CHAPTER 4

TRANSMISSION MEDIA

KEY POINTS

- The transmission media that are used to convey information can be classified as guided or unguided. Guided media provide a physical path along which the signals are propagated; these include twisted pair, coaxial cable, and optical fiber. Unguided media employ an antenna for transmitting through air, vacuum, or water.
- Traditionally, twisted pair has been the workhorse for communications of all sorts. Higher data rates over longer distances can be achieved with coaxial cable, and so coaxial cable has often been used for high-speed local area network and for high-capacity long-distance trunk applications. However, the tremendous capacity of optical fiber has made that medium more attractive than coaxial cable, and thus optical fiber has taken over much of the market for high-speed LANs and for long-distance applications.
- Unguided transmission techniques commonly used for information communications include broadcast radio, terrestrial microwave, and satellite. Infrared transmission is used in some LAN applications.

In a data transmission system, the **transmission medium** is the physical path between transmitter and receiver. Recall from Chapter 3 that for **guided media**, electromagnetic waves are guided along a solid medium, such as copper twisted pair, copper coaxial cable, and optical fiber. For unguided media, wireless transmission occurs through the atmosphere, outer space, or water.

The characteristics and quality of a data transmission are determined both by the characteristics of the medium and the characteristics of the signal. In the case of guided media, the medium itself is more important in determining the limitations of transmission.

For unguided media, the bandwidth of the signal produced by the transmitting antenna is more important than the medium in determining transmission characteristics. One key property of signals transmitted by antenna is directionality. In general, signals at lower frequencies are omnidirectional; that is, the signal propagates in all directions from the antenna. At higher frequencies, it is possible to focus the signal into a directional beam.

In considering the design of data transmission systems, key concerns are data rate and distance: the greater the data rate and distance the better. A number of design factors relating to the transmission medium and the signal determine the data rate and distance:

- **Bandwidth:** All other factors remaining constant, the greater the bandwidth of a signal, the higher the data rate that can be achieved.
- **Transmission impairments:** Impairments, such as attenuation, limit the distance. For guided media, twisted pair generally suffers more impairment than coaxial cable, which in turn suffers more than optical fiber.
- **Interference:** Interference from competing signals in overlapping frequency bands can distort or wipe out a signal. Interference is of particular concern for unguided media but is also a problem with guided media. For guided media,

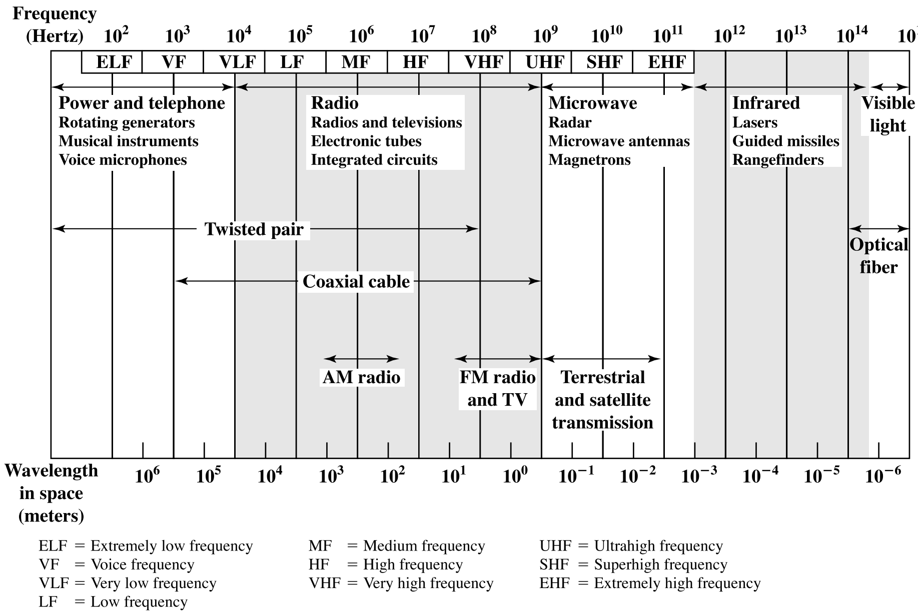


Figure 4.1 Electromagnetic Spectrum for Telecommunications

interference can be caused by emanations from nearby cables. For example, twisted pairs are often bundled together and conduits often carry multiple cables. Interference can also be experienced from unguided transmissions. Proper shielding of a guided medium can minimize this problem.

- **Number of receivers:** A guided medium can be used to construct a point-to-point link or a shared link with multiple attachments. In the latter case, each attachment introduces some attenuation and distortion on the line, limiting distance and/or data rate.

Figure 4.1 depicts the electromagnetic spectrum and indicates the frequencies at which various guided media and unguided transmission techniques operate. In this chapter we examine these guided and unguided alternatives. In all cases, we describe the systems physically, briefly discuss applications, and summarize key transmission characteristics.

4.1 GUIDED TRANSMISSION MEDIA

For guided transmission media, the transmission capacity, in terms of either data rate or bandwidth, depends critically on the distance and on whether the medium is point-to-point or multipoint. Table 4.1 indicates the characteristics typical for the common guided media for long-distance point-to-point applications; we defer a discussion of the use of these media for multipoint LANs to Part Four.

Table 4.1 Point-to-Point Transmission Characteristics of Guided Media [GLOV98]

	Frequency Range	Typical Attenuation	Typical Delay	Repeater Spacing
Twisted pair (with loading)	0 to 3.5 kHz	0.2 dB/km @ 1kHz	50 μs/km	2 km
Twisted pairs (multi-pair cables)	0 to 1 MHz	3 dB/km @ 1kHz	5 μs/km	2 km
Coaxial cable	0 to 500 MHz	7 dB/km @ 10 MHz	4 μs/km	1 to 9 km
Optical fiber	180 to 370 THz	0.2 to 0.5 dB/km	5 μs/km	40 km

THz = TeraHerz = 10^{12} Hz.

The three guided media commonly used for data transmission are twisted pair, coaxial cable, and optical fiber (Figure 4.2). We examine each of these in turn.

Twisted Pair

The least expensive and most widely used guided transmission medium is twisted pair.

Physical Description

A twisted pair consists of two insulated copper wires arranged in a regular spiral pattern. A wire pair acts as a single communication link. Typically, a number of these pairs are bundled together into a cable by wrapping them in a tough protective sheath. Over longer distances, cables may contain hundreds of pairs. The twisting tends to decrease the crosstalk interference between adjacent pairs in a cable. Neighboring pairs in a bundle typically have somewhat different twist lengths to reduce the crosstalk interference. On long-distance links, the twist length typically varies from 5 to 15 cm. The wires in a pair have thicknesses of from 0.4 to 0.9 mm.

Applications

By far the most common transmission medium for both analog and digital signals is twisted pair. It is the most commonly used medium in the telephone network and is the workhorse for communications within buildings.

In the telephone system, individual residential telephone sets are connected to the local telephone exchange, or "end office," by twisted-pair wire. These are referred to as **subscriber loops**. Within an office building, each telephone is also connected to a twisted pair, which goes to the in-house private branch exchange (PBX) system or to a Centrex facility at the end office. These twisted-pair installations were designed to support voice traffic using analog signaling. However, by means of a modem, these facilities can handle digital data traffic at modest data rates.

Twisted pair is also the most common medium used for digital signaling. For connections to a digital data switch or digital PBX within a building, a data rate of 64 kbps is common. Twisted pair is also commonly used within a building for local area networks supporting personal computers. Data rates for such products are typically in the neighborhood of 10 Mbps. However, twisted-pair networks with data rates of to 1 Gbps have been developed, although these are quite limited in terms of

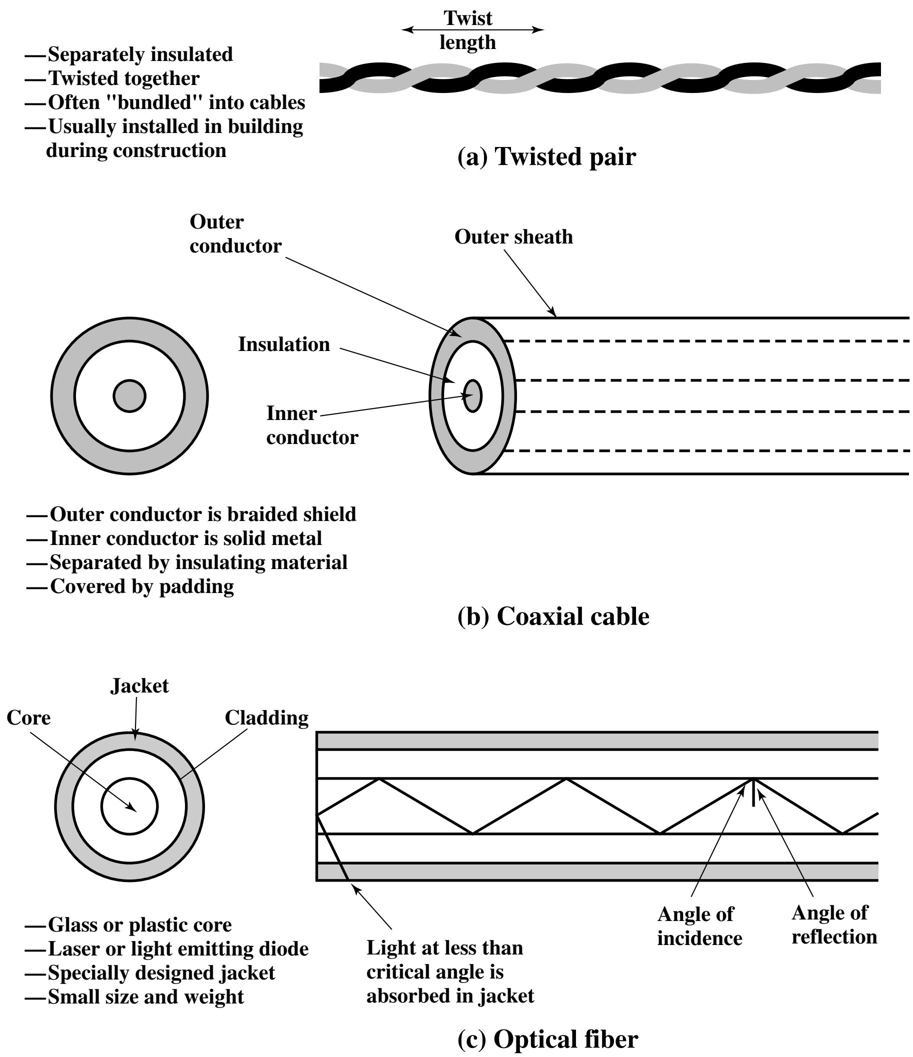


Figure 4.2 Guided Transmission Media

the number of devices and geographic scope of the network. For long-distance applications, twisted pair can be used at data rates of 4 Mbps or more.

Twisted pair is much less expensive than the other commonly used guided transmission media (coaxial cable, optical fiber) and is easier to work with.

Transmission Characteristics

Twisted pair may be used to transmit both analog and digital transmission. For analog signals, amplifiers are required about every 5 to 6 km. For digital transmission (using either analog or digital signals), repeaters are required every 2 or 3 km.

Compared to other commonly used guided transmission media (coaxial cable, optical fiber), twisted pair is limited in distance, bandwidth, and data rate. As

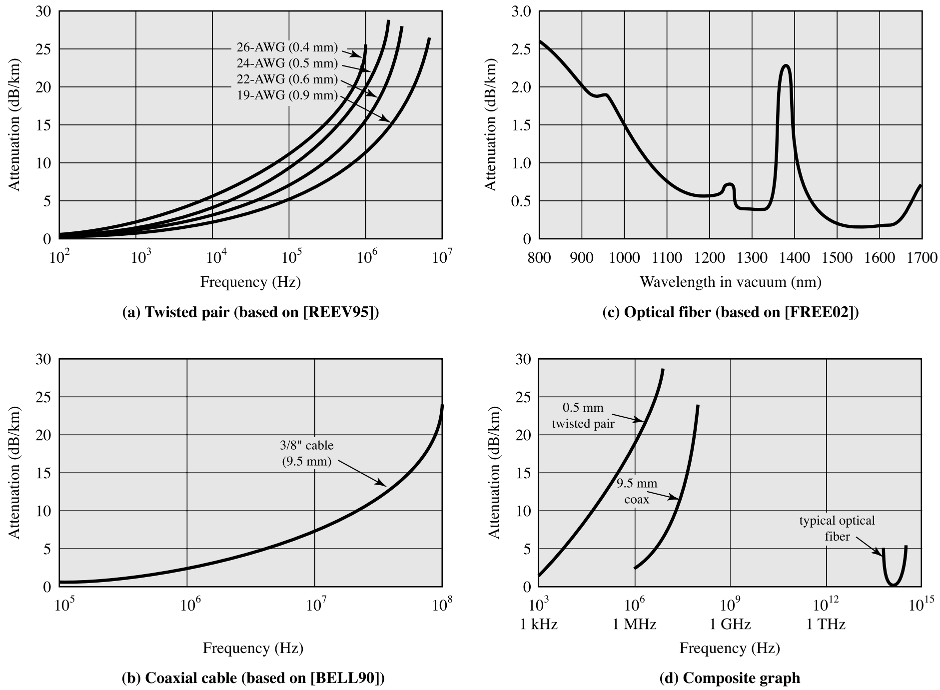


Figure 4.3 Attenuation of Typical Guided Media

Figure 4.3a shows, the attenuation for twisted pair is a very strong function of frequency. Other impairments are also severe for twisted pair. The medium is quite susceptible to interference and noise because of its easy coupling with electromagnetic fields. For example, a wire run parallel to an ac power line will pick up 60-Hz energy. Impulse noise also easily intrudes into twisted pair. Several measures are taken to reduce impairments. Shielding the wire with metallic braid or sheathing reduces interference. The twisting of the wire reduces low-frequency interference, and the use of different twist lengths in adjacent pairs reduces crosstalk.

For point-to-point analog signaling, a bandwidth of up to about 1 MHz is possible. This accommodates a number of voice channels. For long-distance digital point-to-point signaling, data rates of up to a few Mbps are possible; for very short distances, data rates of up to 1 Gbps have been achieved in commercially available products.

Unshielded and Shielded Twisted Pair

Twisted pair comes in two varieties: unshielded and shielded. Unshielded twisted pair (UTP) is ordinary telephone wire. Office buildings, by universal practice, are prewired with excess unshielded twisted pair, more than is needed for simple telephone support. This is the least expensive of all the transmission media commonly used for local area networks and is easy to work with and easy to install.

Unshielded twisted pair is subject to external electromagnetic interference, including interference from nearby twisted pair and from noise generated in the environment. A way to improve the characteristics of this medium is to shield the twisted pair with a metallic braid or sheathing that reduces interference. This shielded twisted pair (STP) provides better performance at higher data rates. However, it is more expensive and more difficult to work with than unshielded twisted pair.

Category 3 and Category 5 UTP

Most office buildings are prewired with a type of 100-ohm twisted pair cable commonly referred to as voice grade. Because voice-grade twisted pair is already installed, it is an attractive alternative for use as a LAN medium. Unfortunately, the data rates and distances achievable with voice-grade twisted pair are limited.

In 1991, the Electronic Industries Association published standard EIA-568, *Commercial Building Telecommunications Cabling Standard*, which specifies the use of voice-grade unshielded twisted pair as well as shielded twisted pair for in-building data applications. At that time, the specification was felt to be adequate for the range of frequencies and data rates found in office environments. Up to that time, the principal interest for LAN designs was in the range of data rates from 1 Mbps to 16 Mbps. Subsequently, as users migrated to higher-performance workstations and applications, there was increasing interest in providing LANs that could operate up to 100 Mbps over inexpensive cable. In response to this need, EIA-568-A was issued in 1995. The new standard reflects advances in cable and connector design and test methods. It covers 150-ohm shielded twisted pair and 100-ohm unshielded twisted pair.

EIA-568-A recognizes three categories of UTP cabling:

- **Category 3:** UTP cables and associated connecting hardware whose transmission characteristics are specified up to 16 MHz
- **Category 4:** UTP cables and associated connecting hardware whose transmission characteristics are specified up to 20 MHz
- **Category 5:** UTP cables and associated connecting hardware whose transmission characteristics are specified up to 100 MHz

Of these, it is Category 3 and Category 5 cable that have received the most attention for LAN applications. Category 3 corresponds to the voice-grade cable found in abundance in most office buildings. Over limited distances, and with proper design, data rates of up to 16 Mbps should be achievable with Category 3. Category 5 is a data-grade cable that is becoming increasingly common for preinstallation in new office buildings. Over limited distances, and with proper design, data rates of up to 100 Mbps should be achievable with Category 5.

A key difference between Category 3 and Category 5 cable is the number of twists in the cable per unit distance. Category 5 is much more tightly twisted, with a typical twist length of 0.6 to 0.85 cm, compared to 7.5 to 10 cm for Category 3. The tighter twisting of Category 5 is more expensive but provides much better performance than Category 3.

Table 4.2 summarizes the performance of Category 3 and 5 UTP, as well as the STP specified in EIA-568-A. The first parameter used for comparison, attenuation, is fairly straightforward. The strength of a signal falls off with distance over any transmission medium. For guided media attenuation is generally exponential and therefore is typically expressed as a constant number of decibels per unit distance.

Table 4.2 Comparison of Shielded and Unshielded Twisted Pair

	Attenuation (dB per 100 m)			Near-end Crosstalk (dB)		
Frequency (MHz)	**Category 3 UTP**	**Category 5 UTP**	**150-ohm STP**	**Category 3 UTP**	**Category 5 UTP**	**150-ohm STP**
1	2.6	2.0	1.1	41	62	58
4	5.6	4.1	2.2	32	53	58
16	13.1	8.2	4.4	23	44	50.4
25	—	10.4	6.2	—	41	47.5
100	—	22.0	12.3	—	32	38.5
300	—	—	21.4	—	—	31.3

Near-end crosstalk as it applies to twisted pair wiring systems is the coupling of the signal from one pair of conductors to another pair. These conductors may be the metal pins in a connector or wire pairs in a cable. The near end refers to coupling that takes place when the transmit signal entering the link couples back to the receiving conductor pair at that same end of the link (i.e., the near transmitted signal is picked up by the near receive pair).

Since the publication of EIA-568-A, there has been ongoing work on the development of standards for premises cabling, driven by two issues. First, the Gigabit Ethernet specification requires the definition of parameters that are not specified completely in any published cabling standard. Second, there is a desire to specify cabling performance to higher levels, namely Enhanced Category 5 (Cat 5E), Category 6, and Category 7. Tables 4.3 and 4.4 summarize these new cabling schemes and compare them to the existing standards.

Coaxial Cable

Physical Description

Coaxial cable, like twisted pair, consists of two conductors, but is constructed differently to permit it to operate over a wider range of frequencies. It consists of a hollow outer cylindrical conductor that surrounds a single inner wire conductor (Figure 4.2b). The inner conductor is held in place by either regularly spaced insulating

Table 4.3 Twisted Pair Categories and Classes

	Category 3 Class C	**Category 5 Class D**	**Category 5E**	**Category 6 Class E**	**Category 7 Class F**
Bandwidth	16 MHz	100 MHz	100 MHz	200 MHz	600 MHz
Cable Type	UTP	UTP/FTP	UTP/FTP	UTP/FTP	SSTP
Link Cost (Cat 5 = 1)	0.7	1	1.2	1.5	2.2

UTP = Unshielded twisted pair
FTP = Foil twisted pair
SSTP = Shielded screen twisted pair

Table 4.4 High-Performance LAN Copper Cabling Alternatives [JOHN98]

Name	Construction	Expected Performance	Cost
Category 5 UTP	Cable consists of 4 pairs of 24 AWG (0.50 mm) copper with thermoplastic polyolefin or fluorinated ethylene propylene (FEP) jacket. Outside sheath consists of polyvinylchlorides (PVC), a fire-retardant polyolefin or fluoropolymers.	Mixed and matched cables and connecting hardware from various manufacturers that have a reasonable chance of meeting TIA Cat 5 Channel and ISO Class D requirements. No manufacturer's warranty is involved.	1
Enhanced Cat 5 UTP (Cat 5E)	Cable consists of 4 pairs of 24 AWG (0.50 mm) copper with thermoplastic polyolefin or fluorinated ethylene propylene (FEP) jacket. Outside sheath consists of polyvinylchlorides (PVC), a fire-retardant polyolefin or fluoropolymers. Higher care taken in design and manufacturing.	Category 5 components from one supplier or from multiple suppliers where components have been deliberately matched for improved impedance and balance. Offers ACR performance in excess of Cat 5 Channel and Class D as well as a 10-year or greater warranty.	1.2
Category 6 UTP	Cable consists of 4 pairs of 0.50 to 0.53 mm copper with thermoplastic polyolefin or fluorinated ethylene propylene (FEP) jacket. Outside sheath consists of polyvinylchlorides (PVC), a fire-retardant polyolefin or fluoropolymers. Extremely high care taken in design and manufacturing. Advanced connector designs.	Category 6 components from one supplier that are extremely well matched. Channel zero ACR point (effective bandwidth) is guaranteed to 200 MHz or beyond. Best available UTP. Performance specifications for Category 6 UTP to 250 MHz are under development.	1.5
Foil Twisted Pair	Cable consists of 4 pairs of 24 AWG (0.50 mm) copper with thermoplastic polyolefin or fluorinated ethylene propylene (FEP) jacket. Pairs are surrounded by a common metallic foil shield. Outside sheath consists of polyvinylchlorides (PVC), a fire-retardant polyolefin, or fluoropolymers.	Category 5 components from one supplier or from multiple suppliers where components have been deliberately designed to minimize EMI susceptibility and maximize EMI immunity. Various grades may offer increased ACR performance.	1.3
Shielded Foil Twisted Pair	Cable consists of 4 pairs of 24 AWG (0.50 mm) copper with thermoplastic polyolefin or fluorinated ethylene propylene (FEP) jacket. Pairs are surrounded by a common metallic foil shield, followed by a braided metallic shield. Outside sheath consists of polyvinylchlorides (PVC), a fire-retardant polyolefin, or fluoropolymers.	Category 5 components from one supplier or from multiple suppliers where components have been deliberately designed to minimize EMI susceptibility and maximize EMI immunity. Offers superior EMI protection to FTP.	1.4
Category 7 Shielded-Screen Twisted Pair	Also called PiMF (for Pairs in Metal Foil), SSTP of 4 pairs of 22-23AWG copper with a thermoplastic polyolefin or fluorinated ethylenepropylene (FEP) jacket. Pairs are individually surrounded by a helical or longitudinal metallic foil shield, followed by a braided metallic shield. Outside sheath of polyvinylchlorides (PVC), a fire-retardant polyolefin, or fluoropolymers.	Category 7 cabling provides positive ACR to 600 to 1200 MHz. Shielding on the individual pairs gives it phenomenal ACR.	2.2

ACR = Attenuation to crosstalk ratio
EMI = Electromagnetic interference

rings or a solid dielectric material. The outer conductor is covered with a jacket or shield. A single coaxial cable has a diameter of from 1 to 2.5 cm. Coaxial cable can be used over longer distances and support more stations on a shared line than twisted pair.

Applications

Coaxial cable is perhaps the most versatile transmission medium and is enjoying widespread use in a wide variety of applications. The most important of these are

- Television distribution
- Long-distance telephone transmission
- Short-run computer system links
- Local area networks

Coaxial cable is widely used as a means of distributing TV signals to individual homes—cable TV. From its modest beginnings as Community Antenna Television (CATV), designed to provide service to remote areas, cable TV reaches almost as many homes and offices as the telephone. A cable TV system can carry dozens or even hundreds of TV channels at ranges up to a few tens of kilometers.

Coaxial cable has traditionally been an important part of the long-distance telephone network. Today, it faces increasing competition from optical fiber, terrestrial microwave, and satellite. Using frequency division multiplexing (FDM, see Chapter 8), a coaxial cable can carry over 10,000 voice channels simultaneously.

Coaxial cable is also commonly used for short-range connections between devices. Using digital signaling, coaxial cable can be used to provide high-speed I/O channels on computer systems.

Transmission Characteristics

Coaxial cable is used to transmit both analog and digital signals. As can be seen from Figure 4.3b, coaxial cable has frequency characteristics that are superior to those of twisted pair, and can hence be used effectively at higher frequencies and data rates. Because of its shielded, concentric construction, coaxial cable is much less susceptible to interference and crosstalk than twisted pair. The principal constraints on performance are attenuation, thermal noise, and intermodulation noise. The latter is present only when several channels (FDM) or frequency bands are in use on the cable.

For long-distance transmission of analog signals, amplifiers are needed every few kilometers, with closer spacing required if higher frequencies are used. The usable spectrum for analog signaling extends to about 500 MHz. For digital signaling, repeaters are needed every kilometer or so, with closer spacing needed for higher data rates.

Optical Fiber

Physical Description

An optical fiber is a thin (2 to 125 μm), flexible medium capable of guiding an optical ray. Various glasses and plastics can be used to make optical fibers. The lowest losses have been obtained using fibers of ultrapure fused silica. Ultrapure fiber is difficult to manufacture; higher-loss multicomponent glass fibers are more economical and still provide good performance. Plastic fiber is even less costly and can be used for short-haul links, for which moderately high losses are acceptable.

An optical fiber cable has a cylindrical shape and consists of three concentric sections: the core, the cladding, and the jacket (Figure 4.2c). The **core** is the innermost section and consists of one or more very thin strands, or fibers, made of glass or plastic; the core has a diameter in the range of 8 to 100 μm. Each fiber is surrounded by its own **cladding**, a glass or plastic coating that has optical properties different from those of the core. The interface between the core and cladding acts as a reflector to confine light that would otherwise escape the core. The outermost layer, surrounding one or a bundle of cladded fibers, is the **jacket**. The jacket is composed of plastic and other material layered to protect against moisture, abrasion, crushing, and other environmental dangers.

Applications

One of the most significant technological breakthroughs in data transmission has been the development of practical fiber optic communications systems. Optical fiber already enjoys considerable use in long-distance telecommunications, and its use in military applications is growing. The continuing improvements in performance and decline in prices, together with the inherent advantages of optical fiber, have made it increasingly attractive for local area networking. The following characteristics distinguish optical fiber from twisted pair or coaxial cable:

- **Greater capacity:** The potential bandwidth, and hence data rate, of optical fiber is immense; data rates of hundreds of Gbps over tens of kilometers have been demonstrated. Compare this to the practical maximum of hundreds of Mbps over about 1 km for coaxial cable and just a few Mbps over 1 km or up to 100 Mbps to 1 Gbps over a few tens of meters for twisted pair.
- **Smaller size and lighter weight:** Optical fibers are considerably thinner than coaxial cable or bundled twisted-pair cable—at least an order of magnitude thinner for comparable information transmission capacity. For cramped conduits in buildings and underground along public rights-of-way, the advantage of small size is considerable. The corresponding reduction in weight reduces structural support requirements.
- **Lower attenuation:** Attenuation is significantly lower for optical fiber than for coaxial cable or twisted pair (Figure 4.3c) and is constant over a wide range.
- **Electromagnetic isolation:** Optical fiber systems are not affected by external electromagnetic fields. Thus the system is not vulnerable to interference, impulse noise, or crosstalk. By the same token, fibers do not radiate energy, so there is little interference with other equipment and there is a high degree of security from eavesdropping. In addition, fiber is inherently difficult to tap.
- **Greater repeater spacing:** Fewer repeaters mean lower cost and fewer sources of error. The performance of optical fiber systems from this point of view has been steadily improving. Repeater spacing in the tens of kilometers for optical fiber is common, and repeater spacings of hundreds of kilometers have been demonstrated. Coaxial and twisted-pair systems generally have repeaters every few kilometers.

Five basic categories of application have become important for optical fiber:

- Long-haul trunks
- Metropolitan trunks
- Rural exchange trunks
- Subscriber loops
- Local area networks

Long-haul fiber transmission is becoming increasingly common in the telephone network. Long-haul routes average about 1500 km in length and offer high capacity (typically 20,000 to 60,000 voice channels). These systems compete economically with microwave and have so underpriced coaxial cable in many developed countries that coaxial cable is rapidly being phased out of the telephone network in such countries. Undersea optical fiber cables have also enjoyed increasing use.

Metropolitan trunking circuits have an average length of 12 km and may have as many as 100,000 voice channels in a trunk group. Most facilities are installed in underground conduits and are repeaterless, joining telephone exchanges in a metropolitan or city area. Included in this category are routes that link long-haul microwave facilities that terminate at a city perimeter to the main telephone exchange building downtown.

Rural exchange trunks have circuit lengths ranging from 40 to 160 km and link towns and villages. In the United States, they often connect the exchanges of different telephone companies. Most of these systems have fewer than 5000 voice channels. The technology used in these applications competes with microwave facilities.

Subscriber loop circuits are fibers that run directly from the central exchange to a subscriber. These facilities are beginning to displace twisted pair and coaxial cable links as the telephone networks evolve into full-service networks capable of handling not only voice and data, but also image and video. The initial penetration of optical fiber in this application is for the business subscriber, but fiber transmission into the home will soon begin to appear.

A final important application of optical fiber is for local area networks. Standards have been developed and products introduced for optical fiber networks that have a total capacity of 100 Mbps to 10 Gbps and can support hundreds or even thousands of stations in a large office building or a complex of buildings.

The advantages of optical fiber over twisted pair and coaxial cable become more compelling as the demand for all types of information (voice, data, image, video) increases.

Transmission Characteristics

Optical fiber transmits a signal-encoded beam of light by means of **total internal reflection**. Total internal reflection can occur in any transparent medium that has a higher index of refraction than the surrounding medium. In effect, the optical fiber acts as a waveguide for frequencies in the range of about 10^{14} to 10^{15} Hertz; this covers portions of the infrared and visible spectra.

Figure 4.4 shows the principle of optical fiber transmission. Light from a source enters the cylindrical glass or plastic core. Rays at shallow angles are reflected and propagated along the fiber; other rays are absorbed by the surrounding

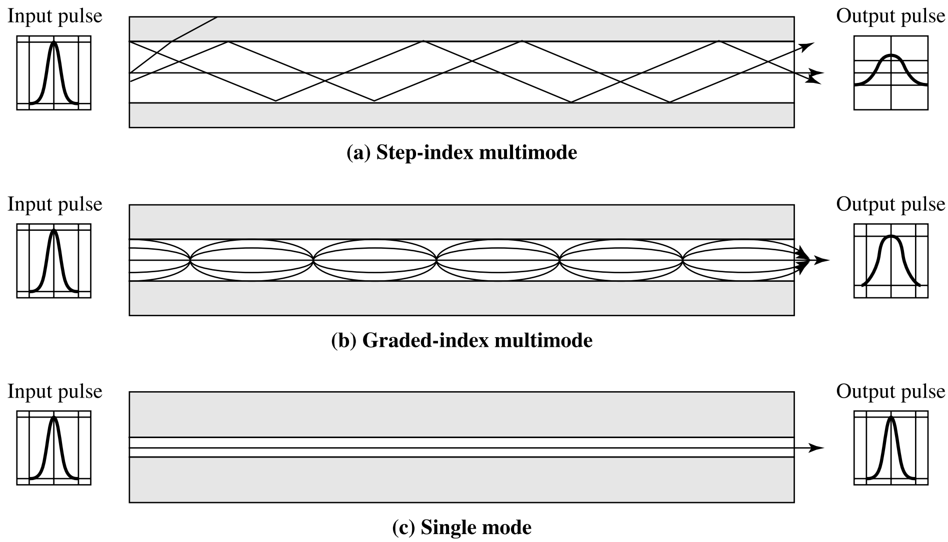


Figure 4.4 Optical Fiber Transmission Modes

material. This form of propagation is called **step-index multimode**, referring to the variety of angles that will reflect. With multimode transmission, multiple propagation paths exist, each with a different path length and hence time to traverse the fiber. This causes signal elements (light pulses) to spread out in time, which limits the rate at which data can be accurately received. Put another way, the need to leave spacing between the pulses limits data rate. This type of fiber is best suited for transmission over very short distances. When the fiber core radius is reduced, fewer angles will reflect. By reducing the radius of the core to the order of a wavelength, only a single angle or mode can pass: the axial ray. This **single-mode** propagation provides superior performance for the following reason. Because there is a single transmission path with single-mode transmission, the distortion found in multimode cannot occur. Single-mode is typically used for long-distance applications, including telephone and cable television. Finally, by varying the index of refraction of the core, a third type of transmission, known as **graded-index multimode**, is possible. This type is intermediate between the other two in characteristics. The higher refractive index (discussed subsequently) at the center makes the light rays moving down the axis advance more slowly than those near the cladding. Rather than zig-zagging off the cladding, light in the core curves helically because of the graded index, reducing its travel distance. The shortened path and higher speed allows light at the periphery to arrive at a receiver at about the same time as the straight rays in the core axis. Graded-index fibers are often used in local area networks.

Two different types of light source are used in fiber optic systems: the light-emitting diode (LED) and the injection laser diode (ILD). Both are semiconductor devices that emit a beam of light when a voltage is applied. The LED is less costly, operates over a greater temperature range, and has a longer operational life. The ILD, which operates on the laser principle, is more efficient and can sustain greater data rates.

Table 4.5 Frequency Utilization for Fiber Applications

Wavelength (in vacuum) Range (nm)	Frequency Range (THz)	Band Label	Fiber Type	Application
820 to 900	366 to 333		Multimode	LAN
1280 to 1350	234 to 222	S	Single mode	Various
1528 to 1561	196 to 192	C	Single mode	WDM
1561 to 1620	192 to 185	L	Single mode	WDM

WDM = wavelength division multiplexing (see Chapter 8)

There is a relationship among the wavelength employed, the type of transmission, and the achievable data rate. Both single mode and multimode can support several different wavelengths of light and can employ laser or LED light sources. In optical fiber, based on the attenuation characteristics of the medium and on properties of light sources and receivers, four transmission windows are appropriate, shown in Table 4.5.

Note the tremendous bandwidths available. For the four windows, the respective bandwidths are 33 THz, 12 THz, 4 THz, and 7 THz. This is several orders of magnitude greater than the bandwidth available in the radio-frequency spectrum.

One confusing aspect of reported attenuation figures for fiber optic transmission is that, invariably, fiber optic performance is specified in terms of wavelength rather than frequency. The wavelengths that appear in graphs and tables are the wavelengths corresponding to transmission in a vacuum. However, on the fiber, the velocity of propagation is less than the speed of light in a vacuum (c); the result is that although the frequency of the signal is unchanged, the wavelength is changed.

Example 4.1 For a wavelength in vacuum of 1550 nm, the corresponding frequency is $f = c/\lambda = (3 \times 10^8)/(1550 \times 10^{-9}) = 193.4 \times 10^{12} = 193.4$ THz. For a typical single mode fiber, the velocity of propagation is approximately $v = 2.04 \times 10^8$. In this case, a frequency of 193.4 THz corresponds to a wavelength of $\lambda = v/f = (2.04 \times 10^8)/(193.4 \times 10^{12}) = 1055$ nm. Therefore, on this fiber, when a wavelength of 1550 nm is cited, the actual wavelength on the fiber is 1055 nm.

The four transmission windows are in the infrared portion of the frequency spectrum, below the visible-light portion, which is 400 to 700 nm. The loss is lower at higher wavelengths, allowing greater data rates over longer distances. Many local applications today use 850-nm LED light sources. Although this combination is relatively inexpensive, it is generally limited to data rates under 100 Mbps and distances of a few kilometers. To achieve higher data rates and longer distances, a 1300-nm LED or laser source is needed. The highest data rates and longest distances require 1500-nm laser sources.

Figure 4.3c shows attenuation versus wavelength for a typical optical fiber. The unusual shape of the curve is due to the combination of a variety of factors that contribute to attenuation. The two most important of these are absorption and scattering. In this context, the term *scattering* refers to the change in direction of light rays after they strike small particles or impurities in the medium.

4.2 WIRELESS TRANSMISSION

Three general ranges of frequencies are of interest in our discussion of wireless transmission. Frequencies in the range of about 1 GHz (gigahertz = 10^9 Hertz) to 40 GHz are referred to as **microwave frequencies**. At these frequencies, highly directional beams are possible, and microwave is quite suitable for point-to-point transmission. Microwave is also used for satellite communications. Frequencies in the range of 30 MHz to 1 GHz are suitable for omnidirectional applications. We refer to this range as the **radio** range.

Another important frequency range, for local applications, is the infrared portion of the spectrum. This covers, roughly, from 3×10^{11} to 2×10^{14} Hz. Infrared is useful to local point-to-point and multipoint applications within confined areas, such as a single room.

For unguided media, transmission and reception are achieved by means of an antenna. Before looking at specific categories of wireless transmission, we provide a brief introduction to antennas.

Antennas

An antenna can be defined as an electrical conductor or system of conductors used either for radiating electromagnetic energy or for collecting electromagnetic energy. For transmission of a signal, electrical energy from the transmitter is converted into electromagnetic energy by the antenna and radiated into the surrounding environment (atmosphere, space, water). For reception of a signal, electromagnetic energy impinging on the antenna is converted into electrical energy and fed into the receiver.

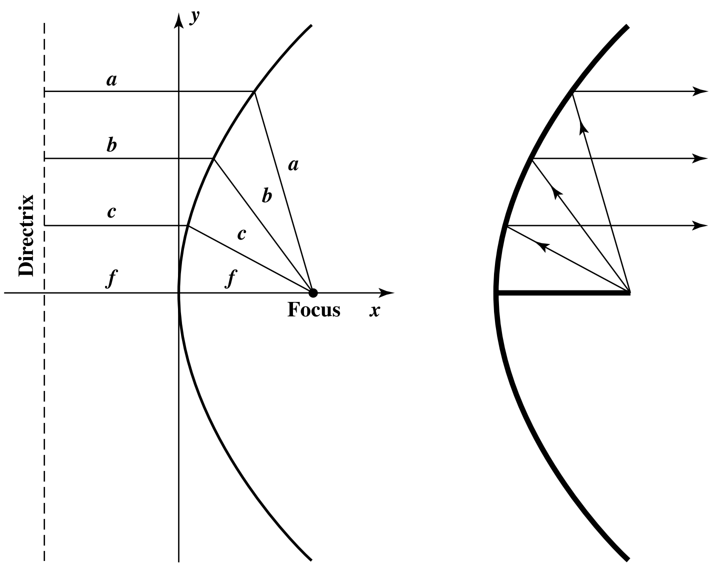
In two-way communication, the same antenna can be and often is used for both transmission and reception. This is possible because any antenna transfers energy from the surrounding environment to its input receiver terminals with the same efficiency that it transfers energy from the output transmitter terminals into the surrounding environment, assuming that the same frequency is used in both directions. Put another way, antenna characteristics are essentially the same whether an antenna is sending or receiving electromagnetic energy.

An antenna will radiate power in all directions but, typically, does not perform equally well in all directions. A common way to characterize the performance of an antenna is the radiation pattern, which is a graphical representation of the radiation properties of an antenna as a function of space coordinates. The simplest pattern is produced by an idealized antenna known as the isotropic antenna. An

isotropic antenna is a point in space that radiates power in all directions equally. The actual radiation pattern for the isotropic antenna is a sphere with the antenna at the center.

Parabolic Reflective Antenna

An important type of antenna is the **parabolic reflective antenna**, which is used in terrestrial microwave and satellite applications. You may recall from your precollege geometry studies that a parabola is the locus of all points equidistant from a fixed line and a fixed point not on the line. The fixed point is called the *focus* and the fixed line is called the *directrix* (Figure 4.5a). If a parabola is revolved about its axis, the surface generated is called a *paraboloid*. A cross section through the paraboloid parallel to its axis forms a parabola and a cross section perpendicular to the axis forms a circle. Such surfaces are used in headlights, optical and radio telescopes, and microwave antennas because of the following property: If a source of electromagnetic energy (or sound) is placed at the focus of the paraboloid, and if the paraboloid is a reflecting surface, then the wave will bounce back in lines parallel to the axis of the paraboloid; Figure 4.5b shows this effect in cross section. In theory, this effect creates a parallel beam without dispersion. In practice, there will be some dispersion, because the source of energy must occupy more than one point. The larger the diameter of the antenna, the more tightly directional is the beam. On reception, if incoming waves are parallel to the axis of the reflecting paraboloid, the resulting signal will be concentrated at the focus.



(a) Parabola

(b) Cross section of parabolic antenna showing reflective property

Figure 4.5 Parabolic Reflective Antenna

Antenna Gain

Antenna gain is a measure of the directionality of an antenna. Antenna gain is defined as the power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna). For example, if an antenna has a gain of 3 dB, that antenna improves upon the isotropic antenna in that direction by 3 dB, or a factor of 2. The increased power radiated in a given direction is at the expense of other directions. In effect, increased power is radiated in one direction by reducing the power radiated in other directions. It is important to note that antenna gain does not refer to obtaining more output power than input power but rather to directionality.

A concept related to that of antenna gain is the **effective area** of an antenna. The effective area of an antenna is related to the physical size of the antenna and to its shape. The relationship between antenna gain and effective area is

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2} \tag{4.1}$$

where

G = antenna gain
A_e = effective area
f = carrier frequency
c = speed of light ($\approx 3 \times 10^8$ m/s)
λ = carrier wavelength

For example, the effective area of an ideal isotropic antenna is $\lambda^2/4\pi$, with a power gain of 1; the effective area of a parabolic antenna with a face area of A is $0.56A$, with a power gain of $7A/\lambda^2$.

Example 4.2 For a parabolic reflective antenna with a diameter of 2 m, operating at 12 GHz, what is the effective area and the antenna gain? We have an area of $A = \pi r^2 = \pi$ and an effective area of $A_e = 0.56\pi$. The wavelength is $\lambda = c/f = (3 \times 10^8)/(12 \times 10^9) = 0.025$ m. Then

$$G = (7A)/\lambda^2 = (7 \times \pi)/(0.025)^2 = 35{,}186$$
$$G_{dB} = 45.46 \text{ dB}$$

Terrestrial Microwave

Physical Description

The most common type of microwave antenna is the parabolic "dish." A typical size is about 3 m in diameter. The antenna is fixed rigidly and focuses a narrow beam to achieve line-of-sight transmission to the receiving antenna. Microwave antennas are usually located at substantial heights above ground level to extend the range between antennas and to be able to transmit over intervening obstacles. To achieve long-distance transmission, a series of microwave relay towers is used, and point-to-point microwave links are strung together over the desired distance.

Applications

The primary use for terrestrial microwave systems is in long haul telecommunications service, as an alternative to coaxial cable or optical fiber. The microwave facility requires far fewer amplifiers or repeaters than coaxial cable over the same distance but requires line-of-sight transmission. Microwave is commonly used for both voice and television transmission.

Another increasingly common use of microwave is for short point-to-point links between buildings. This can be used for closed-circuit TV or as a data link between local area networks. Short-haul microwave can also be used for the so-called bypass application. A business can establish a microwave link to a long-distance telecommunications facility in the same city, bypassing the local telephone company.

Another important use of microwave is in cellular systems, examined in Chapter 14.

Transmission Characteristics

Microwave transmission covers a substantial portion of the electromagnetic spectrum. Common frequencies used for transmission are in the range 1 to 40 GHz. The higher the frequency used, the higher the potential bandwidth and therefore the higher the potential data rate. Table 4.6 indicates bandwidth and data rate for some typical systems.

As with any transmission system, a main source of loss is attenuation. For microwave (and radio frequencies), the loss can be expressed as

$$L = 10\log\left(\frac{4\pi d}{\lambda}\right)^2 \text{dB} \tag{4.2}$$

where d is the distance and λ is the wavelength, in the same units. Thus, loss varies as the square of the distance. In contrast, for twisted-pair and coaxial cable, loss varies exponentially with distance (linear in decibels). Thus repeaters or amplifiers may be placed farther apart for microwave systems—10 to 100 km is typical. Attenuation is increased with rainfall. The effects of rainfall become especially noticeable above 10 GHz. Another source of impairment is interference. With the growing popularity of microwave, transmission areas overlap and interference is always a danger. Thus the assignment of frequency bands is strictly regulated.

The most common bands for long-haul telecommunications are the 4-GHz to 6-GHz bands. With increasing congestion at these frequencies, the 11-GHz band is

Table 4.6 Typical Digital Microwave Performance

Band (GHz)	Bandwidth (MHz)	Data Rate (Mbps)
2	7	12
6	30	90
11	40	135
18	220	274

now coming into use. The 12-GHz band is used as a component of cable TV systems. Microwave links are used to provide TV signals to local CATV installations; the signals are then distributed to individual subscribers via coaxial cable. Higher-frequency microwave is being used for short point-to-point links between buildings; typically, the 22-GHz band is used. The higher microwave frequencies are less useful for longer distances because of increased attenuation but are quite adequate for shorter distances. In addition, at the higher frequencies, the antennas are smaller and cheaper.

Satellite Microwave

Physical Description

A communication satellite is, in effect, a microwave relay station. It is used to link two or more ground-based microwave transmitter/receivers, known as earth stations, or ground stations. The satellite receives transmissions on one frequency band (uplink), amplifies or repeats the signal, and transmits it on another frequency (downlink). A single orbiting satellite will operate on a number of frequency bands, called **transponder channels**, or simply **transponders**.

Figure 4.6 depicts in a general way two common configurations for satellite communication. In the first, the satellite is being used to provide a point-to-point link between two distant ground-based antennas. In the second, the satellite provides communications between one ground-based transmitter and a number of ground-based receivers.

For a communication satellite to function effectively, it is generally required that it remain stationary with respect to its position over the earth. Otherwise, it would not be within the line of sight of its earth stations at all times. To remain stationary, the satellite must have a period of rotation equal to the earth's period of rotation. This match occurs at a height of 35,863 km at the equator.

Two satellites using the same frequency band, if close enough together, will interfere with each other. To avoid this, current standards require a 4° spacing (angular displacement as measured from the earth) in the 4/6-GHz band and a 3° spacing at 12/14 GHz. Thus the number of possible satellites is quite limited.

Applications

The communication satellite is a technological revolution as important as fiber optics. Among the most important applications for satellites are the following:

- Television distribution
- Long-distance telephone transmission
- Private business networks

Because of their broadcast nature, satellites are well suited to television distribution and are being used extensively in the United States and throughout the world for this purpose. In its traditional use, a network provides programming from a central location. Programs are transmitted to the satellite and then broadcast down to a number of stations, which then distribute the programs to individual

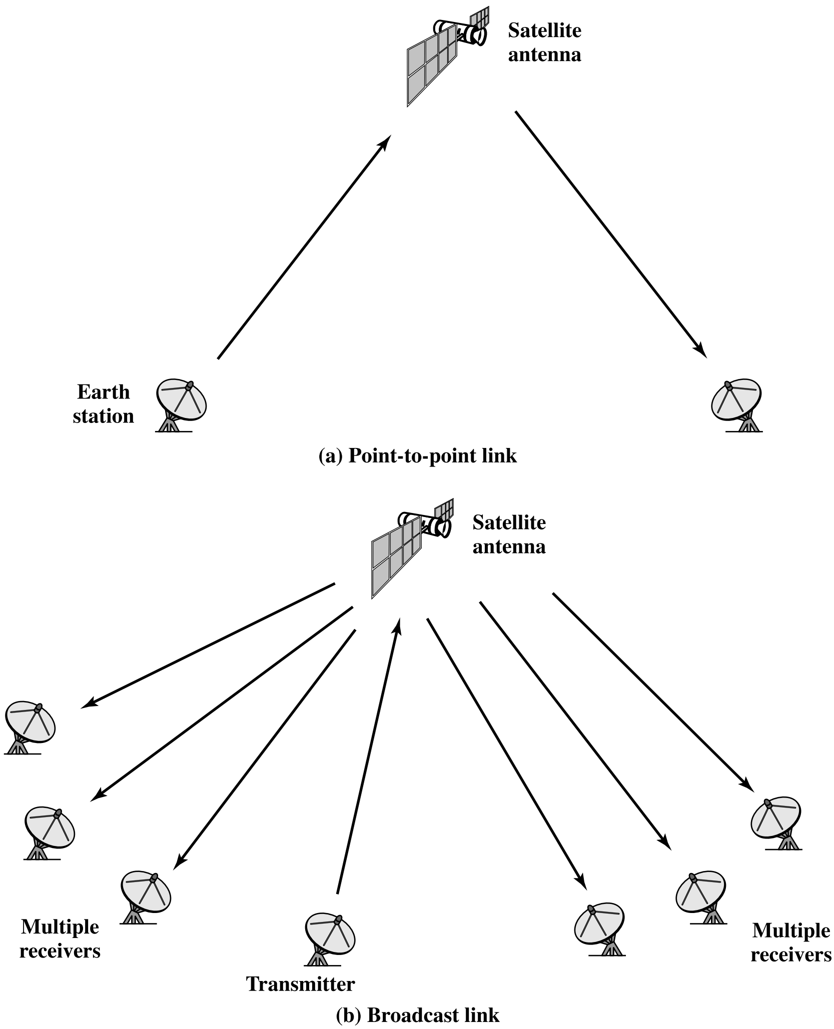


Figure 4.6 Satellite Communication Configurations

viewers. One network, the Public Broadcasting Service (PBS), distributes its television programming almost exclusively by the use of satellite channels. Other commercial networks also make substantial use of satellite, and cable television systems are receiving an ever-increasing proportion of their programming from satellites. The most recent application of satellite technology to television distribution is direct broadcast satellite (DBS), in which satellite video signals are transmitted directly to the home user. The decreasing cost and size of receiving antennas have made DBS economically feasible, and a number of channels are either already in service or in the planning stage.

Satellite transmission is also used for point-to-point trunks between telephone exchange offices in public telephone networks. It is the optimum medium for highusage international trunks and is competitive with terrestrial systems for many long-distance intranational links.

Finally, there are a number of business data applications for satellite. The satellite provider can divide the total capacity into a number of channels and lease these channels to individual business users. A user equipped with the antennas at a number of sites can use a satellite channel for a private network. Traditionally, such applications have been quite expensive and limited to larger organizations with high-volume requirements. A recent development is the very small aperture terminal (VSAT) system, which provides a low-cost alternative. Figure 4.7 depicts a typical VSAT configuration. A number of subscriber stations are equipped with low-cost VSAT antennas. Using some discipline, these stations share a satellite transmission capacity for transmission to a hub station. The hub station can exchange messages with each of the subscribers and can relay messages between subscribers.

Transmission Characteristics

The optimum frequency range for satellite transmission is in the range 1 to 10 GHz. Below 1 GHz, there is significant noise from natural sources, including galactic, solar, and atmospheric noise, and human-made interference from various electronic devices. Above 10 GHz, the signal is severely attenuated by atmospheric absorption and precipitation.

Most satellites providing point-to-point service today use a frequency bandwidth in the range 5.925 to 6.425 GHz for transmission from earth to satellite (uplink) and a bandwidth in the range 3.7 to 4.2 GHz for transmission from satellite to earth (downlink). This combination is referred to as the 4/6-GHz band. Note that the uplink and downlink frequencies differ. For continuous operation without interference, a satellite cannot transmit and receive on the same frequency. Thus signals received from a ground station on one frequency must be transmitted back on another.

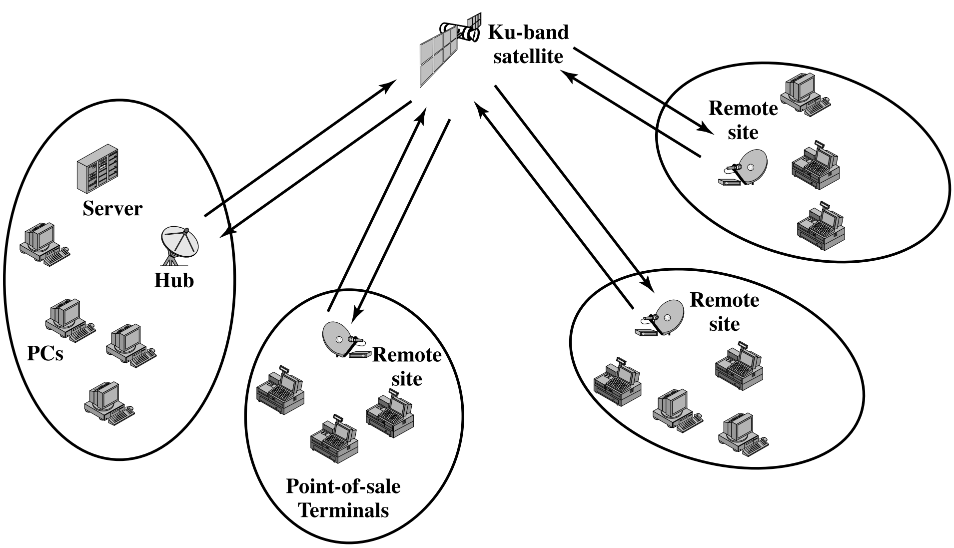


Figure 4.7 Typical VSAT Configuration

The 4/6-GHz band is within the optimum zone of 1 to 10 GHz but has become saturated. Other frequencies in that range are unavailable because of sources of interference operating at those frequencies, usually terrestrial microwave. Therefore, the 12/14-GHz band has been developed (uplink: 14 to 14.5 GHz; downlink: 11.7 to 12.2 GHz). At this frequency band, attenuation problems must be overcome. However, smaller and cheaper earth-station receivers can be used. It is anticipated that this band will also saturate, and use is projected for the 20/30-GHz band (uplink: 27.5 to 30.0 GHz; downlink: 17.7 to 20.2 GHz). This band experiences even greater attenuation problems but will allow greater bandwidth (2500 MHz versus 500 MHz) and even smaller and cheaper receivers.

Several properties of satellite communication should be noted. First, because of the long distances involved, there is a propagation delay of about a quarter second from transmission from one earth station to reception by another earth station. This delay is noticeable in ordinary telephone conversations. It also introduces problems in the areas of error control and flow control, which we discuss in later chapters. Second, satellite microwave is inherently a broadcast facility. Many stations can transmit to the satellite, and a transmission from a satellite can be received by many stations.

Broadcast Radio

Physical Description

The principal difference between broadcast radio and microwave is that the former is omnidirectional and the latter is directional. Thus broadcast radio does not require dish-shaped antennas, and the antennas need not be rigidly mounted to a precise alignment.

Applications

Radio is a general term used to encompass frequencies in the range of 3 kHz to 300 GHz. We are using the informal term **broadcast radio** to cover the VHF and part of the UHF band: 30 MHz to 1 GHz. This range covers FM radio and UHF and VHF television. This range is also used for a number of data networking applications.

Transmission Characteristics

The range 30 MHz to 1 GHz is an effective one for broadcast communications. Unlike the case for lower-frequency electromagnetic waves, the ionosphere is transparent to radio waves above 30 MHz. Thus transmission is limited to the line of sight, and distant transmitters will not interfere with each other due to reflection from the atmosphere. Unlike the higher frequencies of the microwave region, broadcast radio waves are less sensitive to attenuation from rainfall.

As with microwave, the amount of attenuation due to distance obeys Equation (4.2), namely $10 \log\left(\frac{4\pi d}{\lambda}\right)^2$ dB. Because of the longer wavelength, radio waves suffer relatively less attenuation.

A prime source of impairment for broadcast radio waves is multipath interference. Reflection from land, water, and natural or human-made objects can create multiple paths between antennas. This effect is frequently evident when TV reception displays multiple images as an airplane passes by.

Infrared

Infrared communications is achieved using transmitters/receivers (transceivers) that modulate noncoherent infrared light. Transceivers must be within the line of sight of each other either directly or via reflection from a light-colored surface such as the ceiling of a room.

One important difference between infrared and microwave transmission is that the former does not penetrate walls. Thus the security and interference problems encountered in microwave systems are not present. Furthermore, there is no frequency allocation issue with infrared, because no licensing is required.

4.3 WIRELESS PROPAGATION

A signal radiated from an antenna travels along one of three routes: ground wave, sky wave, or line of sight (LOS). Table 4.7 shows in which frequency range each predominates. In this book, we are almost exclusively concerned with LOS communication, but a short overview of each mode is given in this section.

Ground Wave Propagation

Ground wave propagation (Figure 4.8a) more or less follows the contour of the earth and can propagate considerable distances, well over the visual horizon. This effect is found in frequencies up to about 2 MHz. Several factors account for the tendency of electromagnetic wave in this frequency band to follow the earth's curvature. One factor is that the electromagnetic wave induces a current in the earth's surface, the result of which is to slow the wavefront near the earth, causing the wavefront to tilt downward and hence follow the earth's curvature. Another factor is diffraction, which is a phenomenon having to do with the behavior of electromagnetic waves in the presence of obstacles.

Electromagnetic waves in this frequency range are scattered by the atmosphere in such a way that they do not penetrate the upper atmosphere.

The best-known example of ground wave communication is AM radio.

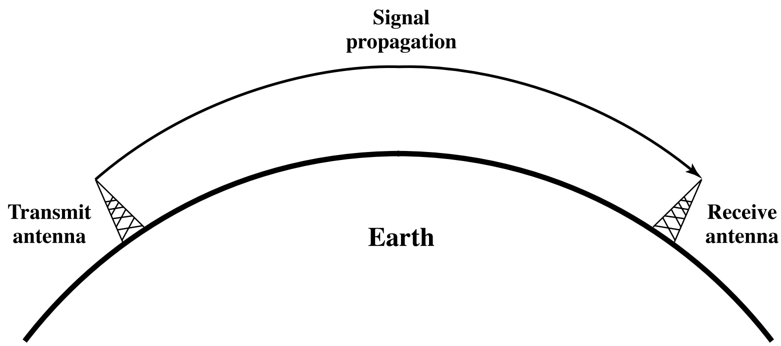
Sky Wave Propagation

Sky wave propagation is used for amateur radio, CB radio, and international broadcasts such as BBC and Voice of America. With sky wave propagation, a signal from an earth-based antenna is reflected from the ionized layer of the upper atmosphere (ionosphere) back down to earth. Although it appears the wave is reflected from the ionosphere as if the ionosphere were a hard reflecting surface, the effect is in fact caused by refraction. Refraction is described subsequently.

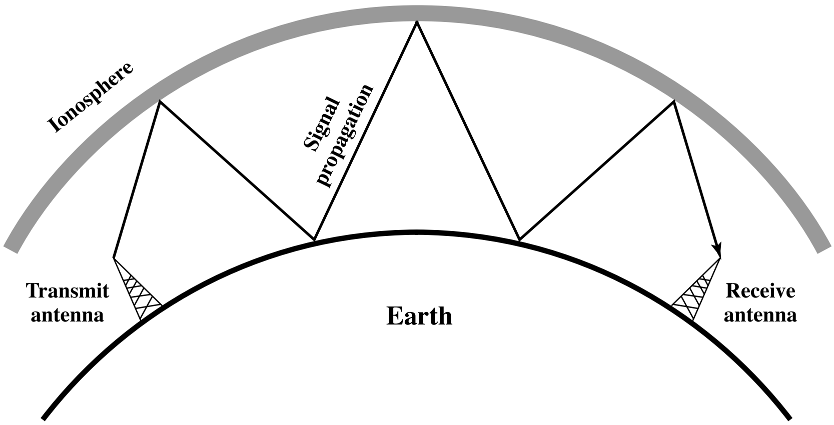
A sky wave signal can travel through a number of hops, bouncing back and forth between the ionosphere and the earth's surface (Figure 4.8b). With this propagation mode, a signal can be picked up thousands of kilometers from the transmitter.

Table 4.7 Frequency Bands

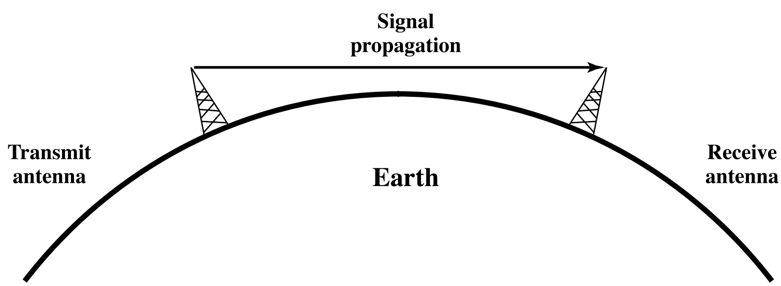
Band	Frequency Range	Free-Space Wavelength Range	Propagation Characteristics	Typical Use
ELF (extremely low frequency)	30 to 300 Hz	10,000 to 1000 km	GW	Power line frequencies; used by some home control systems
VF (voice frequency)	300 to 3000 Hz	1000 to 100 km	GW	Used by the telephone system for analog subscriber lines
VLF (very low frequency)	3 to 30 kHz	100 to 10 km	GW; low attenuation day and night; high atmospheric noise level	Long-range navigation; submarine communication
LF (low frequency)	30 to 300 kHz	10 to 1 km	GW; slightly less reliable than VLF; absorption in daytime	Long-range navigation; marine communication radio beacons
MF (medium frequency)	300 to 3000 kHz	1000 to 100 m	GW and night SW; attenuation low at night, high in day; atmospheric noise	Maritime radio; direction finding; AM broadcasting
HF (high frequency)	3 to 30 MHz	100 to 10 m	SW; quality varies with time of day, season, and frequency	Amateur radio; international broadcasting, military communication; long-distance aircraft and ship communication
VHF (very high frequency)	30 to 300 MHz	10 to 1 m	LOS; scattering because of temperature inversion; cosmic noise	VHF television; FM broadcast and two-way radio, AM aircraft communication; aircraft navigational aids
UHF (ultra high frequency)	300 to 3000 MHz	100 to 10 cm	LOS; cosmic noise	UHF television; cellular telephone; radar; microwave links; personal communications systems
SHF (super high frequency)	3 to 30 GHz	10 to 1 cm	LOS; rainfall attenuation above 10 GHz; atmospheric attenuation due to oxygen and water vapor	Satellite communication; radar; terrestrial microwave links; wireless local loop
EHF (extremely high frequency)	30 to 300 GHz	10 to 1 mm	LOS; atmospheric attenuation due to oxygen and water vapor	Experimental; wireless local loop
Infrared	300 GHz to 400 THz	1 mm to 770 nm	LOS	Infrared LANs; consumer electronic applications
Visible light	400 THz to 900 THz	770 nm to 330 nm	LOS	Optical communication



(a) Ground-wave propagation (below 2 MHz)



(b) Sky-wave propagation (2 to 30 MHz)



(c) Line-of-sight (LOS) propagation (above 30 MHz)

Figure 4.8 Wireless Propagation Modes

Line-of-Sight Propagation

Above 30 MHz, neither ground wave nor sky wave propagation modes operate, and communication must be by line of sight (Figure 4.8c). For satellite communication, a signal above 30 MHz is not reflected by the ionosphere and therefore a signal can be transmitted between an earth station and a satellite overhead that is not beyond the horizon. For ground-based communication, the transmitting and receiving antennas must be within an *effective* line of sight of each other. The term *effective* is used because microwaves are bent or refracted by the atmosphere. The amount and even the direction of the bend depends on conditions, but generally microwaves are bent with the curvature of the earth and will therefore propagate farther than the optical line of sight.

Refraction

Before proceeding, a brief discussion of refraction is warranted. Refraction occurs because the velocity of an electromagnetic wave is a function of the density of the medium through which it travels. In a vacuum, an electromagnetic wave (such as light or a radio wave) travels at approximately 3×10^8 m/s. This is the constant, c, commonly referred to as the speed of light, but actually referring to the speed of light in a vacuum.[1] In air, water, glass, and other transparent or partially transparent media, electromagnetic waves travel at speeds less than c.

When an electromagnetic wave moves from a medium of one density to a medium of another density, its speed changes. The effect is to cause a one-time bending of the direction of the wave at the boundary between the two media. Moving from a less dense to a more dense medium, the wave will bend toward the more dense medium. This phenomenon is easily observed by partially immersing a stick in water.

The **index of refraction**, or **refractive index**, of one medium relative to another is the sine of the angle of incidence divided by the sine of the angle of refraction. The index of refraction is also equal to the ratio of the respective velocities in the two media. The absolute index of refraction of a medium is calculated in comparison with that of a vacuum. Refractive index varies with wavelength, so that refractive effects differ for signals with different wavelengths.

Although an abrupt, one-time change in direction occurs as a signal moves from one medium to another, a continuous, gradual bending of a signal will occur if it is moving through a medium in which the index of refraction gradually changes. Under normal propagation conditions, the refractive index of the atmosphere decreases with height so that radio waves travel more slowly near the ground than at higher altitudes. The result is a slight bending of the radio waves toward the earth.

Optical and Radio Line of Sight

With no intervening obstacles, the optical line of sight can be expressed as:

$$d = 3.57\sqrt{h}$$

where d is the distance between an antenna and the horizon in kilometers and h is the antenna height in meters. The effective, or radio, line of sight to the horizon is expressed as (Figure 4.9)

$$d = 3.57\sqrt{Kh}$$

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[1]The exact value is 299,792,458 m/s.

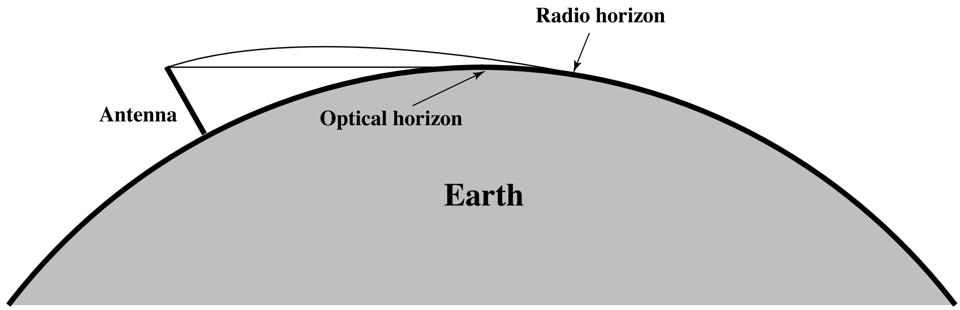


Figure 4.9 Optical and Radio Horizons

where K is an adjustment factor to account for the refraction. A good rule of thumb is $K = 4/3$. Thus, the maximum distance between two antennas for LOS propagation is $3.57\left(\sqrt{Kh_1} + \sqrt{Kh_2}\right)$, where h_1 and h_2 are the heights of the two antennas.

Example 4.3 The maximum distance between two antennas for LOS transmission if one antenna is 100 m high and the other is at ground level is

$$d = 3.57\sqrt{Kh} = 3.57\sqrt{133} = 41 \text{ km}$$

Now suppose that the receiving antenna is 10 m high. To achieve the same distance, how high must the transmitting antenna be? The result is

$$41 = 3.57\left(\sqrt{Kh_1} + \sqrt{13.3}\right)$$

$$\sqrt{Kh_1} = \frac{41}{3.57} - \sqrt{13.3} = 7.84$$

$$h_1 = 7.84^2/1.33 = 46.2 \text{ m}$$

This is a savings of over 50 m in the height of the transmitting antenna. This example illustrates the benefit of raising receiving antennas above ground level to reduce the necessary height of the transmitter.

4.4 LINE-OF-SIGHT TRANSMISSION

Section 3.3 discussed various transmission impairments common to both guided and wireless transmission. In this section, we extend the discussion to examine some impairments specific to wireless line-of-sight transmission.

Free Space Loss

For any type of wireless communication the signal disperses with distance. Therefore, an antenna with a fixed area will receive less signal power the farther it is from the transmitting antenna. For satellite communication this is the primary mode of signal loss. Even if no other sources of attenuation or impairment are assumed, a transmitted signal attenuates over distance because the signal is being spread over a larger and larger area. This form of attenuation is known as **free space loss**, which can be express in terms of the ratio of the radiated power P_t to the power P_r received by the antenna or, in decibels, by taking 10 times the log of that ratio. For the ideal isotropic antenna, free space loss is

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

where

P_t = signal power at the transmitting antenna
P_r = signal power at the receiving antenna
λ = carrier wavelength
d = propagation distance between antennas
c = speed of light (3×10^8 m/s)

where d and λ are in the same units (e.g., meters).

This can be recast as

$$\begin{aligned} L_{dB} &= 10 \log \frac{P_t}{P_r} = 20 \log \sqrt{\frac{4\pi d}{\lambda}} = -20 \log(\lambda) + 20 \log(d) + 21.98 \text{ dB} \\ &= 20 \log \sqrt{\frac{4\pi f d}{c}} = 20 \log(f) + 20 \log(d) - 147.56 \text{ dB} \end{aligned} \tag{4.3}$$

Figure 4.10 illustrates the free space loss equation.[2]

For other antennas, we must take into account the gain of the antenna, which yields the following free space loss equation:

$$\frac{P_t}{P_r} = \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(cd)^2}{f^2 A_r A_t}$$

where

G_t = gain of the transmitting antenna
G_r = gain of the receiving antenna
A_t = effective area of the transmitting antenna
A_r = effective area of the receiving antenna

[2]As was mentioned in Appendix 3A, there is some inconsistency in the literature over the use of the terms *gain* and *loss*. Equation (4.3) follows the convention of Equation (2.2).

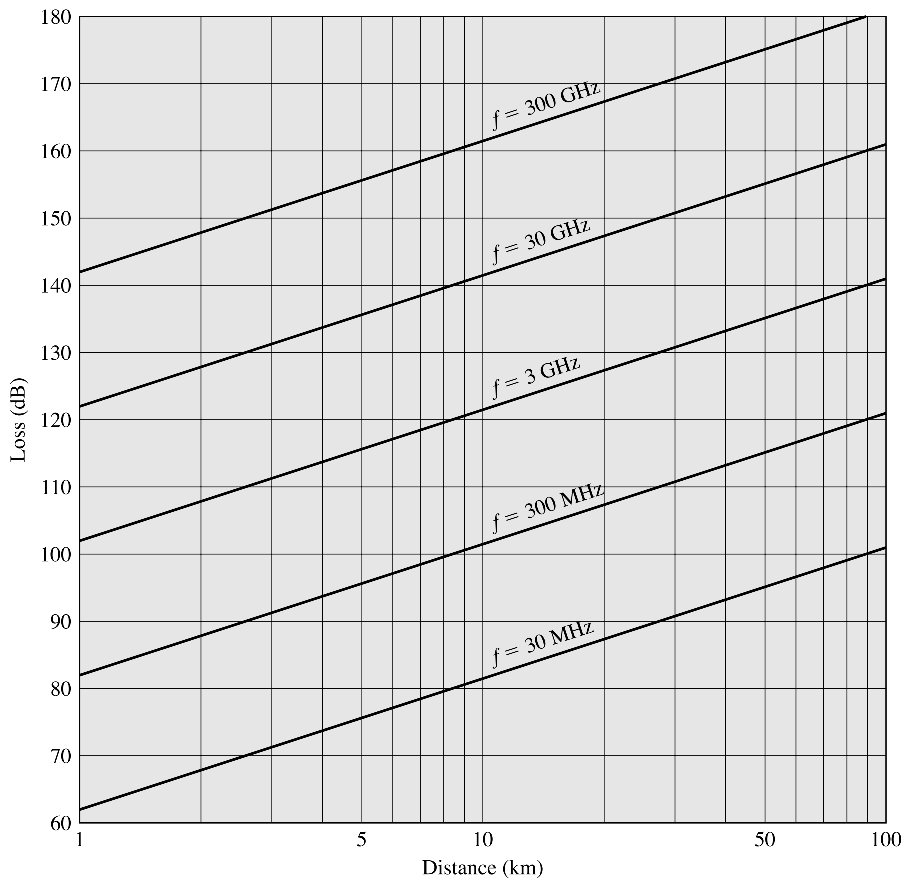


Figure 4.10 Free Space Loss

The third fraction is derived from the second fraction using the relationship between antenna gain and effective area defined in Equation (4.1). We can recast the loss equation as

$$\begin{aligned} L_{\mathrm{dB}} &= 20\log(\lambda) + 20\log(d) - 10\log(A_t A_r) \\ &= -20\log(f) + 20\log(d) - 10\log(A_t A_r) + 169.54\,\mathrm{dB} \end{aligned} \tag{4.4}$$

Thus, for the same antenna dimensions and separation, the longer the carrier wavelength (lower the carrier frequency f), the higher is the free space path loss. It is interesting to compare Equations (4.3) and (4.4). Equation (4.3) indicates that as the frequency increases, the free space loss also increases, which would suggest that at higher frequencies, losses become more burdensome. However, Equation (4.4) shows that we can easily compensate for this increased loss with antenna gains.

In fact, there is a net gain at higher frequencies, other factors remaining constant. Equation (4.3) shows that at a fixed distance an increase in frequency results in an increased loss measured by $20\log(f)$. However, if we take into account antenna gain, and fix antenna area, then the change in loss is measured by $-20\log(f)$; that is, there is actually a decrease in loss at higher frequencies.

Example 4.4 Determine the isotropic free space loss at 4 GHz for the shortest path to a synchronous satellite from earth (35,863 km). At 4 GHz, the wavelength is $(3 \times 10^8)/(4 \times 10^9) = 0.075$ m. Then,

$$L_{\mathrm{dB}} = -20\log(0.075) + 20\log(35.853 \times 10^6) + 21.98 = 195.6\ \mathrm{dB}$$

Now consider the antenna gain of both the satellite- and ground-based antennas. Typical values are 44 dB and 48 dB, respectively. The free space loss is

$$L_{\mathrm{dB}} = 195.6 - 44 - 48 = 103.6\ \mathrm{dB}$$

Now assume a transmit power of 250 W at the earth station. What is the power received at the satellite antenna? A power of 250 W translates into 24 dBW, so the power at the receiving antenna is $24 - 103.6 = -79.6$ dBW.

Atmospheric Absorption

An additional loss between the transmitting and receiving antennas is atmospheric absorption. Water vapor and oxygen contribute most to attenuation. A peak attenuation occurs in the vicinity of 22 GHz due to water vapor. At frequencies below 15 GHz, the attenuation is less. The presence of oxygen results in an absorption peak in the vicinity of 60 GHz but contributes less at frequencies below 30 GHz. Rain and fog (suspended water droplets) cause scattering of radio waves that results in attenuation. In this context, the term *scattering* refers to the production of waves of changed direction or frequency when radio waves encounter matter. This can be a major cause of signal loss. Thus, in areas of significant precipitation, either path lengths have to be kept short or lower-frequency bands should be used.

Multipath

For wireless facilities where there is a relatively free choice of where antennas are to be located, they can be placed so that if there are no nearby interfering obstacles, there is a direct line-of-sight path from transmitter to receiver. This is generally the case for many satellite facilities and for point-to-point microwave. In other cases, such as mobile telephony, there are obstacles in abundance. The signal can be reflected by such obstacles so that multiple copies of the signal with varying delays

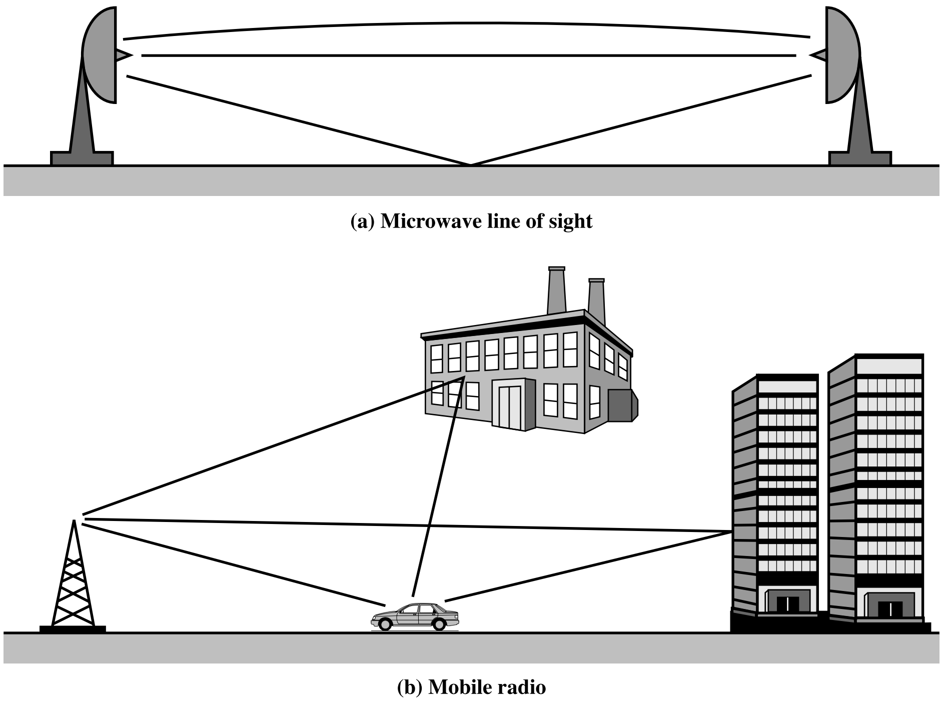


Figure 4.11 Examples of Multipath Interference

can be received. In fact, in extreme cases, there may be no direct signal. Depending on the differences in the path lengths of the direct and reflected waves, the composite signal can be either larger or smaller than the direct signal. Reinforcement and cancellation of the signal resulting from the signal following multiple paths can be controlled for communication between fixed, well-sited antennas, and between satellites and fixed ground stations. One exception is when the path goes across water, where the wind keeps the reflective surface of the water in motion. For mobile telephony and communication to antennas that are not well sited, multipath considerations can be paramount.

Figure 4.11 illustrates in general terms the types of multipath interference typical in terrestrial, fixed microwave and in mobile communications. For fixed microwave, in addition to the direct line of sight, the signal may follow a curved path through the atmosphere due to refraction and the signal may also reflect from the ground. For mobile communications, structures and topographic features provide reflection surfaces.

Refraction

Radio waves are refracted (or bent) when they propagate through the atmosphere. The refraction is caused by changes in the speed of the signal with altitude or by other spatial changes in the atmospheric conditions. Normally, the speed of the signal increases with altitude, causing radio waves to bend downward. However, on occasion, weather conditions may lead to variations in speed with height that differ significantly from the typical variations. This may result in a situation in which only a fraction or no part of the line-of-sight wave reaches the receiving antenna.

4.5 RECOMMENDED READING AND WEB SITES

Detailed descriptions of the transmission characteristics of the transmission media discussed in this chapter can be found in [FREE98]. [REEV95] provides an excellent treatment of twisted pair and optical fiber. [BORE97] is a thorough treatment of optical fiber transmission components. Another good paper on the subject is [WILL97]. [FREE02] is a detailed technical reference on optical fiber. [STAL00] discusses the characteristics of transmission media for LANs in greater detail.

For a more thorough treatment on wireless transmission and propagation, see [STAL02] and [RAPP96]. [FREE97] is an excellent detailed technical reference on wireless topics.

BORE97 Borella, M., et al., "Optical Components for WDM Lightwave Networks." *Proceedings of the IEEE*, August 1997.

FREE97 Freeman, R. *Radio System Design for Telecommunications*. New York: Wiley, 1997.

FREE98 Freeman, R. *Telecommunication Transmission Handbook*. New York: Wiley, 1998.

FREE02 Freeman, R. *Fiber-Optic Systems for Telecommunications*. New York: Wiley, 2002.

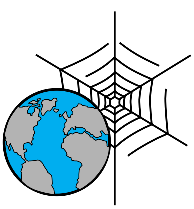
RAPP96 Rappaport, T. *Wireless Communications*. Upper Saddle River, NJ: Prentice Hall, 1996.

REEV95 Reeve, W. *Subscriber Loop Signaling and Transmission Handbook*. Piscataway, NJ: IEEE Press, 1995.

STAL00 Stallings, W. *Local and Metropolitan Area Networks, 4th Edition*. Upper Saddle River, NJ: Prentice Hall, 2000.

STAL02 Stallings, W. *Wireless Communications and Networks*. Upper Saddle River, NJ: Prentice Hall, 2002.

WILL97 Willner, A. "Mining the Optical Bandwidth for a Terabit per Second." *IEEE Spectrum*, April 1997.



Recommended Web Sites:

- **Siemon Company:** Good collection of technical articles on cabling, plus information about cabling standards
- **Wireless Developer Network:** News, tutorials, and discussions on wireless topics

4.6 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

antenna	line of sight (LOS)	satellite
antenna gain	microwave frequencies	shielded twisted pair (STP)
atmospheric absorption	multipath	sky wave propagation
attenuation	omnidirectional antenna	terrestrial microwave
coaxial cable	optical fiber	transmission medium
directional antenna	optical LOS	twisted pair
effective area	parabolic reflective antenna	unguided media
free space loss	radio	unshielded twisted pair (UTP)
ground wave propagation	radio LOS	wavelength division multiplexing (WDM)
guided media	reflection	wireless transmission
index of refraction	refraction	
infrared	refractive index	
isotropic antenna	scattering	

Review Questions

4.1 Why are the wires twisted in twisted-pair copper wire?

4.2 What are some major limitations of twisted-pair wire?

4.3 What is the difference between unshielded twisted pair and shielded twisted pair?

4.4 Describe the components of optical fiber cable.

4.5 What are some major advantages and disadvantages of microwave transmission?

4.6 What is direct broadcast satellite (DBS)?

4.7 Why must a satellite have distinct uplink and downlink frequencies?

4.8 Indicate some significant differences between broadcast radio and microwave.

4.9 What two functions are performed by an antenna?

4.10 What is an isotropic antenna?

4.11 What is the advantage of a parabolic reflective antenna?

4.12 What factors determine antenna gain?

4.13 What is the primary cause of signal loss in satellite communications?

4.14 What is refraction?

4.15 What is the difference between diffraction and scattering?

Problems

4.1 Suppose that data are stored on 1.4-Mbyte floppy diskettes that weigh 30 g each. Suppose that an airliner carries 10^4 kg of these floppies at a speed of 1000 km/h over a distance of 5000 km. What is the data transmission rate in bits per second of this system?

4.2 A telephone line is known to have a loss of 20 dB. The input signal power is measured as 0.5 W, and the output noise level is measured as 4.5 μW. Using this information, calculate the output signal-to-noise ratio in dB.

4.3 Given a 100-Watt power source, what is the maximum allowable length for the following transmission media if a signal of 1 watt is to be received?
  a. 24-gauge (0.5 mm) twisted pair operating at 300 kHz
  b. 24-gauge (0.5 mm) twisted pair operating at 1 MHz
  c. 0.375-inch (9.5 mm) coaxial cable operating at 1 MHz
  d. 0.375-inch (9.5 mm) coaxial cable operating at 25 MHz
  e. optical fiber operating at its optimal frequency

4.4 Coaxial cable is a two-wire transmission system. What is the advantage of connecting the outer conductor to ground?

4.5 Show that doubling the transmission frequency or doubling the distance between transmitting antenna and receiving antenna attenuates the power received by 6 dB.

4.6 It turns out that the depth in the ocean to which airborne electromagnetic signals can be detected grows with the wavelength. Therefore, the military got the idea of using very long wavelengths corresponding to about 30 Hz to communicate with submarines throughout the world. It is desirable to have an antenna that is about one-half wavelength long. How long would that be?

4.7 The audio power of the human voice is concentrated at about 300 Hz. Antennas of the appropriate size for this frequency are impracticably large, so that to send voice by radio the voice signal must be used to modulate a higher (carrier) frequency for which the natural antenna size is smaller.
  a. What is the length of an antenna one-half wavelength long for sending radio at 300 Hz?
  b. An alternative is to use a modulation scheme, as described in Chapter 5, for transmitting the voice signal by modulating a carrier frequency, so that the bandwidth of the signal is a narrow band centered on the carrier frequency. Suppose we would like a half-wave antenna to have a length of 1 meter. What carrier frequency would we use?

4.8 Stories abound of people who receive radio signals in fillings in their teeth. Suppose you have one filling that is 2.5 mm (0.0025 m) long that acts as a radio antenna. That is, it is equal in length to one-half the wavelength. What frequency do you receive?

4.9 You are communicating between two satellites. The transmission obeys the free space law. The signal is too weak. Your vendor offers you two options. The vendor can use a higher frequency that is twice the current frequency or can double the effective area of both of the antennas. Which will offer you more received power or will both offer the same improvement, all other factors remaining equal? How much improvement in the received power do you obtain from the best option?

4.10 For radio transmission in free space, signal power is reduced in proportion to the square of the distance from the source, whereas in wire transmission, the attenuation is a fixed number of dB per kilometer. The following table is used to show the dB reduction relative to some reference for free space radio and uniform wire. Fill in the missing numbers to complete the table.

Distance (km)	Radio (dB)	Wire (dB)
1	−6	−3
2		
4		
8		
16		

4.11 Section 4.2 states that if a source of electromagnetic energy is placed at the focus of the paraboloid, and if the paraboloid is a reflecting surface, then the wave will bounce back in lines parallel to the axis of the paraboloid. To demonstrate this, consider the parabola $y^2 = 2px$ shown in Figure 4.12. Let $P(x_1, y_1)$ be a point on the parabola, and PF be the line from P to the focus. Construct the line L through P parallel to the x-axis and the line M tangent to the parabola at P. The angle between L and M is β, and the angle between PF and M is α. The angle α is the angle at which a ray from F strikes the parabola at P. Because the angle of incidence equals the angle of reflection, the ray reflected from P must be at an angle α to M. Thus, if we can show that $\alpha = \beta$, we have demonstrated that rays reflected from the parabola starting at F will be parallel to the x-axis.

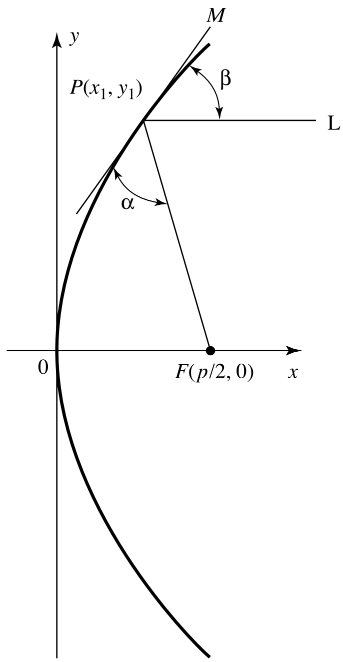


Figure 4.12 Parabolic Reflection

a. First show that $\tan \beta = (p/y_1)$. *Hint:* Recall from trigonometry that the slope of a line is equal to the tangent of the angle the line makes with the positive x-direction. Also recall that the slope of the line tangent to a curve at a given point is equal to the derivative of the curve at that point.

b. Now show that $\tan \alpha = (p/y_1)$, which demonstrates that $\alpha = \beta$. *Hint:* Recall from trigonometry that the formula for the tangent of the difference between two angles α_1 and α_2 is $\tan(\alpha_2 - \alpha_1) = (\tan \alpha_2 - \tan \alpha_1)/(1 + \tan \alpha_2 \times \tan \alpha_1)$.

4.12 It is often more convenient to express distance in km rather than m and frequency in MHz rather than Hz. Rewrite Equation (4.3) using these dimensions.

4.13 Suppose a transmitter produces 50 W of power.

a. Express the transmit power in units of dBm and dBW.

b. If the transmitter's power is applied to a unity gain antenna with a 900-MHz carrier frequency, what is the received power in dBm at a free space distance of 100 m?

c. Repeat (b) for a distance of 10 km.

d. Repeat (c) but assume a receiver antenna gain of 2.

4.14 A microwave transmitter has an output of 0.1 W at 2 GHz. Assume that this transmitter is used in a microwave communication system where the transmitting and receiving antennas are parabolas, each 1.2 m in diameter.

a. What is the gain of each antenna in decibels?
b. Taking into account antenna gain, what is the effective radiated power of the transmitted signal?
c. If the receiving antenna is located 24 km from the transmitting antenna over a free space path, find the available signal power out of the receiving antenna in dBm units.

4.15 Section 4.3 states that with no intervening obstacles, the optical line of sight can be expressed as $d = 3.57\sqrt{h}$, where d is the distance between an antenna and the horizon in kilometers and h is the antenna height in meters. Using a value for the earth's radius of 6370 km, derive this equation. *Hint:* Assume that the antenna is perpendicular to the earth's surface, and note that the line from the top of the antenna to the horizon forms a tangent to the earth's surface at the horizon. Draw a picture showing the antenna, the line of sight, and the earth's radius to help visualize the problem.

4.16 Determine the height of an antenna for a TV station that must be able to reach customers up to 80 km away.

4.17 Suppose a ray of visible light passes from the atmosphere into water at an angle to the horizontal of 30°. What is the angle of the ray in the water? *Note:* At standard atmospheric conditions at the earth's surface, a reasonable value for refractive index is 1.0003. A typical value of refractive index for water is 4/3.