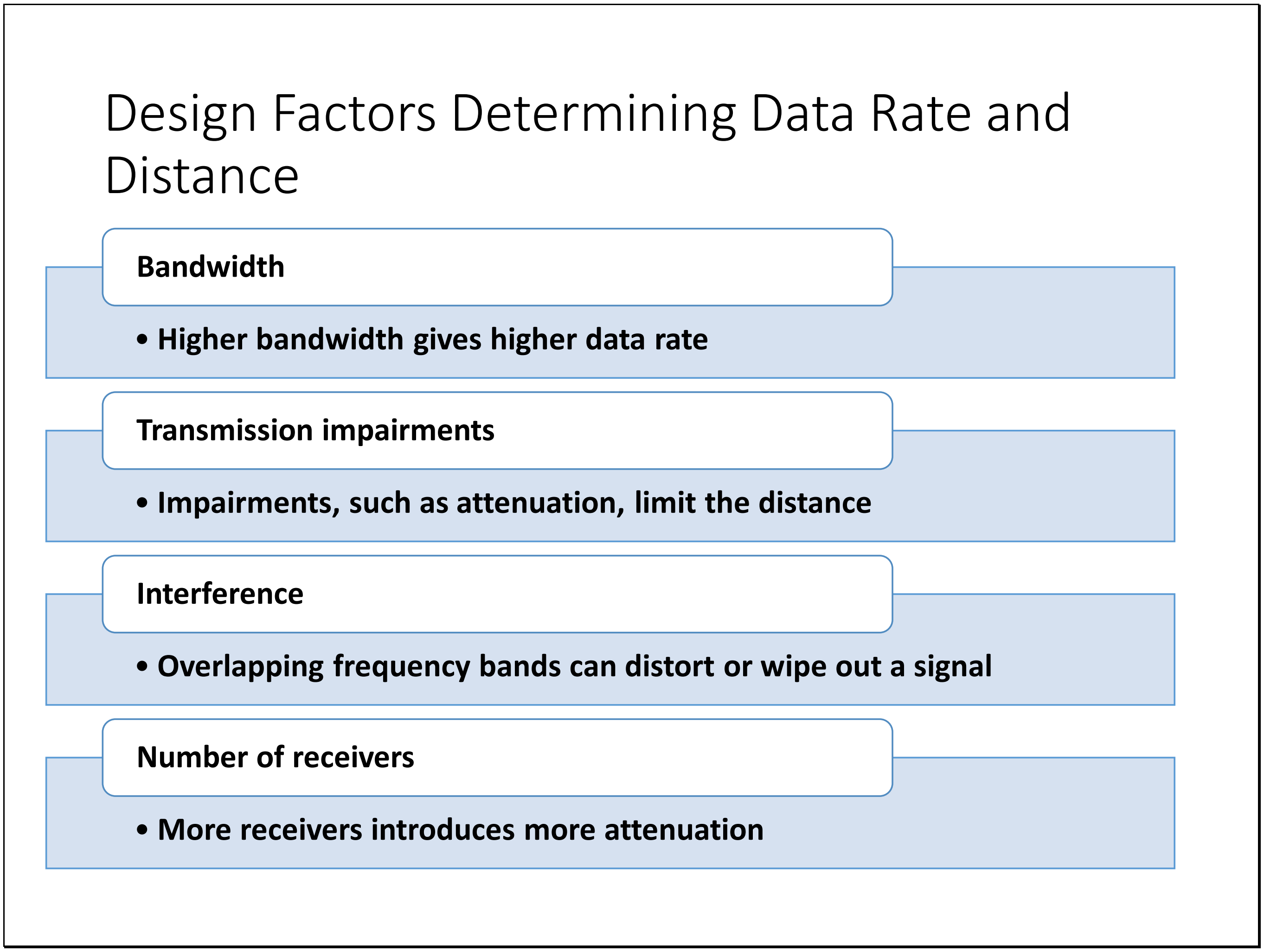
Slide 1

Data and Computer Communications

Transmission Media

“Data and Computer Communications”, 10/e, by William Stallings, Chapter 4 “Transmission Media”.

Slide 2

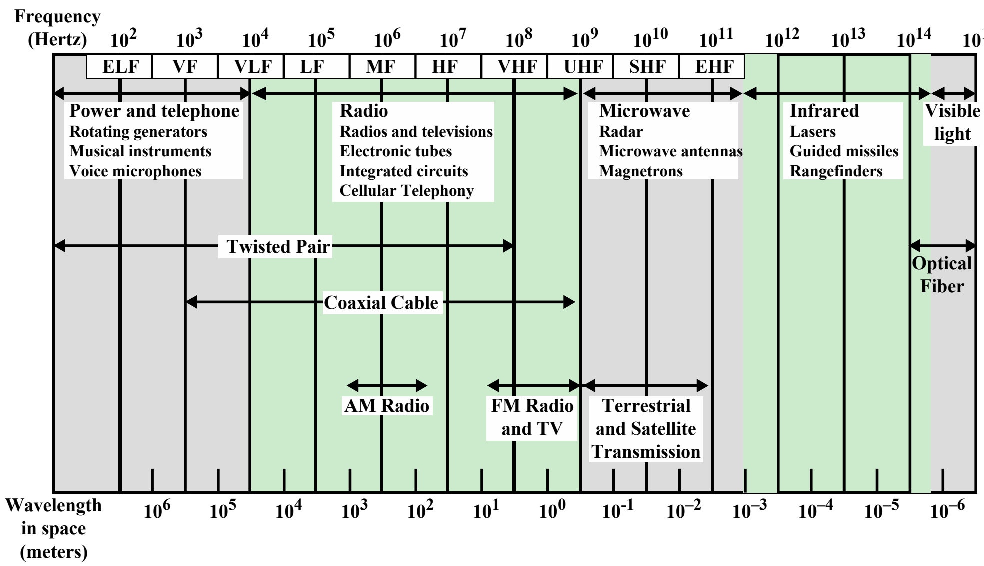


Data rate and distance are the key consideration in data transmission system design; with emphasis placed on achieving the highest data rates over the longest distances. A number of design factors relating to the transmission medium and the signal determine the data rate and distance:

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 cancels out a signal. Interference is of particular concern for unguided media, but is also a problem with guided media. For guided media, interference can be caused by emanations coupling from nearby cables (alien crosstalk) or adjacent conductors under the same cable sheath (internal crosstalk). For example, twisted pairs are often bundled together and conduits often carry multiple cables. Interference can also be caused by electromagnetic coupling 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.



ELF = Extremely low frequency	MF = Medium frequency	UHF = Ultrahigh frequency
VF = Voice frequency	HF = High frequency	SHF = Superhigh frequency
VLF = Very low frequency	VHF = Very high frequency	EHF = Extremely high frequency
LF = Low frequency		

Figure 4.1 Electromagnetic Spectrum for Telecommunications

Laser light:

Qn: Compare | Strength / weakness | between types of cables. (twisted pair, coxial, & fiber).

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.

Twisted pair: — Power & telephone.
freq ($10^1 \to 10^8$) — almost Radio

Coaxial Cables: — part of power & telephone.
freq ($10^3 \to 10^9$) — Radio. — AM.
— FM.

Optical Fiber.
freq ($10^{14} \to 10^{15}$)

Slide 4

Table 4.1

Point-to-Point Transmission Characteristics of Guided Media

	Frequency Range	Typical Attenuation	Typical Delay	Repeater Spacing
Twisted pair (with loading)	0 to 3.5 kHz	0.2 dB/km @ 1 kHz	50 µs/km	2 km
Twisted pairs (multipair cables)	0 to 1 MHz	0.7 dB/km @ 1 kHz	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	186 to 370 THz	0.2 to 0.5 dB/km	5 µs/km	40 km

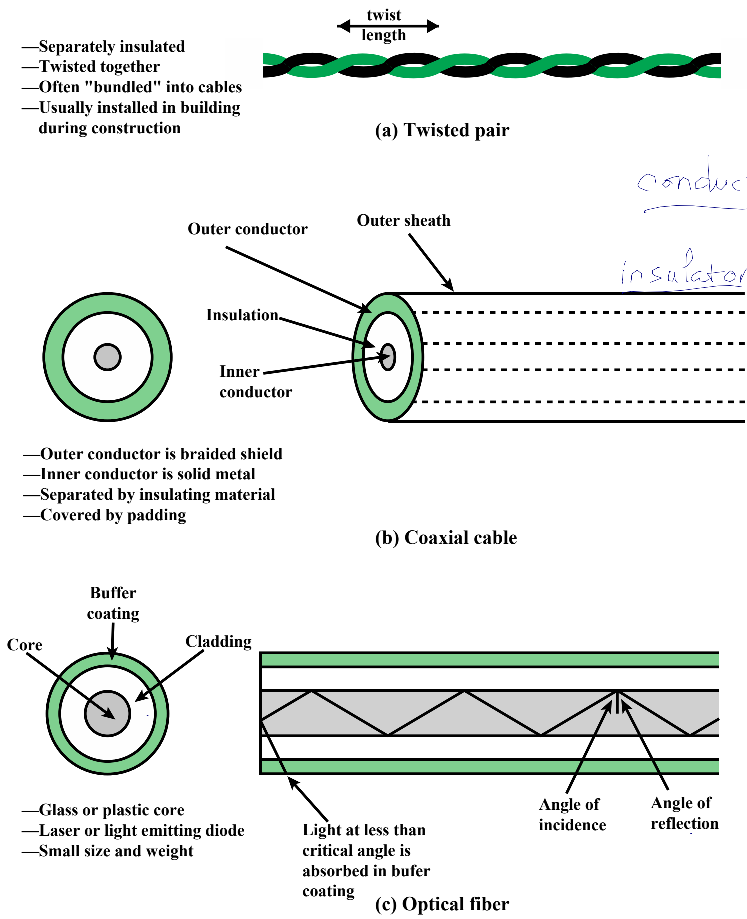
THz = terahertz = 10^{12} Hz

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 local area networks (LANs) to Part Four.

repeater spacing :

Optical fibre > Coaxial Cable > Twisted Pair

40km 1-9km 2km



conductor: allow electron's free movement.

insulator: prevent electron's movement.

Figure 4.2 Guided Transmission Media

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.

Slide 6

Twisted Pair

- Separately insulated
- Twisted together
- Often "bundled" into cables
- Usually installed in building during construction

(a) Twisted pair

Twisted pair is the least expensive and most widely used guided transmission medium

- **Consists of two insulated copper wires arranged in a regular spiral pattern**
- **A wire pair acts as a single communication link**
- **Pairs are bundled together into a cable**
- **Most commonly used in the telephone network and for communications within buildings**

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

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, or jacket. 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.

By far the most common guided 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.

most common guided media for analog signaling.

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. Ethernet operating over twisted-pair cabling is commonly used within a building for local area networks supporting personal computers. Data rates for Ethernet products are typically in the neighborhood of 100 Mbps to 1 Gbps. Emerging twisted-pair cabling Ethernet technology can support data rates of 10Gbps. 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.

Slide 7

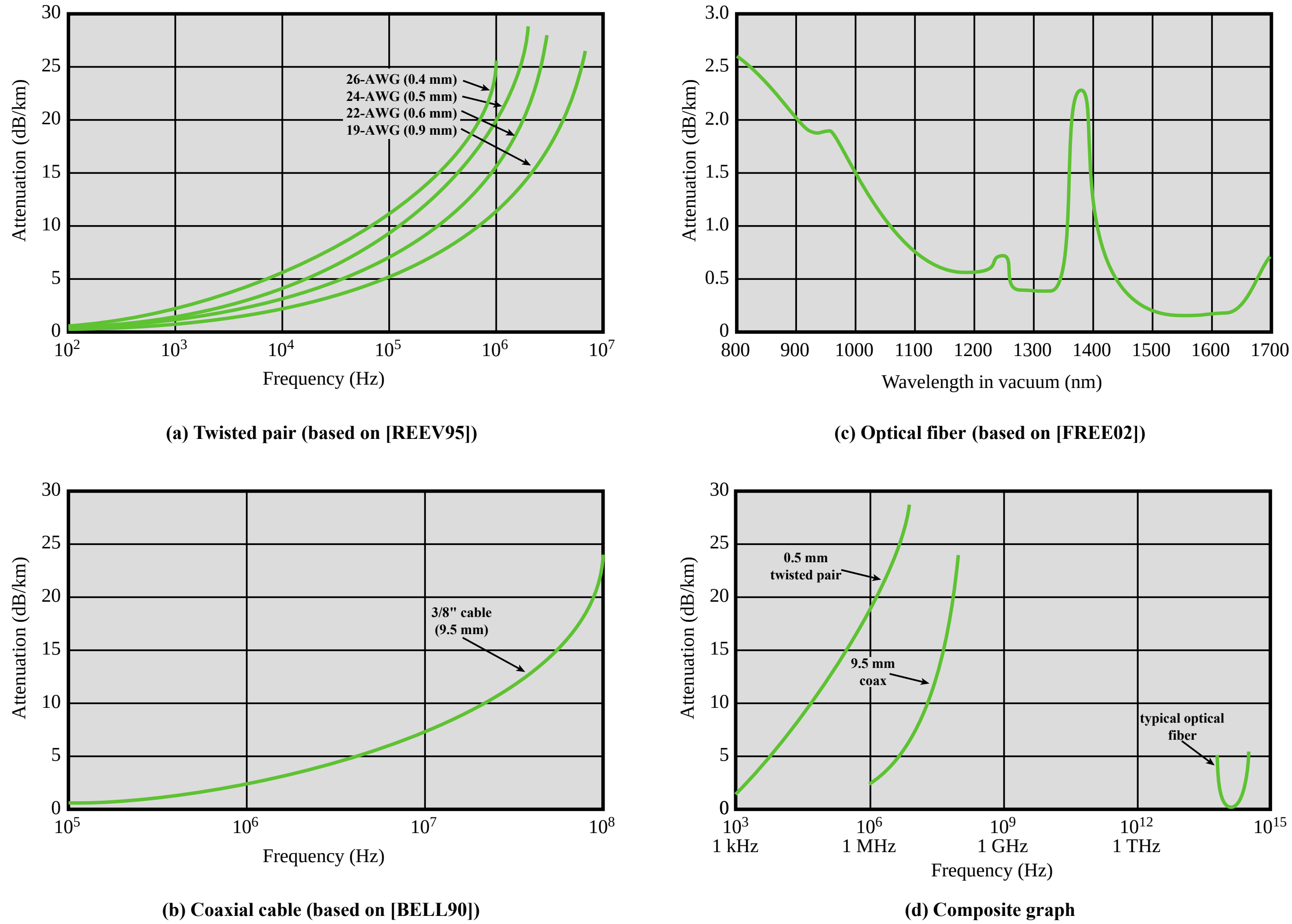


Figure 4.3 Attenuation of Typical Guided Media

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 4.3a shows, the attenuation for twisted pair is a very strong function of frequency. Twisted-pair cabling is also susceptible to signal reflections, or return loss, caused by impedance mismatches along the length of the transmission line and crosstalk from adjacent twisted-pairs or twisted-pair cables. Due to the well-controlled geometry of the twisted-pair itself (pairs are manufactured with a unique and precise twist rate that varies from pair to pair within a cable) and the media's differential mode transmission scheme (discussed in Chapter 5), twisted-pair cabling used for data transmission is highly immune to interference from low frequency (i.e., 60 Hz) disturbers. Note that twisted-pair cabling is usually run separately from cables transmitting ac power in order to comply with local safety codes, which protect low voltage telecommunications installers from high voltage applications. The possibility of electromagnetic interference from high frequency (i.e., greater than 30 MHz) disturbers such as walkie-talkies and other wireless transmitters can be alleviated by using shielded twisted-pair cabling.

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. Ethernet data rates of up to 10Gbps can be achieved over 100 meters of twisted-pair cabling.

Slide 8

Unshielded and Shielded Twisted Pair

Unshielded Twisted Pair (UTP)

- **Consists of one or more twisted-pair cables, typically enclosed within an overall thermoplastic jacket which provides no electromagnetic shielding**
- **Ordinary telephone wire**
- **Subject to external electromagnetic interference**
- **The tighter the twisting, the higher the supported transmission rate and the greater the cost per meter**

Shielded Twisted Pair (STP)

- **Has metal braid or sheathing that reduces interference**
- **Provides better performance at higher data rates**
- **More expensive**

Twisted pair comes in two varieties: unshielded and shielded. As the name implies, unshielded twisted pair (UTP) consists of one or more twisted-pair cables, typically enclosed within an overall thermoplastic jacket, which provides no electromagnetic shielding. The most common form of UTP is ordinary voice-grade telephone wire, which is pre-wired in residential and office buildings. For data transmission purposes, UTP may vary from voice-grade to very high-speed cable for local area networks (LANs). For high-speed LANs, UTP typically has four pairs of wires inside the jacket, with each pair twisted with a different number of twists per centimeter to help eliminate interference between adjacent pairs. The tighter the twisting, the higher the supported transmission rate and the greater the cost per meter.

Unshielded twisted pair is subject to external electromagnetic interference, including interference from nearby twisted pair and from noise generated in the environment. In an environment with a number of sources of potential interference (e.g., electric motors, wireless devices, and RF transmitters), shielded twisted pair (STP) may be a preferred solution. Shielded twisted pair cable is manufactured in three different configurations:

- Each pair of wires is individually shielded with metallic foil, generally referred to as foil twisted pair (FTP).

2. There is a foil or braid shield inside the jacket covering all wires (as a group). This configuration is sometimes designated as screened twisted pair (F/UTP).

3. There is a shield around each individual pair, as well as around the entire group of wires. This is referred to as fully-shielded twisted pair or shielded/foil twisted pair (S/FTP).

The shielding reduces interference and provides better performance at higher data rates. However, it may be more expensive and installers familiar with UTP technology may be reluctant to work with a new media type.

Slide 9

Table 4.2

Twisted Pair Categories and Classes

	Category 5e Class D	Category 6 Class E	Category 6A Class E_A	Category 7 Class F	Category 7_A Class F_A
Bandwidth	100 MHz	250 MHz	500 MHz	600 MHz	1,000 MHz
Cable Type	UTP	UTP/FTP	UTP/FTP	S/FTP	S/FTP
Insertion loss (dB)	24	21.3	20.9	20.8	20.3
NEXT loss (dB)	30.1	39.9	39.9	62.9	65
ACR (dB)	6.1	18.6	19	42.1	44.1

UTP = Unshielded twisted pair
FTP = Foil twisted pair
S/FTP = Shielded/foil twisted pair

In 1991, the Electronic Industries Association published standard ANSI/EIA/TIA-568, *Commercial Building Telecommunications Cabling Standard*, which specifies the use of voice- and data-grade UTP and F/UTP cabling 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. With continuing advances in cable and connector design and test methods, this standard has undergone a number of iterations to provide support for higher data rates using higher-quality cable and connectors. The current version is the responsibility of the Telecommunications Industry Association, and was issued in 2009 as four American National Standards Institute (ANSI) standards:

ANSI/TIA-568-C.0 Generic Telecommunications Cabling for Customer Premises: Enables the planning and installation of a structured cabling system for all types of customer premises.

ANSI/TIA-568-C.1 Commercial Building Telecommunications Cabling Standard: Enables the planning and installation of a structured cabling system for commercial buildings.

ANSI/TIA-568-C.2 Balanced Twisted-Pair Telecommunications Cabling and Components Standards: Specifies minimum requirements for balanced twisted-pair telecommunications cabling (e.g. channels and permanent links) and components (e.g. cable, connectors, connecting hardware, patch cords, equipment cords, work area cords, and jumpers) that are used up to and including the telecommunications outlet/connector and between buildings in a campus environment. This Standard also specifies field test procedures and applicable laboratory reference measurement procedures for all transmission parameters.

ANSI/TIA-568-C.3 Optical Fiber Cabling Components Standard: Specifies cable and component transmission performance requirements for premises optical fiber cabling.

The 568-C standards identify a number of categories of cabling and associated components that can be used for premises and campus-wide data distribution. An overlapping standard, jointly issued by the International Standards Organization and the International Electrotechnical Commission (IEC), known as ISO/IEC 11801, second edition, identifies a number of classes of cabling and associated components, which correspond to the 568-C categories.

The categories listed in the table are the following:

Category 5e/Class D: This specification was first published in 2000 in order to address the transmission performance characterization required by applications such as 1-Gbps Ethernet that utilize bi-directional and full four-pair transmission schemes (described in Chapter 12).

Category 6/Class E: In recent years, the majority of structured cabling specified for new buildings has been category 6/class E. This category provides a greater performance margin (also called performance headroom) than category 5e to ensure that the cabling plant could withstand the rigors of the cabling environment and still support 1-Gbps Ethernet when it was time for an application upgrade from 100-Mbps Ethernet. This category was published in 2002, with a targeted lifetime of 10 years, so its use is likely to decline rapidly in new installations.

Category 6A/Class E_A: This specification is targeted at 10-Gbps Ethernet applications.

Category 7/Class F: This specification uses fully-shielded twisted pair (i.e., cabling with an overall shield and individually shielded pairs). The advantage of this category over lower grades of cabling is that the use of both an overall shield and a foil shield around individual pairs dramatically decreases internal pair-to-pair crosstalk and external alien crosstalk. This class is targeted for support of next generation applications beyond 10-Gbps Ethernet.

Category 7A/Class F_A: The requirements for this class are based on class F cabling requirements. The main enhancement is to extend the frequency bandwidth to 1 GHz. This enhancement enables support of all channels of broadband video (e.g. CATV) that operate up to 862 MHz. It is likely that all fully-shielded cabling solutions specified in the near future will be class F_A.

Table 4.2 includes three key performance parameters. Insertion loss in this context refers to the amount of attenuation across the link from the transmitting system to the receiving system. Thus, lower dB values are better. The table shows the amount of attenuation at a frequency of 100 MHz. This is the standard frequency used in tables comparing various classes of twisted pair. However, attenuation is an increasing function of frequency, and the 568 standards specify the attenuation at various frequencies. In accordance with ANSI/TIA-568-C.2 and ISO/IEC 11801 second edition, all transmission characteristics are specified as a worst-case value for a 100 m length. While cabling lengths may be less than 100 m, no provisions are provided in the standards for the scaling of the specified limits. Attenuation in decibels is a linear function of distance, so attenuation for shorter or longer distances is easily calculated. In practice, as is shown in Chapter 12, distances much less than 100 m are typical for Ethernet at data rates of 1 GB and above.

Near-End Crosstalk (NEXT)

- Coupling of signal from one pair of conductors to another
  - Conductors may be the metal pins in a connector or wire pairs in a cable
- Near end refers to coupling that takes place when the transmit signal entering the link couples back to the receive conductor pair at that same end of the link
- Greater NEXT loss magnitudes are associated with less crosstalk noise

Near-end crosstalk (NEXT) loss 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 receive conductor pair at that same end of the link (i.e., the near-end transmitted signal is picked up by the near-receive pair). We can think of this as noise introduced into the system, so higher dB loss values are better; that is, greater NEXT loss magnitudes are associated with less crosstalk noise.

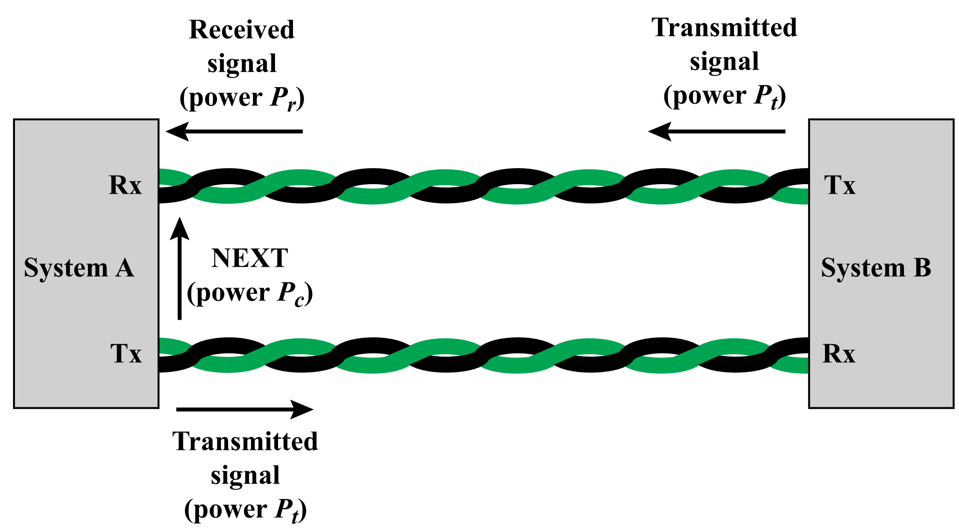
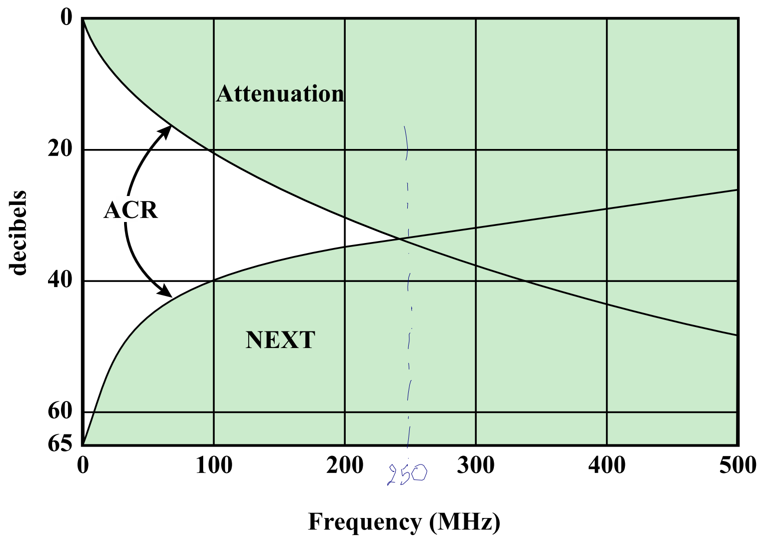


Figure 4.4 Signal Power Relationships (from System A viewpoint)

Figure 4.4 illustrates the relationship between NEXT loss and insertion loss at system A. A transmitted signal from system B, with a transmitted signal power of P_t is received at A with a reduced signal power of P_r. At the same time, system A is transmitting to signal B, and we assume that the transmission is at the same transmit signal power of P_t. Due to crosstalk, a certain level of signal from A's transmitter is induced on the receive wire pair at A with a power level of P_c; this is the crosstalk signal. Clearly, we need to have $P_r > P_c$ to be able to intelligibly receive the intended signal, and the greater the difference between P_r and P_c, the better. Unlike insertion loss, NEXT loss does not vary as a function of the length of the link, because, as Figure 4.4 indicates, NEXT loss is an end phenomenon. NEXT loss varies as a function of frequency, with losses increasing as a function of frequency. That is the amount of signal power from the near-end transmitter that couples over to an adjacent transmission line increases as a function of frequency.

Slide 12



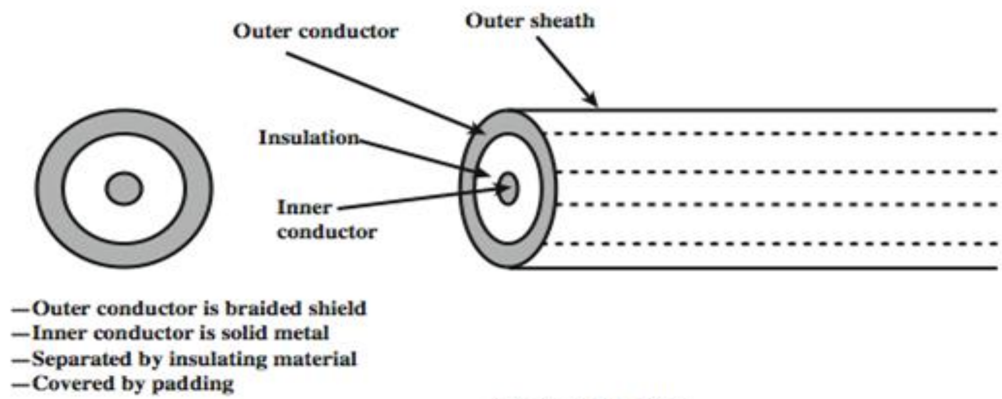
NEXT = near-end crosstalk
ACR = attenuation-to-crosstalk ratio

Figure 4.5 Category 6A Channel Requirements

Figure 4.5 shows attenuation (insertion loss) and NEXT loss as a function of frequency for category 6A twisted pair. As usual, a link of 100 m is assumed. The figure suggests that above a frequency of about 250 MHz, communication is impractical. Yet Table 4.2 indicates that category 6A is specified to operate up to 500 MHz. The explanation is that the 10-Gbps application employs crosstalk cancellation, which effectively provides a positive ACR margin out to 500 MHz. The standard indicates a worst-case situation, and engineering practices, such as crosstalk cancellation, are used to overcome the worst-case limitations.

Slide 13

Coaxial Cable



(b) Coaxial cable

Coaxial cable can be used over longer distances and support more stations on a shared line than twisted pair

- **Consists of a hollow outer cylindrical conductor that surrounds a single inner wire conductor**
- **Is a versatile transmission medium used in a wide variety of applications**
- **Used for TV distribution, long distance telephone transmission and LANs**

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 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.

Coaxial cable is a versatile transmission medium, used in a wide variety of applications. The most important of these are

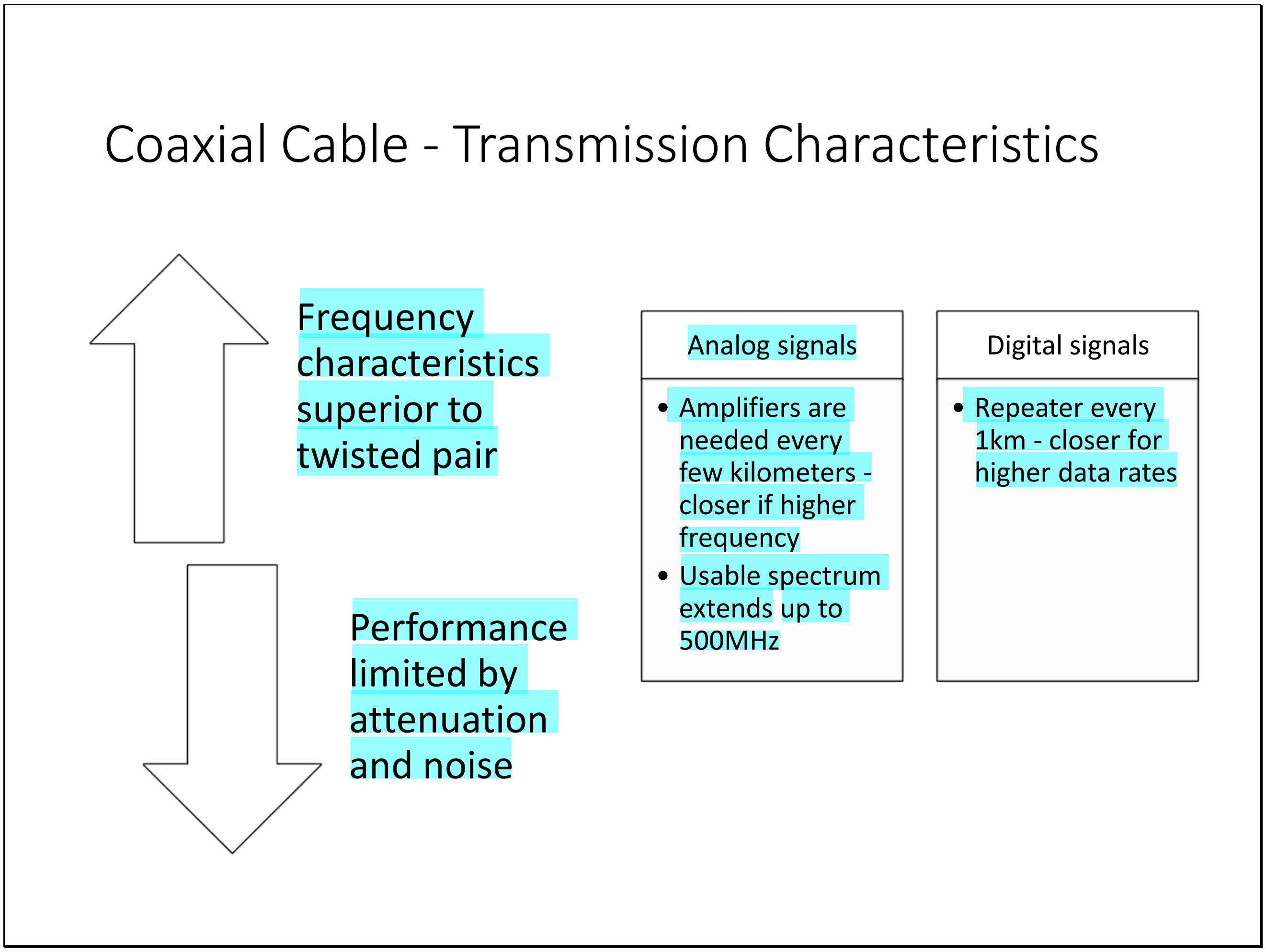
- Television distribution
- Long-distance telephone transmission
- Short-run computer system links
- Local area networks

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.

Slide 14



Coaxial cable is used to transmit both analog and digital signals. 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.

Slide 15

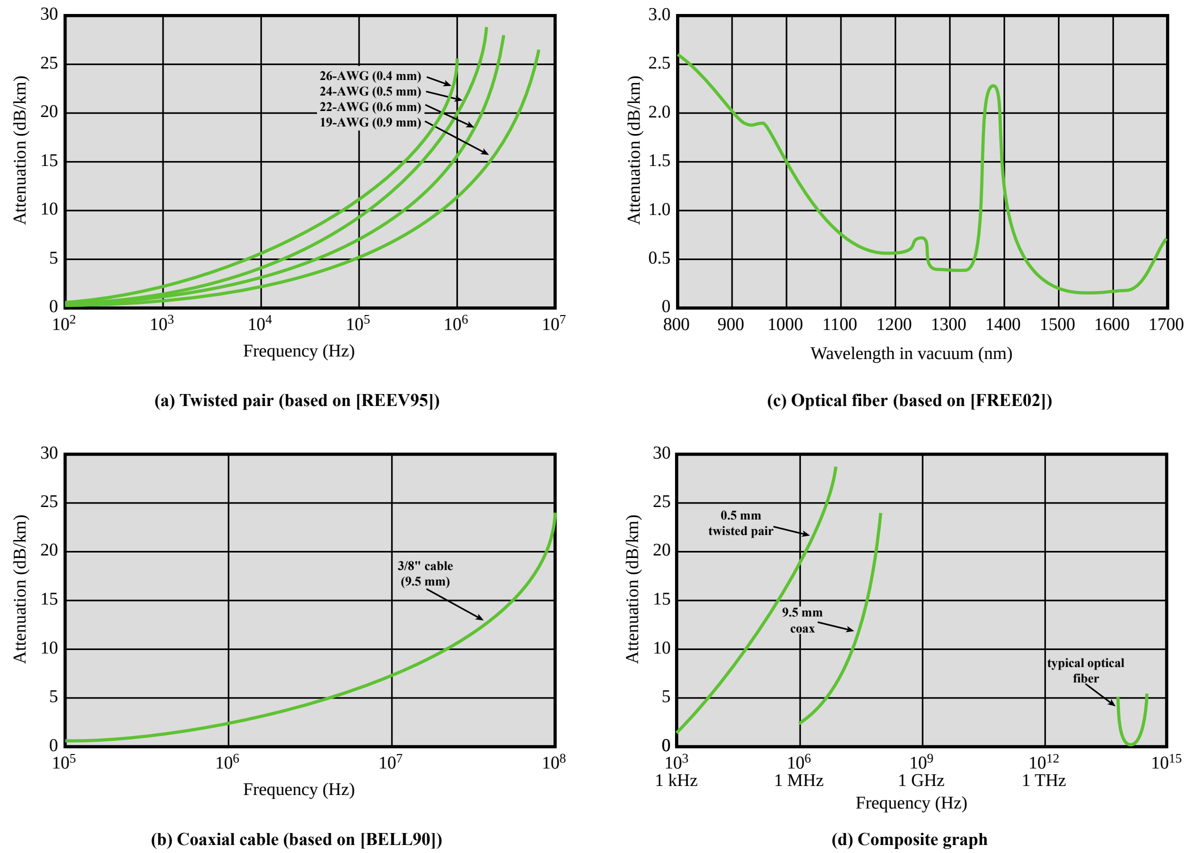
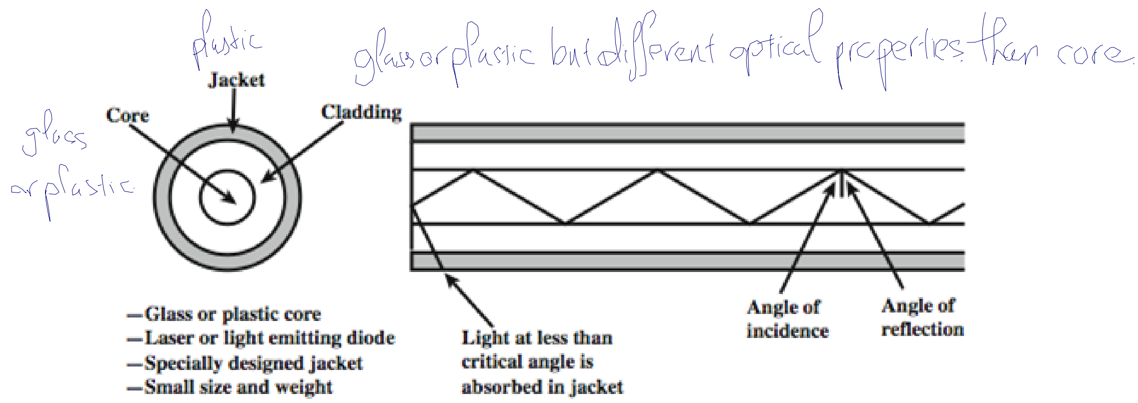


Figure 4.3 Attenuation of Typical Guided Media

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.

Slide 16

Optical Fiber



(c) Optical fiber

Optical fiber is a thin flexible medium capable of guiding an optical ray

- **Various glasses and plastics can be used to make optical fibers**
- **Has a cylindrical shape with three sections – core, cladding, jacket**
- **Widely used in long distance telecommunications**
- **Performance, price and advantages have made it popular to use**

An optical fiber is a thin, 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 strand (also called an optical waveguide) has a cylindrical shape and consists of three concentric sections: the core, the cladding, and the buffer coating (Figure 4.2c). The core is the innermost section and consists of thin strands made of glass or plastic; the core has a diameter in the range of 8 to 62.5 µm. The core is surrounded by a cladding , which is a glass or plastic coating that has optical properties different from those of the core and a diameter of 125 µm. The interface between the core and cladding acts as a reflector to confine light that would otherwise escape the core. The outermost layer is the buffer coating , which is a hard plastic coating that protects the glass from moisture and physical damage.

Fiber optic cable provides protection to the fiber from stress during installation and from the environment once it is installed. Cables may contain from only one to hundreds of fibers inside. The outermost layer of the cable, surrounding one or a bundle of fibers, is the jacket . The jacket is composed of plastic and other materials, layered to protect against moisture, abrasion, crushing, and other environmental dangers.

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.

Slide 17

Optical Fiber - Benefits

- Greater capacity
  - Data rates of hundreds of Gbps over tens of kilometers have been demonstrated
- Smaller size and lighter weight
  - Considerably thinner than coaxial or twisted pair cable
  - Reduces structural support requirements
- Lower attenuation
- Electromagnetic isolation
  - Not vulnerable to interference, impulse noise, or crosstalk
  - High degree of security from eavesdropping
- Greater repeater spacing
  - Lower cost and fewer sources of error

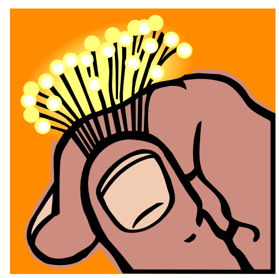
The following characteristics distinguish optical fiber from twisted pair or coaxial cable:

• 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 10 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.

Slide 18

Categories of Application

- Five basic categories of application have become important for optical fiber:
  - Long-haul trunks
  - Metropolitan trunks
  - Rural exchange trunks
  - Subscriber loops
  - Local area networks



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

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

Telephone networks were the first major users of fiber optics. Fiber optic links were used to replace copper or digital radio links between telephone switches, beginning with long-distance links, called long lines or long haul, where fiber's distance and bandwidth capabilities made fiber significantly more cost-effective. Optical fiber is used to connect all central offices and long-distance switches because it has thousands of times the bandwidth of copper wire and can carry signals hundreds of times further before needing a repeater, making the cost of a phone connection over fiber only a few percent of the cost of the same connection on copper.

Long-haul routes average about 1500 km in length and offer high capacity (typically 20,000 to 60,000 voice channels). 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 that 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. With the exception of some rugged or remote locations, the entire telephone backbone is now optical fiber. Cables on the land are run underground or aerially, depending on the geography and local regulations. Connections around the world are run primarily on undersea cables, which now link every continent and most island nations with the exception of Antarctica.

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 has been for the business subscriber, but fiber transmission into the home is now a significant presence in many areas.

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 up to 100 Gbps and can support thousands of stations in a large office building or a complex of buildings.

Slide 19

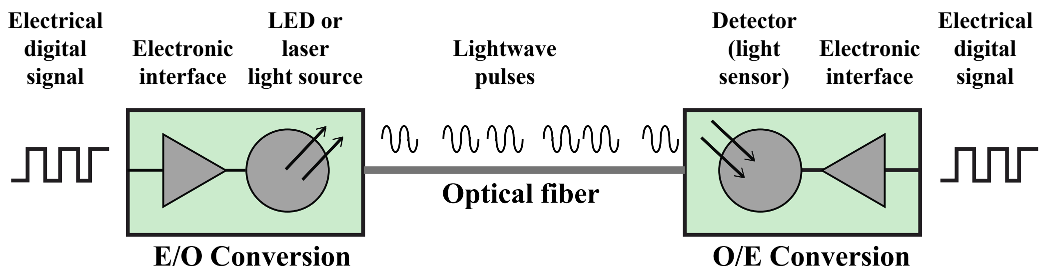


Figure 4.6 Optical Communication

Figure 4.6 shows the general structure of a fiber optic link, which consists of a transmitter on one end of a fiber and a receiver on the other end. Most systems operate by transmitting in one direction on one fiber and in the reverse direction on another fiber for full duplex operation. The transmitter takes as input a digital electrical signal. This signal feeds into a LED or laser light source through an electronic interface. The light source produces a series of lightwave pulses that encode the digital data from the electrical input. The receiver includes a light sensor that detects the incoming light signal and converts it back to a digital electrical signal.

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} Hz; this covers portions of the infrared and visible spectra.

Slide 20

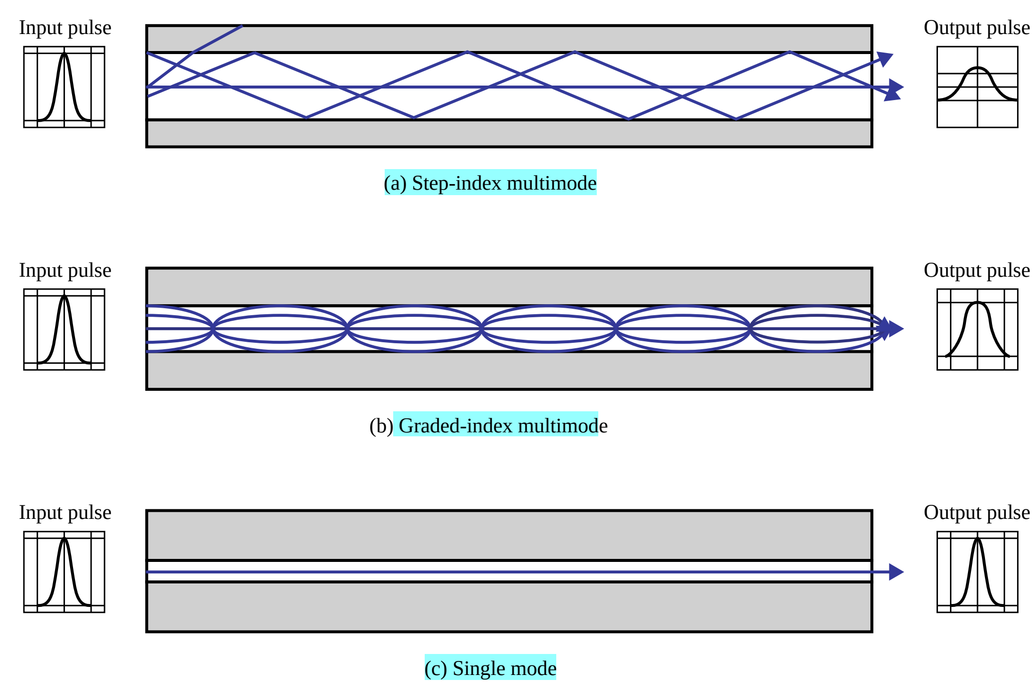


Figure 4.7 Optical Fiber Transmission Modes

Figure 4.7 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 material. This form of propagation is called step-index multimode , referring to the variety of angles that 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 LANs.

Slide 21

Table 4.3

Frequency Utilization for Fiber Applications

Wave length (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

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.
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, as shown in Table 4.3.

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 c, the speed of light in a vacuum; the result is that although the frequency of the signal is unchanged, the wavelength is changed.

$c = \lambda f$

speed of light

Slide 22

Attenuation in Guided Media

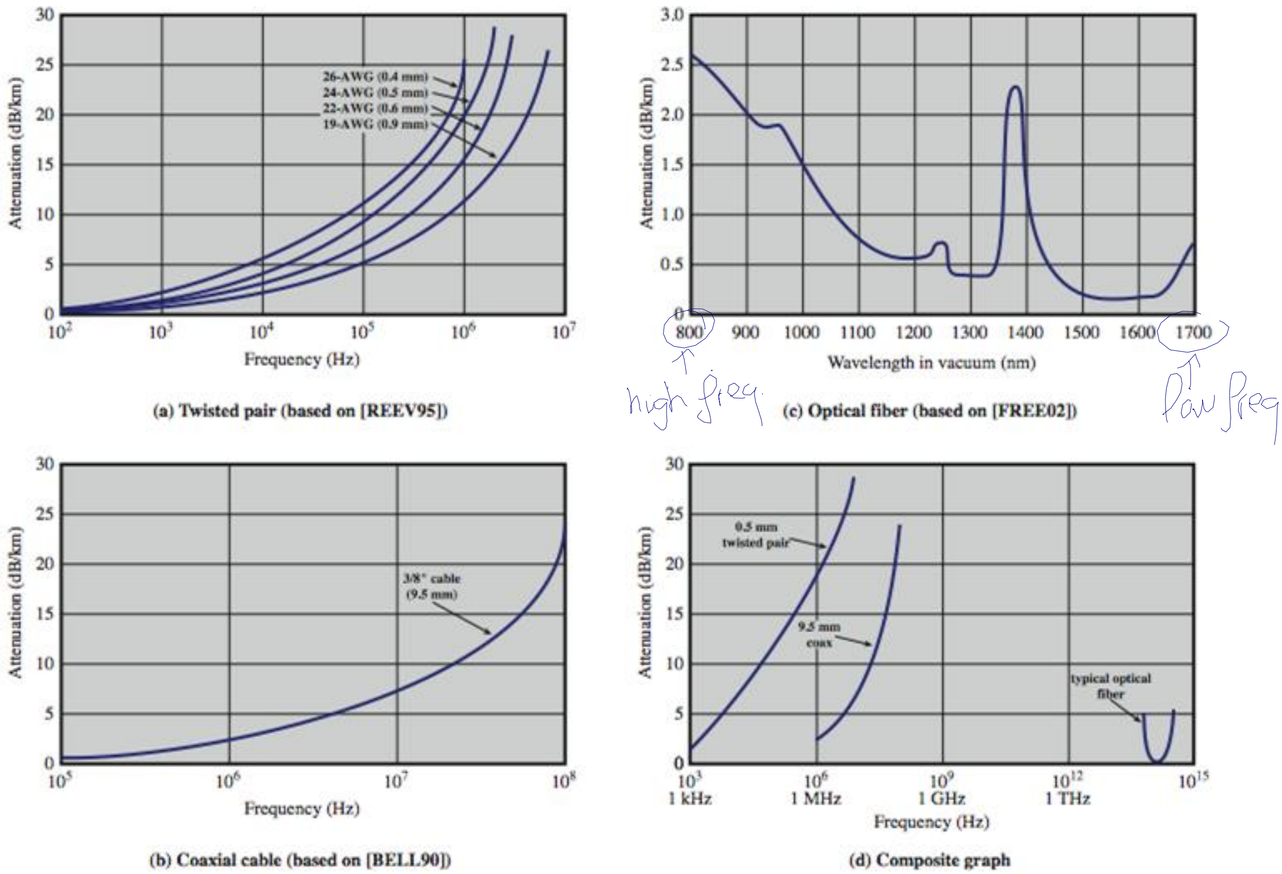
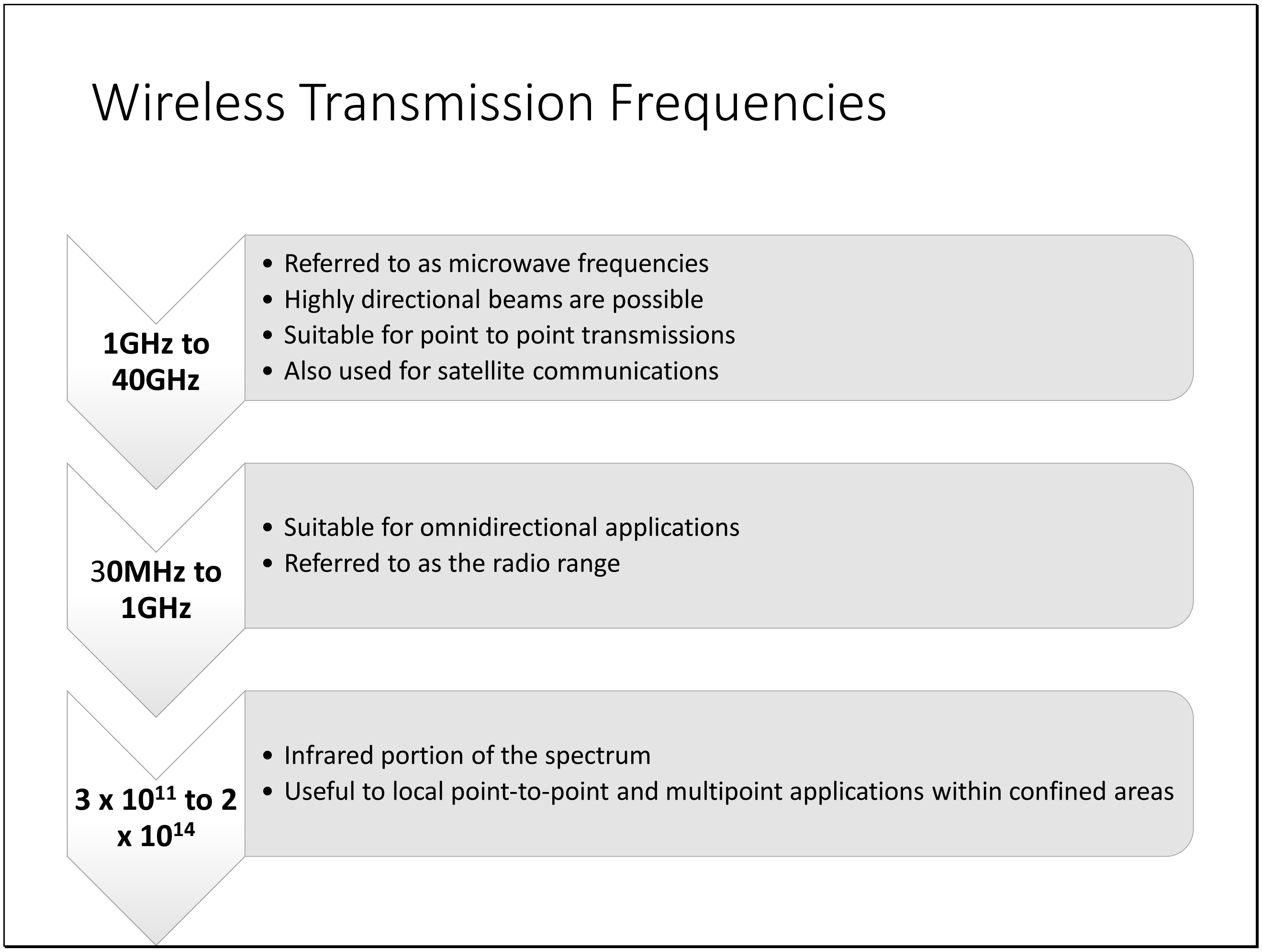


Figure 4.3c shows attenuation versus wavelength for a typical optical fiber. The unusual shape of the curve is due to the combination of a variety of factors that contribute to attenuation. The two most important of these are absorption and scattering. In this context, the term scattering refers to the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

Slide 23



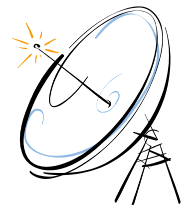
Three general ranges of frequencies are of interest in our discussion of wireless transmission. Frequencies in the range of about 1 GHz (gigahertz = 10^9 hertz) to 40 GHz are referred to as microwave frequencies. At these frequencies, highly directional beams are possible, and microwave is quite suitable 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.

Slide 24

Antennas



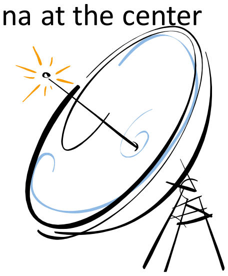
- Electrical conductor or system of conductors used to radiate or collect electromagnetic energy
- Radio frequency electrical energy from the transmitter is converted into electromagnetic energy by the antenna and radiated into the surrounding environment
- Reception occurs when the electromagnetic signal intersects the antenna
- In two way communication, the same antenna can be used for both transmission and reception

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, radio-frequency 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 radio-frequency 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.

Radiation Pattern

- Power radiated in all directions
  - Does not perform equally well in all directions
- **Radiation pattern**
  - A graphical representation of the radiation properties of an antenna as a function of space coordinates
- Isotropic antenna
  - A point in space that radiates power in all directions equally
  - Actual radiation pattern is a sphere with the antenna at the center



An antenna radiates 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.

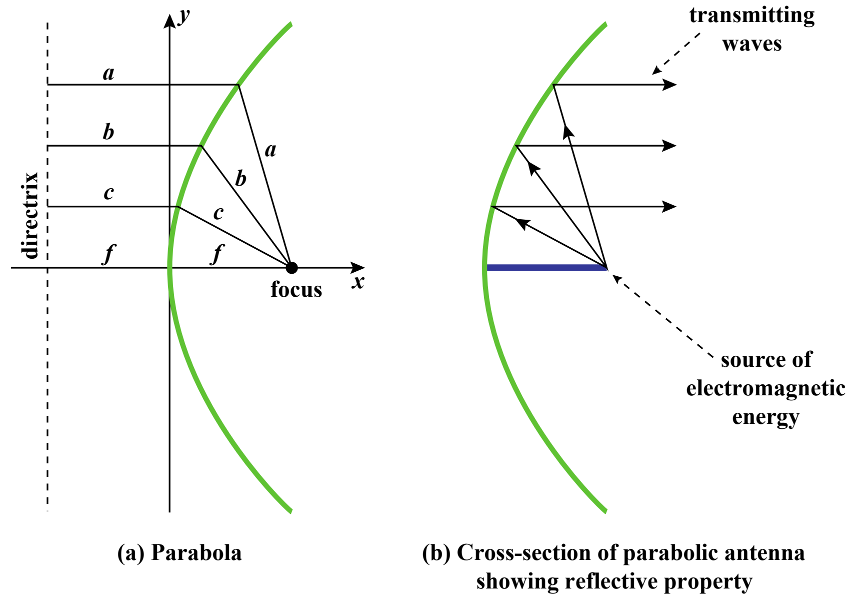
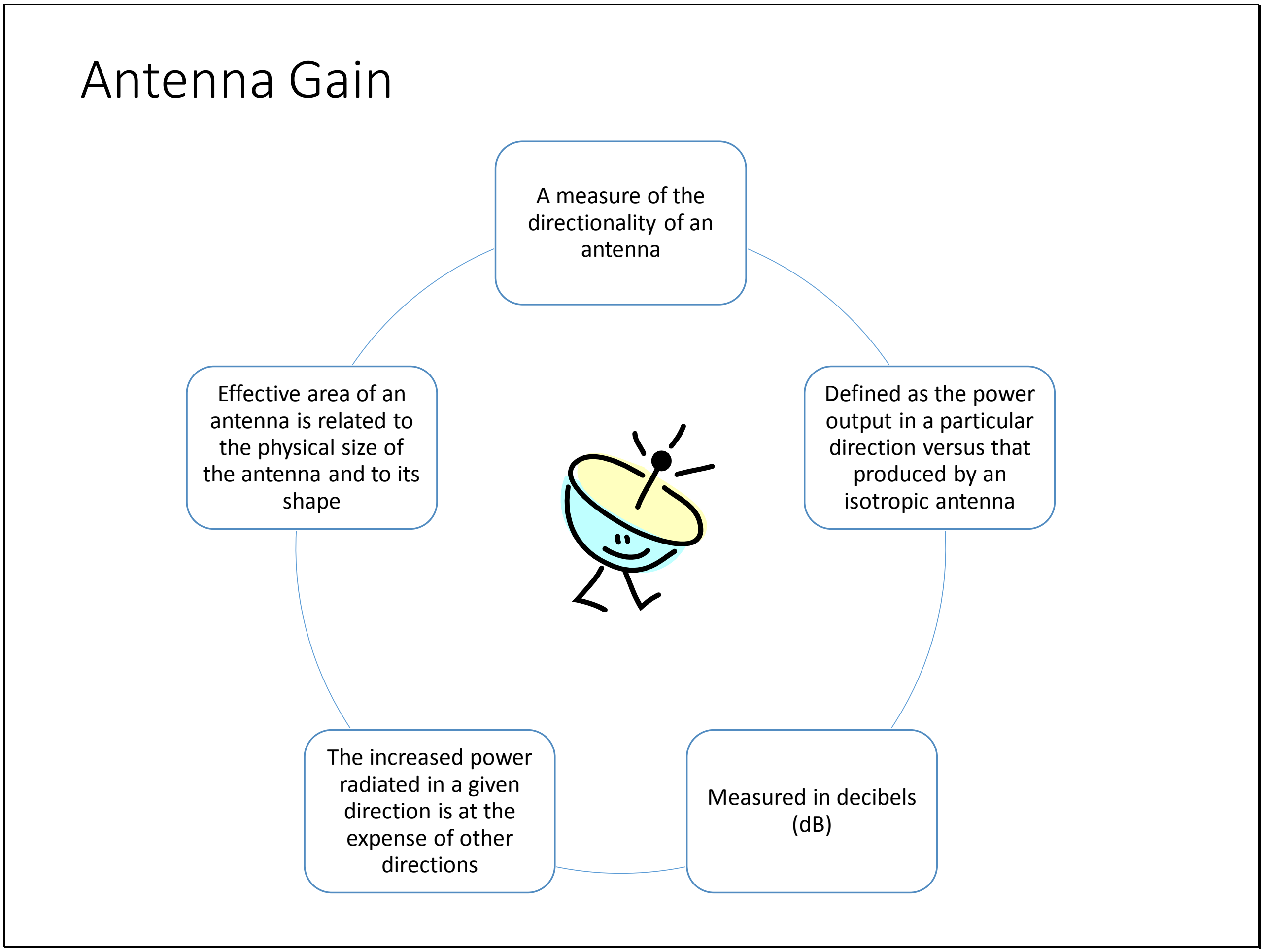


Figure 4.8 Parabolic Reflective Antenna

An important type of antenna is the **parabolic reflective antenna**, which is used in terrestrial microwave and satellite applications. 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 4.8a). 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 automobile 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 bounces back in lines parallel to the axis of the paraboloid; Figure 4.8b shows this effect in cross section. In theory, this effect creates a parallel beam without dispersion. In practice, there is 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 is concentrated at the focus.

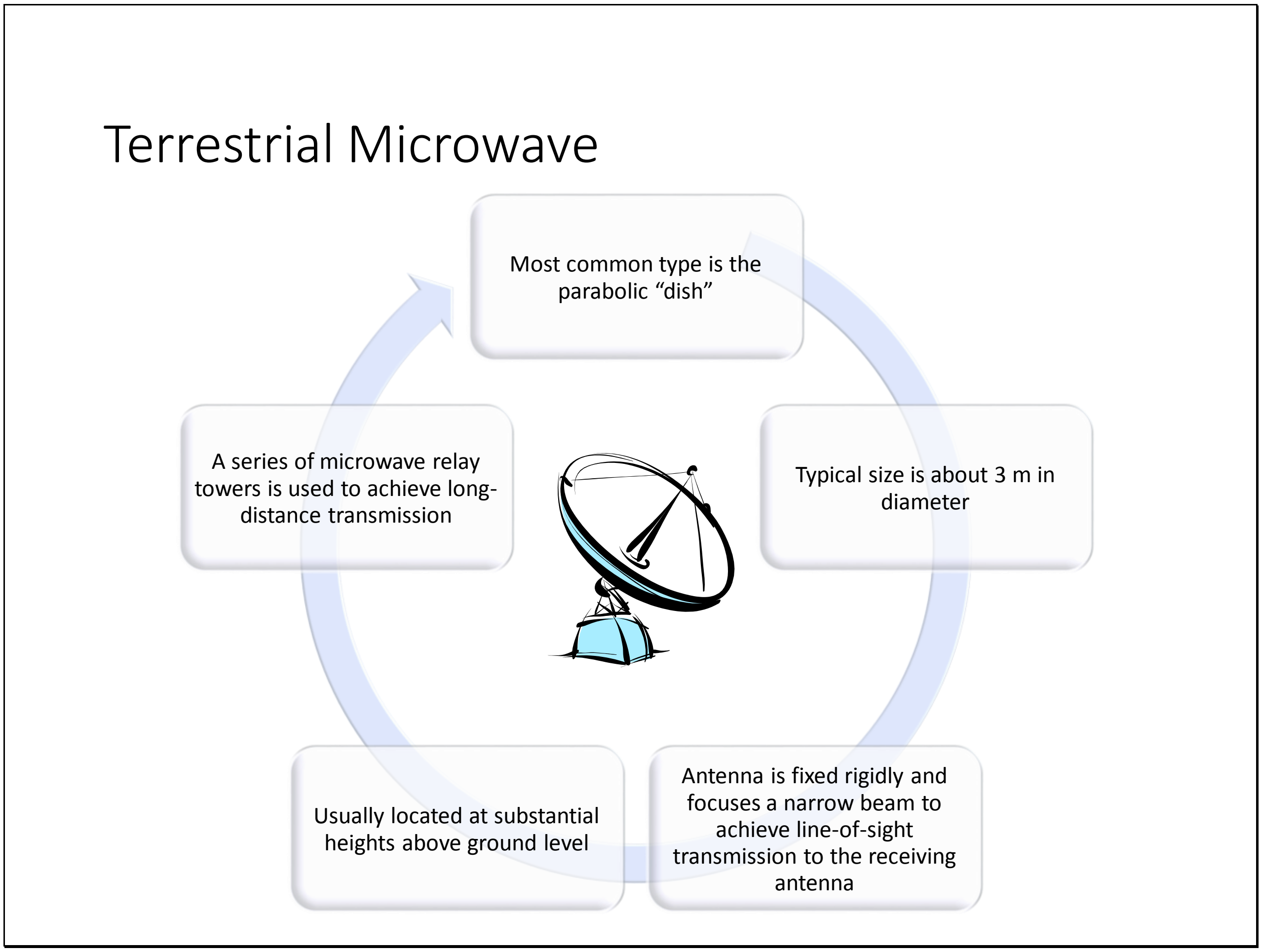
Slide 27



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). Specifically, $G_{dB} = 10 \log (P_2/P_1)$, where G is the antenna gain, P_1 is the radiated power of the directional antenna, and P_2 is the radiated power from the reference 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.

Slide 28



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, with point-to-point microwave links strung together over the desired distance.

Terrestrial Microwave Applications

- Used for long haul telecommunications service as an alternative to coaxial cable or optical fiber
- Used for both voice and TV transmission
- Fewer repeaters but requires line-of-sight transmission
- 1-40GHz frequencies, with higher frequencies having higher data rates
- Main source of loss is attenuation caused mostly by distance, rainfall and interference

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 10.

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 4.4
Typical Digital Microwave Performance

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

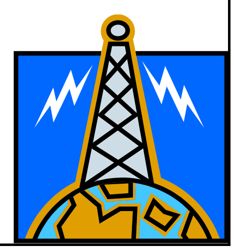
Table 4.4 indicates bandwidth and data rate for some typical systems.

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 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

- A communication satellite is in effect a microwave relay station
- Used to link two or more ground stations
- Receives transmissions on one frequency band, amplifies or repeats the signal, and transmits it on another frequency
  - Frequency bands are called transponder channels



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.

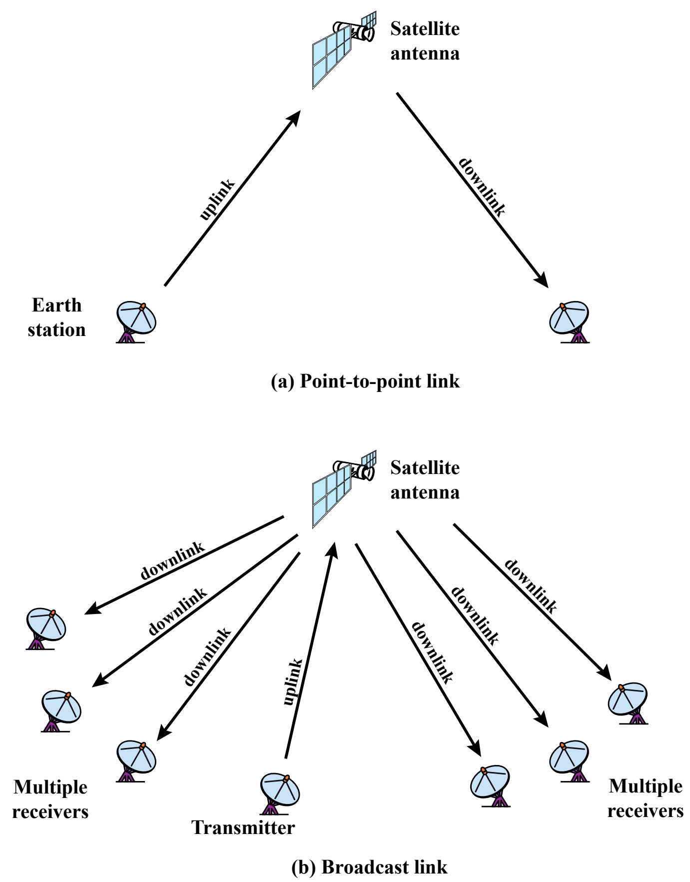


Figure 4.9 Satellite Communication Configurations

Figure 4.9 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.

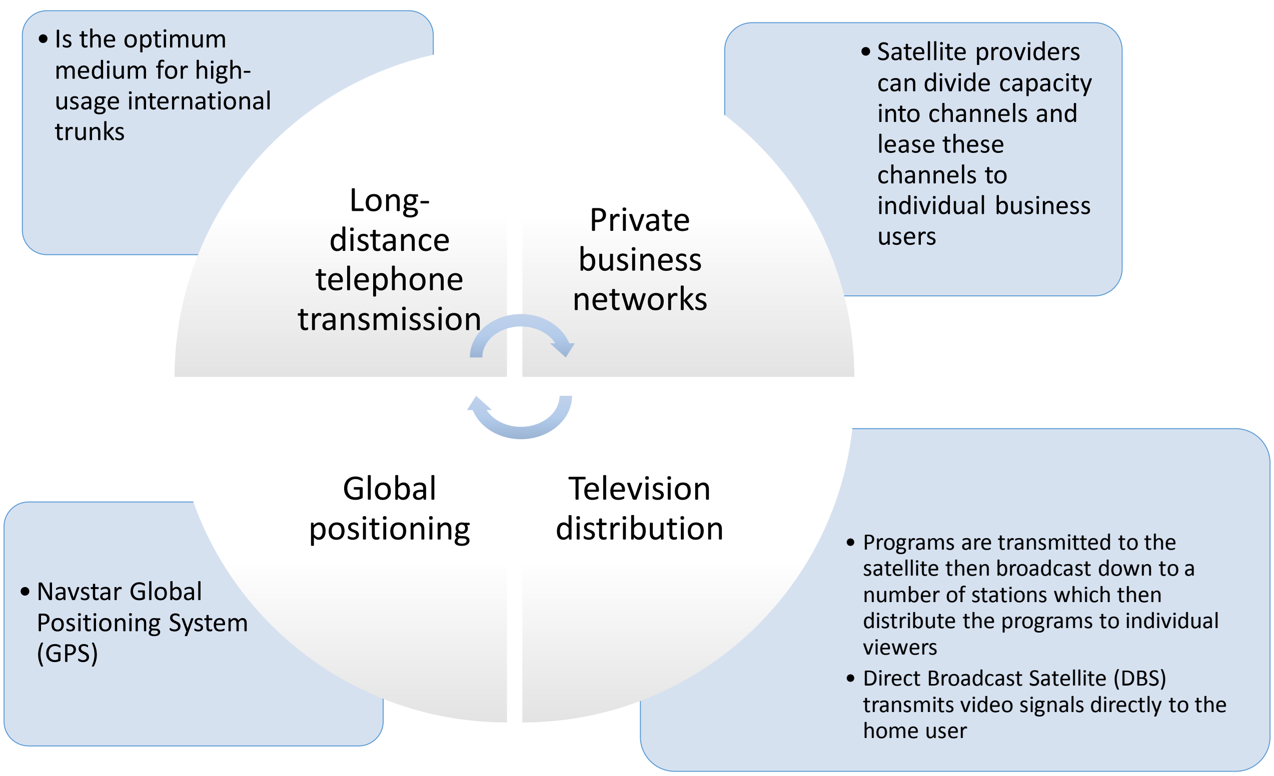
For a communication satellite to function effectively, it is generally required that it remain stationary with respect to its position over the earth. Otherwise, it would not be within the line of sight of its earth stations at all times. To remain stationary, the satellite must have a period of rotation 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, 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.

Slide 33

Satellite Microwave Applications

- Most important applications for satellites are:



Among the most important applications for satellites:

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

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 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.

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

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.

A final application of satellites, which has become pervasive, is worthy of note. The Navstar Global Positioning System, or GPS for short, consists of three segments or components:

- A constellation of satellites (currently 27) orbiting about 20,000 km above the Earth's surface, which transmits ranging signals on two frequencies in the microwave part of the radio spectrum

- A control segment which maintains GPS through a system of ground monitor stations and satellite upload facilities

- The user receivers—both civil and military

Slide 34

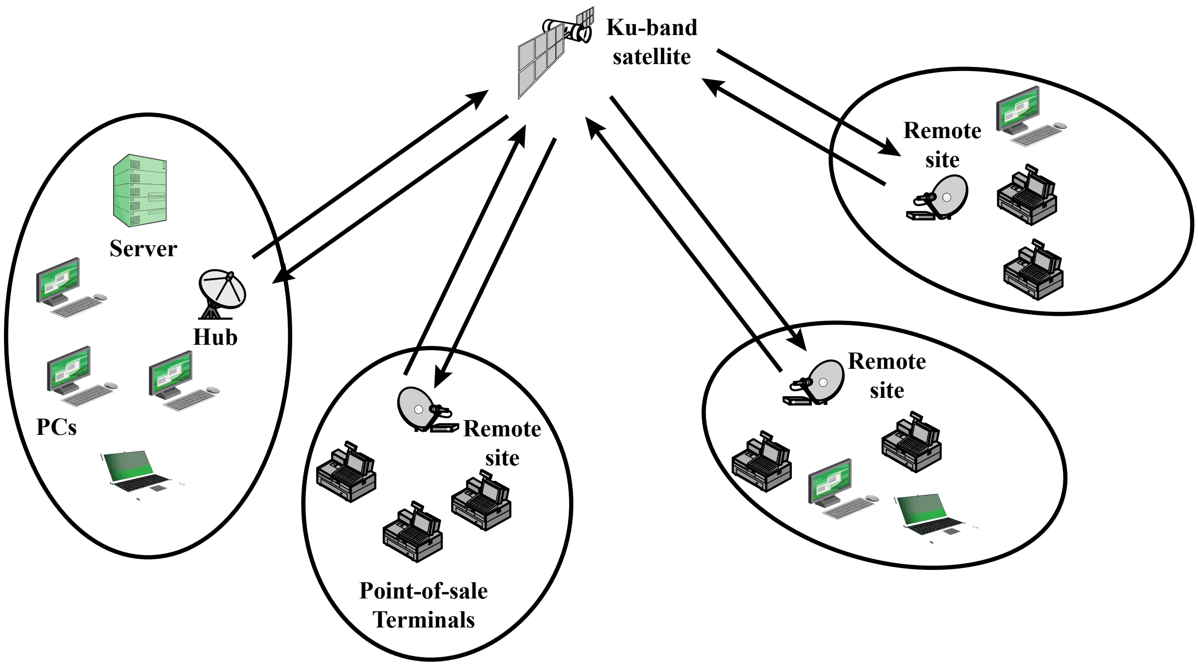


Figure 4.10 Typical VSAT Configuration

Figure 4.10 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.

Each satellite transmits a unique digital code sequence of 1s and 0s, precisely timed by an atomic clock, which is picked up by a GPS receiver's antenna and matched with the same code sequence generated inside the receiver. By lining up or matching the signals, the receiver determines how long it takes the signals to travel from the satellite to the receiver. These timing measurements are converted to distances using the speed of light. Measuring distances to four or more satellites simultaneously and knowing the exact locations of the satellites (included in the signals transmitted by the satellites), the receiver can determine its latitude, longitude, and height while also synchronizing its clock with the GPS time standard which also makes the receiver a precise time piece.

Slide 35

Transmission Characteristics

- The optimum frequency range for satellite transmission is 1 to 10 GHz
  - Below 1 GHz there is significant noise from natural sources
  - Above 10 GHz the signal is severely attenuated by atmospheric absorption and precipitation
- Satellites use a frequency bandwidth range of 5.925 to 6.425 GHz from earth to satellite (uplink) and a range of 3.7 to 4.2 GHz from satellite to earth (downlink)
  - This is referred to as the 4/6-GHz band
  - Because of saturation the 12/14-GHz band has been developed

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.

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

- Broadcast radio is omnidirectional and microwave is directional
- **Radio** is the term used to encompass frequencies in the range of 3kHz to 300GHz
- **Broadcast radio** (30MHz - 1GHz) covers:
  - FM radio and UHF and VHF television band
  - Data networking applications
- Limited to **line of sight**
- Suffers from **multipath interference**
  - Reflections from land, water, man-made objects

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.

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.

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.

Infrared

- Achieved using transceivers that modulate noncoherent infrared light
- Transceivers must be within line of sight of each other directly or via reflection
- Does not penetrate walls
- No licensing is required
- No frequency allocation issues

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.

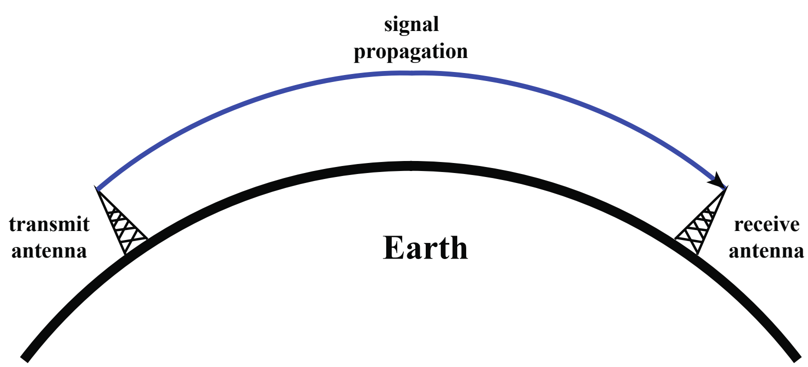
One important difference between infrared and microwave transmission is that the former does not penetrate walls. Thus the security and interference problems encountered in microwave systems are not present. Furthermore, there is no frequency allocation issue with infrared, because no licensing is required.

Slide 38

A signal radiated from an antenna travels along one of three routes: ground wave, sky wave, or line of sight (LOS). Table 4.5 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.

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	1,000 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; military 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; radio astronomy
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

Slide 39



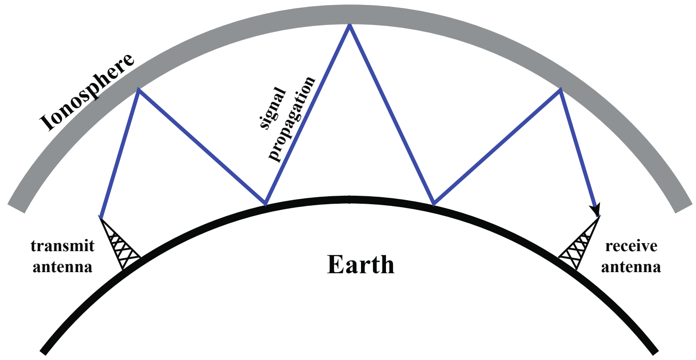
(a) Ground-wave propagation (below 2 MHz)

Figure 4.11 Wireless Propagation Modes

- Ground wave propagation follows the contour of the earth and can propagate distances well over the visual horizon
- This effect is found in frequencies up to about 2MHz
- The best known example of ground wave communication is AM radio

Ground wave propagation (Figure 4.11a) 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.



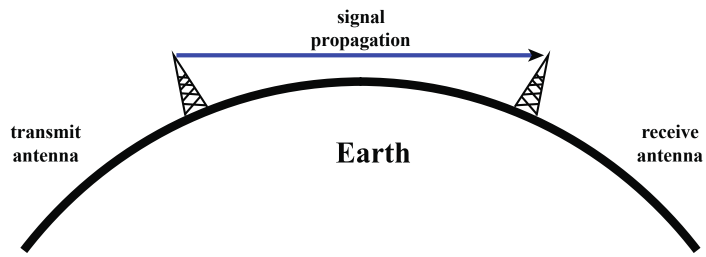
(b) Sky-wave propagation (2 to 30 MHz)

Figure 4.11 Wireless Propagation Modes

- **Sky wave propagation is used for amateur radio and international broadcasts such as *BBC* and *Voice of America***
- **A signal from an earth based antenna is reflected from the ionized layer of the upper atmosphere back down to earth**
- **Sky wave signals can travel through a number of hops, bouncing back and forth between the ionosphere and the earth's surface**

Sky wave propagation is used for amateur 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 4.11b). With this propagation mode, a signal can be picked up thousands of kilometers from the transmitter.



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

Figure 4.11 Wireless Propagation Modes

- **Ground and sky wave propagation modes do not operate above 30 MHz - - communication must be by line of sight**

Above 30 MHz, neither ground wave nor sky wave propagation modes operate, and communication must be by line of sight(Figure 4.11c). 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 depend 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

- Occurs because the velocity of an electromagnetic wave is a function of the density of the medium through which it travels
  - 3×10^8 m/s in a vacuum, less in anything else
- The speed changes with movement between a medium of one density to a medium of another density
- Index of refraction (refractive index)
  - The sine of the angle of incidence divided by the sine of the angle of refraction
  - Is also equal to the ratio of the respective velocities in the two media
  - Varies with wavelength
- Gradual bending
  - Density of atmosphere decreases with height, resulting in bending of radio waves toward the earth

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. 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 bends 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 occurs 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.

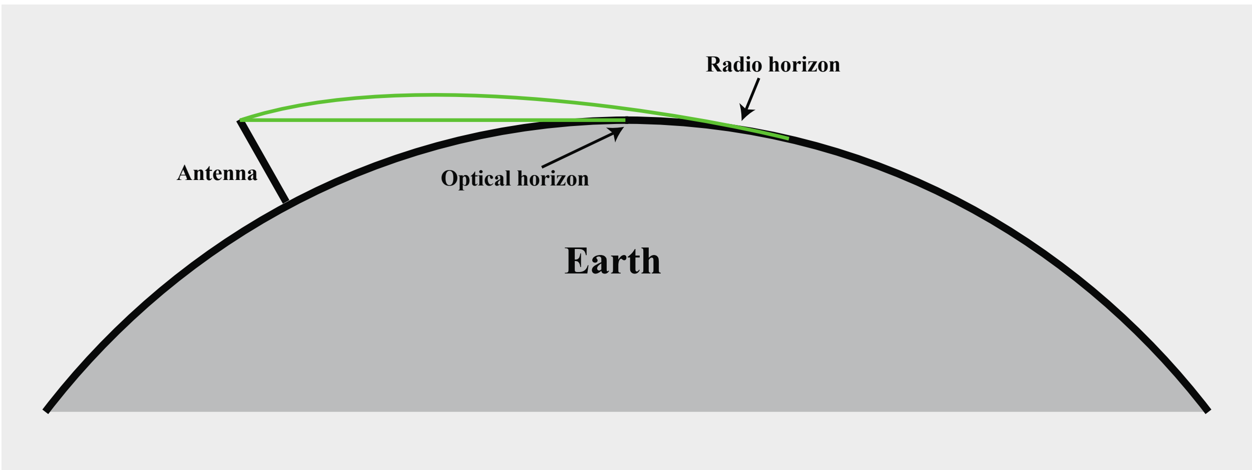
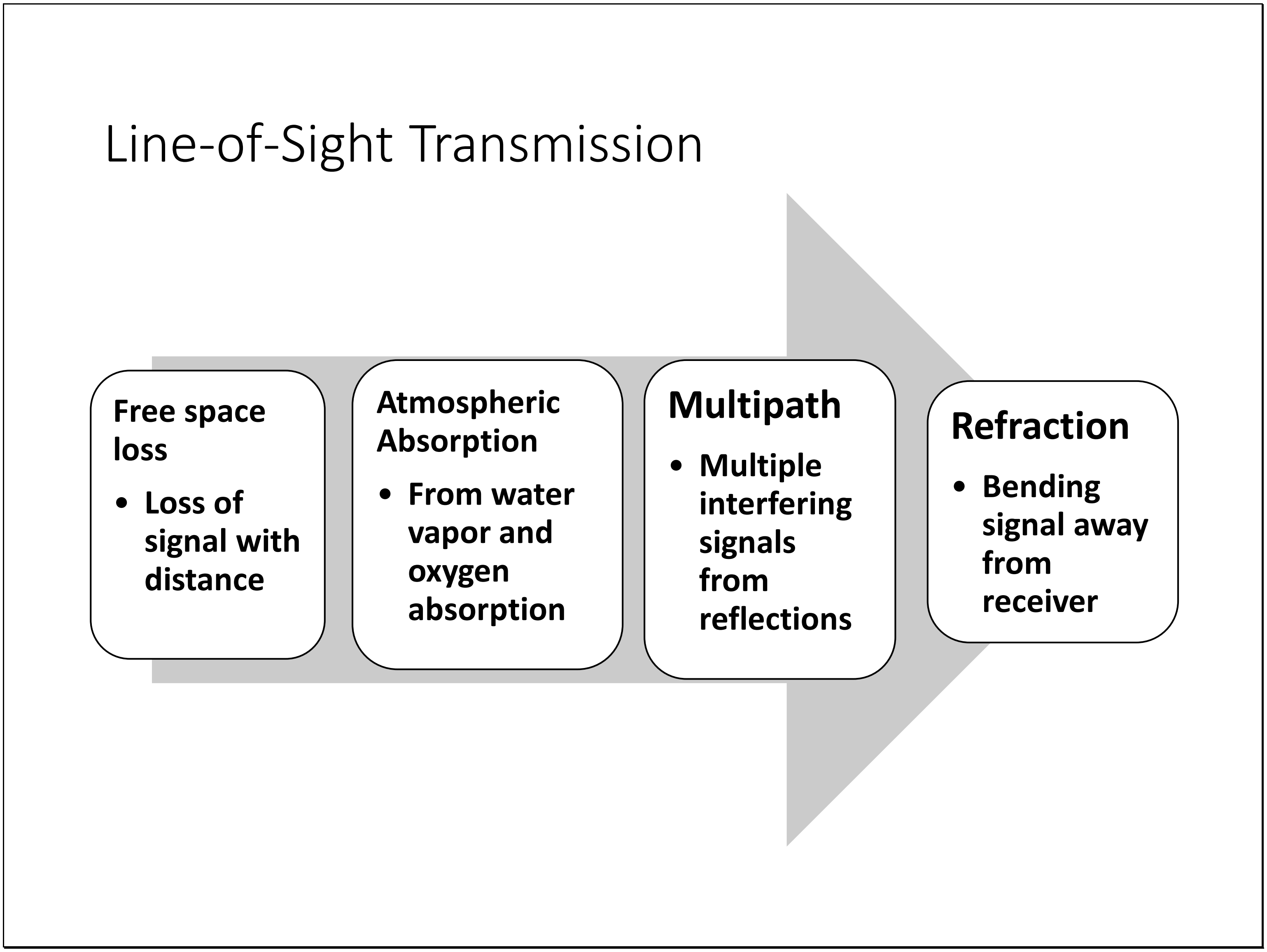


Figure 4.12 Optical and Radio Horizons

The effective, or radio, line of sight to the horizon.

See page 139 in textbook for formulas and examples.

Slide 44



Section 3.3 discusses 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.

For any type of wireless communication the signal disperses with distance. Therefore, an antenna with a fixed area receives 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 expressed 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.

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.

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 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.

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.

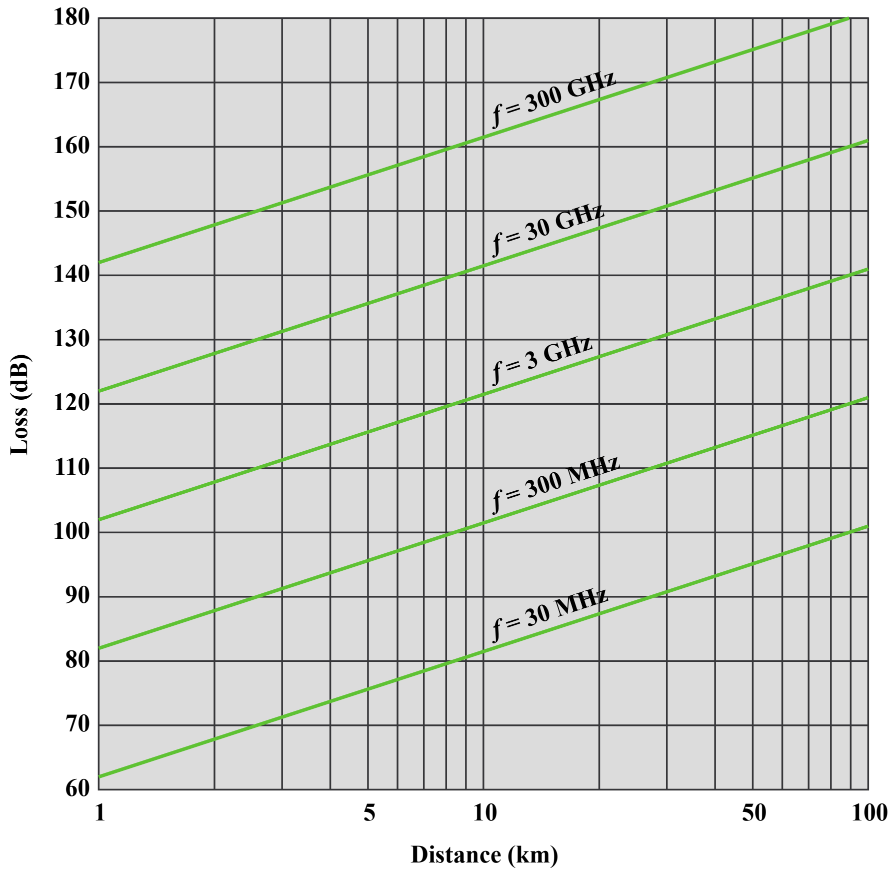


Figure 4.13 Free Space Loss

Figure 4.13 illustrates the free space loss equation.

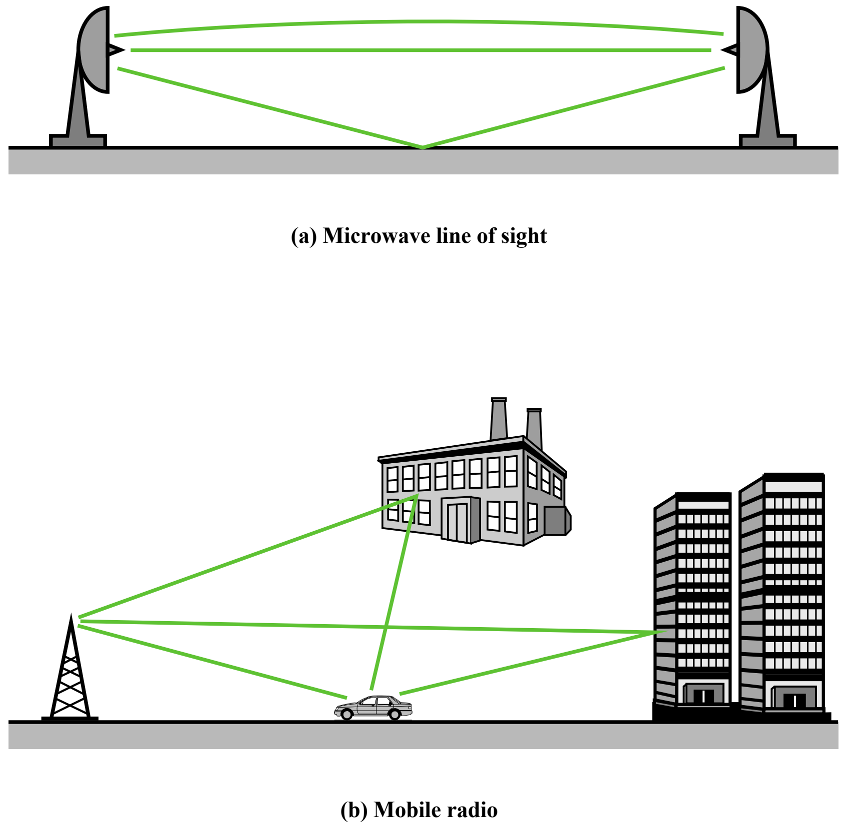
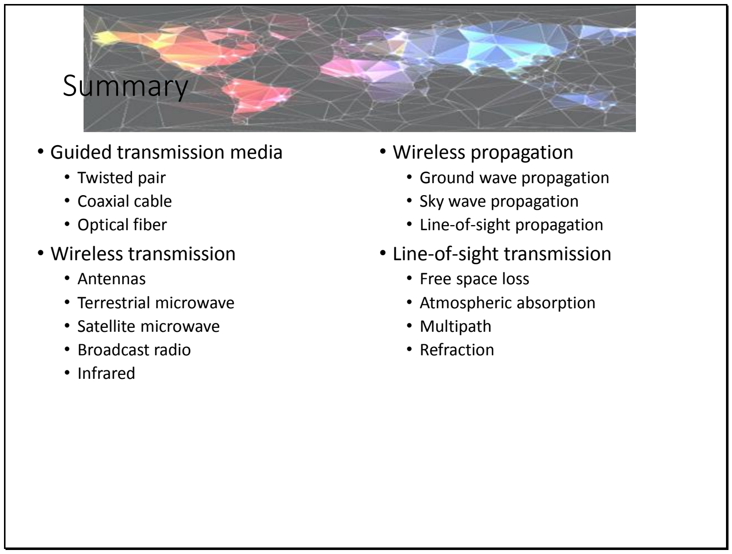


Figure 4.14 Examples of Multipath Interference

Figure 4.14 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.

Slide 47



Chapter 4 summary.