GLOBAL EDITION

Wireless Communication Networks and Systems

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An illustration of the spectrum allocations by the FCC can be seen on the book Web site at corybeardwireless.com. FCC licenses are allocated for different uses so that there are no conflicts. This frequently causes spectrum to be underutilized, so researchers are exploring a new concept known as **dynamic spectrum access**. Here, users would share spectrum among primary and secondary users. If primary users are not active, secondary users could use the spectrum but release the spectrum as soon as primary users need it. A technology known as **cognitive radio** would be implemented in the devices to scan wide bands of frequency to sense when spectrum is being used.

Frequency bands used for the technologies in this textbook are relatively narrow compared to the overall wide spectrum. Several technologies (e.g., IEEE 802.11 and 802.15) use the industrial, scientific, and medical (ISM) bands because those frequencies can be used without a license as long the transmitters stay within power limitations and use a spread spectrum technique. Some of these ISM bands are 915 $\pm$ 13 MHz, 2450 $\pm$ 50 MHz, 5.8 $\pm$ 0.75 GHz, and 57–64 GHz.

Propagation Modes

A signal radiated from an antenna travels along one of three routes: ground wave, sky wave, or **line of sight** (LOS). Table 6.3 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.

Table 6.3 Frequency Bands

Band	Frequency Range	Free Space Wavelength Range	Propagation Characteristics	Typical Use
ELF (extremely low frequency)	30 to 300 Hz	10,000 to 1,000 km	GW	Power line frequencies; used by some home control systems.
VF (voice frequency)	300 to 3000 Hz	1,000 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; 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 to 330 nm	LOS	Optical communication

Ground Wave Propagation **Ground wave propagation** (Figure 6.5a) 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.

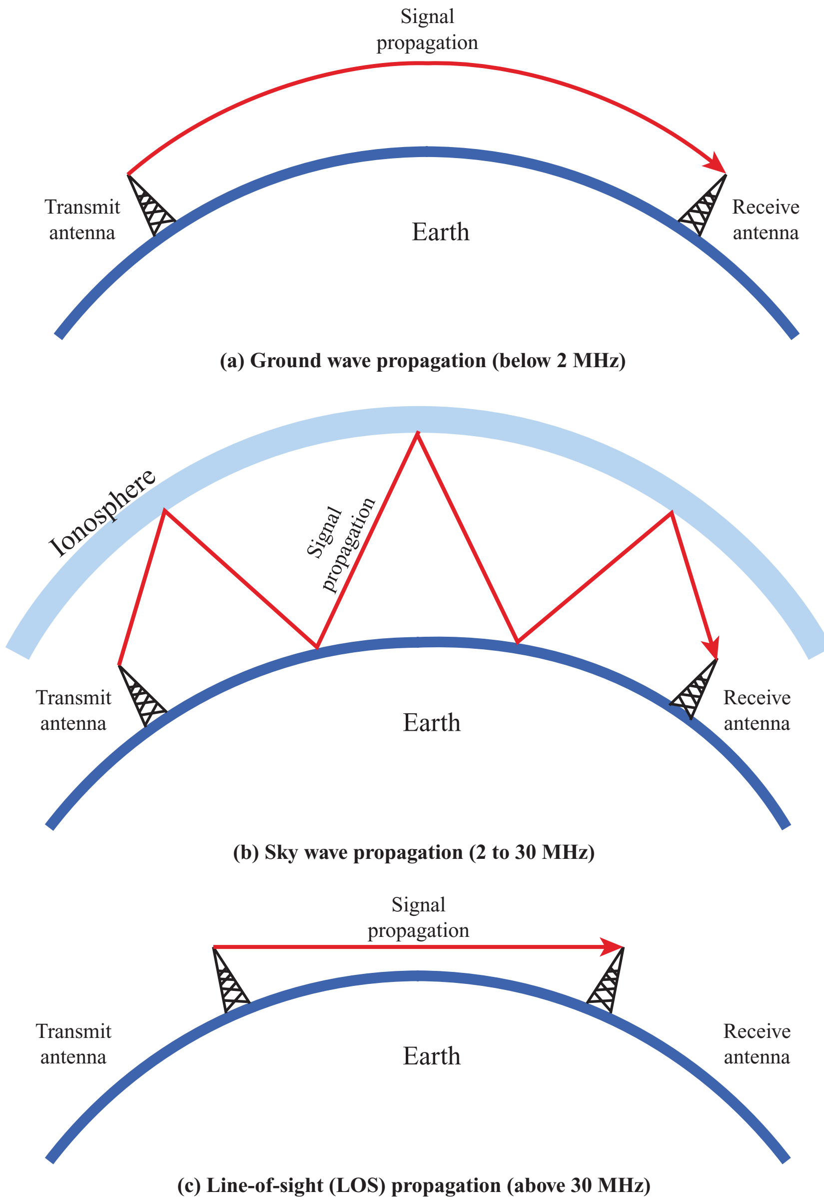

Figure 6.5 Wireless Propagation Modes

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 can be viewed as being reflected from the ionized layer of the upper atmosphere (ionosphere) back down to earth. Although it appears that 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 6.5b). With this propagation mode, a signal can be picked up thousands of kilometers from the transmitter.

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 6.5c). For satellite communication, a signal above 30 MHz is not reflected by the ionosphere and therefore 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 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. This is illustrated in Figure 6.6. If 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 result will look much like Figure 6.6, with the stick appearing shorter and bent.

The index of refraction of one medium relative to another is the sine of the angle of incidence, θ_i, divided by the sine of the angle of refraction, θ_r. 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 Figure 6.6 shows an abrupt, one-time change in direction 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. With sky waves, the density of the ionosphere and its gradual change in density cause the waves to be refracted back toward the earth.

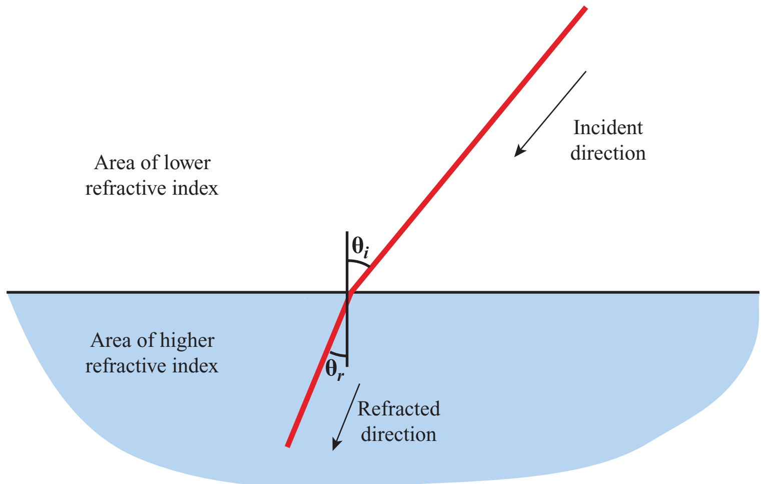

Figure 6.6 Refraction of an Electromagnetic Wave

Optical and Radio Line of Sight With no intervening obstacles, the **optical line of sight** is influenced by the curvature of the earth and 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 6.7)

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

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

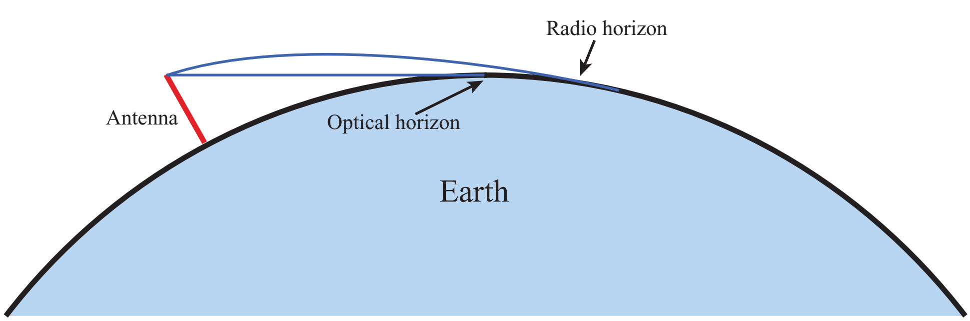

Figure 6.7 Optical and Radio Horizons

Example 6.2 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

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

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

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

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.

Transmission and Reflection Properties

An electromagnetic wave interacts with an object with a combination of transmission through, reflection off, and absorption into the object. This is dependent on the permittivity of the material, which is dependent on several factors, including signal frequency. This means that certain frequencies may pass effectively through an object where others might not. For example, roadway bridges affect AM radio frequencies not those for FM radio. This affects the design of a network of wireless indoor devices, depending on the propagation through the building materials used for floors and walls.

Table 6.4 shows the attenuation that can be seen for different frequencies through a variety of materials [NIST97]. In most cases, attenuation significantly worsens as frequency increases.

Table 6.4 Signal Attenuation through Materials [NIST97]

Materials	**0.5 GHz (dB)**	**1 GHz (dB)**	**2 GHz (dB)**	**5.8 GHz (dB)**	**8 GHz (dB)**
Brick 89 mm	−0.5	−3.7	−5.4	−15.5	−16.0
Brick 267 mm	−3.8	−6.9	−10.6	−38.0	−27.2
Composite Brick 90 mm/Concrete Wall 203 mm	−20.7	−25.0	−33.0	−73.8	−82.4
Masonry 203 mm	−9.5	−11.5	−11.3	−15.5	−18.4
Masonry 610 mm	−26.3	−28.0	−30.0	−47.2	−38.8
Drywall 16 mm	−0.1	−0.3	−0.6	−0.3	−1.0
Concrete 102 mm	−9.7	−12.2	−14.9	−24.1	−27.8
Concrete 305 mm	−32.3	−34.8	−36.0	−74.9	−90.0
Glass 6 mm	−0.2	−0.8	−1.4	−1.0	−1.5
Glass 19 mm	−2.3	−3.1	−3.9	−0.4	−1.0

(*Continued*)