Appendix A: Radio Communication Basics[1]

A

DEFINITIONS OF RADIOCOMMUNICATION TERMS

Amplitude: A measure of the value of a radio wave, measured in volts (see figure A-1).

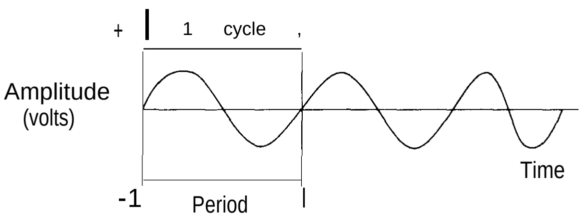
Analog: In analog radio communication, the message or information to be transmitted is impressed onto (modulates) a radio carrier wave, causing some property of the carrier—the amplitude, frequency, or phase—to vary in proportion to the information being sent. Amplitude modulation (AM) and frequency modulation (FM) are two common formats for analog transmission. In order to send analog signals, such as voice and video, over digital transmission media, such as fiber optics or digital radio, they must first be converted into a digital format. See modulation.

Bandwidth: The process of modulating (see below) a radio wave to transmit information produces a radio signal, but also generates additional frequencies called "sidebands" on either side of the carrier (see figure A-2). The total width of frequencies, including the sidebands, occupied by a radio signal is its bandwidth. In practical terms, however, the bandwidth of a signal refers to the amount of spectrum needed to transmit a signal without excessive loss or distortion. It is measured in hertz. In figure A-2, the bandwidth of the signal is 4 kHz. The bandwidth of a radio signal is determined by the amount of information in the signal being sent. More complex signals contain more information, and hence require wider bandwidths. An A radio broadcasting signal, for example, takes 10 kHz, while an FM stereo signal requires 200 kHz, and a color television signal takes up 6 MHz. The bandwidth required by a television channel is 600 times greater than that of an AM radio channel.

Carrier: A radio wave that is used to transmit information. Information to be sent is impressed onto the carrier, which then carries the signal to its destination. At the receiver the carrier is filtered out, allowing the original message to be recovered.

[1] Material in this appendix is derived from Harry Mileaf (ed.), *Electronics One*, revised 2d ed. (Rochelle Park, NJ: Hayden Book Co., Inc., 1976); U.S. Congress, Office of Technology Assessment, *The Big Picture: HDTV & High-Resolution Systems*, OTA-BP-CIT-64 (Washington, DC: U.S. Government Printing Office, 1990); William Stallings, *Data and Computer Communications* (New York, NY: MacMillan Publishing Co., 1985).

FIGURE A-1: Basic Radio Wave



Each cycle of a pure radio wave is identical to every other cycle.

SOURCE: Office of Technology Assessment, based on Harry Mileaf (cd.), Electronics One, revised 2d ed. (Rochelle Park, NJ: Hayden Book Co., 1976) p. 1-10.

Digital: Digital transmission formats can be used to transmit images and voice as well as data. For continuously varying signals such as voice or images, an analog/digital converter changes the analog signal into discrete numbers (represented in binary form by O's and 1's). These binary digits, or bits, can then be sent as a series of "on'' /''off' pulses or can be modulated onto a carrier wave by varying the phase, frequency, or amplitude according to whether the signal is a"1" or a "O." Data is sent in a similar fashion although it does not have to be converted into digital form first. (See figure A-3.)

Frequency: The number of cycles a radio wave completes in one second (see figure A-4). Frequency is measured in hertz (1 cycle per second equals one hertz). Radio frequencies are described as multiples of hertz:

kHz, kilohertz: thousand cycles per second;
MHz, megahertz: million cycles per second;
GHz, gigahertz: billion cycles per second.

The frequency of a radio wave is the inverse/reciprocal of its period. For example, if a wave had a period of 0.1 seconds, its frequency would be 10 hertz.

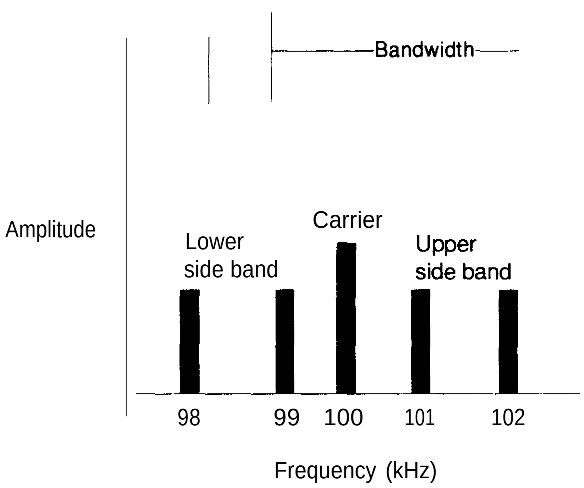
Modulation: The process of encoding information onto a radio wave by varying one of its basic characteristics-amplitude, frequency, or phase —in relation to an input signal such as speech, data, music, or television. The input signal, which contains the information to be transmitted, is called the modulating or baseband signal. The radio wave that carries the information is called the carrier wave. The radio wave that results from the combination of these two waves is called a modulated carrier. Two of the most common types of modulation are amplitude modulation (AM) and frequency modulation (FM) (see figure A-5).

Period: The length of time it takes a radio wave to complete one full cycle (see figure A-l). The inverse of the period is a radio wave's frequency.

Phase: A measure of the shift in position of a radio wave in relation to time (see figure A-6). Phase is often measured in degrees.

Spread Spectrum: Spread spectrum refers to various coding schemes used to modulate data information onto radio waves for transmission. Spread spectrum was originally used by the military to hide its communications in background "noise." Direct sequence spread spectrum systems encode each bit of information with a special code is known only to the transmitter and receiver. The transmitter sends these encoded bits over a

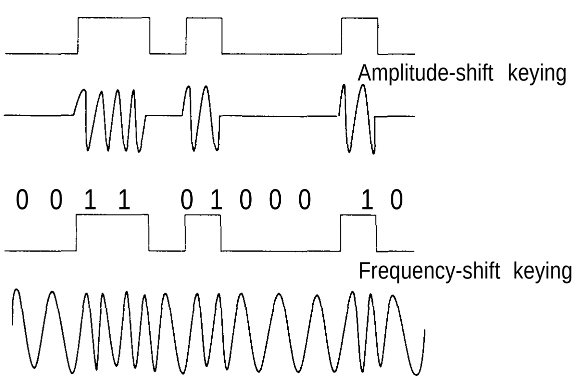
FIGURE A-2. Side-Band Frequencies and Bandwidth



NOTE: This figure represents a 100-kHz earner wave modulated by 1- and 2-kHz frequencies.

SOURCE: Harry Mileaf (cd.), *Electronics One,* revised 2d ed. (Rochelle Park, NJ: Hayden Book Co., 1976) p. 1-31.

FIGURE A-3: Techniques for Modulating an Analog Carrier to Send Information in a Digital Format



SOURCE: U.S. Congress, Office of Technology Assessment, *The Big Picture: HDTV &* High-Resolution Systems, OTA-BP-CIT-64 (Washington, DC: U.S. Government Printing Office, June 1990), figure 3-3, p. 41.

wide range of frequencies assigned for the system. The receiver looks for the special coded bits and reassembles them in the proper order. In frequency-hopping spread spectrum systems, a wide range of frequencies is also used, but the system "hops" from frequency to frequency, transmitting bits of information on each frequency. Only thereceiver knows the hopping pattern and how long the transmitter will stay on each frequency (as little as 100 milliseconds). This allows it to track the data across frequencies and reassemble the original signal.

Spectrum: Each radio signal is actually made up of a number of different radio waves at different frequencies. The spectrum of a radio signal refers to the range of frequencies it contains. In figure A-2, the spectrum of the signal extends from 98 to 102 kHz. The width of the spectrum is called the bandwidth of the signal. More broadly, the radio frequency spectrum consists of all the radio frequencies used for radio communications.

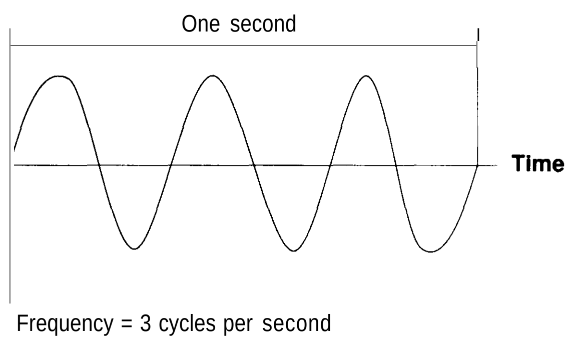
Wavelength: The distance between successive peaks of a continuous radio wave.

SPECTRUM BASICS[2]

Radio Waves

Radio waves are the basic unit of wireless communication.[3] By varying the characteristics of a radio wave—frequency, amplitude, or phase—these waves can be made to communicate information of many types, including audio, video, and data. Radio waves that carry information are called radio signals, and the process of encoding intelligence onto a radio wave so that it can be transmitted over the air is called modulation.[4] In the process of modulation, the information or message to be transmitted-a human voice, recorded music, or a television signal—is impressed onto (modulates) a "carrier" radio wave that is

FIGURE A-4: Frequency of a Continuous Wave



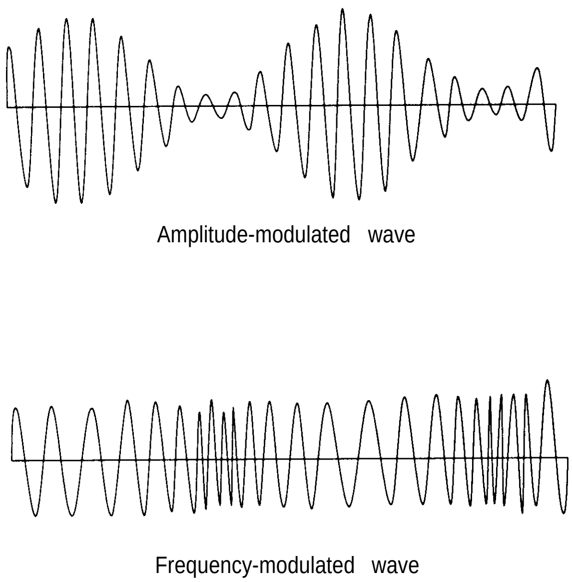
SOURCE: Harry Mileaf (cd.), *Electronics One,* revised 2d ed. (Rochelle Park, NJ: Hayden Book Co., 1976) p. 1-10.

[2] Much of the material in this section comes from Richard Gould, "Allocation of the Radio Frequency Spectrum,'' contractor report prepared for the Office of Technology Assessment, Aug. 10, 1990.

[3] Although the term "radio" is most commonly associated with commercial radio broadcasting services (AM and FM radio), the term also properly encompasses the entire range of wireless communications technologies and services, including television, microwave, radar, shortwave radio, mobile, and satellite communications.

[4] Two of the most familiar modulation techniques are amplitude modulation (AM) and frequency modulation (FM).

FIGURE A-5: Amplitude and Frequency Modulation



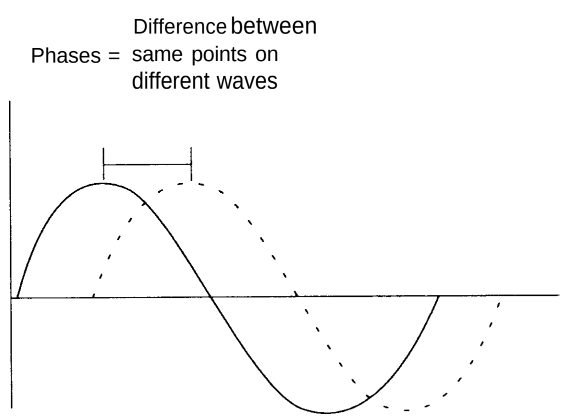
SOURCE: U.S. Congress, Office of Technology Assessment, *The Big Picture: HDTV & High-Resolution Systems,* OTA-BP-CIT-64 (Washington, DC: U.S. Government Printing Office, June 1990), figure 3-1, p. 41.

then transmitted over the air. When a radio signal is received, the information is converted back into its original form (demodulated) by a receiver and output as sound, images, or data.

Radio waves are distinguished from each other by their frequency or their wavelength. Frequency represents the number of cycles a radio wave completes in one second, and is the most common description of a radiocommunication signal. The international unit of frequency measurement is the hertz (Hz), which represents one cycle per second.[5] Radio signals can also be identified by their wavelength. Signals with long wavelengths have lower frequencies, while those at higher frequencies have shorter wavelengths. Commercial AM radio signals, for example, consist of very long waves (approximately 100 to 300 meters), that may complete a million cycles per second (1 megahertz (MHz)). Microwave signals, on the other hand, are very short (as little as 0.3 centimeters) and may complete hundreds of billions of cycles per second (100 gigahertz (GHz)). The relative nature of radio wavelengths is the origin of terms such as "shortwave," which was given to radio frequencies around 2.8 MHz in the 1920s because the wavelengths in that frequency range were shorter than the wavelengths that had previously been used.

The radio spectrum is divided into "bands" that correspond to various groups of radio frequencies. These bands are identified by their frequencies or wavelengths (as above), or by descriptive terms that have been adopted over time. Several types of descriptive names have been attached to various portions of the spectrum (see figure A-7). One method denotes relative position in the spectrum: very low frequency (VLF), high frequency (HF), very high frequency (VHF), superhigh frequency (SHF), etc. Another method derives from usage developed in World War II to keep secret the actual

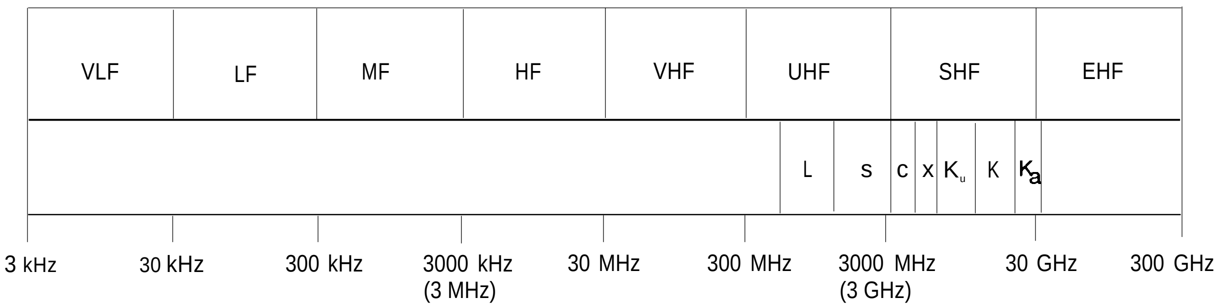
FIGURE A-6: Phase of a Continuous Wave



SOURCE: Harry Mileaf (ed.), *Electronics* One, revised 2d ed. (Rochelle Park, NJ: Hayden Book Co., 1976) p. 1-10.

[5] Multiples of the hertz are indicated by prefixes (see box 2-A): "kilo" for one thousand, "mega" for one million, and "giga" for one billion. Thus, a million hertz-a million cycles per second-is expressed as one megahertz (abbreviated "MHz").

FIGURE A-7: Frequency Band Designations



SOURCE: Off Ice of Technology Assessment, 1991, based on Richard G. Gould, “Allocation of the Radio Frequency Spectrum,” OTA contractor report, Aug. 10, 1990.

frequencies employed by radar and other electronic devices: L-band, S-band, and K-band.[6] The International Telecommunication Union (ITU) classifies frequencies according to band numbers---Band 1, Band 2, etc. Frequency bands are also known by the services that use them-the FM radio broadcast band, for example, occupies the range (band) of frequencies from 88 to 108 MHz.

■ Transmission Characteristics

Several factors affect the transmission of radio signals, and, at different frequencies, some factors will affect radio waves more than others. Attenuation refers to the weakening of a radio signal as it passes through the atmosphere. All radio signals are attenuated as they pass through rain or any kind of water in the air (clouds, snow, sleet), but radio signals at higher frequencies will be attenuated more than those at lower frequencies. For instance, the attenuation of a radio signal passing through a rainstorm will be 10 times as great if the frequency of the signal is doubled from 5 GHz to 10 GHz. This makes radiocommunication, especially over long distances, extremely difficult in the upper (above 10 GHz) frequencies.

Radio waves are also bent and/or reflected as they pass through the atmosphere. Because of changes in the density of the atmosphere with height, radio signals bend as they pass from one atmospheric layer to the next. This bending is called refraction. In addition to refraction, if atmospheric conditions are right, radio waves are also reflected by the ionosphere, the top layer of the Earth’s atmosphere. Ionospheric reflection enables some radio signals to travel thousands of miles, and accounts for the long-distance communication that is possible in the frequency range between about 3 and 30 MHz (the HF band—see below).

Although refraction and reflection are conceptually distinct, and refraction can occur without reflection, it is possible to think of reflection as an extreme case of refraction in the ionosphere.[7] The amount of refraction, or bending, experienced by a radio signal is related to its frequency. Lower frequencies bend (are refracted)

[6] These letter designations are not precise measures of frequency because the band limits are defined differently by different segments of the electronics and telecommunications industries.

[7] All radio waves are bent as they pass from a region of the atmosphere having a certain number of free electrons to a region with a different number of electrons. During the day, energy from the Sun splits the molecules of the gasses far above the surface of the Earth (in the troposphere and the ionosphere), producing many free electrons and creating layers of ionized particles. A radio wave from Earth entering one of these layers will be refracted, and if there are enough free electrons, the bending will be so great that the signal will be reflected back to Earth.

easily and are readily reflected back to Earth. Higher frequency signals experience less refraction than those at lower frequencies, and at progressively higher frequencies, there will be less and less bending. At a certain frequency, atmospheric conditions will be such that there is so little refraction that the signal will not be reflected back to Earth. The point at which this occurs is called the maximum usable frequency (MUF), and is generally in the range of 10 to 15 MHz, although it can be as high as 30 or 40 MHz or as low as 6 MHz, depending on time of day, season, and atmospheric conditions. Below the MUF, radio signals can be used for long-distance communication by reflecting the signal off the ionosphere. Above the MUF, the signal travels straight through the atmosphere and into space.

At higher frequencies, above the MUF, radio signals travel in almost straight lines from the transmitter to receiver, a transmission characteristic referred to as "line-of-sight."[8] Line-of-sight conditions affect radiocommunication above the MUF, but especially affect frequencies above one GHz. The distance a line-of-sight signal can travel is usually limited to the horizon or a little beyond. However, because the Earth is curved, the transmission distance will also be limited depending on the height of the transmitting antenna—the higher the antenna, the farther the signal can travel. For example, if the transmitting antenna is mounted on top of a mountain or a tall tower, the line-of-sight distance will be greater. Satellites, in simple terms, extend line-of-sight to the maximum distance (see figure A-8). Line-of-sight transmission requires that there be no obstacles between the transmitter and receiver—anything standing between the transmitter and receiver, e.g., a building or mountain will block the signal.

Atmospheric conditions have substantial impacts on line-of-sight radiocommunications. Differences in atmospheric temperature or the amount of water vapor in the air, for example, can cause radio signals to travel far beyond the "normal" line-of-sight distance. This condition is called ducting or superrefraction. At such times, signals travel for many miles beyond the horizon as though the Earth were flat. This condition is much more common over large bodies of water than over land. Atmospheric conditions can also bend the signal away from the Earth, shortening the practical transmission distance. The occurrence of these rare conditions complicates radio system design and spectrum management. For line-of-sight systems, too large a radius cannot be assumed for the service area because of the possibility that "subrefraction" or "negative" refraction may keep the signal from reaching the periphery of the service area. On the other hand, the same frequency cannot be used again many miles beyond the horizon because of the possibility that superrefraction may carry an interfering signal far beyond its accustomed limits. One of the basic functions of international spectrum management is to prevent or reduce such interference.

CHARACTERISTICS OF RADIO FREQUENCY BANDS

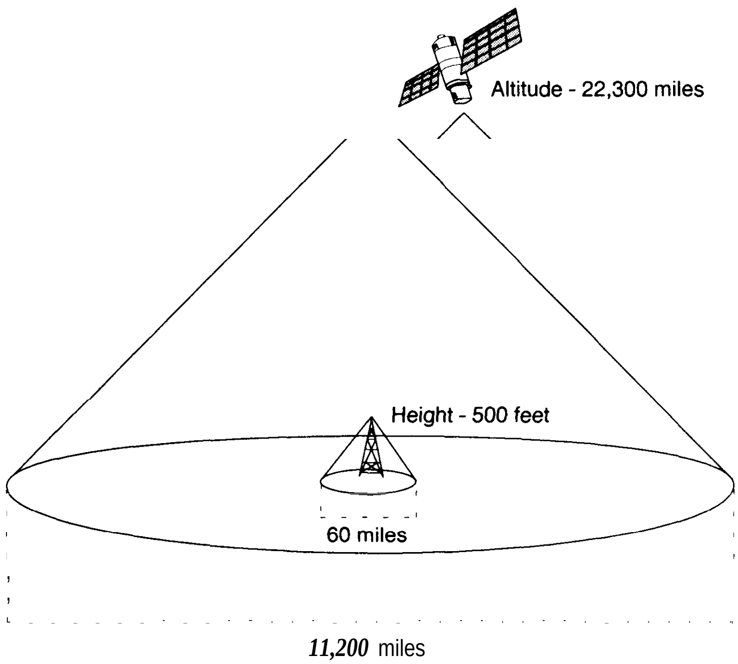
The physical properties of radio waves, combined with the various transmission characteristics discussed above, determine how far and where radio signals can travel, and make different radio frequencies better suited to certain kinds of communications services. The following is a brief description of the various radio bands, some of their uses, and the factors affecting transmission of radio signals in them.

Very Low, Low, and Medium Frequencies: 3 to 3000 kHz

In this portion of the spectrum, encompassing the bands denoted as VLF, low frequency (LF), and medium frequency (MF), radio signals are transmitted in the form of "groundwaves" that travel

[8] It is important to note that refraction does not cease to affect radio waves above the MUF. Even at frequencies in the VHF and UHF bands, radio waves bend slightly as they move through the atmosphere.

FIGURE A-8: Terrestrial and Satellite Transmission Ranges



NOTE: This figure is not drawn to scale.

SOURCE: Office of Technology Assessment, 1991, based on Richard G. Gould, "Allocation of the Radio Frequency Spectrum," OTA contractor report, Aug. 10, 1990.

along the surface of the Earth, following its curvature. Groundwaves lose much of their energy to the Earth as they travel along its surface, and high power is required for long-distance communication throughout this portion of the spectrum. Groundwaves travel farther over water than over land.

At the lower end of this region, transmissions are used for low data-rate communications with submarines and for navigation. The maritime mobile service, for example, has allocations in this band for communication with ships at sea. Conventional AM radio broadcasting stations also operate in a part of this band, at MF, typically between 540 and 1605 kHz. Attenuation during daylight hours limits the range of these AM stations, but at night, when attenuation is lower, AM radio signals can travel very long distances, sometimes even hundreds of miles. To prevent interference at these times to distant radio stations using the same frequency, some stations may be required to reduce the power of transmissions in the direction of those distant stations.

▮ High Frequencies: 3 to 30 MHz

In this frequency range, denoted as HF, propagation of a "skywave" supplements the groundwave. While the groundwave dies out at about 100 miles, the skywave can be bent back to Earth from layers of ionized particles in the atmosphere (the ionosphere). When the signal returns to Earth, it may be reflected again, back toward the ionized layers to be returned to Earth a second time. The signal can make several "bounces" as it travels around the Earth. It is this reflection that makes long-distance communication possible. However, there are occasional—and largely unpredictable-disturbances of the ionosphere, including sunspots, that interfere with HF communications.

Overall, the reliability of HF communications is low, and the quality is often poor.

The HF "shortwave" bands are used primarily by amateur radio operators, governmental agencies for international broadcasting (Voice of America, Radio Moscow), citizens' band radio users, religious broadcasters, and for international aviation and maritime communications. Overseas telephone links using HF radio have, for the most part, been replaced by satellites, and Inmarsat satellites have taken over a major portion of the maritime communications previously provided by HF systems. Likewise, future aeronautical mobile-satellite service (AMSS) systems may also supplement or replace the HF channels now used by airplanes when they are out of range of the VHF stations they communicate with when over or near land.

While little use is made of HF radio systems for domestic communications in industrialized countries like the United States, developing countries still find HF cost-effective for some of their domestic radiocommunication needs. This has led to a conflict over allocating the HF band internationally: the developed world wants to use the band for international broadcasting and long-distance mobile communication, while the developing countries want to retain it for their domestic point-to-point systems.

Very High, Ultrahigh, and Superhigh Frequencies: 30 MHz to 30 GHz

The groundwave, which permits communication beyond the horizon at lower frequencies (VLF, LF, MF), dies out after a short distance in this frequency range. Moreover, the skywave—which is reflected from the ionospheric layers at lower frequencies—tends to pass through the atmosphere at these higher frequencies. Communication in this band is thus limited to little more than line-of-sight distances. For short transmitting antennas, the maximum distance a radio signal can travel may be no more than 25 miles, but this distance can be increased by raising the height of the antenna.

This limitation can also be an advantage: the same frequencies can be reused by stations beyond the normal transmission range. Unfortunately, the distances that these line-of-sight signals can sometimes travel can be quite large, especially if the path is over water. At times, atmospheric conditions may establish a "duct" over a large body of water (see above). As it travels down the length of the duct a signal will be reflected back and forth between the water and the top of the duct, which can be hundreds of feet above the Earth's surface. These trapped signals can travel hundreds of miles. To minimize interference from a ducted signal, stations on the same frequency must be spaced far apart. This requirement limits the frequency reuse that can be achieved.

This part of the spectrum is used by many important communication and entertainment services, including television broadcast signals, FM radio, and land mobile communications. These frequencies are also used by the radiolocation service for long-range radars (1350 MHz to about 2900 MHz), aircraft landing radar (around 9000 MHz), and for point-to-point radio relay systems (various bands between 2000 and 8000 MHz). In recent years, communication satellites have made increasing use of frequencies in this band.[9]

The portion of this band between approximately 1 and 10 GHz is particularly valuable. It is bounded by increasing cosmic and other background noise at its lower end, and by precipitation attenuation at its upper end, but in between, communications can be carried out very well. Today, because of its favorable transmission characteristics, the 1 to 3 GHz band is especially sought after for mobile communications, including personal communication services (PCS), and for new

[9] Satellites operating in the C-band, e.g., use frequencies around 4 and 6 GHz, and are heavily used for transmitting television programming to cable television operators. Ku-band satellites, which generally operate at frequencies around 12 and 14 GHz, are increasingly being used for private communication networks and the delivery of entertainment programming.

broadcasting technologies such as digital audio broadcasting (DAB).

Above 10 GHz

At 10 GHz and above, radio transmissions become increasingly difficult. Greater attenuation of the radio signal takes place because of rain, snow, fog, clouds, and other forms of water in the signal's path. Nevertheless, crowding in the bands below 10 GHz is forcing development of the region above 10 GHz. One desirable feature of the frequencies above 10 GHz, beside the fact that they are relatively unused, is the extremely wide bandwidths that are available. The 3 to 30 MHz, HF band, for example, is 27 MHz wide. That is enough bandwidth for about 9,000 voice channels (at 3 kHz each). However, the frequency range 3 to 30 GHz is 27,000 MHz wide. That bandwidth could accommodate about 9 million voice channels.