandwidth and the signal-to-noise ratio constrain the system's information rate, or *capacity.* Frequency, and thus bandwidth, are measured in cycles (of the sine wave) per second, called Hertz, as discussed in Chapter 2.

*Frequency* is the number of cycles that an electromagnetic wave makes per second. The wave can be thought of as a sinusoidal wave, that is, a wave that goes from a peak to a valley and back to the peak in one cycle. The sinusoidal waveform is the waveform that a pendulum makes as it swings from side to side. It is nature's favorite motion.

*Amplitude* is the height of the cycle at the top of the waveform. It is a measure of the strength of the electrical signal.

Most telecommunications signals, such as voice or television or data, are made up of many waves of different frequencies. The difference between the highest of these frequencies and the lowest of these frequencies is the *bandwidth* of the signal. A signal may have a natural range or bandwidth; the transmission medium may allow only some of this bandwidth; or regulations may allow only portions of a natural bandwidth to be transmitted.

So,. frequency equals the number of cycles per unit time, or $F = N/T$.

Conversely, $T = N/F$. Relationships between frequency, time, bandwidth and amplitude for three transmission conditions are shown in Figure 4.1.

Table 4.1 shows the bandwidths for some common signals.

**FIGURE 4.1**
Relationships among frequency, cycles, amplitude, and time.

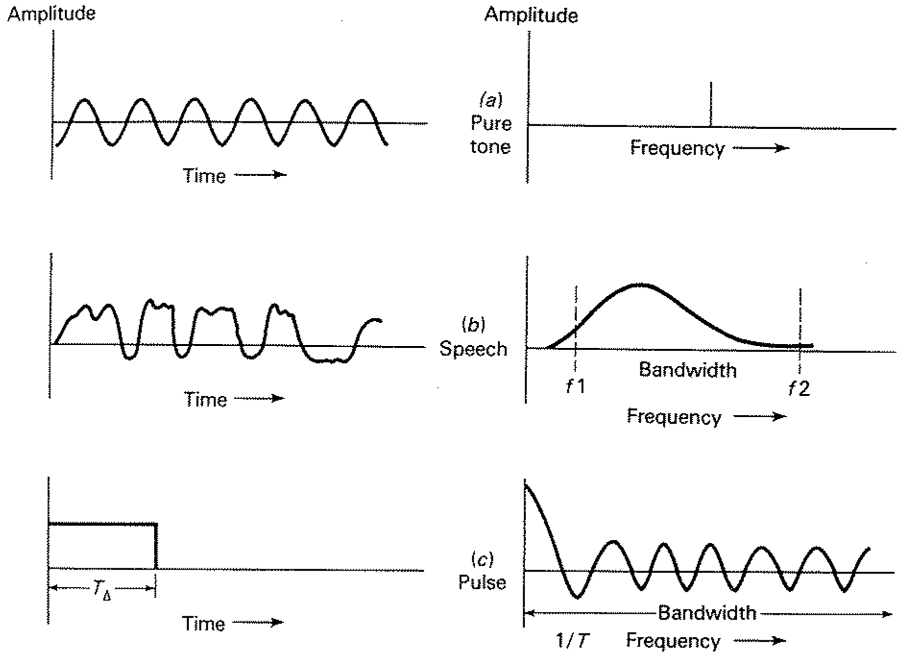


**TABLE 4.1**
BANDWIDTHS OF SOME COMMON SIGNALS

| Signal | Bandwidth* |
|---|---|
| Telegraphy | 40 Hz |
| Speech | 4000 Hz, or 4 KHz |
| Hi-fi music | 20,000 KHz |
| Color television | 6 million Hz, or 6 MHz |
| Satellite (recent) | 500 million Hz, or 0.5 GHz |

*1000 hertz = 1 kilohertz; 1 million hertz = 1 megahertz; 1 billion hertz = 1 giga hertz.

Most signals contain significant components at only a small range of frequencies, but theoretically any signal with a definite beginning, that is, a sharp start, and a definite end has some component frequencies up to infinity and most of these frequencies have very small amplitudes, that is, very small power. This means, of course, that pulses such as those in a telegraph signal have numerous frequency components, and although the telegraph signal may look like a dot or a dash, a bandwidth of 40 Hz is required for accurate telegraph transmission.

From Figure 4.1(*c*) we can see that a pulse of length $T$ has significant frequencies up to $1/T$. Thus if the pulse is shorter, that is, $T$ is very small, a *larger* bandwidth will be required to transmit that pulse. But because bandwidth is expensive we often send signals through *filters*, which pass only a specific band of frequencies. We do that on the telephone so that the human voice, which has an enormous range of frequencies, is passed through a filter, which only allows a range of about 30 to 3400 Hz. This has been found to be quite sufficient for voice recognition and understanding. But in many countries where the telephone system bandwidth is not quite that large, it is often difficult to understand, let alone recognize, a voice by the sound alone.

A different use of the term "bandwidth" concerns the form of human communication transmitted. Print (including electronic messaging) can transmit only *linguistic* or semantic information; audio can also transmit *paralinguistic* cues such as laughter or loudness; video can further communicate *kinesic* information such as body posture and fleeting nonverbal signs; while interpersonal interaction also communicates *proxemics* such as physical closeness. These dimensions of human communication require greater bandwidth than simple transmission of text or voice alone.

### 4.2.3 Analog and Digital Transmission

Electrical signals are created for the purpose of sending information. *Analog* signals are signals that are "analogous" to the information; that is, they reflect the characteristics of the information to be transmitted. Thus, when you speak into the telephone, the carbon microphone vibrates as your voice vibrates and creates a signal that is analogous to your voice. The telephone typically uses analog transmission.

For a variety of reasons it is useful to digitize the signal or break it up into many pieces by sampling the original signal. The number of pieces depends on the frequency of the signal, acceptable error rate, and other factors, described below. *Digital* signals are transmitted in this manner. In modern telecommunications systems using digital transmission, each sampled signal is assigned a binary number (0 or 1).

## 4.3 MODULATION AND MULTIPLEXING

### 4.3.1 Transmitting Discrete Signals

When you broadcast a signal from one place to another there is a transmitting antenna in which a signal originates, and at a distance there is a receiving antenna or wire in which a signal is produced, similar to but weaker than in the originating wire. To transmit a telegraph signal over the air we need to produce a changing signal in our first wire; we do this with an underlying signal, or *carrier*. The carrier is in the form of sinusoidal signal and it can be made to transmit Morse code simply by turning it on and off, as shown in Figure 4.2*c*.

Let us now see how we send a telegraph signal (4.2*a*) over the air. Following the digital terminology of binary notation, we label the dash 1 and the dot 0. We know that the transmitted signal will be somewhat distorted even before it gets into the transmission system; it must pass through some wires and other devices before it combines with the carrier. So in Figure 4.2*b* we see the familiar shape of a signal that has been distorted by certain losses. In Figure 4.2*c* we see what happens when our signal is combined with or superimposed on the underlying carrier; this is called *modulation* and is the process of impressing information on the carrier in a form suited to its distribution channel. *Demodulation* is the process that recovers the original signal from the transformed one for delivery to the receiver.

Modulation is designed to match the signal transmitted to channel attributes. This matching may involve (1) matching the signal wavelength to the antenna; (2) reducing noise and interference, sometimes at the cost of larger bandwidth; (3) assigning frequencies unique to the source; or (4) overcoming limitations in the equipment by putting the signal in a more tractable frequency (Thoma, 1981).

The carrier is mediated by turning it on and off. This modulation technique is called on-off keying (OOK). We are changing the amplitude of the carrier from 1 to 0; thus on-off keying is a form of *amplitude modulation*. It is the AM on your radio and is an important way of transmitting voice.

Now assume that there is some noise on the transmission line. In Figure 4.2*e* we show what happens when the now noisy signal is *demodulated*, or separated from the carrier; that is, "decoded" from the previously "encoded" signal resulting from the modulation process. This is done by a process of *filtering*. Figure 4.2*f* shows what the receiver sends on to the instrument the recipient will be using to read the message sent. This device is known as a *detector* because it is able to pick out the 1s and 0s from the filtered (but as-yet-not-ready) message for the recipient. Note that in Figure 4.2*f* the presence of noise leads to errors. One of the transmitted 0s—the second bit—is received as a 1!

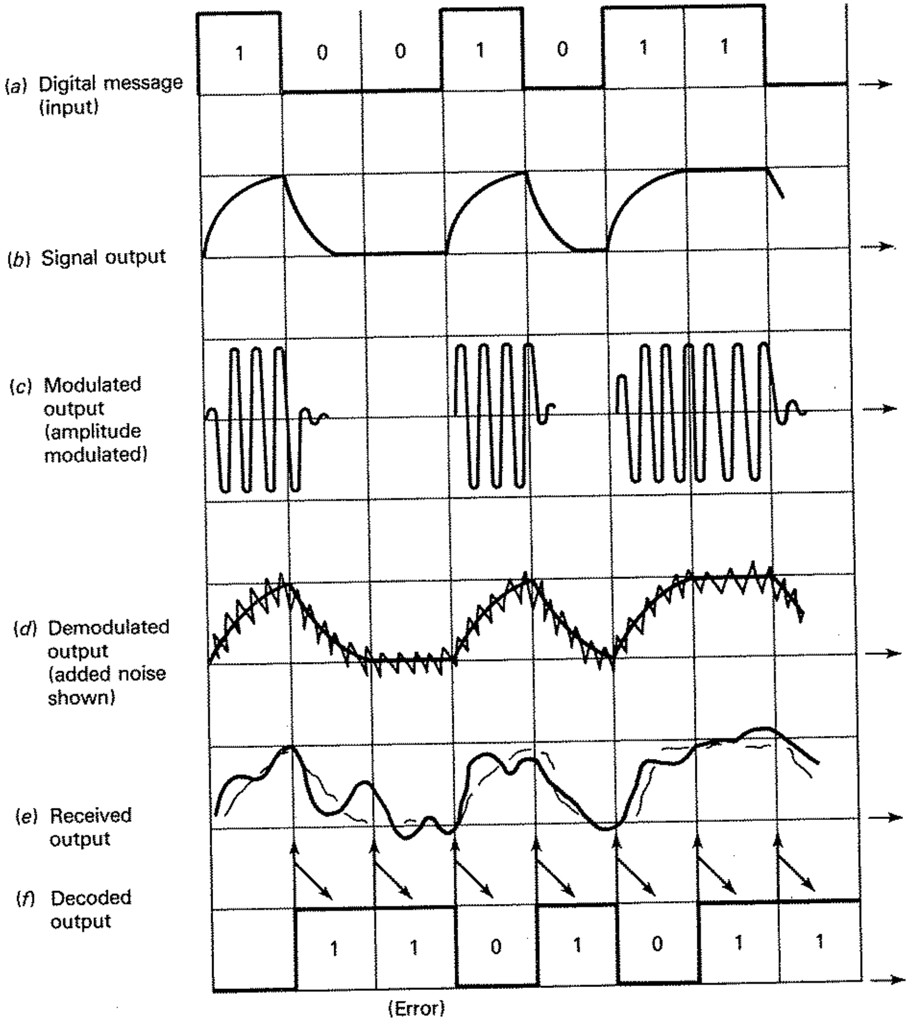


**FIGURE 4.2**
Noise and signal transmission.

Another method of sending pulses is to vary the frequency of the underlying signal or carrier as shown in Figure 4.3. The lower frequency would represent a 0, and the higher frequency a 1. This kind of modulation is referred to as

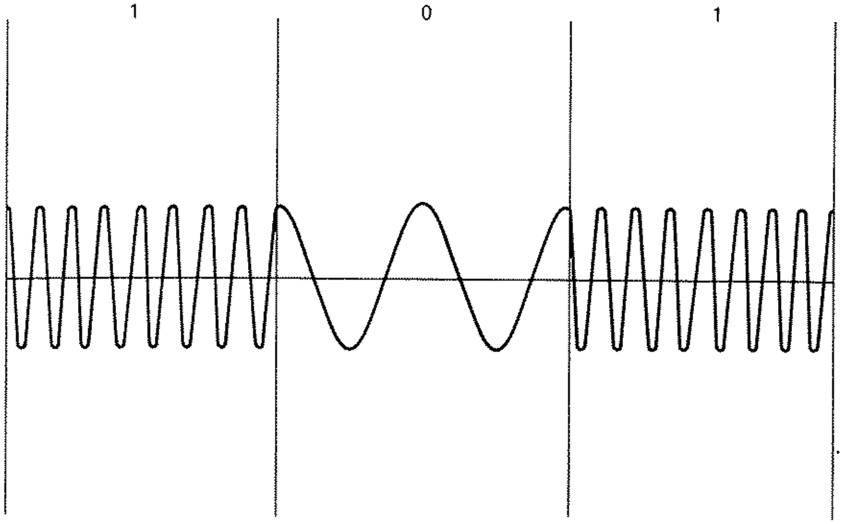


**FIGURE 4.3**
Frequency-shift keying.

*frequency-shift keying* (FSK). It is a form of frequency modulation, which is the basis of high fidelity music systems. Frequency-modulated (FM) signals are less sensitive to noise than are amplitude-modulated signals. Thus, the probability of an error is less, and consequently they are often used for data communications. But FM systems are more complicated to build and somewhat more expensive. The ability to send data via a digital signal over the telephone, which is not a digital system, is made possible through FSK.

There is a third technique for indicating a 1 or 0, involving changing the *phase* of the carrier signal, rather than its amplitude or frequency. Put simply, this involves altering the time when the signal starts moving. Note that in Figure 4.3 the 1 and 0 signals begin at the same point in the same shape of the carrier, at the top of the curve. But if we begin the 0 at the bottom of the curve and the 1 at the top, the signal is shifted to the right for the 0 and effectively to the left for the 1, as in Figure 4.4. *Phase-shift keying* (PSK) is even more immune to noise than is FSK but requires more complex equipment and is more expensive.

### 4.3.2 Transmitting Continuous (Analog) Signals

**Modulation** Up to now we have been discussing systems for sending a discrete number of signals. What about sending more complicated signals, such as voice or television?

When we speak or sing our vocal tract produces sound waves. These waves are very complex, unlike the single frequency of a tuning fork. We can "compose" this very complicated voice signal by adding up a number of simple standard signals, our familiar sine waves as described in Chapter 2 and shown in Figure 4.1*a*. The representation of a signal in terms of amplitudes, frequencies, and phases of its sinusoidal components is called *frequency-domain representation*. The sinusoidal signals in the sum all have different frequencies, and the range of values of frequencies (that is, the difference between the highest and the lowest frequencies) is, as we've discussed, called the *bandwidth* of the signal. Figure 4.5 shows how a voice signal is really made up of a number of component signals ($F_n$ through $F_{n\text{-}6}$) and thus requires bandwidth in the amount of $F_n - F_{n\text{-}6}$.

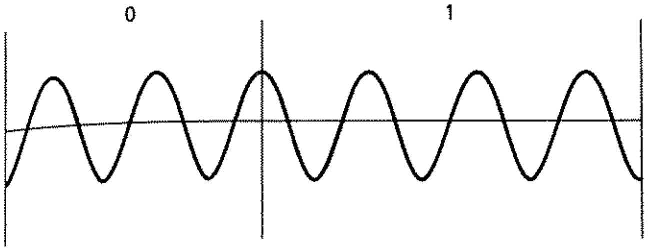
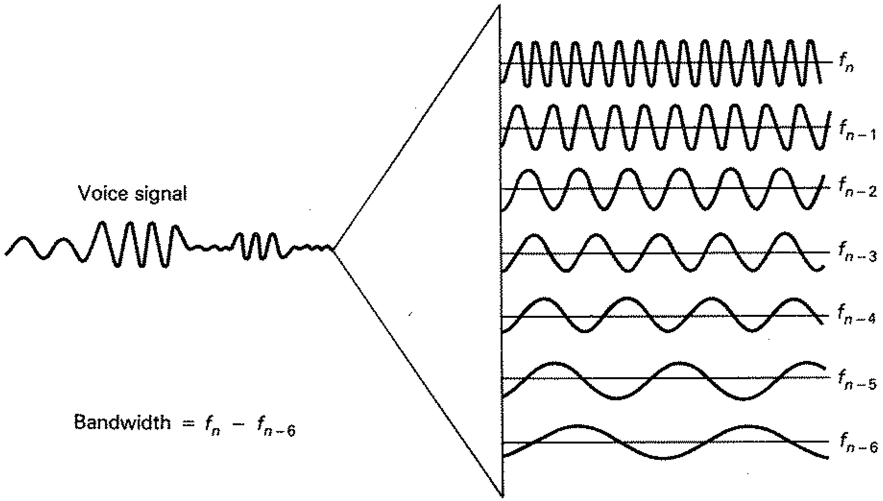


**FIGURE 4.4**
Phase shift keying.

Different communication channels transmit signals best at different frequencies. If we take the voice pressure of two people speaking to each other, transform it with a telephone microphone, and try to send it through the air, we would find it extremely difficult. For one, we would need very large devices (antennas) and an enormous amount of power. We have to somehow alter the

**FIGURE 4.5**
Bandwidth and frequency components of a voice signal.



"air," if you will, and make it more amenable for the transmission of speech, or frequencies in the neighborhood of 30 Hz to 3400 Hz, an alteration we have already defined as *modulation*.

Earlier, in Figure 4.2*c*, we showed the process by which a digital signal is transformed by modulation and recovered by means of demodulation. Now we consider modulation in terms of analog rather than digital signals.

Figure 4.6 shows how the signal modulates the higher-frequency carrier, resulting in a modulated carrier. This is really a curious way of putting it. It would seem that the signal is modulated by the carrier, hence we say, the modulated signal. In effect, it makes little difference because what is transmitted is a modulated signal where the original signal is in the *amplitude envelope* of the modulated carrier, as shown in Figure 4.6*c*.

Now if we shift to the frequency domain (Figure 4.7), amplitude modulation corresponds to *shifting* the frequency of the signal. Note that the effect of multiplying the carrier amplitude by the signal, which is what we do when we modulate a carrier with a signal, or a signal with a carrier, is to produce a new signal with frequency components above and below the carrier.

The frequencies above and below the carrier, as shown on either side of the carrier in Figure 4.7*c*, are called the *sidebands*. In recent years engineers have learned how to use these sidebands to transmit two different signals, thereby making more efficient use of valuable bandwidth or spectrum. For example, agricultural and weather teletext information could be transmitted to rural farmers via the sideband of the local National Oceanic and Atmospheric Administration stations (Rice & Paisley, 1982).

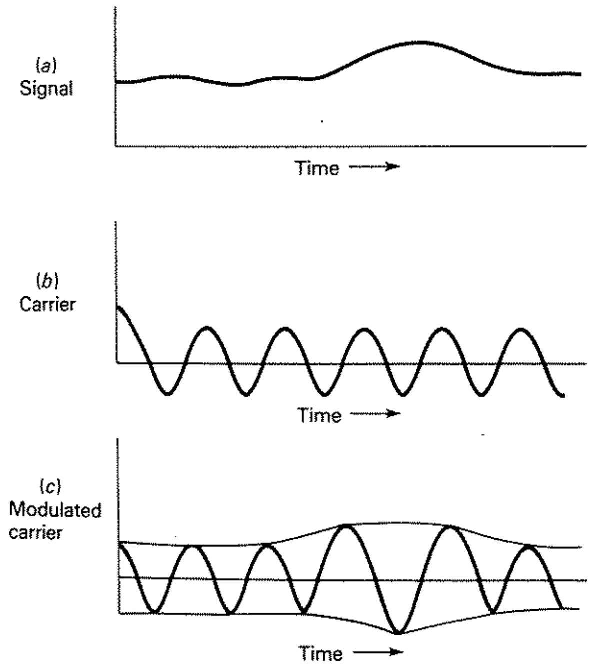


**FIGURE 4.6**
Amplitude modulation and amplitude envelope (in time domain).

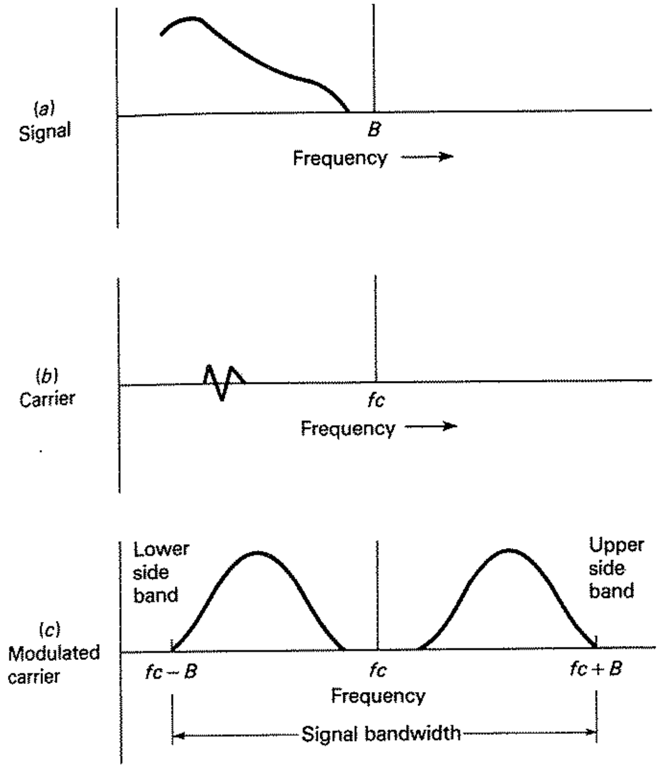


**FIGURE 4.7**
Amplitude modulation and frequency sidebands (in frequency domain).

The bandwidth of the resultant FM signal is more difficult to calculate than that for the AM signal. In the latter, distance between the sidebands and bandwidth can be conserved by using only one of the sidebands without losing the information in the signal. But in the case of frequency modulation, bandwidth depends on how much we choose to vary the frequency as the amplitude of the signal changes. In FM radio, stations generally choose to occupy about 150 Hz of bandwidth around their assigned frequency.

In frequency modulation the carrier *frequency* is varied with changes in the amplitude of the signal. In Figure 4.8*a* the modulating signal is a triangular one, called by engineers, for obvious reasons, a sawtooth wave. We must first produce an amplitude-modulated carrier, as shown in Figure 4.8*b*, and use it to create a frequency-modulated carrier, as in Figure 4.8*c*.

How do we choose between AM and FM? What are the benefits and drawbacks of each? Here are some general rules of thumb:

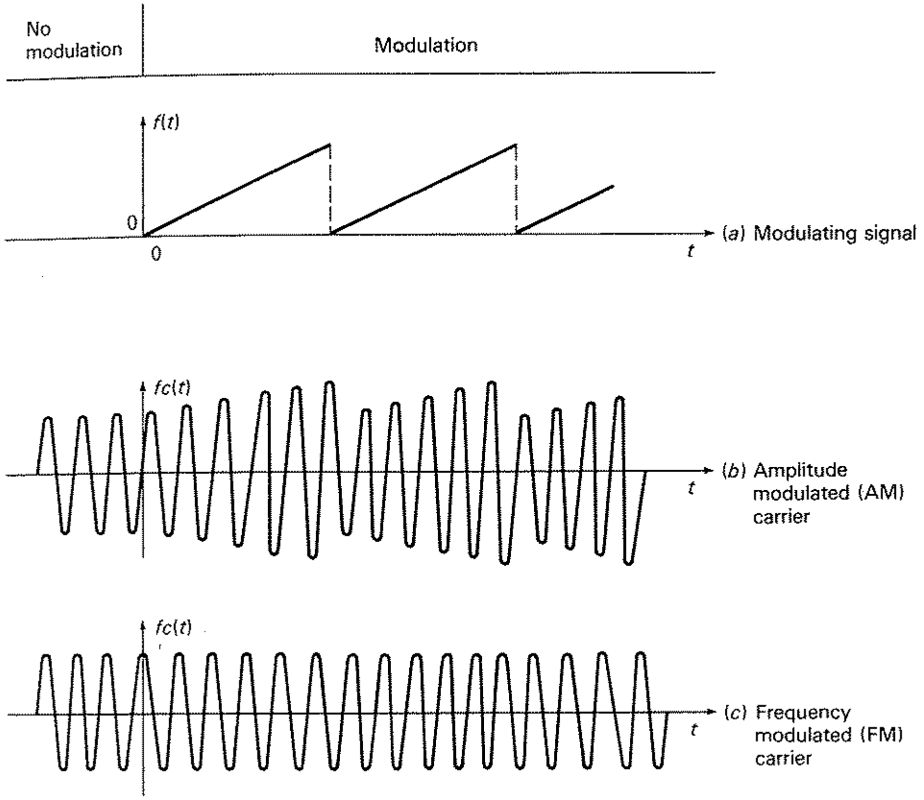


**FIGURE 4.8**
Amplitude and frequency modulation of signal.

- In FM the bandwidth can be increased and the signal-to-noise ratio improved without increasing signal power.
- In AM the signal-to-noise ratio can only be increased by sending a more powerful signal.
- FM receivers are somewhat more complicated than AM receivers and, consequently, more costly.
- AM transmitters are more difficult to build than higher-frequency FM transmitters.

So take your pick of benefits and costs. With the continuing reduction in the cost of electronic components, the difference in price between FM and AM receivers has become quite small, but the cost of transmission has continued to rise. Yet if a great many signals can be packed into a channel the transmission cost per signal could be low. This might favor AM, but at a cost of power.

**Multiplexing** Several times we have mentioned the possibility of sending more than one signal on a channel at the same time. This can be done by shifting the frequency of the signal, thereby giving each signal a different part of the channel space, or spectrum. The process of putting several signals on one channel is called *multiplexing*.

Each signal can be recovered by *demultiplexing*, which separates the various signals so that we can demodulate the signal we are after. Separating these signals is done by filtering, a process that removes the unwanted signals and leaves us with the signal, the only signal, we wish to receive. This is exactly what happens when we tune our radio or TV set. We select one of the several frequencies that are available or broadcast, by means of the demultiplexing, demodulating, and filtering processes.

If it were not possible to multiplex, our telephone systems would require an enormous number of wires, which, given the present cost of copper, would be extremely expensive. Even with extensive switching systems, we would still require a large number of wires, one for each potential simultaneous conversation between two points.

This multiplexing of signals allows for fewer wires between major population centers. Indeed, because variations in population density make telephone traffic density very different in different parts of the country it is uneconomical to provide a facility for, say, 600 channels with only 10 to 20 channels in use. But a single 600-channel system costs less than fifty 12-channel systems, owing to savings in the number of transmission lines and amplifiers. Thus, there is a need for a number of transmission systems, each optimized for a particular channel capacity. This is made possible by the technique of multiplexing. But as we increase the number of signals, we use up more and more of our precious bandwidth.

There are other ways to multiplex signals that are now becoming very popular primarily because the semiconductor chip has made equipment available that can rapidly *sample* analog signals, thereby turning them into candidates for digital transmission without seriously destroying the accuracy of the message being communicated.

**Sampling** We have seen how we can modulate the amplitude of a sinusoidal carrier with a signal in order to transmit it more easily. And we have seen how we can recover the original signal. We can also modulate the amplitude of *pulses*. This ability to use pulses to describe a wave form is at the heart of modern data communications. In Figure 4.9 we can see that the input signal is pretty well reflected in the modulated signal, yet there are spaces between the pulses. What if we could fill the spaces with other pulses that represent other analog signals? Wouldn't that allow us to send many different signals on the same channel?

To do so and still maintain the accuracy of the original signal at the receiving

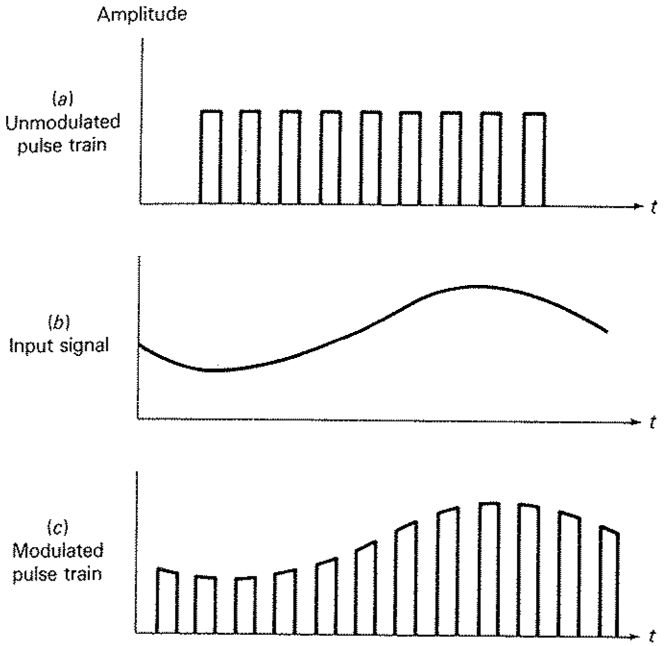


**FIGURE 4.9**
Pulse amplitude modulation.

end has three important requirements. First, we must determine the sampling rate, that is, the number of pulses per second we need in order to represent the signal accurately. Second, we must have the equipment that can perform this sampling rapidly and accurately. And third, we must have the facilities to recapture the original signal from the pulses accurately and, of course, in the analog form we need in order to interpret the message.

So we have turned this discussion around—from how the amplitude of pulses can be modulated to how an analog signal can be sampled for other types of modulation.

**Pulse-Amplitude Modulation** Figure 4.10 shows what happens when we transmit an analog signal at different sampling rates. If we sample at a very low rate it is clear that the original signal will not likely be reproduced; or it may be reproduced in some very imaginative but inaccurate ways. Remember, the signal is not a straight line that can be determined or defined by just two points. We can increase the sampling rate by 50 percent by the adding of another point on the curve or another sample. It is more likely that the original signal will be recognizable, but there still is a great deal of room for imagination. Finally we can greatly increase the sampling rate—say, by a factor of 100. The original signal is then very clearly and quite accurately reproduced. However, sampling at an extremely high rate adds little to the quality of the signal. And with sampling at a very low rate we risk missing some of the variations in the signal. The key requirement is that the sampling rate, or pulse rate, be at least *twice* the highest frequency of the signal itself. For a TV signal of 6 MHz we must sample at a rate of at least 12 MHz.

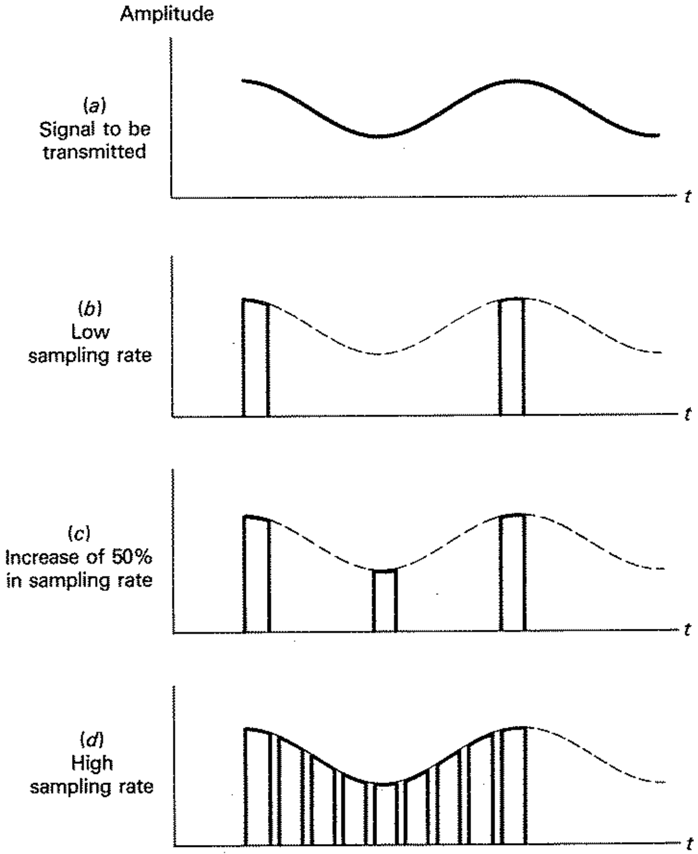


**FIGURE 4.10**
Sampling for pulse amplitude modulation.

Once we have the train of pulses that represent the transmitted signal, we can use this train to modulate a carrier, which will transmit the signal. This form of modulation is very similar to amplitude modulation, except that we are modulating a train of pulses rather than a sinusoid; it is called *pulse-amplitude modulation* (PAM).

**Time-Division Multiplexing** As we noted previously, there are spaces between the pulses in our pulse-amplitude train. These unused spaces in time can be used to send samples of another signal or, for that matter, many signals.

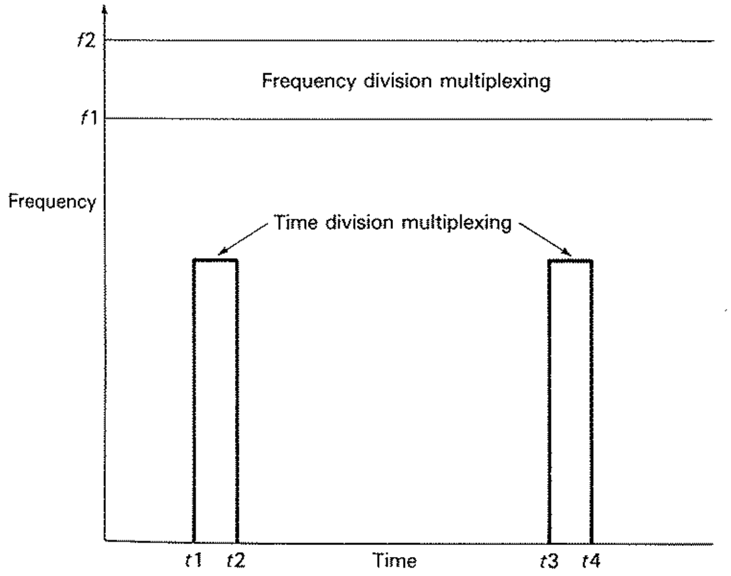
Multiplexing signals in this way is called *time-division multiplexing* (TDM). *Time-division multiplexing* and *frequency-division multiplexing* are two fundamentally different ways to divide up the capacity of a channel among several messages or conversations. The latter essentially divides up a fixed narrow bandwidth continuously, while the former allocates a wider bandwidth for short periods of time. In Figure 4.11 we represent these ways of using time.

Remember that the bandwidth necessary to send a pulse-amplitude-modulated (PAM) signal depends on the width of the pulse. For a pulse of width $T$, the bandwidth is proportional to $1/T$. In order to use TDM on many signals, if we use very short pulses we must use larger bandwidths.

PAM systems are relatively simple and have become very attractive for many data transmission situations as well as for sending multiple voice signals along a single channel. PAM systems are not to be confused with digital systems; they are not completely digital, since the amplitudes of the pulses transmitted vary continously with the original analog signal variations. Very often the PAM signals are further digitized before transmission. The digital signals are encoded into any equivalent form desired.

**Quantization** The process of digitizing the original PAM signals is called *quantization.* It consists of breaking the amplitudes of the PAM signals up into a prescribed number of discrete amplitude levels. Unlike the sampling process that produced the PAM signal, this results in an irretrievable (but usually inconsequential) loss of information distinguishing fine amplitude variations, since it is impossible to reconstitute the original analog signal from its quantized version.

**FIGURE 4.11**
Time and frequency division multiplexing.



The demodulated signal will differ from the derived signal and the overall effect will appear as noise. In the case of sound transmission this manifests itself as background crackle. In the case of picture transmission the continuous gradation of grays from black to white is replaced by a discrete number of grays and the picture will also look a bit noisy. This *quantization noise* can be reduced by increasing the sampling rate or by increasing the number of levels $M$ used. Experiments have shown that 8 to 16 levels appear to be sufficient for good intelligibility of speech.

One form of TDM is pulse-code modulation.

**Pulse-Code Modulation** If we transmit these quantized signal samples as pulses of varying heights, we would merely have PAM, or quantized PAM. But with discrete or numbered voltage levels each level can be coded in some arbitrary way before transmission. The ability to code these signals once they are in some quantized form allows for very highly efficient use of transmission bandwidth. This method of signal modulation is called *pulse-code modulation* (PCM).

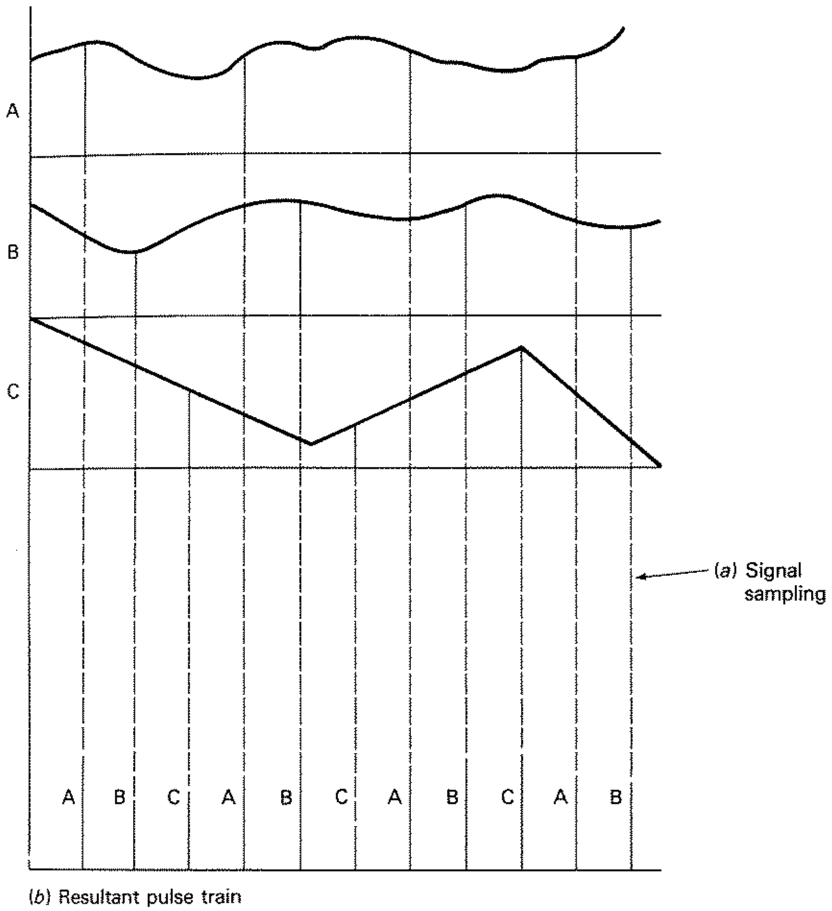
Coding is important in data transmission for at least one significant reason; it provides the best way we know of overcoming the problem of noise. All a receiver has to do when it is listening for a binary-coded signal is to recognize the presence or absence of a pulse. The shape of the pulse is not important, just its presence or absence! Indeed, the exact amplitude is unimportant. By transmitting binary pulses of high enough amplitude we can ensure correct detection of the pulse in the presence of noise with as low an error rate as required.

Pulse-coded modulation has another benefit over other forms of modulation. As a signal is transmitted through some channel the signal becomes weaker, while noise tends to increase; the signal-to-noise ratio gets worse and worse. But with PCM transmission it is possible to place very simple devices known as pulse-regenerator circuits at intervals along the line spaces close enough to insure that the signal-to-noise ratio is fairly high at each circuit. The circuit must only determine whether a pulse is present and then regenerate a perfect pulse or, if there is no pulse present, regenerate no signal at all. The signal-to-noise ratio does not change between transmission and reception, a most important feature of PCM transmission.

An example of PCM is shown in Figure 4.12, using three different messages. We sample each of these message signals at different times and then put all of these pulses together in a string, or train. If each of these signals is of a different bandwidth, sampling will have to be at the rate determined by the signal with the *largest* bandwidth.

## 4.4 NETWORKS AND SWITCHING

In this section we concentrate primarily on transmission concepts and systems, leaving the bulk of the discussion concerning switching to Chapter 5. We shall,



(b) Resultant pulse train

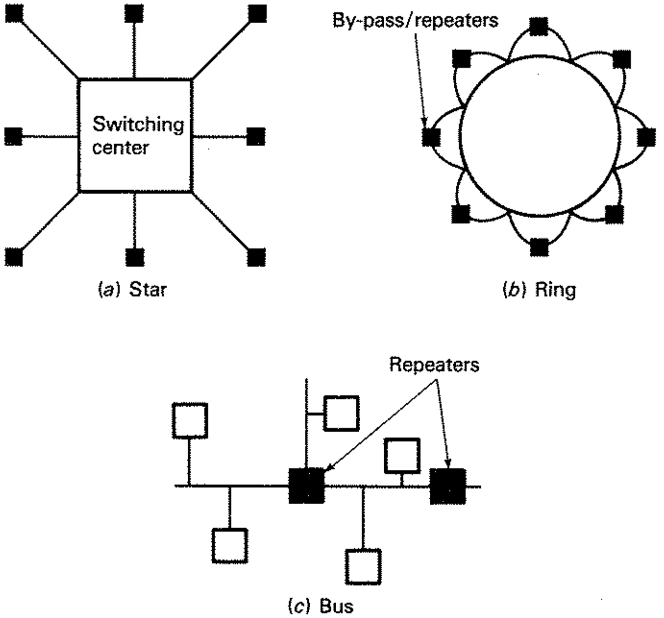
**FIGURE 4.12**
Pulse code modulation.

however, conclude this section with a brief discussion of some basic switching concepts that bear directly on the transmission of signals.

### 4.4.1 Networks

Establishing system performance at a given cost is constrained by the desired error rate (or subjective reception quality), bandwidth, transmission speed, and network configuration (Thoma, 1981). Network "architectures" are, in one sense, designed to accommodate different levels of system usage. For example, the telephone system was initially designed for voice conversations, which involve infrequent node usage and gaps in actual transmission through a physical circuit for the duration of the call. This requires a bandwidth of only 3 KHz or so, insufficient by itself for efficient data transmission. Packet-switched networks, designed specifically for high-speed data transmission, provide efficient, reliable routing among dispersed nodes, not by an assigned physical circuit. A variety of network topologies have developed over time to connect nodes (people, locations, etc.) in appropriate ways. Conceptually, the simplest network topology would be to provide a switch for all possible nodes (a "point-to-point" network). For $n$ nodes, this means $n(n-1)$ switches, or 90 switches for 10 people. Figure 4.13 shows various network configurations. A centrally switched network (a star) dramatically reduces the number of switches and the amount of linkage but requires a highly reliable and complex switch. A ring structure simply connects all nodes in a circle, which reduces errors but requires some sort of bypass at each node to lessen the ring's vulnerability to failure. A bus topology is less vulnerable to failure, since repeaters are not required at each node, as in the ring, and the bus is easily reconfigurable. But errors can be mistaken as message collisions in applications such as local area networks. The arrangement of equipment on the network is the *architecture* of the network. In practice, several of these networks are connected together to form the communication system. You might want the information to flow in a specific order, from one level to another. This system of providing levels of networks is the network *hierarchy;* it is a concept, a way of structuring the architecture.

**FIGURE 4.13**
Network configurations.



(a) Star

(b) Ring

(c) Bus

### 4.4.2 The Public-Switched Network

The nation's telephone network is a public-switched network. Because it evolved over many years and through the development of many transmission technologies it provides an excellent opportunity to examine and compare the many modes of transmission now available for the delivery of information electronically. The network consists of three major transmission systems. A fourth is now emerging and cannot yet be considered a full member of the network, but over the next decade or so it may become a full-fledged member of the public-switched network. These four systems are discussed below.

**The Local-Loop Transmission System** The local-loop transmission system is the network that connects the household through the telephone headset into the local exchanges and from there to the long-distance system of transmission. Until now the major mode of transmission has been the twisted pair—telephone lines—but in recent years cable television systems have been claiming that they can also provide local-loop services. Several experimental projects have, indeed, shown that with special care and at somewhat higher cost than is required for the one-way video transmission for which cable television has been designed, it is possible to provide local-loop transmission for voice and data through the cable system. We shall discuss cable as a transmission medium in the next section.

Another candidate for local-loop services is radio, especially in the form of cellular radio. We shall also discuss this transmission medium in the next section.

**Line-Haul Transmission System** Line-haul long-distance, or *trunk*, circuits refer to the transmission paths needed to carry a subscriber-to-subscriber connection between local exchanges to which all subscribers are connected by local loops.

Over long distances signals are attenuated and distorted as we saw in Section 4.2 above. At some point along the long line the signal could fall dangerously near the noise in the system and be lost entirely (Figure 4.14*a*). If we increase or amplify the signal at points along the line, we will increase the power of both the signal and the noise (Figure 4.14*b*). If we choose the right time to do this, the signal will always be greater than the noise.

Figure 4.14 shows what happens to analog signals; the repeaters are amplifiers like those in your high fidelity and radio systems. But with the advent of digital systems we cannot use amplifiers; instead we use *regenerators*.

The principle of a regenerator is quite simple; since a digitized voice signal has only two levels, unlike the analog signal which can have an infinite number of levels, the digital signal can be 1 or 0 only. These signals can easily be detected. As soon as the regenerator knows that a 1 (a signal) has come down the line, no matter how weak the signal, it immediately pops forth with another one. Since noise is quite different from the well-formed 1s and 0s, the regenerator simply avoids the noise, which is effectively suppressed in the retransmission. Regenerators are usually spaced close enough to insure reliable detection, at about one mile apart for a 24- or 30-channel line-haul—trunk or long-line—system.

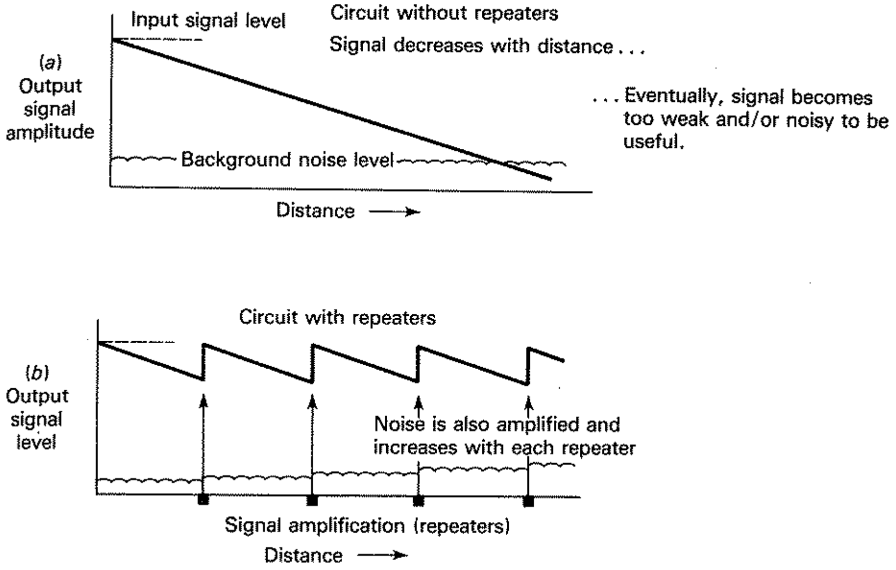
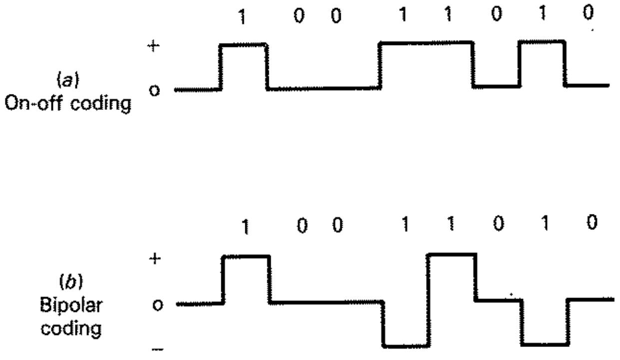


**FIGURE 4.14**
Signal attenuation.

Because the parameters of the transmission line may distort the distinction between the 1s and 0s of the digital pulse, you could receive an almost level signal which would appear as a changing direct current, one which would be very difficult to detect. For this reason line-haul signals use *bipolar* signaling in which alternate 1s are sent with opposite polarity, as shown in Figure 4.15.

Because the use of regenerators or amplifiers in a circuit means that signals can only travel in one direction, line-haul transmission lines must have four wires

**FIGURE 4.15**
Bipolar coding.

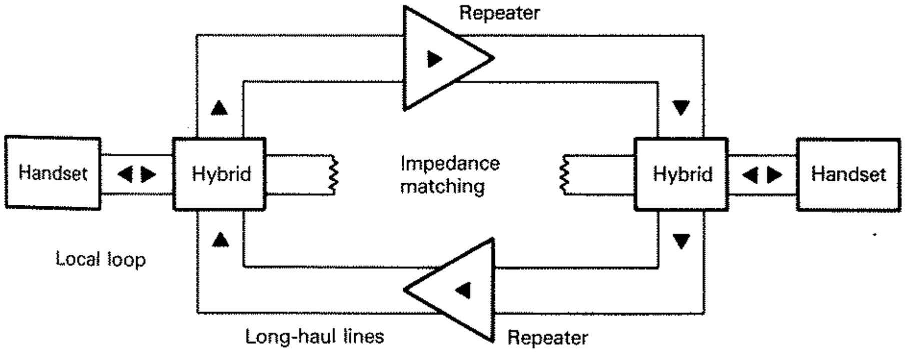


or two circuits—one in each direction—for two-way communication. Local loops are two-wire and bidirectional, and it is necessary to convert between these circuits and the four-wire circuits needed in the line-haul or long-line circuits. The device to do this is called a *hybrid* and is illustrated in Figure 4.16.

Sometimes there is leakage across the hybrid and echos appear. *Echo suppressors* are voice-actuated switching devices used at each end of a four-wire circuit. They operate on the principle that when one party in a conversation is talking, the other one is listening and does not need a talking path until the roles of the two parties are reversed. In this way the echo loop is broken.

**Local-Area Networks** Described in more detail in Chapters 6 and 7, local-area networks (LANs) are being developed for intraorganizational transmission of multiple multiplexed channels (voice mail, telephone, data, video, electronic messaging, etc.) with programmable communication processing. We discuss them here because these networks can just as easily be used between geographically dispersed facilities of an organization and consequently could replace the local-loop network. Furthermore, cable television is currently being tested as a LAN. They allow the interconnection of otherwise incompatible peripherals without separate wired circuits for each. LANs provide these services in a *decentrailized* mode, while local private branch exchanges (PBXs) or mainframe computers can provide the services in a *centralized* switching mode. One mode of transmission access uses a *token loop,* whereby a node waits for an electronic token to approach and then transmits the message in burst mode, followed by the token to prevent overlapping messages. LAN transmission media include *fiber optics;* cable in what is called the *base-band* mode (50 megabits per second (Mbps), 2 km range—half-duplex primarily for data) and cable in the *broadband* mode (140 Mbps, 15 km range—full-duplex primarily for video and integrated services). Hybrids are already emerging, and although corporations are still treading lightly, LANs are the key for the integrated office of the future. Xerox's Ethernet and Wang's Wangnet are competing for early dominance in local-area networks, and IBM's entry will likely set the standards, although there are already over 12,000 personal computer local networks using the local loop of the telephone network.

**FIGURE 4.16**
The use of hybrids in long-haul switched networks.



**The Telegraph-Transmission System** Morse is known for the development of modern telegraphy in 1837, although Wheatstone and Gohe in England also made primary contributions. Indeed electrical telegraphy was first suggested in 1753. The first public telegram was sent in 1844; soon Edison demonstrated sending messages in each direction. Modern carrier modulation makes possible the transmission of several hundred simultaneous messages. The first use of microwave transmission of telegrams, between New York and Philadelphia, showed the advantages of such technology over telegraph wires. Indeed, 18 telegraph circuits can also be sent over one telephone voice circuit; with time-division multiplexing, the number rises to nearly 200. However, even though telegraphy requires only one line (the circuit is closed by grounding to the earth), the traditional use of two wires for telephone maintains telegraph tariffs at artificially high levels. Further, modern telegraphy typically allows immediate printout by the receiving station and does not even use Morse code! Facsimile is one kind of automatic telegraphy, whereby differential current impulses transmit the intensity of shading in the original document.

The telegraph never achieved the reach in the United States that it has in Europe. Telephone quickly overtook telegraph in the United States, while in Europe switched telegraph or telex has become a major transmission system. In the United States automatic telegraphy or facsimile currently uses telephone lines, as does the telegraph. As modern telephone systems become digital, we can expect fully digital facsimile in the manner of high-speed data transmission.

### 4.4.3 Basic Switching Concepts

The details of modern switching will be fully discussed in Chapter 5. Here, we shall define the three general types of switching found in today's telecommunication systems (Dordick, Bradley, & Nanus, 1983).

*Line-switched systems,* also called circuit-switched systems, are analogous to the POTS (Plain Old Telephone Services) network, in which routing is set up prior to message transmission. The circuit is then engaged for the duration of the call. This type of network provides the lowest possible transport delay and, with the development of highly reliable digital networks, has the potential of offering relatively error-free transmission through the use of multiplexing.

*Message-switched systems* were developed largely to overcome the problems of error generation attendant upon the use of analog lines for digital messages. In message-switched systems, messages from each terminal are received at a buffer, which stores the transmission until it is complete. When the entire message has been received, it is sent to a concentrator, where it is given an address and coded for identification and error correction, together comprising the message's overhead. The message is then packed into the line with other outgoing messages and sent off to its destination.

*Packet-switched systems* are message-switched systems with the messages divided into blocks of uniform length, each of which carries its own overhead characters. While this additional burden of overhead tends to add congestion to a network, efficiencies in throughput are achieved by having the option of sending each packet by a different route. This multiple-switching scheme gives packet-switched networks the capability of effectively minimizing transport time and eliminating blocking.

## 4.5 CURRENT MAJOR TRANSMISSION MEDIA

In this section we shall briefly discuss the major transmission media currently in use. We begin with the wired transmission media and conclude with the over-the-air or broadcast transmission media. We shall describe the media here, and in the final section we shall summarize by comparing the media with each other.

### 4.5.1 Twisted-Pair Transmission

The twisted pair, such as the two copper wires connecting the telephone to the local exchange and the telegraph between its local offices, is the backbone of the nation's telecommunications system. It is simply a pair of copper wires which have been made extraordinarily versatile by the nature of the termination systems and equipment connected to it. Theoretically, there are no limits to the number of circuits these wires can carry. However, as we shall see, when used for the delivery of high-speed data or many voice channels, the higher frequencies create the undesirable "skin effect." The electrons tend to gather on the surface of the wire, and this increases the resistance or impedance of the wires, requiring many repeaters or amplifiers along the line in order to deliver quality signals.

### 4.5.2 Coaxial Cable

There is not much space on the surface of a ¼-in-diameter wire, so as the frequencies of signal transmission are increased in order to accommodate different kinds of multiplexing, the skin effect, that is, the resistance owing to electron crowding on the wire surface, increases.

To combat this effect two conductors were put in one cable, one inside the other, but insulated from each other. In this way more wire surface was made available and the resistance or attenuation decreased. This is coaxial cable.

Coaxial-cable transmission has been and continues to be an important long-distance (or line-haul) transmission medium. It is also the medium for cable television.

Telephone use of coaxial cable began in 1936, and the coaxial cable became an important transmission mode during World War II. A single coaxial cable can provide over 13,000 simultaneous voice channels. For cable television, recently installed 450 MHz systems can provide more than 60 channels of television. Typically cable is used to provide transmission *downstream* in residential applications, although data, voice, and video are possible upstream, either by a second cable or by multiplexing flows on one cable. However, using the telephone for responses in closed-circuit instructional applications, or for selecting program content in teletext, still seems a satisfactory and economic way to link users with the service provider.

### 4.5.3 Submarine Cables

Overseas radiotelephony began in 1927 by bouncing low-frequency waves off the atmosphere, but this is easily disturbed by atmospheric conditions. In 1956 the first transatlantic telephone cable carried 36 voice circuits.* Modern coaxial cable can replace 1500 twisted-pair telephone lines. Underwater cable telephony interleaves different messages from different users by means of *time-assigned speech interpolation* (TASI) to send multiple messages during natural gaps in conversation. This process increases transmission efficiency, security, and privacy but often complicates cost accounting!

The transmission costs of submarine cable are very competitive with those of satellite. Indeed, despite the attraction of the satellite (less maintenance, greater bandwidth, and often somewhat lower line costs) submarine cables continue to be laid. One reason is that while the international satellite is owned by an international organization, INTELSAT, and must share its returns with 106 member nations, a submarine cable is owned and operated by the telecommunications ministry (usually called PT&Ts—Post, Telegraph, & Telephone) of the nation and return revenues to that PT&T.

The United States, however, wishes to encourage satellite use. Because of TASI, the transmission costs of submarine cables are declining more rapidly than those of satellites, yet FCC regulation restricts the laying of such cables by U.S. companies, to foster the more expensive satellite plant.

### 4.5.4 Optical-Fiber Transmission†

Cable transmission, twisted-pair copper wire, and even new *millimeter waveguide* transmission (providing 230,000 to 460,000 circuits) may well be bypassed by optical fibers. Optical fibers can transmit analog or digital signals by means of concentrated monochromatic light pulses through high-quality glass fibers

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*The first submarine telegraph cables were laid in 1858, but they failed after three weeks.

†See the 1982 September/October and later issues of *International Fiber Optics and Communications*, available from Information Gatekeepers, 167 Covey Road, MA 02146, for a directory of products, standards, and suppliers.

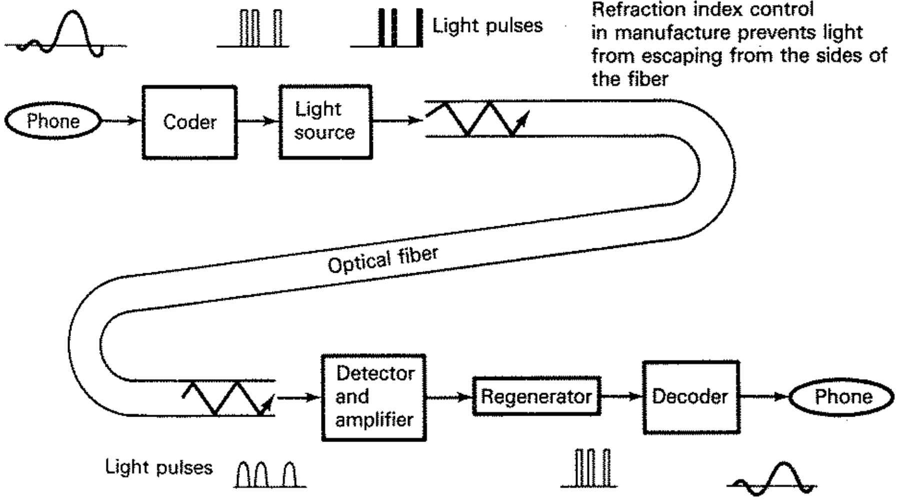
almost as thin as human hair. The light source can be laser or light-emitting diodes (LED) with photoelectric receptors (see Figure 4.17). The figure shows that a signal is converted to pulses of monochromatic light, which are transmitted into the optical fiber at a critical angle. This angle ensures that the light pulses are reflected completely and entirely within the fiber until received, amplified, regenerated, and decoded. Receptors, splicing, and sharp angles still provide difficulties for this infant technology, but it has tremendous advantages: silicon to make the glass is plentiful and cheap; fibers are noninductive and thus prevent cross talk from adjacent fibers, are interference-free, have low attenuation, are immune to short circuits, explosions, and sparks, and avoid spectrum-related licensing and regulation constraints. Optical-fiber transmission media can extend 26 km before repeaters are necessary and at rates of 90 Mbps. (At this speed 1342 voice channels will be provided by each optical fiber used to support Olympic communications in Los Angeles.) Speeds of 1 gigabit per second (Gbps) have been achieved experimentally. Up to 672 voice lines can be currently multiplexed simultaneously.

Although fiber-optics systems currently have high development costs, AT&T predicts an eventual growth rate of 2000 miles per year in its system. The Yankee Group predicts that the use of fiber optics by local telephone companies will compete with cable company services in 10 or 20 years. Some pilot fiber installations for CATV provide 35 GHz TV signals.

### 4.5.5 Radio Transmission

The first commercial radio broadcast was the transmission of the 1920 presidential election results by station KDKA in Pittsburgh, Pennsylvania. The Radio Control Act of 1927 and the Communications Act of 1934 were designed primarily to resolve frequency interference problems caused by the proliferation of new stations. But recognizing the public interest inherent in the limited electromagnetic spectrum the FCC also set forth regulatory concepts that sought to satisfy the public interest, convenience, and necessity and foster localism. Because broadcasting used scarce public resources and was therefore regulated by the market, broadcasting was regulated in the public interest.

**FIGURE 4.17**
Fiber optic transmission.



The use of cable and microwave relays made possible the development of networks and the local affiliate structure of today's broadcasting system. More recently, a broader spectrum has been made available for a variety of point-to-point transmission services, including digital termination services (DTS) and operational fixed services (OFS). A portion of the electromagnetic or radio spectrum between citizens' band and amateur radio and VHF television was set aside for this service. Mobile radio telephone services, including paging services, are probably the fastest growing communication service throughout the world. Because of this, the narrow spectrum allocated to mobile radio or radio telephone has become extremely crowded.

The most promising means for overcoming the shortages has been *cellular radio*. Cellular radio breaks up an area (say, a city) into small cells consisting of small (less than 15-mile radius) adjacent cells within census regions but broadcasting at hundreds of different frequencies. Receivers shift from frequency to frequency as they pass through these cells. Each cell can handle over 200 conversations simultaneously. *Digital-packet radio transmission* sends digital pulses in burst mode, using the full mobile frequency band at each burst, to base stations which retransmit the pulse within the local area or distribute it via wire networks. Both developments will allow data transmission from mobile terminals and vastly increase the number of mobile radio telephone, and beeper services.

### 4.5.6 Microwave Transmission

When the FCC allocated spectrum to services, it recognized that new services might soon outgrow their assigned bandwidths. This did indeed occur, and there were and still are enormous pressures on the FCC to reallocate frequencies. Over the years this has been done, especially in the 1 meter and below portion of the spectrum.

This portion has seen some of the most innovative applications, including long-line telephone transmission and the nationwide distribution of video and data. AT&T provided the first nationwide microwave distribution in 1948 and before long was responsible for network video distribution until the advent of the satellite in 1972.

Microwave transmission is radio transmission at high frequencies and provides extensive backbone channels for video, radio, data, telegraph, and telephony. For example, two-thirds of all long-distance calls now travel by land-based microwave. AT&T even provides some digital service through analog microwave data links, called *data under voice* (DUV). (Indeed, telephone signals can be modulated to be transmitted over power-distribution lines.) Until recently, microwave was used primarily for local distribution, particularly for short, high-traffic routes within urban areas. Multipoint distribution services involve redistribution from satellite or cable circuits to local CATV networks or rooftop antennas. Initial costs for microwave systems are quite high, although operating costs are relatively low. Such transmission is reliable, and extra *circuits* within established capacity are inexpensive, but incremental capacity or additional routes are expensive. Owing to the high frequency, microwave links must be line-of-sight and rarely exceed 30 km.

Line-haul microwave transmission systems require numerous relays. These relays receive or accept signals at one frequency—signals that are very weak because they have come long distances. The signal is amplified and retransmitted at a different frequency; otherwise the retransmitted signal would overwhelm or blank out the received signal.

### 4.5.7 Video Transmission

An image-scanning device was first invented by a German, Paul Nipkow, in 1884; in the 1920s Zworkyin and Farnsworth developed successful scanning tubes. This quickly led to the first public television transmission in England in 1927, and in the United States at the 1939 world's fair.

Video transmission requires considerable bandwidth. Sideband signals correspond to the difference and sum of carrier and modulating frequencies. Radio sidebands occupy little bandwidth, so stations may be only 10 kilocycles apart. But the video frequency range is 4 MHz (400 times more bandwidth), so the additional sideband signals demand good station separation, typically 170 miles for stations on the same channel. The 12 UHF frequencies range from 54 MHz to 213 MHz, whereas the 70 VHF frequencies (added in 1952 by the FCC owing to high demand for TV station frequencies) range from 470 to 890 MHz.

Video is not often thought of as a transmission medium; video is perceived as indelibly connected to its programming and seen solely as an entertainment medium. However, as we are now learning, we can use the video transmission medium for the transmission of electronic publishing or teletext. There are other uses for this valuable spectrum. Consider, for example, the use of video spectrum during the early-morning off hours when a station is not broadcasting for the delivery of educational programs to waiting school videotaping facilities, or the use of the vertical interval for the transmission of financial information (coded, of course) to members of a banking network for storage and use the next morning. While there are certain legal restrictions in place today, the ongoing restructuring of the nation's telecommunications industry may see changes in these rules.

The high frequencies required for video transmission, as with microwave, limit transmission to line of sight. That is why the first cable systems were installed to provide service to the valleys in the Appalachian region.

As an example of the impact of bandwidth constraints, consider AT&T's Picturephone. It originally required 1 MHz, or 5.6 Mbps. Compression techniques brought this down to 1.5 Mbps. Reduction to 200 kilobits per second (Kbps) leads to the blurring of moving images; at 56 Kbps (digital voice channel) the Picturephone would be little different from *slow-scan video*. Slow-scan requires much less memory storage as well as bandwidth and indeed would serve most video conferencing needs at much lower costs (see Chapter 9). One explanation for its marketing failure is that the bulk of information transmitted between people is textual or numeric, and this doesn't require expensive large bandwidth. Various aspects of video transmission are discussed in Chapters 7 and 11.

Low-power television (LPTV), until recently used only in rural areas to rebroadcast distant signals which otherwise would have passed those areas, offers new potential for local broadcasting. These 1000-watt stations will cover only a 10- to 15-mile radius, so many more can exist than current broadcast stations requiring the 170-mile separation. Community television may develop, depending on responses by cable TV operators and FCC decisions.

### 4.5.8 Satellites

It was Arthur C. Clarke, known now primarily for his science fiction writing *(2001)*, who as a young engineer in 1945 suggested putting satellites 22,300 miles above the equator. They would then revolve around the Earth at the same speed as a spot on land below them, appearing stationary. Clarke now lives in Sri Lanka, and has an antenna in his yard to receive transmission from *geosynchronous* satellites.

The Russian Sputnik in 1957 was the first human-made satellite; now dozens are in geostationary orbit (see Figure 4.18). For example, Cable News Network is transmitted via Transponder 14 of SatCom satellite F3, located at 131°W, using 3.98 MHz and horizontal polarization. Auxiliary services include 1½ minutes-per-hour radio news carried on its 6.3-MHz voice subcarrier.*

Current satellites operate at 4 to 6 GHz (the C-band) and 12 to 13 CHz (K-band) (see Figure 4.18). The 4- to 6-GHz range must be shared with microwave frequency assignments, while there are only a limited number of orbital locations available because satellites must be separated by 3°, and there are only about 75° of arc over the North American continent. (The more extreme the location over the ends of the continent, the narrower the angle at the receiving end and the more difficulties in reception.) Thus the hyperpower

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*The various issues of *Satguide*—P.O. Box 1048, Hailey, ID 83333—provides a complete listing of all current and known future domestic satellites delivering CATV. Included are frequency, polarization, latitude, transponder identification, ownership, services, and addresses. A complete commercial satellite directory is also available from Phillips Publishing, 7315 Wisconsin Avenue, Bethesda, MD 20814.

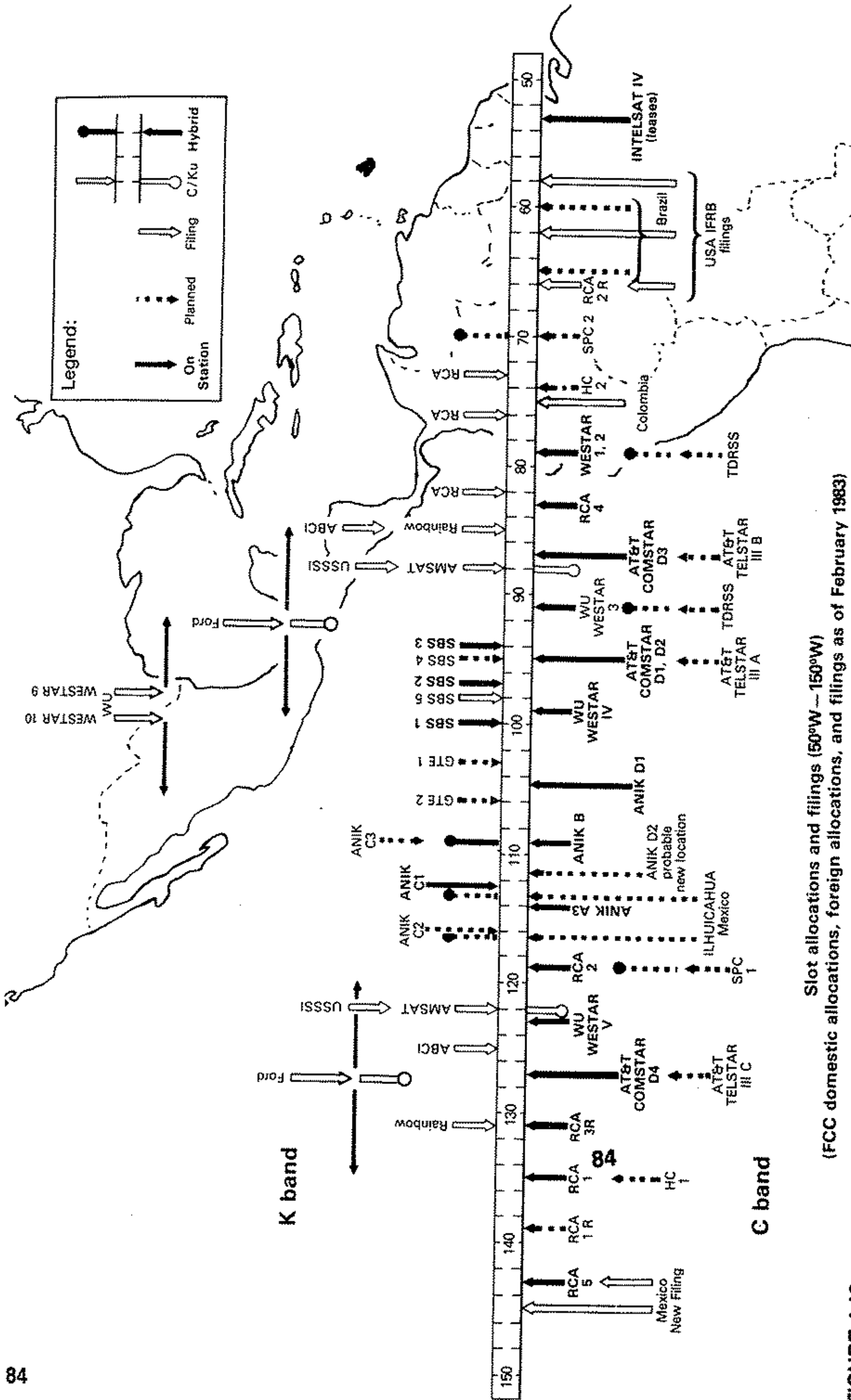


FIGURE 4.18
Communication satellite orbital locations and frequency bands in the Western hemisphere.
*Source:* Hughes Aircraft. We thank Paul Visher for his assistance.)

satellites were designed to provide more efficient transmission. A 500-MHz bandwidth at 12-GHz transmission equals 220,000 telephone channels and 100 TV channels, using spot beams. A more powerful satellite allows the use of spot beams to provide focused transmission at a specific frequency; it also allows smaller (hence cheaper and more mobile) ground antennas. For a 12-GHz transmission, a 1-meter dish is sufficient. [See Rice & Parker (1979) for applications of high-powered communication satellites for rural areas.] These higher frequencies, however, are affected by rain and are less able to reuse the same frequency by transmitting polarized signals. Satellites are, essentially, microwave relays in space; they accept signals at one frequency and retransmit them at another.

Satellites in general have the advantage of tremendous bandwidth and are theoretically insensitive to the distance between origination and reception. Indeed, Satellite Business Systems intends to bypass AT&T entirely in delivering intercorporate communications cross-country. AT&T estimates that the point at which satellites become more economic is 3000 circuits for distances greater than 1500 miles. They are not unbiased, however, and some studies have shown economic use of satellites between points separated by only 1 mile (Parker, 1982).

Typically, signals are sent to the satellite, converted to different frequencies and amplified, beamed to a central switching station, retransmitted and rebeamed to the receiver. The amplifiers are called *transponders,* and satellites tend to have 12 to 24 of these. These "hops" create a very small delay in final reception, which is still a problem for data transmission and sometimes noticeable in long-distance telephoning.

A satellite's age (lifetimes are officially around 7 years), orbital location, power and efficiency, user categories, and the number of stations capable of receiving its signals affect its desirability and, hence, its cost. In 1980 the cost of a full circuit for 1 year was approximately $40,000 leased from COMSAT, the U.S. operator for the INTELSAT system. A domestic satellite circuit leases at approximately $12,000 to $15,000 per year. Heavy users lease an entire transponder (around $1 million per year) or even send up their own satellites. Indeed, Hughes was the first company to put a commercial satellite into orbit by means of NASA's space shuttle.

## 4.6 SYSTEM COMPARISONS

Communication system designers seek to provide high-quality communication at the lowest possible cost. Their task is made difficult as well as more feasible by the range of alternatives they have to work with. Not only is there a rich mix of transmission media, but there are several ways of using these media. Telecommunication engineers are always trading off bandwidth, time, distance, and cost. Further, they trade off line capacity or bandwidth against terminal hardware, for example, choosing a relatively narrow bandwidth link while using time-division

**FIGURE 4.19**
TRANSMISSION TIMES FOR SELECTED CONTENT.

| | Typical number of bits | Lowest approximate transmission times (seconds) at 9.6 KBps* |
|---|---|---|
| A page or a full CRT screen of text (uncompressed) | 1–4 × 10⁴ | 1–4 |
| Facsimile image, black and white, two-tone (compressed) | 2–6 × 10⁵ | 20–60 |
| Full-page, three-color image, high quality (heavily compressed) | 2–10 × 10⁴ | 200–1000 |
| A 20-cm floppy disk, single-sided, double-density | 5 × 10⁶ | 500 |
| A 720-m reel of computer tape (type 6250 BPI) or two medium-sized disk units (IBM 3310) | 1 × 10⁹ | 100,000<br>(29 hours) |
| One second of digitized telephone speech at pulse-code modulation | 6.4 × 10⁴ | 7 |
| One second of digitized telephone speech (heavily compressed) | 2.4 × 10⁵ | 0.25 |
| One second of Picturephone (moving video image) | 6.3 × 10⁴ | 660 |

*9.6 KBps is the highest commercially available transmission rate over an analog voice channel.
*Source:* Mandley, T. "Assessing the New Services." *IEEE Spectrum*, October 1979, 46–47.

multiplexing at a somewhat higher cost in terminals. But since copper costs money and microwave bandwidth is as scarce as satellite bandwidth will certainly become, TDM methods, despite the higher cost of terminal hardware, become more economical.

Since line costs are proportional to the distance covered, multiplexing avoids the need for separate circuits for each user. As terminal costs are fixed, multiplexing becomes more economic than individual circuits only beyond a certain distance. For a particular multiplex system, the minimum distance at which it has an economic advantage is called the *prove-in point.*

Another factor to consider are multiplexing hierarchies. These hierarchies can be considered essentially network transmission architectures designed to provide the system designer with various options for delivering information rapidly and economically. In analog or voice transmission systems, the basic architecture of hierarchy is a 600-circuit *mastergroup,* which is made up of 10 *supergroups,* which in turn are composed of 5 multiplexed *groups,* each of which multiplexes 12 voice lines. In Europe, CCITT (Commité Consultantif International de Téléphonique et Télégraphique) standards call for a 960-circuit mastergroup composed of 16 multiplexed supergroups.

The AT&T System has developed a set of building blocks for its digital architecture based on the T1 carrier. This T1 carrier, developed in 1933, can provide 24 voice signals at 1.544 Mbps. The T2 carrier uses 4 multiplexed T1 streams, while the T3 carrier uses 7 multiplexed T2 streams. Finally the T4 carrier can provide 4032 voice circuits at 274 Mbps by utilizing 6 multiplexed T3 streams. In Europe, the basic level has 30 voice channels and 2 signalling channels, at 2.048 Mbps, and is multiplexed into groups of four.

The larger-capacity multiplex systems (higher in the hierarchy) will only be economic on certain routes where sufficient trunk traffic can be concentrated to utilize the available capacity. These routes or corridors can be created by planning the network design to feed local loops into appropriate points in the line-haul system. Cost savings can be achieved even though route distances for most calls are increased for point-to-point routing. In other words it may be economical to go a longer way to reach a line-haul node that will carry local traffic cheap enough to overcome the somewhat higher cost of the local loop rather than going directly into a shorter point-to-point connection over a more expensive long-distance circuit. This may certainly be the case for satellite networks.

In the next several figures we show some comparisons for several typical line-haul possibilities. Figure 2.13 compares channels by frequency, while Figure 4.19 compares channels by transmission speed. Figure 4.20 compares some media by capacities and frequency, while Figure 4.21 graphically reveals the declining costs of these media.

Note that the most recent TD3 microwave system carries 18,000 circuits. Microwave radio has about a 3-to-1 cost advantage over cable in the same range of capacities. Enormous cost advantages accrue from satellite usage at this capacity level. But it has been argued that without the terrestrial systems provided by both cable and microwave, satellites by themselves might be considered too vulnerable to both human-made and solar-made interference and would not be depended upon so heavily.

There are, of course, other considerations of cost that must be taken into account when designing line-haul systems. For example, terrain is extremely important—the microwave radio-relay systems must operate within line of sight of each other—so usually towers are spaced at 30-km intervals. And at very remote sites there may not be any power available to operate the towers. The same holds true for long strings of cable; power is needed to operate the repeaters.

When we branch circuits off the "main stem" we have to accommodate the various hierarchies we discussed above, and this requires a considerable amount of equipment. In the design of the network—its topology—this must be taken into consideration or the benefits of multiplexing are lost in the cost of switching at the branches.

Finally, as the line-haul system becomes more and more digital, there is the problem of feeding analog signals into it. Unless the analog signals from the local loops are digitized, the electronic switching at the interfaces of the line-haul local loop with lower-cost long-distance systems cannot be used and therefore the cost

**FIGURE 4.20**
ADVANCES IN FOUR TRANSMISSION SYSTEMS.

Coaxial Cable Systems

| Type | Date introduced | Repeater spacing | Voice-frequency channels/coax | Voice-frequency channels/route |
|---|---|---|---|---|
| L 1 | 1940 | 8 miles | 600 | 1,800 |
| L 3 | 1953 | 4 miles | 1,860 | 16,470 |
| L 4 | 1967 | 2 miles | 3,600 | 32,400 |
| L 5 | 1973 | 1 mile | 10,800 | 108,000 |

Microwave radio systems

| Type | Date introduced | No. of two-way radio channels | Voice circuits per channel | Frequency band in GHz |
|---|---|---|---|---|
| **TD2** | **1948** | **5** | **480** | **3.7–4.2** |
| **TH1** | **1959** | **8** | **1,860** | **5.9–6.4** |
| **TD3** | **1966** | **12** | **1,200** | **3.7–4.2** |
| **TD4** | **1973** | **12** | **1,500** | **3.7–4.2** |

Transatlantic cable systems

| Type | Date introduced | No. of channels | Repeater spacing (in nautical miles) |
|---|---|---|---|
| TAT 1 | 1956 | 36 | 20 |
| TAT 3 | 1963 | 138 | 20 |
| TAT 5 | 1970 | 845 | 10 |
| TAT 6 | 1976 | 4,000 | 5.1 |

AT&T digital transmission systems

| Type | Date introduced | No. of voice channels | Medium | Transmission speed |
|---|---|---|---|---|
| T 1 | 1963 | 24* | Wire-pair | 1.544 MBps |
| T 2 | 1973 | 96* | Coax/shielded pair | 6.3 MBps |
| T 4 | 1975 | 4,032* | Coax | 274.0 MBps |
| WT4 | 1980s | 230,000† | Wave guide | 274.0 MBps |
| WT4A | 1980s | 460,000† | Wave guide | 274.0 MBps |

*Requires two circuits (one each direction).
†Two-way channels: 60 Frequency division channels each direction, digital modulation.

savings not realized. This requires additional analog-to-digital and digital-to-analog converters at the local loops and increases the cost of operation. But as more and more local loops become digital, cost disadvantages will disappear.

The Japanese have shown a keen interest in comparing attributes such as information cost per distance as an indication of media efficiency. A recent trend

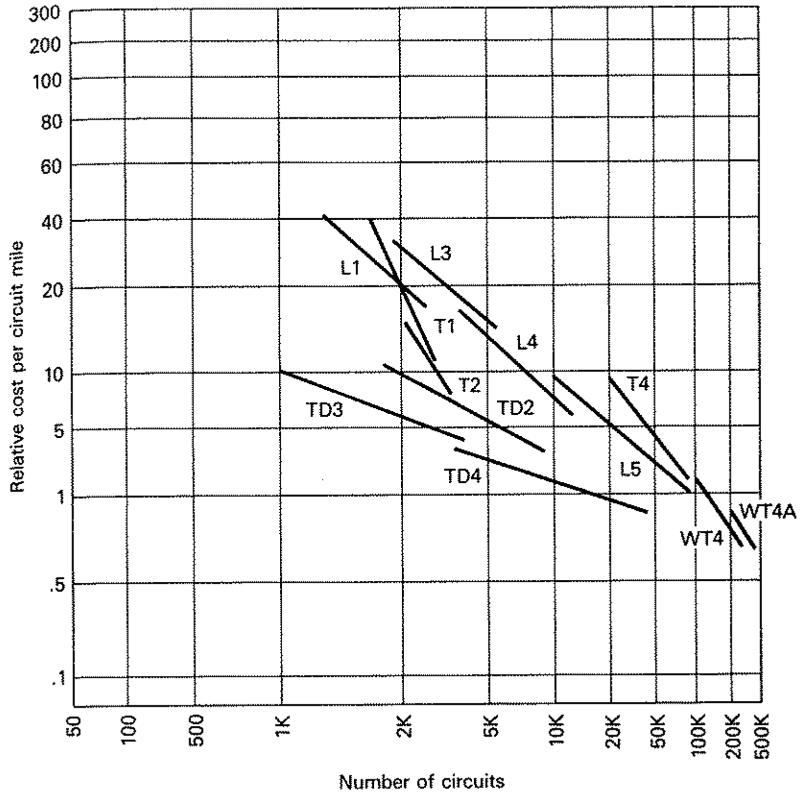
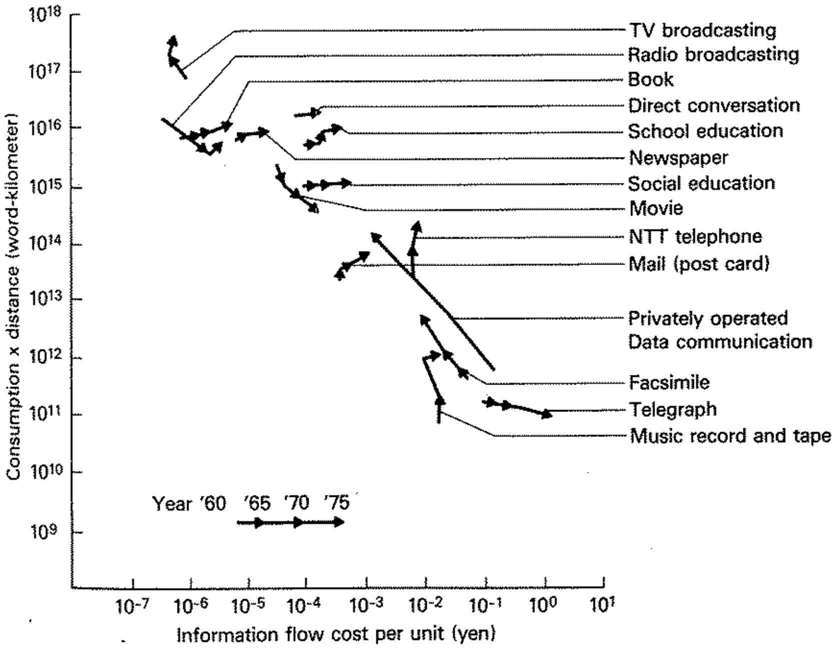


**FIGURE 4.20**
Advances in four transmission systems.

**FIGURE 4.21**
Declines in circuit-mile costs for three transmission systems. (*Source:* Ito, 1980. Reproduced by permission.)



graph appears in Figure 4.22 (Ito, 1981). You can see the steady decline in movie and telegraph transmission efficiency, the equilibrium level of telephone efficiency, and the increased efficiency of video and digital transmission.

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