2.1 CHAPTER OBJECTIVE

Telecommunication deals with conveying information with electrical signals. This chapter prepares the telecommunication novice with some very basic elements of telecommunications. We are concerned about the transport and delivery of information. The first step introduces the reader to early signaling techniques prior to the middle of the nineteenth century when Samuel Morse opened the first electrical communication circuit in 1843.

The next step is to present some of the basic concepts of electricity; this is mandatory for an understanding of how telecommunications works from a technical perspective. For an introduction to electricity, the user should consult Appendix A. After completion of this chapter, the reader of this text should have a grasp of electrical communications and its units of measure. Specifically, we will introduce an electrical signal and how it can carry intelligence. We will differentiate analog and digital transmission with a very first approximation.

Binary digital transmission will then be introduced starting with binary numbers and how they can be represented electrically in a simple fashion. We then delve into conducted transmission. That is the transport of an electrical signal on a copper-wire pair, on coaxial cable, and then by light in a fiber-optic strand of glass. Radio transmission and the concept of modulation will then be introduced.

2.2 SIGNALS IN EVERYDAY LIFE

Prior to the advent of practical electrical communication, human beings had been signaling over a distance in all kinds of ways. The bell in the church tower called people to religious services or “for whom the bell tolls”—the announcement of a death. We knew a priori several things about church bells. We knew approximately when services were to begin, and we knew that a long, slow tolling of the bells announced death. Thus we could distinguish one from the other, namely a call to religious services or the announcement of death. Let’s call lesson 1 a priori knowledge.

The Greeks used a relay of signal fires to announce the fall of Troy. They knew a priori that, a signal fire in the distance announced victory at Troy. We can assume that “no fire” meant defeat. The fires were built in a form of relay, where a distant fire was
just visible with the naked eye, the sight of which caused the lighting of a second fire, and then a third, fourth, and so on, in a line of fires on nine hills terminating in Queen Clytemnestra’s palace in Argos, Greece. It also announced the return of her husband from the battle of Troy.

Human beings communicated with speech, which developed and evolved over thousands of years. This was our principal form of communication. However, it wasn’t exactly “communication at a distance.” Speech distance might be measured in feet or meters.

At the same time there was visual communication with body language and facial expressions. This form of communication had even more limited distance. Then there was semaphore, which was very specialized and required considerable training. Semaphore was slow but could achieve some miles of distance using the manual version.

Semaphore consisted of two flags, one in each hand. A flag could assume any one of six positions 45 degrees apart. The two flags then could have six times six, or 36, unique positions. This accommodated the 25-letter alphabet and 10 numbers. The letters i and j became one letter for the 26-letter alphabet.

A similar system used in fixed locations, often called signal hills or telegraph hills, was made up of a tower with a movable beam mounted on a post. Each end of a beam had a movable indicator or arm that could assume seven distinct positions, 45 degrees apart. With two beams, there were 49 possibilities, easily accommodating the alphabet, ten digits, and punctuation. The origin of this “telegraph” is credited to the French in the very late eighteenth century. It was used for defense purposes linking Toulon to Paris. There were 120 towers some three to six miles apart. It took 40 minutes to transmit signals across the system, with about three signals per minute. It was called the Chappe semaphore, named after its inventor. Weather and darkness, of course, were major influences. One form of railroad signals using the signal arm is still in use in some areas today.

The American Indian used smoke signals by day and fires at night. The use of a drum or drums for distance communication was common in Africa.

Electrical telegraph revolutionized distance communications. We accept the date of 1843 for its practical inception. It actually has roots well prior to this date. Many of the famous names in the lore of electricity became involved. For example, Hans Christian Oersted of Denmark proposed the needle telegraph in 1819. Gauss and Weber built a 2.3-km (1.4-mile), two-wire telegraph line using a technique known as the galvanometer-mirror device in 1833 in Germany. Then there was the Cooke and Wheatstone five-needle telegraph, which was placed into operation in 1839 in the United Kingdom. All these names are very familiar to those of us who are well-read in the history of the development and application of electricity. The five-needle telegraph was meant for railroad application and used a code of 20 letters and 10 numerals to meet railway requirements.

It was while the United States Congress in 1837 was considering a petition to authorize a New York to New Orleans Chappe semaphore line that Samuel F. B. Morse argued for the U.S. government to support his electrical telegraph. The government appropriated the money in early 1843. The first operational line was between New York and Baltimore. Within 20 years the telegraph covered the United States from coast to coast. The first phase of electrical communications was completed. It revolutionized our lives (Ref. 1).

2.3 BASIC CONCEPTS OF ELECTRICITY FOR COMMUNICATIONS

2.3.1 Early Sources of Electrical Current

Rather crude dry cell batteries were employed in the earlier periods of telegraph as an electrical current source. Their development coincided with the Morse telegraph
Figure 2.1a  Graphic notation of a single dry cell.

Figure 2.1b  Graphic notation of a “battery” of dry cells.

Figure 2.1c  How dry cells can be connected in series to increase voltage.

(2.3.2 The Electrical Telegraph: An Early Form of Long-Distance Communications)

Let’s connect a battery terminal (or electrode) with a length of copper wire looping it back to the other electrode. A buzzer or other sound-generating device is inserted into that loop at the farthest end of the wire before looping back; we now have the essentials of a telegraph circuit. This concept is shown in Figure 2.2. The loop has a certain resistance, which is a function of its length and the diameter of the wire. The longer we make the loop, the greater the resistance. As the length increases (the resistance increases), the current in the loop decreases. There will be some point where the current (in amperes) is so low that the buzzer will not work. The maximum loop length can be increased by using wire with a greater diameter. It can be increased still further by using electrical repeaters placed near the maximum length point. Another relay technique involved a human operator. At the far end of the loop an operator copied the message and retransmitted it down the next leg of the circuit.
2.3.2.1 Conveying Intelligence over the Electrical Telegraph. This model of a simple telegraph circuit consists of a copper wire loop with a buzzer inserted at the distant end where the wire pair loops around. At the near end, which we may call the transmitting end, there is an electrical switch, which we will call a key. The key consists of two electrical contacts, which, when pressed together, make contact, thereby closing the circuit and permitting current to flow. The key is spring-loaded, which keeps it normally in the open position (no current flow).

To convey intelligence, the written word, a code was developed by Morse, consisting of three elements: a dot, where the key was held down for a very short period of time; a dash, where the key was held down for a longer period of time; and a space, where the key was left in the “up” position and no current flowed. By adjusting the period of time of spaces, the receiving operator could discern the separation of characters (A, B, C, ..., Z) and separation of words, where the space interval was longer. Table 2.1 shows the landline and international versions of the Morse code. By land-line, we mean a code used to communicate over land by means of wire conductors. The international Morse code was developed somewhat later and was used by radio.

Table 2.1 Two Versions of the Morse Code

| Column A: the American Morse Code; Column B: the International Morse Code |
A more practical telegraph system is illustrated in Figure 2.3. Note that the figure has just one metallic wire connecting the west station to the east station. The second wire is replaced with ground. The earth is a good conductor, and so we use earth, called ground, as the second conductor (or wire). Such a telegraph system is called single-wire ground return. Such a system was widely in use when my wife and I did a stint for the ITU (International Telecommunication Union) in Ecuador in 1967–1969.

This is a similar circuit as shown in Figure 2.2. In this case, when both keys are closed, a DC (direct current) circuit is traced from a battery in the west station through the key and relay at that point to the line wire, and from there it is traced through the relay and key at the east station and back through the earth (ground) to the battery. The relays at each end, in turn, control the local circuits, which include a separate battery and a sounder (e.g., buzzer or other electric sounding device). Opening and closing the key at one end, while the key at the other end is closed, causes both sounders to operate accordingly.

A relay is a switch that is controlled electrically. It consists of (a) wire wrapped around an iron core and (b) a hinged metal strip, which is normally open. When current flows through the windings (i.e., the wire wrapped around the core), a magnetic field is set up, thereby drawing the hinged metal strip into a closed position and causing current to flow in the secondary circuit. It is a simple open-and-closed device such that when current flows there is a contact closure (the metal strip) and when there is no current through the windings, the circuit is open. Of course there is a spring on the metal strip, holding it open except when current flows.

Twenty years after Morse first demonstrated his telegraph on a Baltimore–Washington route, telegraph covered the country from coast to coast. It caused a revolution in communications. Its use is still prevalent in many parts of the world, as I discussed above.

2.3.3 What Is Frequency?

To understand more advanced telecommunication concepts, we need a firm knowledge of frequency and related parameters such as band and bandwidth, wavelength, period, and phase. Let us first define frequency and relate it to everyday life.

The IEEE defines frequency as “the number of complete cycles of sinusoidal variation per unit time.” The time unit we will use is the second. For those readers with a mathematical bent, if we plot \( y = \sin x \), where \( x \) is expressed in radians, a “sine wave” is developed as shown in Figure 2.4.

Figure 2.5 shows two sine waves; the left side illustrates a lower frequency, and the right side shows a higher frequency. The amplitude, measured in this case as voltage, is the excursion, up or down, at any singular point. Amplitude expresses the intensity at that point. If we spoke of amplitude without qualifying it at some point, it would be the
Figure 2.4 A sine wave. Here frequency is the number of times per second that a wave cycle (one peak and one trough) repeats at a given amplitude. $A$ is the amplitude and $\lambda$ is the wavelength. $\pi$ is $\pi$ radians or $180^\circ$ and $2\pi$ is the radian value at $360^\circ$.

Figure 2.5 A simple sine wave. (a) Lower frequency. (b) Higher frequency. Note that the wavelength is shown traditionally as $\lambda$ (the Greek letter lambda) and that part $a$ has a longer wavelength than part $b$.

maximum excursion in the negative or positive direction (up or down). In this case it is 6 volts. If it is in the “down” direction, it would be $-6$ volts, based on Figure 2.5; and in the “up” direction it would be $+6$ volts.

Frequency is an important aspect of music. For example, the key of A is 440 Hz and middle C is 263 Hz. Note that the unit of measurement of frequency used to be cycles per second (prior to 1963) and now the unit of measure is Hz named for Heinrich Hertz, a German physicist credited with the discovery of radio waves. Simple sine waves can be produced in the laboratory with a signal generator, which is an electronic oscillator that can be tuned to different frequencies. An audio signal generator can be tuned to 263 Hz, middle C, and we can hear it if the generator output is connected to a loudspeaker. These are sound frequencies.

When we listen to the radio on the AM broadcast band, we may listen to a talk show on WOR, at a frequency of 710 kHz (kilohertz, meaning 710,000 Hz). On the FM band in the Phoenix, AZ, area, we may tune to a classical music station, KBAQ, at 89.5 MHz (89,500,000 Hz). These are radio frequencies.
Metric prefixes are often used, when appropriate, to express frequency as illustrated in the above paragraph. For example, kilohertz (kHz), megahertz (MHz), and gigahertz (GHz) are used for Hz \times 1000, Hz \times 1,000,000, and Hz \times 1,000,000,000. Thus 38.71 GHz is 38,710,000,000 Hz.

Wavelength is conventionally measured in meters and is represented by the symbol \( \lambda \). It is defined as the distance between successive peaks or troughs of a sinusoidal wave (i.e., D in Figure 2.5). Both sound and radio waves each travel with a certain velocity of propagation. Radio waves travel at 186,000 mi/sec in a vacuum, or \( 3 \times 10^8 \) m/sec.\(^1\) If we multiply frequency in hertz times the wavelength in meters, we get a constant, the velocity of propagation. In a vacuum (or in free space),

\[
F \lambda = 3 \times 10^8 \text{ m/sec},
\]

where \( F \) is measured in hertz, and \( \lambda \) is measured in meters (m). This is an important concept that will be freely used in the remainder of this text.

**Example 1.** The international calling and distress frequency is 500 kHz. What is the equivalent wavelength in meters?

\[
500,000 \lambda = 3 \times 10^8 \text{ m/sec} \\
\lambda = \frac{3 \times 10^8}{5 \times 10^5} \\
= 600 \text{ m}.
\]

**Example 2.** A line-of-sight millimeter-wave radio\(^2\) link operates at 38.71 GHz. What is the equivalent wavelength at this frequency?

\[
38.71 \times 10^9 \lambda = 3 \times 10^8 \text{ m/sec} \\
\lambda = \frac{3 \times 10^8}{38.71 \times 10^9} \\
\lambda = 0.00775 \text{ m or 7.75 mm}.
\]

Figure 2.6 is an outline drawing of the radio frequency spectrum from nearly zero Hz to 100 GHz. The drawing shows several frequency bands assigned to specific services.

### 2.3.3.1 Introduction to Phase

The IEEE defines *phase* as “a relative measurement that describes the temporal relationship between two signals that have the same frequency.” We can plot a sine wave (representing a certain frequency) by the method shown in Figure 2.7, where the horizontal lines are continuation of points a, b, c, and so on, and the vertical lines \( a', b', c', \) and so on, are equally spaced and indicate *angular degrees of rotation*. The intersection of lines a and \( a' \), b and \( b' \), and so on, indicates points on the sine wave curve.

To illustrate what is meant by *phase relation*, we turn to the construction of a sine wave using a circle as shown in Figure 2.7. In the figure the horizontal scale (the abscissa) represents time and the vertical scale (the ordinate) represents instantaneous values of

---

\(^1\)Sound waves travel at 1076 ft/sec (331 m/sec) in air at 0°C and with 1 atmosphere of atmospheric pressure. However, our interest here is in radio waves, not sound waves.

\(^2\)This is termed *millimeter* radio because wavelengths in this region are measured in millimeters (i.e., for frequencies above 30 GHz) rather than in centimeters or meters.
Figure 2.6 The radio-frequency spectrum showing some frequency band assignments.
current or voltage. The complete curve shows values of current (or voltage) for all instants during one complete cycle. It is convenient and customary to divide the time scale into units of degrees rather than seconds, considering one complete cycle as being completed always in 360 degrees or units of time (regardless of the actual time taken in seconds). The reason for this convention becomes obvious from the method of constructing the sine
wave as shown in Figure 2.7, where, to plot the complete curve, we take points around the circumference of the circle through 360 angular degrees. It needs to be kept in mind that in the sense now used, the degree is a measure of time in terms of the frequency, not of an angle.

We must understand phase and phase angle because it will be used in our discussions of modulation and of certain types of distortion that can limit the rate of transmitting information and/or corrupt a wanted signal (Ref. 2).

An example of two signals of the same frequency, in phase and with different amplitudes, is illustrated in Figure 2.8a, and another example of two signals of the same frequency and amplitude, but 180 degrees out of phase, is shown in Figure 2.8b. Note the use of $\pi$ in the figure, meaning $\pi$ radians or $180^\circ$, $2\pi$ radians or $360^\circ$. See Appendix A, Section A.9.

### 2.4 ELECTRICAL SIGNALS

#### 2.4.1 Introduction to Transmission

*Transmission* may be defined as the electrical transfer of a signal, message, or other form of intelligence from one location to another. Traditionally, transmission has been one of the two major disciplines of telecommunication. *Switching* is the other principal specialty. Switching establishes a connection from user X to some distant user Y. Simplistically, we can say that transmission is responsible for the transport of the signal from user X to user Y. In the old days of telephony, these disciplines were separate with strong demarcation between one and the other. Not so today. The demarcation line is fast disappearing. For example, under normal circumstances in the PSTN, a switch provides network timing that is vital for digital transmission.

What we have been dealing with so far is *baseband* transmission. This is the transmission of a raw electrical signal described in Section 2.3.2. This type of baseband signal is very similar to the 1s and 0s transmitted electrically from a PC. Another type of baseband signal is the alternating current derived from the mouthpiece of a telephone handset (subset). Here the alternating current is an electrical facsimile of the voice sound wave impinging on the telephone microphone.

Baseband transmission can have severe distance limitations. We will find that the signal can only be transmitted so far before being corrupted one way or another. For example, a voice signal transmitted from a standard telephone set over a fairly heavy copper wire pair (19 gauge) may reach a distant subset earpiece some 30 km or less distant before losing all intelligibility. This is because the signal strength is so very low that it becomes inaudible.

To overcome this distance limitation, we may turn to *carrier* or *radio* transmission. Both transmission types involve the generation and conditioning of a radio signal. Carrier transmission usually implies (not always) the use of a conductive medium such as wire pair, coaxial cable, or fiber-optic cable to carry a radio or light-derived signal. Radio transmission always implies radiation of the signal in the form of an electromagnetic wave. We listen to the radio or watch television. These are received and displayed or heard as the result the reception of radio signals.

#### 2.4.2 Modulation

At the transmitting side of a telecommunication link a radio carrier is generated. The carrier is characterized by a frequency, described in Section 2.3.3. This single radio frequency carries no useful information for the user. *Useful* information may include voice,
data, or image (typically facsimile or television). Modulation is the process of impinging that useful information on the carrier, and demodulation is the recovery of that information from the carrier at the distant end near the destination user.

The IEEE defines modulation as “a process whereby certain characteristics of a wave, often called the carrier, are varied or selected in accordance with a modulating function.” The modulating function is the information baseband described above.

There are three generic forms of modulation:

1. Amplitude modulation (AM)
2. Frequency modulation (FM)
3. Phase modulation (PM).

Item 1 (amplitude modulation) is where a carrier is varied in amplitude in accordance with information baseband signal. In the case of item 2 (frequency modulation), a carrier is varied in frequency in accordance with the baseband signal. For item 3 (phase modulation) a carrier is varied in its phase in accordance with the information baseband signal.

Figure 2.9 graphically illustrates amplitude, frequency, and phase modulation. The modulating signal is a baseband stream of bits: 1s and 0s. We deal with digital transmission (e.g., 1s and 0s) extensively in Chapters 6 and 10.

Prior to 1960, all transmission systems were analog. Today, in the PSTN, all telecommunication systems are digital, except for the preponderance of subscriber access lines. These are the subscriber loops described in Chapter 1. Let us now distinguish and define analog and digital transmission.

2.4.2.1 Analog Transmission. Analog transmission implies continuity as contrasted with digital transmission that is concerned with discrete states. Many signals can be used in either the analog or digital sense, the means of carrying the information being the distinguishing feature. The information content of an analog signal is conveyed by the value or magnitude of some characteristic(s) of the signal such as amplitude, frequency, or phase of a voltage, the amplitude or duration of a pulse, the angular position of a shaft, or the pressure of a fluid. Typical analog transmission are the signals we hear on AM and FM radio and what we see (and hear) on television. In fact, television is rather unique. The video itself uses amplitude modulation; the sound subcarrier uses frequency modulation, and the color subcarrier employs phase modulation. All are in analog formats.

2.4.2.2 Digital Transmission. The information content of a digital signal is concerned with discrete states of the signal, such as the presence or absence of a voltage (see Section 2.3.2); a contact is the open or closed position, or a hole or no hole in certain positions on a card or paper tape. The signal is given meaning by assigning numerical values or other information to the various combinations of the discrete states of the signal. We will be dealing extensively with digital transmission as the argument in this text proceeds.

2.4.3 Binary Digital Signals

In Section 2.4.1, we defined a digital waveform as one that displayed discreteness. Suppose we consider the numbers 0 through 9. In one case, only integer values are permitted in this range, no in-between values such as 3.761 or 8.07. This is digital where we can only
Figure 2.9 Illustration of amplitude, frequency, and phase modulation, where the modulating signal is the binary digital sequence 00110100010, an electrical baseband signal.

assign integer values between 0 and 9. These are discrete values. On the other hand, if we can assign any number value between 0 and 9, there could be an infinite number of values such as 7.01648754372100. This, then, is analog. We have continuity, no discreteness.

Consider now how neat it would be if we had only two values in our digital system. Arbitrarily, we'll call them a 1 and a 0. This is indeed a binary system, just two possible values. It makes the work of a decision circuit really easy. Such a circuit has to decide on just one of two possibilities. Look at real life: A light is on or it is off; two values, on and off. A car engine is running or not running, and so on. In our case of interest, we denominate one value a 1 and denominate the other a 0. We could have a condition where current flows, and we'll call that condition a 1; no current flowing we'll call a 0 (Ref. 3).³

³The reader with insight will note an ambiguity here. We could reverse the conditions, making the 1 state a 0 and the 0 state a 1. We address this issue in Chapter 10.
Of course we are defining a binary system with a number base of 2. Our day-to-day numbers are based on a decimal number system where the number base is 10. There is a review of binary arithmetic in Appendix B.

The basic key in binary digital transmission is the bit, which is the smallest unit of information in the binary system of notation. It is the abbreviation of the term binary digit. It is a unit of information represented by either a “1” or a “0.”

A 1 and a 0 do not carry much information, yet we do use just one binary digit in many applications. One of the four types of telephone signaling is called supervisory signaling. The only information necessary in this case is that the line is busy or it is idle. We may assign the idle state a 0 and the busy state a 1. Another application where only a single binary digit is required is in built-in test equipment (BITE). In this case, we accept one of two conditions: A circuit, module, or printed circuit board (PCB) is operational or it is not. BITE automates the troubleshooting of electronic equipment.

To increase the information capacity of a binary system is to place several bits (binary digits) contiguously together. For instance, if we have a 2-bit code, there are four possibilities: 00, 01, 10, and 11. A 3-bit code provides eight different binary sequences, each 3 bits long. In this case we have 000, 001, 010, 011, 100, 101, 110, and 111. We could assign letters of the alphabet to each sequence. There are only eight distinct possibilities, so only eight letters can be accommodated. If we turn to a 4-bit code, 16 distinct binary sequences can be developed, each 4 bits long. A 5-bit code will develop 32 distinct sequences, and so on.

As a result, we can state that for a binary code of length $n$, we will have $2^n$ different possibilities. The American Standard Code for Information Interchange (ASCII) is a 7-bit code (see Section 10.4); it will then have $2^7$, or 128, binary sequence possibilities. When we deal with pulse code modulation (PCM) (Chapter 6) as typically employed on the PSTN, a time slot contains 8 bits. We know that an 8-bit binary code has 256 distinct 8-bit sequences (i.e., $2^8 = 256$).

Consider the following important definitions when dealing with the bit and binary transmission. Bit rate is defined as the number of bits (those 1s and 0s) that are transmitted per second. Bit error rate (BER) is the number of bit errors measured or expected per unit of time. Commonly, the time unit is the second. An error, of course, is where a decision circuit declares a 1 when it was supposed to be a 0, or declares a 0 when it was supposed to be a 1 (Ref. 4).

2.5 INTRODUCTION TO TRANSPORTING ELECTRICAL SIGNALS

To transport electrical signals, a transmission medium is required. There are four types of transmission media:

1. Wire pair
2. Coaxial cable
3. Fiber-optic cable
4. Radio

2.5.1 Wire Pair

As one might imagine, a wire pair consists of two wires. The wires commonly use a copper conductor, although aluminum conductors have been employed. A basic impairment of wire pair is loss. Loss is synonymous with attenuation. Loss can be defined
as the dissipation of signal strength as a signal travels along a wire pair, or any other transmission medium for that matter. Loss or attenuation is usually expressed in decibels (dB). In Appendix C the reader will find a tutorial on decibels and their applications in telecommunications.

Loss causes the signal power to be dissipated as a signal passes along a wire pair. Power is expressed in watts. For this application, the use of milliwatts may be more practical. If we denominate loss with the notation \( L_{dB} \), then

\[
L_{dB} = 10 \log \left( \frac{P_1}{P_2} \right),
\]

(2.2)

where \( P_1 \) is the power of the signal where it enters the wire pair, and \( P_2 \) is the power level of the signal at the distant end of the wire pair. This is the traditional formula defining the decibel in the power domain. See Appendix C.

**Example 1.** Suppose a 10-mW (milliwatt), 1000-Hz signal is launched into a wire pair. At the distant end of the wire pair the signal is measured at 0.2 mW. What is the loss in decibels on the line for this signal?

\[
L_{dB} = 10 \log \left( \frac{10}{0.2} \right)
\]

\[
= 10 \log(50)
\]

\[
\approx 17 \text{ dB}
\]

All logarithms used in this text are to the base 10. Appendix B provides a review of logarithms and their applications.

The opposite of loss is *gain*. An attenuator is a device placed in a circuit to purposely cause loss. An *amplifier* does just the reverse; that is, it gives a signal gain. An amplifier increases a signal’s intensity. We will use the following graphic symbol for an attenuator:

![Attenuator Symbol](image)

We will also use the following symbol for an amplifier:

![Amplifier Symbol](image)

Wire-pair transmission suffers other impairments besides loss. One of these impairments is *crosstalk*. Most of us have heard crosstalk on our telephone line. It appears as another, “foreign” conversation having nothing to do with our telephone call. One basic cause of crosstalk is from other wire pairs sharing the same cable as our line. These other conversations are electrically induced into our line. To mitigate this impairment, physical twists are placed on each wire pair in the cable. Generally there are 2 to 12 twists per foot of wire pair. From this we get the term *twisted pair*. The following figure shows a
Another impairment causes a form of delay distortion on the line, which is cumulative and varies directly with the length of the line as well as with the construction of the wire itself. It has little effect on voice transmission, but can place definition restrictions on data rate for digital/data transmission on the pair. The impairment is due to the capacitance between one wire and the other of the pair, between each wire and ground, and between each wire and the shield, if a shield is employed. Delay distortion is covered in greater depth in Chapters 6 and 10.

2.5.1.1 Capacitance. Direct-current (DC) circuits are affected by resistance, whereas alternating-current (AC) circuits, besides resistance, are affected by the properties of inductance and capacitance. In this subsection, we provide a brief description of capacitance. Also see Appendix A, Section A.8.

Capacitance is somewhat analogous to elasticity. While a storage battery stores electricity as another form of energy (i.e., chemical energy), a capacitor stores electricity in its natural state. An analogy of capacitance is a closed tank filled with compressed air. The quantity of air, since air is elastic, depends upon the pressure as well as the size or capacity of the tank. If a capacitor is connected to a direct source of voltage through a switch, as shown in Figure 2.10, and the switch is suddenly closed, there will be a rush of current in the circuit. This current will charge the capacitor to the same voltage value as the battery, but the current will decrease rapidly and become zero when the capacitor is fully charged.

Let us define a capacitor as two conductors separated by an insulator. A conductor conducts electricity. Certain conductors conduct electricity better than others. Platinum and gold are very excellent conductors, but very expensive. Copper does not conduct electricity as well as gold and platinum, but is much more cost-effective. An insulator carries out the opposite function of a conductor. It tends to prevent the flow of electricity through it. Some insulators are better than others regarding the conduction of electricity. Air is an excellent insulator. However, we well know that air can pass electricity if the voltage is very high. Consider lightning, for example. Other examples of insulators are bakelite, celluloid, fiber, formica, glass, lucite, mica, paper, rubber, and wood.

![Figure 2.10 A simple capacitive circuit.](image-url)
The insulated conductors of every circuit, such as our wire pair, have to a greater or lesser degree this property of capacitance. The capacitance of two parallel open wires or a pair of cable conductors of any considerable length is appreciable in practice.

2.5.1.2 Bandwidth (Hz) of a Twisted Pair. The usable bandwidth of twisted wire pair varies with the type of wire pair used and its length. Ordinary wire pair used in the PSTN subscriber access plant can support 2 MHz over about 1 mile of length. Special Category 5 twisted pair displays a 67-dB loss at 100 MHz over a length of 1000 ft.

2.5.1.3 Bandwidth Defined. The IEEE defines bandwidth as “the range of frequencies within which performance, with respect to some characteristic, falls within specific limits.” One such limit is the amplitude of a signal within the band. Here it is commonly defined at the points where the response is 3 dB below the reference value. This 3-dB power bandwidth definition is illustrated graphically in Figure 2.11.

2.5.2 Coaxial Cable Transmission

Up to this point we have been discussing two parallel conductors, namely, wire pair. An entirely different configuration of two conductors may be used to advantage where high and very high radio frequencies are involved. This is a coaxial configuration. Here the conducting pair consists of a cylindrical tube with a single wire conductor going down its center as shown in Figure 2.12. In practice the center conductor is held in place accurately by a surrounding insulating material that may take the form of a solid core, discs, or beads strung along the axis of the wire or a spirally wrapped string. The nominal impedance is 75 ohms, and special cable is available with a 50-ohm impedance.

![Figure 2.11](image1.png)  
*Figure 2.11* The concept of the 3-dB power bandwidth.

![Figure 2.12](image2.png)  
*Figure 2.12* A pictorial representation of a coaxial cable section.
Impedance can be defined as the combined effect of a circuit’s resistance, inductance, and capacitance taken as a single property and is expressed in ohms for any given sine wave frequency. Further explanation of impedance will be found in Appendix A.

From about 1953 to 1986, coaxial cable was widely deployed for long-distance, multichannel transmission. Its frequency response was exponential. In other words, its loss increased drastically as frequency was increased. For example, for 0.375-inch coaxial cable, the loss at 100 kHz was about 1 dB and the loss at 10 MHz was about 12 dB. Thus, equalization was required. Equalization tends to level out the frequency response. With the advent of fiber-optic cable with its much greater bandwidth and comparatively flat frequency response, the use of coaxial cable on long-distance circuits fell out of favor. It is still widely used as a (radio-frequency) (RF) transmission line connecting a radio to its antenna. It is also extensively employed in cable television plant, especially in the “last mile” or “last 100 ft” of connectivity to a subscriber’s television set.

2.5.3 Fiber-Optic Cable

Fiber-optic cable is the favored transmission medium for very wideband terrestrial links, including undersea applications. It is also used for cable television “super trunks.” The bandwidth of fiber-optic strand can be measured in terahertz (THz). In fact, the whole usable RF spectrum can be accommodated on just one such strand. Such a strand is about the diameter of a human hair. It can carry one serial bit stream at 10 Gbps (gigabits per second) transmission rate, or by wave division multiplexing methods (WDM), an aggregate of 100 Gbps or more. Fiber-optic transmission will be discussed further in Chapter 9.

Fiber-optic systems can be loss-limited or dispersion-limited. If a fiber-optic link is limited by loss, it means that as the link is extended in distance, the signal has dissipated so much that it becomes unusable. The maximum loss that a link can withstand and still operate satisfactorily is a function of the type of fiber, wavelength of the light signal, the bit rate and error rate, signal type (e.g., TV video), power output of the light source (transmitter), and the sensitivity of the light detector (receiver).

Dispersion-limited means that a link’s length is limited by signal corruption. As a link is lengthened, there may be some point where the bit error rate (BER) becomes unacceptable. This is caused by signal energy of a particular pulse that arrives later than other signal energy of the same pulse. There are several reasons why energy elements of a single light pulse may become delayed compared to other elements. One may be that certain launched modes arrive at the distant end before other modes. Another may be that certain frequencies contained in a light pulse arrive before other frequencies. In either case, delayed power spills into the subsequent bit position, which can confuse the decision circuit. The decision circuit determines whether the pulse represented a 1 or a 0. The higher the bit rate, the worse the situation becomes. Also, the delay increases as a link is extended.

The maximum length of fiber-optic links range from 20 miles (32 km) to several hundred miles (km) before requiring a repeater. This length can be extended by the use of amplifiers and/or repeaters, where each amplifier can impart a 20- to 40-dB gain. A fiber-optic repeater detects, demodulates, and then remodulates a light transmitter. In the process of doing this, the digital signal is regenerated. A regenerator takes a corrupted and distorted digital signal and forms a brand new, nearly perfect digital signal.

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5In the world of fiber optics, wavelength is used rather than frequency. We can convert wavelength to frequency using Eq. (2.1). One theory is that fiber-optic transmission was developed by physicists who are more accustomed to wavelength than to frequency.
A simplified model of a fiber-optic link is illustrated in Figure 2.13. In this figure, the driver conditions the electrical baseband signal prior to modulation of the light signal; the optical source is the transmitter where the light signal is generated and modulated; the fiber-optic transmission medium consists of a fiber strand, connectors, and splices; the optical detector is the receiver where the light signal is detected and demodulated; and the output circuit conditions the resulting electrical baseband signal for transmission to the electrical line (Ref. 3).

A more detailed discussion of fiber-optic systems will be found in Chapter 9.

### 2.5.4 Radio Transmission

Up to now we have discussed guided transmission. The signal is guided or conducted down some sort of a “pipe.” The “pipes” we have covered included wire pair, coaxial cable, and fiber-optic cable. Radio transmission, on the other hand, is based on radiated emission.

The essential elements of any radio system are (1) a transmitter for generating and modulating a “high-frequency”\(^6\) carrier wave with an information baseband, (2) a transmitting antenna that will radiate the maximum amount of signal energy of the modulated carrier in the desired direction, (3) a receiving antenna that will intercept the maximum amount of the radiated energy after its transmission through space, and (4) a receiver to select the desired carrier wave, amplify the signal, detect it, or separate the signal from the carrier. Although the basic principles are the same in all cases, there are many different designs of radio systems. These differences depend upon the types of signals to be transmitted, type of modulation (AM, FM, or PM or a hybrid), where in the frequency spectrum (see Figure 2.6) in which transmission is to be affected, and licensing restrictions. Figure 2.14 is a generalized model of a radio link.

The information transport capacity of a radio link depends on many factors. The first factor is the application. The following is a brief list of applications with some relevant RF bandwidths:

- Line-of-sight microwave, depending on the frequency band: 2, 5, 10, 20, 30, 40, 60 MHz.
- SCADA (system control and data acquisition): up to 12 kHz in the 900-MHz band.

\(^6\)In the context of this book, “high-frequency” takes on the connotation of any signal from 400 MHz to 100 GHz.
Satellite communications, geostationary satellites: 500 MHz or 2.5-GHz bandwidths broken down into 36- and 72-MHz segments.

Cellular radio: 25-MHz bandwidth in the 800/900-MHz band. The 25-MHz band is split into two 12.5-MHz segments for two competitive providers.

Personal communication services (PCS): 200-MHz band just below 2.0 GHz, broken down into various segments such as licensed and unlicensed users.

Cellular/PCS by satellite (e.g., Iridium, Globalstar), 10.5-MHz bandwidth in the 1600-MHz band.

Local multipoint distribution system (LMDS) in 28/38-GHz bands, 1.2-GHz bandwidth for CATV, Internet, data, and telephony services (Ref. 5).

Bandwidth is also determined by the regulating authority (e.g., the FCC in the United States) for a particular service/application. Through bit packing techniques, described in Chapter 9, the information carrying capacity of a unit of bandwidth is considerably greater than 1 bit per Hz of bandwidth. On line-of-sight microwave systems, 5, 6, 7, and 8 bits per hertz of bandwidth are fairly common.

Figure 2.14 A generic model of a typical radio link.