RF and Microwave Wireless Systems. Kai Chang
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CHAPTER EIGHT

Wireless Communication Systems

8.1 INTRODUCTION

The RF and microwave wireless communication systems include radiolinks, troposcatter/diffraction, satellite systems, cellular/cordless/personal communication systems (PCSs)/personal communication networks (PCNs), and wireless local-area networks (WLANs). The microwave line-of-sight (LOS) point-to-point radiolinks were widely used during and after World War II. The LOS means the signals travel in a straight line. The LOS link (or hop) typically covers a range up to 40 miles. About 100 LOS links can cover the whole United States and provide transcontinental broadband communication service. The troposcatter (scattering and diffraction from troposphere) can extend the microwave LOS link to several hundred miles. After the late 1960s, geostationary satellites played an important role in telecommunications by extending the range dramatically. A satellite can link two points on earth separated by 8000 miles (about a third of the way around the earth). Three such satellites can provide services covering all major population centers in the world. The satellite uses a broadband system that can simultaneously support thousands of telephone channels, hundreds of TV channels, and many data links. After the mid-1980s, cellular and cordless phones became popular. Wireless personal and cellular communications have enjoyed the fastest growth rate in the telecommunications industry. Many satellite systems are being deployed for wireless personal voice and data communications from any part of the earth to another using a hand-held telephone or laptop computer.

8.2 FRIIS TRANSMISSION EQUATION

Consider the simplified wireless communication system shown in Fig. 8.1. A transmitter with an output power P_t is fed into a transmitting antenna with a gain G_t. The signal is picked up by a receiving antenna with a gain G_r. The received power is P_r and the distance is R. The received power can be calculated in the following if we assume that there is no atmospheric loss, polarization mismatch, impedance mismatch at the antenna feeds, misalignment, and obstructions. The antennas are operating in the far-field regions.

The power density at the receiving antenna for an isotropic transmitting antenna is given as

$$S_I = \frac{P_t}{4\pi R^2} \quad (\mathrm{W/m^2}) \tag{8.1}$$

Since a directive antenna is used, the power density is modified and given by

$$S_D = \frac{P_t}{4\pi R^2} G_t \quad (\mathrm{W/m^2}) \tag{8.2}$$

The received power is equal to the power density multiplied by the effective area of the receiving antenna

$$P_r = \frac{P_t G_t}{4\pi R^2} A_{\mathrm{er}} \quad (\mathrm{W}) \tag{8.3}$$

The effective area is related to the antenna gain by the following expression:

$$G_r = \frac{4\pi}{\lambda_0^2} A_{\mathrm{er}} \quad \text{or} \quad A_{\mathrm{er}} = \frac{G_r \lambda_0^2}{4\pi} \tag{8.4}$$

Substituting (8.4) into (8.3) gives

$$P_r = P_t \frac{G_t G_r \lambda_0^2}{(4\pi R)^2} \tag{8.5}$$

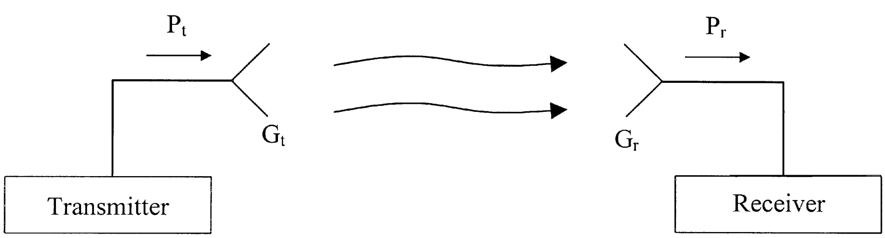

FIGURE 8.1 Simplified wireless communication system.

This equation is known as the Friis power transmission equation. The received power is proportional to the gain of either antenna and inversely proportional to R^2.

If $P_r = S_{i,\min}$, the minimum signal required for the system, we have the maximum range given by

$$R_{\max} = \left[\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 S_{i,\min}} \right]^{1/2} \tag{8.6}$$

To include the effects of various losses due to misalignment, polarization mismatch, impedance mismatch, and atmospheric loss, one can add a factor L_{sys} that combines all losses. Equation (8.6) becomes

$$R_{\max} = \left[\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 S_{i,\min} L_{\text{sys}}} \right]^{1/2} \tag{8.7}$$

where $S_{i,\min}$ can be related to the receiver parameters. From Fig. 8.2, it can be seen that the noise factor is defined in Chapter 5 as

$$F = \frac{S_i/N_i}{S_o/N_o} \tag{8.8}$$

Therefore

$$\begin{aligned} S_i = S_{i,\min} &= N_i F \left(\frac{S_o}{N_o} \right)_{\min} \\ &= kTBF \left(\frac{S_o}{N_o} \right)_{\min} \end{aligned} \tag{8.9}$$

where k is the Boltzmann constant, T is the absolute temperature, and B is the receiver bandwidth. Substituting (8.9) into (8.7) gives

$$R_{\max} = \left[\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 kTBF (S_o/N_o)_{\min} L_{\text{sys}}} \right]^{1/2} \tag{8.10}$$

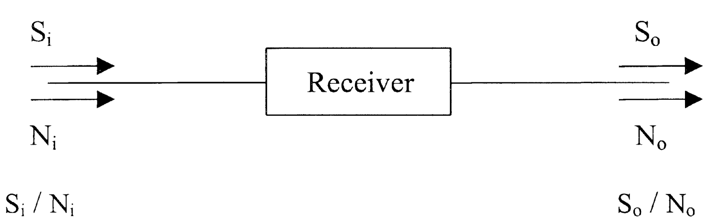

FIGURE 8.2 Receiver input and output SNRs.

where P_t = transmitting power (W)

G_t = transmitting antenna gain in ratio (unitless)

G_r = receiving antenna gain in ratio (unitless)

λ_0 = free-space wavelength (m)

$k = 1.38 \times 10^{-23}$ J/K (Boltzmann constant)

T = temperature (K)

B = bandwidth (Hz)

F = noise factor (unitless)

$(S_o/N_o)_{\min}$ = minimum receiver output SNR (unitless)

L_{sys} = system loss in ratio (unitless)

$R_{\max}$ = maximum range (m)

The output SNR for a distance of R is given as

$$\frac{S_o}{N_o} = \frac{P_t G_t G_r}{kTBFL_{\text{sys}}} \left(\frac{\lambda_0}{4\pi R} \right)^2 \tag{8.11}$$

From Eq. (8.10), it can be seen that the range is doubled if the output power is increased four times. In the radar system, it would require the output power be increased by 16 times to double the operating distance.

From (Eq. 8.11), it can be seen that the receiver output SNR ratio can be increased if the transmission distance is reduced. The increase in transmitting power or antenna gain will also enhance the output SNR ratio as expected.

Example 8.1 In a two-way communication, the transmitter transmits an output power of 100 W at 10 GHz. The transmitting antenna has a gain of 36 dB, and the receiving antenna has a gain of 30 dB. What is the received power level at a distance of 40 km (a) if there is no system loss and (b) if the system loss is 10 dB?

Solution

$$f = 10 \text{ GHz} \qquad \lambda_0 = \frac{c}{f} = 3 \text{ cm} = 0.03 \text{ m}$$

$$P_t = 100 \text{ W} \qquad G_t = 36 \text{ dB} = 4000 \qquad G_r = 30 \text{ dB} = 1000$$

(a) From Eq. (8.5),

$$\begin{aligned} P_r &= P_t \frac{G_t G_r \lambda_0^2}{(4\pi R)^2} \\ &= 100 \times \frac{4000 \times 1000 \times (0.03)^2}{(4\pi \times 40 \times 10^3)^2} = 1.425 \times 10^{-6} \text{ W} \\ &= 1.425\ \mu\text{W} \end{aligned}$$

(b) $L_{sys} = 10$ dB:

$$P_r = P_t \frac{G_t G_r \lambda_0^2}{(4\pi R)^2} \frac{1}{L_{sys}}$$

Therefore

$$P_r = 0.1425\ \mu\text{W}$$ ■

8.3 SPACE LOSS

Space loss accounts for the loss due to the spreading of RF energy as it propagates through free space. As can be seen, the power density ($P_t/4\pi R^2$) from an isotropic antenna is reduced by $1/R^2$ as the distance is increased. Consider an isotropic transmitting antenna and an isotropic receiving antenna, as shown in Fig. 8.3. Equation (8.5) becomes

$$P_r = P_t \left(\frac{\lambda_0}{4\pi R}\right)^2 \tag{8.12}$$

since $G_r = G_t = 1$ for an isotropic antenna. The term space loss (SL) is defined by

$$\text{SL in ratio} = \frac{P_t}{P_r} = \left(\frac{4\pi R}{\lambda_0}\right)^2 \tag{8.13}$$

$$\text{SL in dB} = 10 \log \frac{P_t}{P_r} = 20 \log\left(\frac{4\pi R}{\lambda_0}\right) \tag{8.14}$$

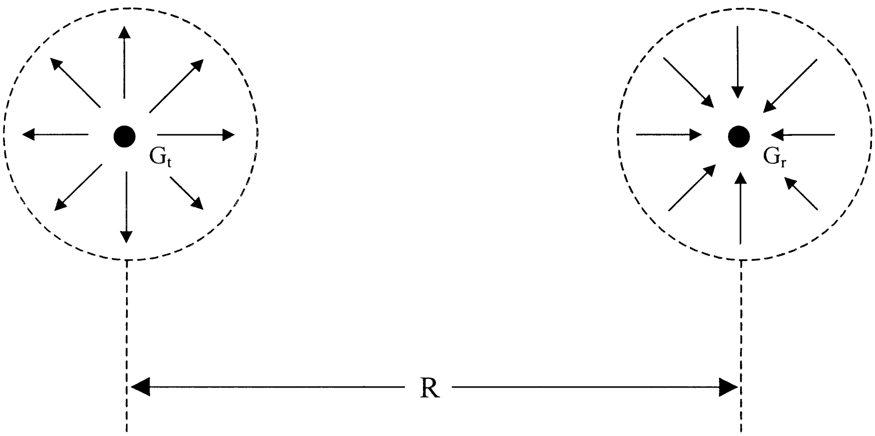

FIGURE 8.3 Two isotropic antennas separated by a distance *R*.

Example 8.2 Calculate the space loss at 4 GHz for a distance of 35,860 km.

Solution From Eq. (8.13),

$$\lambda_0 = \frac{c}{f} = \frac{3 \times 10^8}{4 \times 10^9} = 0.075 \text{ m}$$

$$\text{SL} = \left(\frac{4\pi R}{\lambda_0}\right)^2 = \left(\frac{4\pi \times 3.586 \times 10^7}{0.075}\right)^2$$

$$= 3.61 \times 10^{19} \quad \text{or } 196 \text{ dB}$$

■

8.4 LINK EQUATION AND LINK BUDGET

For a communication link, the Friis power transmission equation can be used to calculate the received power. Equation (8.5) is rewritten here as

$$P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi R}\right)^2 \frac{1}{L_{\text{sys}}} \tag{8.15}$$

This is also called the link equation. System loss L_{sys} includes various losses due to, for example, antenna feed mismatch, pointing error, atmospheric loss, and polarization loss.

Converting Eq. (8.15) in decibels, we have

$$10 \log P_r = 10 \log P_t + 10 \log G_t + 10 \log G_r - 20 \log\left(\frac{4\pi R}{\lambda_0}\right) - 10 \log L_{\text{sys}} \tag{8.16a}$$

or

$$P_r = P_t + G_t + G_r - SL - L_{\text{sys}} \quad \text{(in dB)} \tag{8.16b}$$

From Eq. (8.16), one can set up a table, called a link budget, to calculate the received power by starting from the transmitting power, adding the gain of the transmitting antenna and receiving antenna, and subtracting the space loss and various losses.

Consider an example for a ground-to-satellite communication link (uplink) operating at 14.2 GHz as shown in Fig. 8.4 [1]. The ground station transmits an output power of 1250 W. The distance of transmission is 23,074 statute miles, or 37,134 km (1 statute mile = 1.609347219 km). The receiver in the satellite has a

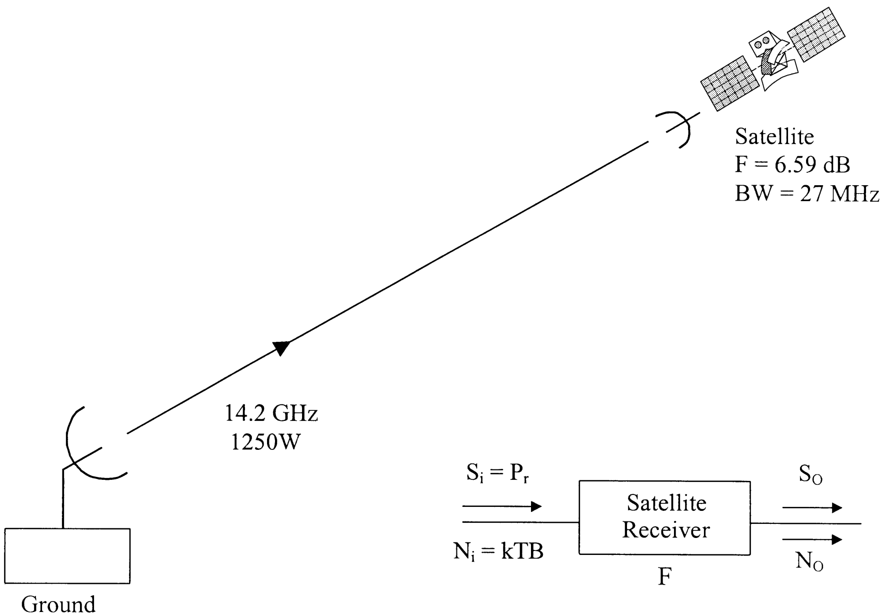

FIGURE 8.4 Ground-to-satellite communication uplink.

noise figure of 6.59 dB, and the bandwidth per channel is 27 MHz. At the operating frequency of 14.2 GHz, the free-space wavelength equals 0.0211 m. The space loss can be calculated by Eq. (8.14):

$$\text{SL in dB} = 20\log\left(\frac{4\pi R}{\lambda_0}\right) = 207.22\ \text{dB}$$

The following link budget chart can be set up:

Ground transmit power (P_t)	+30.97 dBW (1250 W)
Ground antenna feed loss	−2 dB
Ground antenna gain (G_t)	+ 54.53 dB
Ground antenna pointing error	−0.26 dB
Margin	−3 dB
Space loss	−207.22 dB
Atmospheric loss	−2.23 dB
Polarization loss	−0.25 dB
Satellite antenna feed loss	0 dB
Satellite antenna gain (G_r)	+37.68 dB
Satellite antenna pointing error	−0.31 dB
Satellite received power (P_r)	−92.09 dBW
	or − 62.09 dBm

The same P_r can be obtained by using Eq. (8.15) using L_{sys}, which includes the losses due to antenna feed, antenna pointing error, atmospheric loss, polarization loss, and margin. From the above table, L_{sys} is given by

$$\begin{aligned} L_{\text{sys}} &= -2\text{ dB} - 0.26\text{ dB} - 3\text{ dB} - 2.23\text{ dB} - 0.25\text{ dB} - 0.31\text{ dB} \\ &= -8.05\text{ dB} \end{aligned}$$

With the received power P_r at the input of the satellite receiver, one can calculate the receiver output SNR. From the definition of the noise factor, we have

$$F = \frac{S_i/N_i}{S_o/N_o} \tag{8.17}$$

The output SNR is given as

$$\frac{S_o}{N_o} = \frac{S_i}{N_i}\frac{1}{F} = \frac{S_i}{kTBF} = \frac{P_r}{kTBF} \tag{8.18}$$

For a satellite receiver with a noise figure of 6.59 dB and a bandwidth per channel of 27 MHz, the output SNR ratio at room temperature (290 K) used to calculate the standard noise power is

$$\begin{aligned} \frac{S_o}{N_o} \text{ in dB} &= 10 \log \frac{S_o}{N_o} = 10 \log \frac{P_r}{kTBF} \\ &= 10 \log P_r - 10 \log kTBF \\ &= -92.09\text{ dBW} - (-123.10\text{ dBW}) \\ &= 31.01\text{ dB or } 1262 \end{aligned} \tag{8.19}$$

This is a good output SNR. The high SNR will ensure system operation in bad weather and with a wide temperature variation. The atmospheric loss increases drastically during a thunderstorm. The satellite receiver will experience fairly big temperature variations in space.

Example 8.3 At 10 GHz, a ground station transmits 128 W to a satellite at a distance of 2000 km. The ground antenna gain is 36 dB with a pointing error loss of 0.5 dB. The satellite antenna gain is 38 dB with a pointing error loss of 0.5 dB. The atmospheric loss in space is assumed to be 2 dB and the polarization loss is 1 dB. Calculate the received input power level and output SNR. The satellite receiver has a noise figure of 6 dB at room temperature. A bandwidth of 5 MHz is required for a channel, and a margin (loss) of 5 dB is used in the calculation.

Solution First, the space loss is calculated:

$$\lambda_0 = c/f = 0.03 \text{ m} \qquad R = 2000 \text{ km}$$

$$\text{Space loss in dB} = 20 \log\left(\frac{4\pi R}{\lambda_0}\right) = 178.5 \text{ dB}$$

The link budget table is given below:

Ground transmit power	+21.1 dBW (or 128 W)
Ground antenna gain	+36 dB
Ground antenna pointing error	−0.5 dB
Space loss	−178.5 dB
Atmospheric loss	−2 dB
Polarization loss	−1 dB
Satellite antenna gain	+38 dB
Satellite antenna pointing error	−0.5 dB
Margin	−5 dB
Received signal power	−92.4 dBW
	or − 62.4 dBm

The output S_o/N_o in decibels is given by Eq. (8.19):

$$\begin{aligned}\frac{S_o}{N_o} \text{ in dB} &= 10 \log \frac{P_r}{kTBF} \\ &= 10 \log P_r - 10 \log kTBF \\ &= -92.4 \text{ dBW} - (-130.99 \text{ dBW}) \\ &= 38.59 \text{ dB}\end{aligned}$$

The same results can be obtained by using Eqs. (8.15) and (8.11) rewritten below:

$$P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi R}\right)^2 \frac{1}{L_{\text{sys}}}$$

$$\frac{S_o}{N_o} = \frac{P_t G_t G_r}{kTBF\, L_{\text{sys}}} \left(\frac{\lambda_0}{4\pi R}\right)^2$$

Now

$$
\begin{array}{llll}
P_t & = 128\ \text{W} & G_t & = 36\ \text{dB} = 3981 \\
G_r & = 38\ \text{dB} = 6310 & \lambda_0 & = 0.03\ \text{m} \\
k & = 1.38 \times 10^{-23}\ \text{J/K} & T & = 290\ \text{K} \\
B & = 5\ \text{MHz} = 5 \times 10^6\ \text{Hz} & F & = 6\ \text{dB} = 3.98
\end{array}
$$

$$
\begin{aligned}
L_{\text{sys}} &= 0.5\ \text{dB} + 2\ \text{dB} + 1\ \text{dB} + 0.5\ \text{dB} + 5\ \text{dB} = 9\ \text{dB} = 7.94 \\
R &= 2000\ \text{km} = 2 \times 10^6\ \text{m} \\
P_r &= 128\ \text{W} \times 3981 \times 6310 \times \left(\frac{0.03\ \text{m}}{4\pi \times 2 \times 10^6\ \text{m}} \right)^2 \frac{1}{7.94} \\
&= 5.770 \times 10^{-10}\ \text{W} \\
&= -92.39\ \text{dBW} \\
\frac{S_o}{N_o} &= \frac{128\ \text{W} \times 3981 \times 6310}{1.38 \times 10^{-23}\ \text{W/sec/K} \times 290\ \text{K} \times 5 \times 10^6/\text{sec} \times 3.98 \times 7.94} \\
&\quad \times \left(\frac{0.03\ \text{m}}{4\pi \times 2 \times 10^6\ \text{m}} \right)^2 \\
&= 7245 \text{ or } 38.60\ \text{dB}
\end{aligned}
$$

8.5 EFFECTIVE ISOTROPIC RADIATED POWER AND *G/T* PARAMETERS

The effective isotropic radiated power (EIRP) is the transmitted power that would be required if the signal were being radiated equally into all directions instead of being focused. Consider an isotropic antenna transmitting a power P_t' and a directional antenna transmitting P_t as shown in Fig. 8.5, with a receiver located at a distance R from the antennas. The received power from the isotropic antenna is

$$
P_r' = \frac{P_t'}{4\pi R^2} A_{\text{er}} = \frac{P_t'}{4\pi R^2} \frac{G_r \lambda_0^2}{4\pi} = P_t' G_r \left(\frac{\lambda_0}{4\pi R} \right)^2 \tag{8.20}
$$

The received power from a directive antenna is, from Eq. (8.5),

$$
P_r = P_t G_t G_r \left(\frac{\lambda_0}{4\pi R} \right)^2 \tag{8.21}
$$

where

$$
P_r' = P_r, \qquad P_t' = P_t G_t = \text{EIRP} \tag{8.22}
$$

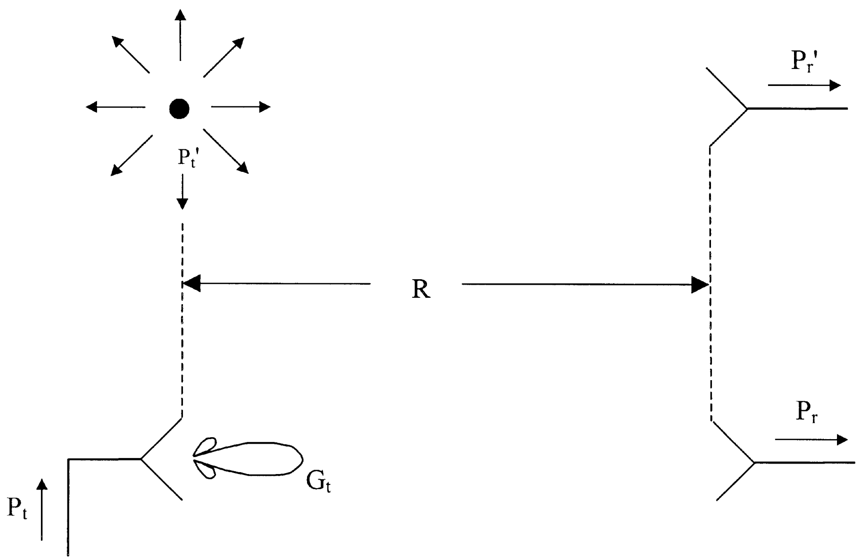

FIGURE 8.5 Definition of EIRP.

Thus EIRP is the amount of power that would be transmitted by an isotropic radiator given the measured receiver power. In a communication system, the larger the EIRP, the better the system. Therefore, we have

$$\text{EIRP} \equiv P_t G_t = \frac{P_r}{G_r}\left(\frac{4\pi R}{\lambda_0}\right)^2 \tag{8.23}$$

Example 8.4 A transmitting antenna has a gain of 40 dB and transmits an output power level of 100 W. What is the EIRP?

Solution

$$P_t = 100 \text{ W} = 20 \text{ dBW}$$
$$G_t = 40 \text{ dB} = 10{,}000$$
$$\text{EIRP} = P_t G_t = 1 \times 10^6 \text{ W or } 60 \text{ dBW}$$

■

The G/T parameter is a figure of merit commonly used for the earth station to indicate its ability to receive weak signals in noise, where G is the receiver antenna gain (G_r) and T is the system noise temperature (T_s).

The output SNR for a communication is given in Eq. (8.11) and rewritten here as

$$\frac{S_o}{N_o} = \frac{P_t G_t G_r}{kTBF\, L_{\text{sys}}}\left(\frac{\lambda_0}{4\pi R}\right)^2 \tag{8.24}$$

Substituting EIRP, space loss, and the G/T parameter into the above equation, we have

$$\frac{S_o}{N_o} = \frac{(\text{EIRP})(G_r/T_s)T_s}{(\text{space loss})kTBF\ L_{\text{sys}}} \tag{8.25}$$

It can be seen from the above equation that the output SNR ratio is proportional to EIRP and G_r/T_s but inversely proportional to the space loss, bandwidth, receiver noise factor, and system loss.

8.6 RADIO/MICROWAVE LINKS

A radio/microwave link is a point-to-point communication link using the propagation of electromagnetic waves through free space. Very and ultrahigh frequencies (VHF, UHF) are used extensively for short-range communications between fixed points on the ground. Frequently LOS propagation is not possible due to the blockage of buildings, trees, or other objects. Scattering and diffraction around the obstacles will be used for receiving with higher loss, as shown in Fig. 8.6*a*. Other examples of single-stage radio/microwave links are cordless phones, cellular phones, pager systems, CB radios, two-way radios, communications between aircraft and ships, and communications between air and ground. Figure 8.6*b* shows some examples.

For long-range communication between fixed points, microwave relay systems are used. If the points are close enough such that the earth's curvature can be neglected and if there is no obstruction, the link can be established as a single stage. For longer distances, multiple hops or a relay system is required, as shown in Fig. 8.7*a*. The relay station simply receives, amplifies, and retransmits the signals. In mountainous areas, it is possible to use a passive relay station located between the two relay stations. The passive station consists of a reflecting mirror in the direct view of each station, as shown if Fig. 8.7*b*. Many telephone and TV channels are transmitted to different areas using microwave links.

Tropospheric scattering is used for microwave links for long-distance communications (several hundred miles apart). There is no direct LOS between the stations. Microwaves are scattered by the nonhomogeneous regions of the troposphere at altitudes of 20 km, as shown in Fig. 8.8. Since only a small fraction of energy is scattered to the receiving antenna, high transmitting power, low receiver noise, and high antenna gain are required for reasonable performance. The operation can be improved by frequency diversity using two frequencies separated by 1% and by space diversity using two receiving antennas separated by a hundred wavelengths. Several received signals will be obtained with uncorrelated variation. The strongest can then be selected. Even longer distances can be established using ionospheric reflection. Layers of the ionosphere are located at altitudes of approximately 100 km.

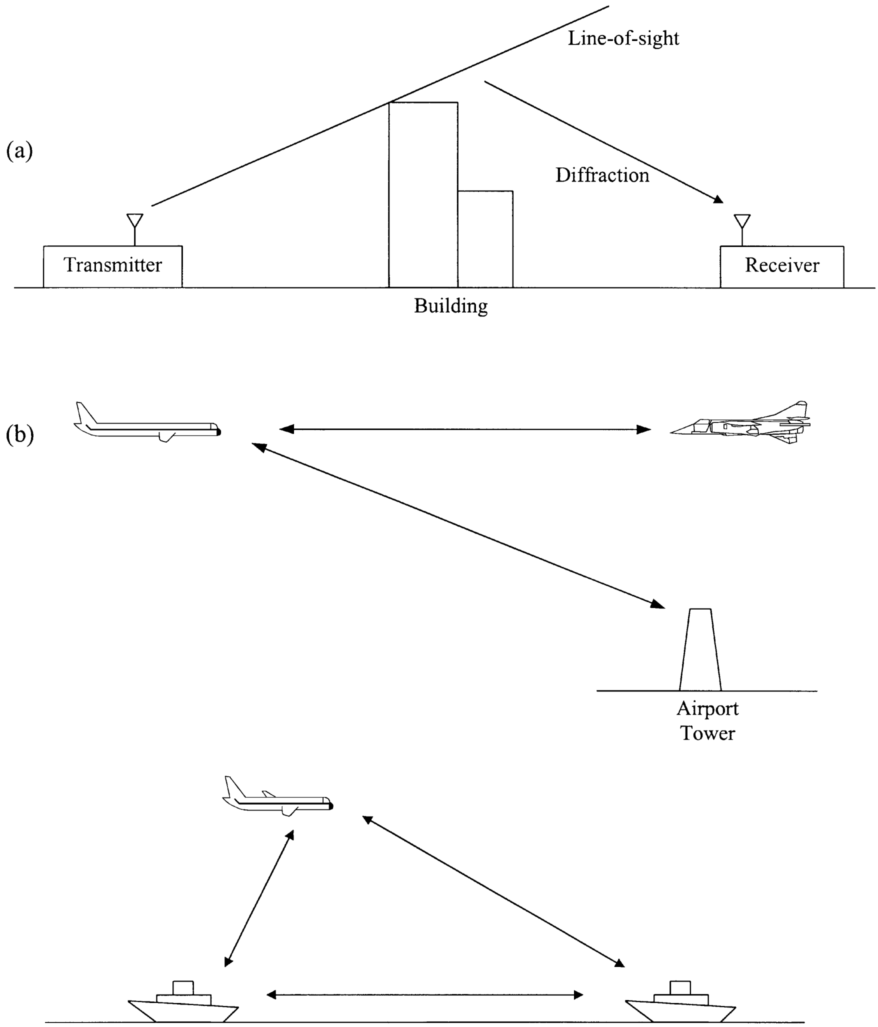

FIGURE 8.6 Radio/microwave links.

Communication links over thousands of miles can be established by using successive reflections of the waves between the earth's surface and the ionospheric layers. This method is still used by amateur radio and maritime communications.

8.7 SATELLITE COMMUNICATION SYSTEMS

In 1959, J. R. Pierce and R. Kompfner described the transoceanic communication by satellites [2]. Today, there are many communication satellites in far geosynchronous orbit (GEO) (from 35,788 to 41,679 km), near low earth orbit (LEO) (from 500 to

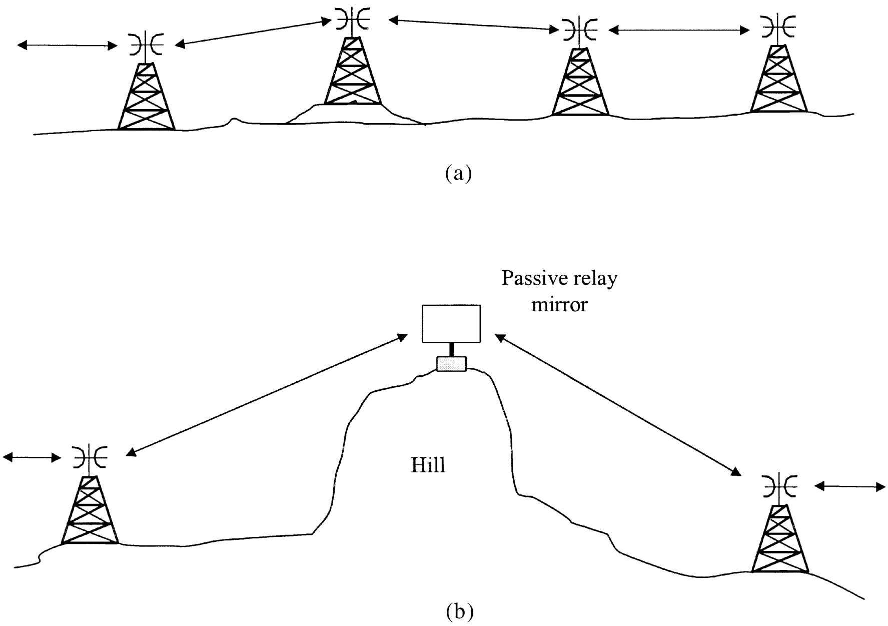

FIGURE 8.7 Microwave relay systems: (*a*) relay stations; (*b*) relay stations with a passive relay mirror.

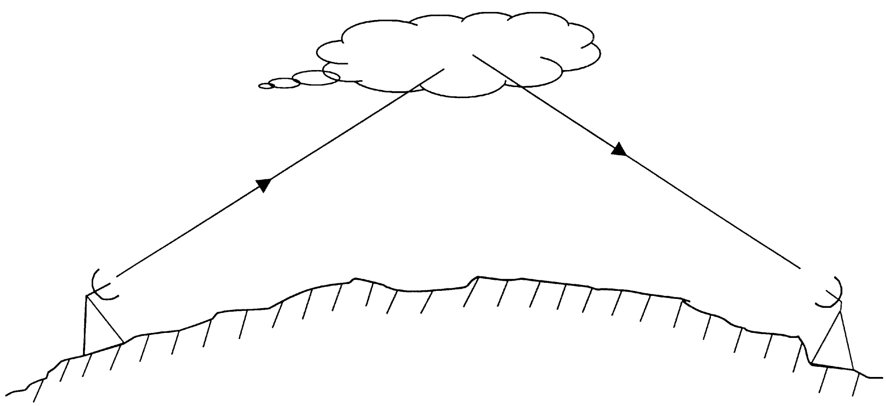

FIGURE 8.8 Tropospheric scatter link.

2000 km), and at medium-altitude orbit (MEO), in between the GEO and LEO orbits [3, 4]. Technological advances have resulted in more alternatives in satellite orbits, more output power in transmitters, lower noise in receivers, higher speed in modulation and digital circuits, and more efficient solar cells. Satellite communications have provided reliable, instant, and cost-effective communications on regional, domestic, national, or global levels. Most satellite communications use a fixed or mobile earth station. However, recent developments in personal communications have extended the direct satellite link using a hand-held telephone or laptop computer.

A simple satellite communication link is shown in Fig. 8.9. The earth station A transmits an uplink signal to the satellite at frequency f_U. The satellite receives, amplifies, and converts this signal to a frequency f_D. The signal at f_D is then transmitted to earth station B. The system on the satellite that provides signal receiving, amplification, frequency conversion, and transmitting is called a repeater or transponder. Normally, the uplink is operating at higher frequencies because higher frequency corresponds to lower power amplifier efficiency. The efficiency is less important on the ground than on the satellite. The reason for using two different uplink and downlink frequencies is to avoid the interference, and it allows simultaneous reception and transmission by the satellite repeaters. Some commonly used uplink and downlink frequencies are listed in Table 8.1. For example, at the C-band, the 4-GHz band (3.7–4.2 GHz) is used for downlink and the 6-GHz band (5.925–6.425 GHz) for uplink.

The repeater enables a flow of traffic to take place between several pairs of stations provided a multiple-access technique is used. Frequency division multiple access (FDMA) will distribute links established at the same time among different frequencies. Time division multiple access (TDMA) will distribute links using the same frequency band over different times. The repeater can distribute thousands of telephone lines, many TV channels, and data links. For example, the INTELSAT repeater has a capacity of 1000 telephone lines for a 36-MHz bandwidth.

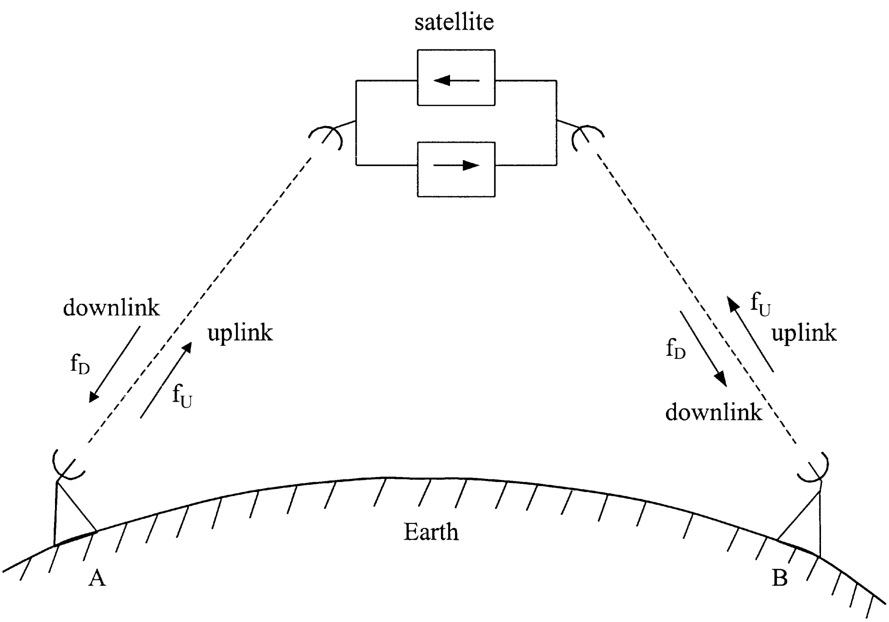

FIGURE 8.9 Satellite communication link.

TABLE 8.1 Commerical Satellite Communication Frequencies

Band	Uplink Frequency (GHz)	Downlink Frequency (GHz)
L	1.5	1.6
C	6	4
X	8.2	7.5
Ku	14	12
Ka	30	20
Q	44	21

The earth stations and satellite transponders consist of many RF and microwave components. As an example, Fig. 8.10 shows a simplified block diagram operating at the Ku-band with the uplink at 14–14.5 GHz and downlink at 11.7–12.2 GHz. The earth terminal has a block diagram shown in Fig. 8.11. It consists of two upconverters converting the baseband frequency of 70 MHz to the uplink frequency. A power amplifier (PA) is used to boost the output power before transmitting. The received signal is amplified by a low-noise RF amplifier (LNA) before it is downconverted to the baseband signal. The block diagram for the transponder on the satellite is shown in Fig. 8.12. The transponder receives the uplink signal (14–14.5 GHz). It amplifies the signal and converts the amplified signal to the downlink frequencies (11.7–12.2 GHz). The downlink signal is amplified by a power amplifier before transmitting. A redundant channel is ready to be used if any component in the regular channel is malfunctional. The redundant channel consists of the same components as the regular channel and can be turned on by a switch.

Figure 8.13 shows an example of a large earth station used in the INTELSAT system [5]. A high-gain dish antenna with Cassegrain feed is normally used. Because of the high antenna gain and narrow beam, it is necessary to track the satellite accurately within one-tenth of a half-power beamwidth. The monopulse technique is commonly used for tracking. The high-power amplifiers (HPAs) are either traveling-wave tubes (TWTs) or klystrons, and the LNAs are solid-state devices such as MESFETs. Frequency division multiple access and TDMA are generally used for modulation and multiple access of various channels and users.

8.8 MOBILE COMMUNICATION SYSTEMS AND WIRELESS CELLULAR PHONES

Mobile communication systems are radio/wireless services between mobile and land stations or between mobile stations. Mobile communication systems include maritime mobile service, public safety systems, land transportation systems, industrial systems, and broadcast and TV pickup systems. Maritime mobile service is between ships and coast stations and between ship stations. Public safety systems

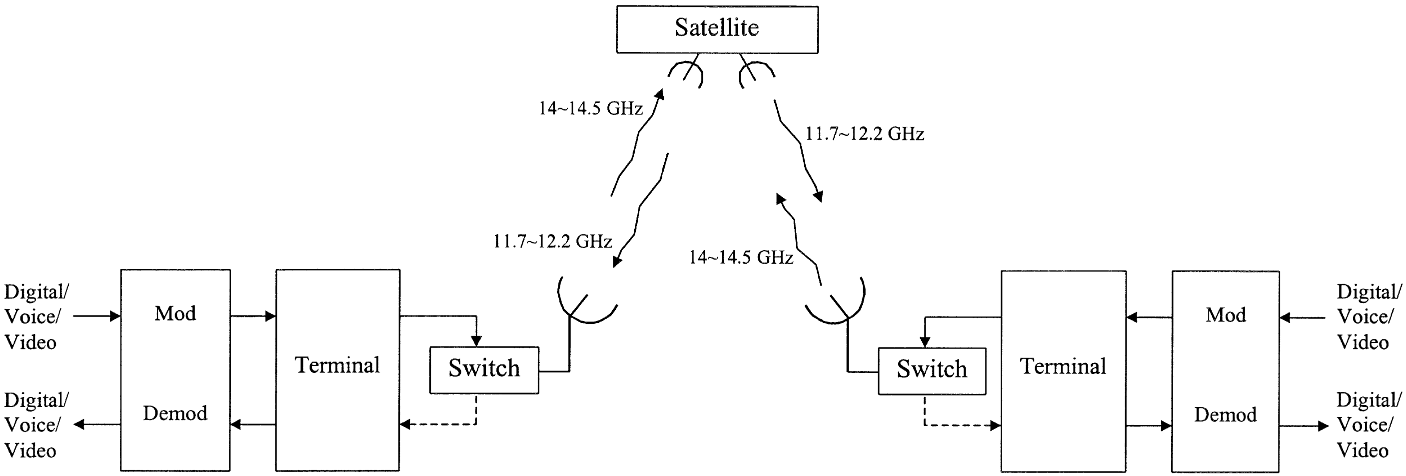

FIGURE 8.10 Simplified Ku-band satellite link.

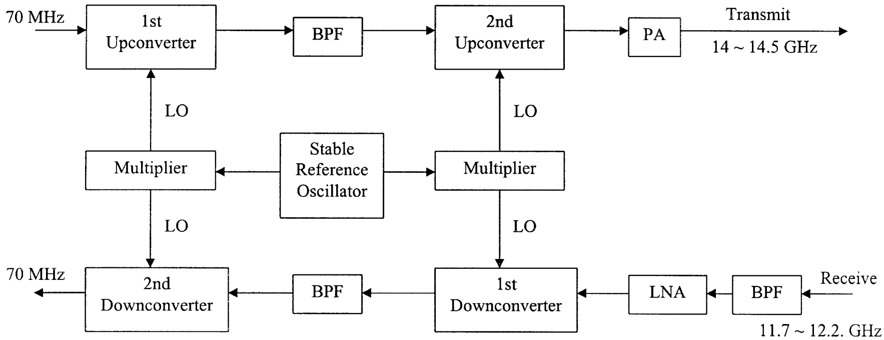

FIGURE 8.11 Block diagram for earth station terminal.

include police, fire, ambulance, highway, forestry, and emergency services. Land transportation systems cover the communications used by taxis, buses, trucks, and railroads. The industrial systems are used for communications by power, petroleum, gas, motion picture, press relay, forest products, ranchers, and various industries and factories.

Frequency allocations for these services are generally in HF, VHF, and UHF below 1 GHz. For example, the frequency allocations for public safety systems are [6] 1.605–1.750, 2.107–2.170, 2.194–2.495, 2.505–2.850, 3.155–3.400, 30.56–32.00, 33.01–33.11, 37.01–37.42, 37.88–38.00, 39.00–40.00, 42.00–42.95, 44.61–46.60, 47.00–47.69, 150.98–151.49, 153.73–154.46, 154.62–156.25, 158.7–159.48, 162.00–172.40, 453.00–454.00, and 458.0–459.0 MHz. The frequency allocations for the land transportation services are 30.56–32.00, 33.00–33.01, 43.68–44.61, 150.8–150.98, 152.24–152.48, 157.45–157.74, 159.48–161.57, 452.0–453.0, and 457.0–458.0 MHz.

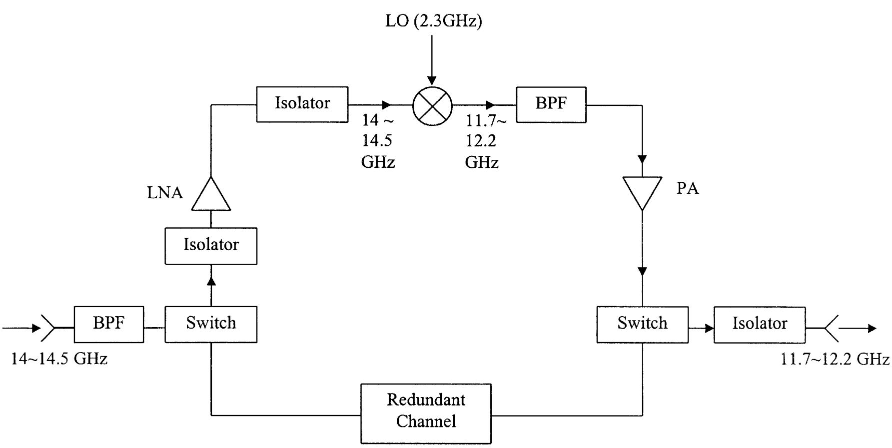

FIGURE 8.12 Block diagram for satellite transponder.

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FIGURE 8.13 Satellite earth station. (From reference [5], with permission from McGraw-Hill.)

Land mobile communications have a long history. In the 1920s, one-way broadcasts were made to police cars in Detroit. The system was expanded to 194 municipal police radio stations and 5000 police cars in the 1930s. During World War II, several hundred thousand portable radio sets were made for military use. In the late 1940s, Bell System proposed the cellular concept. Instead of the previously used "broadcast model of a high-power transmitter," placed at a high elevation covering a large area, the new model used a low-power transmitter covering a small area called a "cell." Each cell has a base station that communicates with individual users. The base stations communicate to each other through a switching office and, from there, to satellites or the outside world. Figure 8.14 shows the concept of cells. There is a base station in each cell, and the actual cell shape may not be hexagonal. The system has the following features:

1. Since each cell covers a small area, low-power transmitters can be used in the base stations.
2. Frequencies can be reused with a sufficient separation distance between two cells. For example, the cells in Fig. 8.14 using the same letters (A, B, C, D, . . .) are in the same frequency.
3. Large cells can be easily reduced to small cells over a period of time through splitting when the traffic is increased.
4. The base station can pass a call to other stations without interruption (i.e., handoff and central control).

The first-generation cellular telephone system that started in the mid-1980s used analog modulation (FM). The second-generation system used digital modulation and TDMA. Some recent systems use code division multiple access (CDMA) to increase the capacity, especially in big cities. Table 8.2 summarizes the analog and digital cellular and cordless phone services. The information shown is just an example since the technology has changed very rapidly. Digital cellular phone systems offer greater user capacity, improved spectral efficiency, and enhanced voice quality and security. In Europe, the Global System for Mobile Communication (GSM) is a huge, rapidly expanding system. A typical GSM 900 (operating at 900 MHz) cell can be located up to a 35 km radius. GSM uses TDMA or FDMA operation.

8.9 PERSONAL COMMUNICATION SYSTEMS AND SATELLITE PERSONAL COMMUNICATION SYSTEMS

Personal communication systems, personal communication networks (PCNs), or local multipoint distribution service (LMDS) operate at higher frequencies with wider bandwidths. The systems offer not only baseline voice services like cellular phones but also voice-mail, messaging, database access, and on-line services, as shown in Fig. 8.15. Table 8.3 shows the frequency allocations for PCSs designated by the Federal Communications Commission.

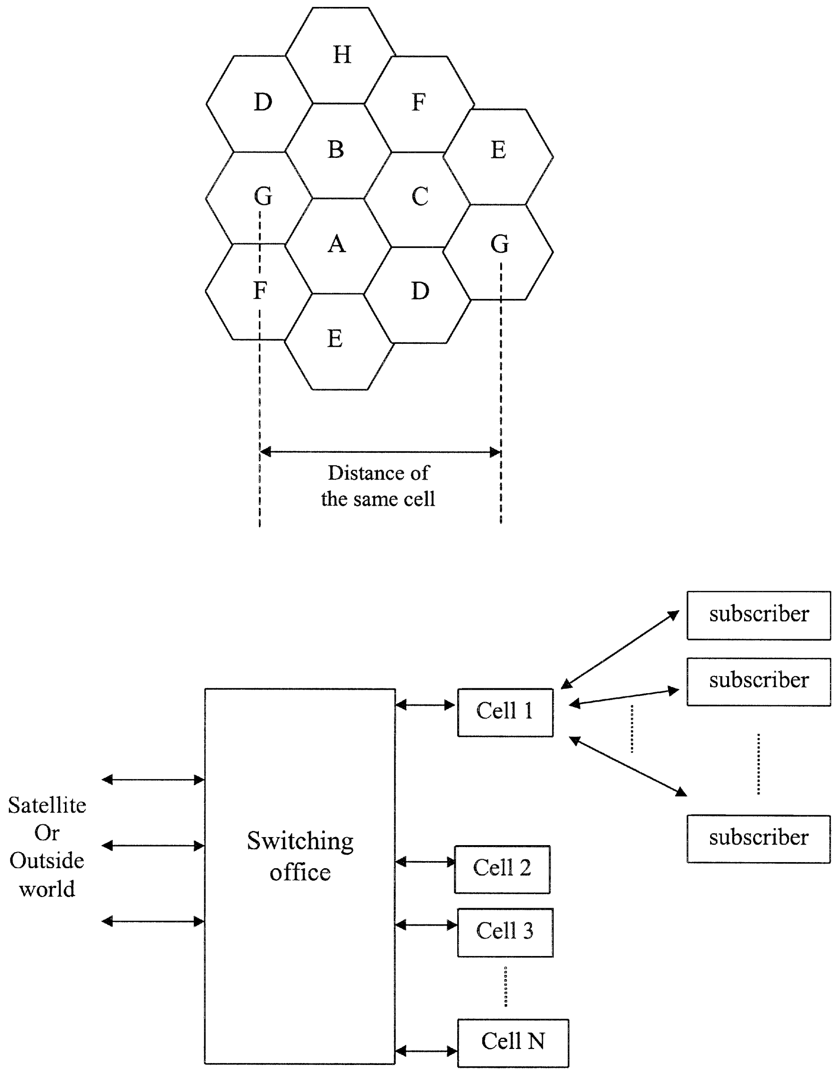

FIGURE 8.14 Concept of cellular systems.

The direct link between satellites and PCSs can provide data and voice communications anywhere in the world, even in the most remote regions of the globe. At least six satellite systems are under development for wireless personal voice and data communications using a combination of wireless telephones, wireless modems, terrestrial cellular telephones, and satellites. Many companies and consortia have invested billions of dollars to launch satellites capable of providing paging, voice, data, fax, and video conferencing worldwide. A few examples are given in Tables 8.4 and 8.5.

TABLE 8.2 Analog and Digital Cellular and Cordless Phone Services

	Analog Cellular Telephones			Analog Cordless Telephones		
Standard	Advanced Mobile Phone Service (AMPS)	Total Access Communication System (TACS)	Nordic Mobile Telephone (NMT)	Cordless Telephone (CTO)	Japanese Cordless Telephone (JCT)	Cordless Telephone 1 (CTI/CTI+)
Mobile frequency range (MHz)	Rx: 869–894, Tx: 824–849	ETACS: Rx: 916–949, Tx: 871–904 NTACS: Rx: 860–870, Tx: 915–925	NMT-450: Rx: 463–468, Tx: 453–458 NMT-900: Rx: 935–960, Tx: 890–915	2/48 (U.K.), 26/41 (France), 30/39 (Australia), 31/40 (The Netherlands, Spain), 46/49 (China, S. Korea, Taiwan, US), 48/74 (China)	254–380	CTI: 915/960, CTI+: 887/932
Multiple-access method	FDMA	FDMA	FDMA	FDMA	FDMA	FDMA
Duplex method	FDD	FDD	FDD	FDD	FDD	FDD
Number of channels	832	ETACS: 1000, NTACS: 400	NMT-450: 200, NMT-900: 1999	10, 12, 15 or 20	89	CTI: 40, CTI+: 80
Channel spacing	30 kHz	ETACS: 25 kHz, NTACS: 12.5 kHz	NMT-450: 25 kHz, NMT-900: 12.5 kHz	40 kHz	12.5 kHz	25 kHz
Modulation	FM	FM	FM	FM	FM	FM
Bit rate	n/a	n/a	n/a	n/a	n/a	n/a

TABLE 8.2 (*Continued*)

	Digital Cellular Telephones				Digital Cordless Telephones/PCN			
Standard	North American Digital Cellular (IS-54)	North American Digital Cellular (IS-95)	Global System for Mobile Communications (GSM)	Personal Digital Cellular (PDC)	Cordless Telephone 2 (CT2/CT2+)	Digital European Cordless Telephone (DECT)	Personal Handy Phone System (PHS)	DCS 1800
Mobile frequency range (MHz)	Rx: 869–894, Tx: 824–849	Rx: 869–894, Tx: 824–849	Rx: 935–960, Tx: 890–915	Rx: 810–826, Tx: 940–956; Rx: 1429–1453, Tx: 1477–1501	CT2: 864/868: CT2+: 930/931, 940/941	1880–1990	1895–1907	Rx: 1805–1880, Tx: 1710–1785
Multiple access method	TDMA/FDM	CDMA/FDM	TDMA/FDM	TDMA/FDM	TDMA/FDM	TDMA/FDM	TDMA/FDM	TDMA/FDM
Duplex method	FDD	FDD	FDD	FDD	TDD	TDD	TDD	FDD
Number of channels	832 (3 users/ channel)	20 (798 users/ channel)	124 (8 users/ channel)	1600 (3 users/ channel)	40	10 (12 users/ channel)	300 (4 users/ channel)	750 (16 users/ channel)
Channel spacing	30 kHz	1250 kHz	200 kHz	25 kHz	100 kHz	1.728 MHz	300 kHz	200 kHz
Modulation	$\pi/4$ DQPSK	BPSK/ OQPSK	GMSK (0.3 Gaussian filter)	$\pi/4$ DQPSK	GFSK (0.5 Gaussian filter)	GFSK (0.5 Gaussian filter)	$\pi/4$ DQPSK	GMSK (0.3 Gaussian filter)
Bit rate	48.6 kb/sec	1.288 Mb/sec	270.833 kb/sec	42 kb/sec	72 kb/sec	1.152 Mb/sec	384 kb/sec	270.833 kb/sec

Source: From reference [7], with permission from IEEE.

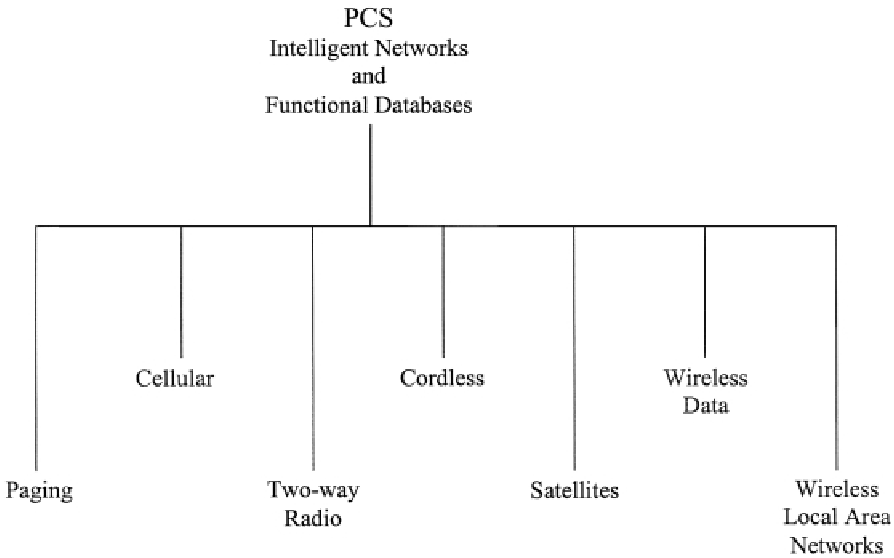

FIGURE 8.15 Personal communication systems.

With the combination of wireless telephones, wireless modems, terrestrial cellular telephones, WLANs, and satellites, the ultimate vision for PCSs is a wireless go-anywhere communicator [8]. In general, outdoor communications would be handled by PCS carriers connected to public voice and data networks through telephone, cable, and satellite media. The PCS microcells and WLANs with base stations could be installed indoors. Figure 8.16 shows an artist's picture of this vision [8]. The WLAN is for wireless indoor radio communication services or high-data-rate communications. The system employs a central microcell hub (base station) that services cordless phones and computer workstations whose transceivers are networking with the hub through wireless communications. Since the cell is small, inexpensive low-power base stations can be used. Several WLAN microcells are shown in Fig. 8.16. Table 8.6 shows some WLANs frequency allocations. One

TABLE 8.3 PCS Frequency Allocations

Channel Block	Frequency (MHz)	Service Area
A (30 MHz)	1850–1865/1930–1945	Major trading areas
B (30 MHz)	1865–1880/1945–1960	Major trading areas
C (20 MHz)	1880–1890/1960–1970	Basic trading areas
D (10 MHz)	2130–2135/2180–2185	Basic trading areas
E (10 MHz)	2135–2140/2185–2190	Basic trading areas
F (10 MHz)	2140–2145/2190–2195	Basic trading areas
G (10 MHz)	2145–2150/2195–2200	Basic trading areas

Source: Federal communications commission.

TABLE 8.4 Satellite Personal Communication Systems Under Development

	Globalstar	Teledesic	Iridium	American Mobile Satellite Corp.	Spaceway	Odyssey
Headquarters	Palo Alto, CA	Kirkland, WA	Washington, DC	Reston, VA	El Segundo, CA	Redondo Beach, CA
Investors	Loral Corp., Qualcomm, Alcatel (France), Dacom Corp. (S. Korea), and Deutsche Aerospace (Germany) and others	Startup company backed with funding from William Gates, chairman of Microsoft, and Craig McCaw, chairman of McCaw Cellular	Motorola, Sprint, STET (Italy), Bell Canada, DDI (Japan)	Hughes Communications, McCaw Cellular, Mtel, Singapore Telecomm	Wholly owned and operated by Hughes Communications	TRW, Teleglobe of Canada
Estimated cost to build	$1.8 billion	$9 billion	$3.4 billion	$550 million	$660 million	$1.3 billion
Description	Worldwide voice, data, fax, and paging services using 48 LEO satellites	A worldwide network of 840 satellites will offer voice, data, fax and two-way video communications	66 satellites will offer worldwide voice, data, fax, and paging services	Satellite network will provide voice, data, fax, and two-way messaging throughout North America, targeting customers in regions not served by cellular systems	Dual-satellite system offering voice, data, and two-way videoconferencing in North America	12 satellite system offering voice, data, and fax services

Source: From reference [7], with permission from IEEE.

TABLE 8.5 System Parameters of Several Satellite Personal Communication Systems

System	Iridium (Motorola)	Odyssey (TRW)	Globalstar (Loral and Qualcomm)
No. of satellites	66	12	48
Class	LEO	MEO	LEO
Lifetime in years	5	15	7.5
Orbit altitude (km)	781	10,354	1390
Orientation	Circular	Circular	Circular
Initial geographical coverage	Global	CONUS, Offshore U.S., Europe, Asia/Pacific	CONUS
Service markets	Cellular like voice, mobile FAX, paging, messaging, data transfer	Cellular like voice, mobile FAX, paging, messaging, data transfer	Cellular like voice, mobile FAX, paging, messaging, data transfer
Voice cost/minute	$3.00	$0.65	$0.30
User terminal types	Hand-held, vehicular, transportable	Hand-held, vehicular, transportable	Hand-held, vehicular, transportable
Estimated cost	$3000	$250–500	$500–700
Wattage	0.4	0.5	1
Uplink bands	L-band (1616.5–1625.5 MHz)	L-band (1610.0–1626.5 MHz)	L-band (1610.0–1626.5 MHz)
Downlink bands	L-band	S-band (2483.5–2500 MHz)	S-band (2483.5–2500 MHz)
Methods of access	FDMA	CDMA	CDMA

Source: From reference [7], with permission from IEEE.

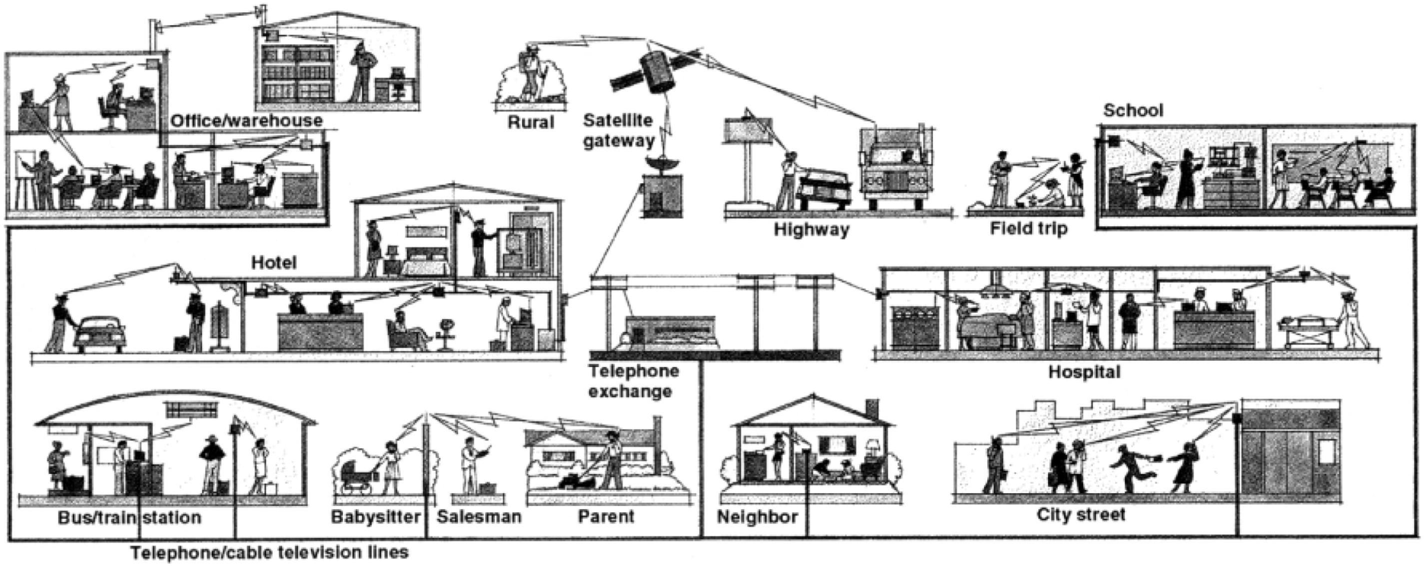

FIGURE 8.16 Personal wireless communications. (From reference [8], with permission from IEEE.)

TABLE 8.6 Wireless Local-Area Network Frequency Bands

Unlicensed	Licensed	No license
ISM	Narrowband	Infrared
0.902–0.928 GHz	Microwave	(IR)
2.400–2.483 GHz	18.82–18.87 GHz	No FCC regulation
5.725–5.825 GHz	19.16–19.21 GHz	
Spread-Spectrum $P_0 < 1$ watt		

Source: From reference [7], with permission from IEEE.

application of WLANs is wireless offices. With the rapid pace of office relocation and changing assignments, WLANs eliminate the need for running wires over, under, and through offices.

PROBLEMS

8.1 (a) What is the required receiver antenna gain in decibels for a CW communication system with a transmitted power of 1 kW operating at 30 GHz? The transmit antenna is a dish with a diameter of 1 m and 55% efficiency. The receiver requires an input signal S_{min} of 10^{-6} W for good reception. The maximum range of the system is designed to be 100 km for the ideal case. Neglect the system losses. (b) What is the range if the transmitted power is doubled to 2 kW? What is the range if the transmitted power is 200 kW?

8.2 A communication system has a transmitter with an output power of 1000 W at 10 GHz. The transmit antenna is a dish with a diameter of 4 m. The receive antenna is a dish with a diameter of 2 m. Assume that the antennas have 55% efficiencies. The distance of communication is 50 km. The receiver has a bandwidth of 25 MHz and noise figure of 10 dB operating at room temperature (290 K), (a) Calculate the received power in watts. (b) Calculate the SNR ratio at the output port of the receiver. Assume that the overall system loss is 6 dB.

8.3 A mobile communication system has the following specifications:

Transmitter power output = 10 W
Transmitter antenna gain = 10 dB
Overall system loss = 10 dB
Receiver noise figure = 4 dB
Operating frequency = 2 GHz

Receiver antenna gain = 2 dB
Temperature = 290 K
Receiver bandwidth = 3 MHz
Required minimum output SNR for the receiver = 15 dB

Calculate the maximum range in km.

8.4 In a communication system, if the receiver output SNR is increased, determine if the EIRP is (increased, decreased), the range is (increased, decreased), the receiver noise is (increased, decreased), and the operating bandwidth is (increased, decreased). What is the EIRP for the transmitter given in Problem 8.3?

8.5 In Section 8.4, the link budget for a satellite communication uplink case was discussed. For a downlink case, the frequency is 12.1 GHz. The satellite antenna gain at this frequency is 36.28 dB. The satellite tube's output power is 200 W. The atmospheric loss at this frequency is 1.52 dB. The ground terminal antenna gain is 53.12 dB, and the ground terminal receiver noise figure is 4.43 dB. All other parameters are the same as the uplink case. Calculate (a) the space loss in decibels, (b) the received power in watts, (c) the received carrier-to-noise power ratio (at the receiver output) in decibels, and (d) the EIRP in decibels relative to 1 W (dBW). (e) If the bandwidth is 20 MHz, design the terminal antenna gain to maintain the same SNR ratio as in part (c). In (b), give a table showing the link budget.

8.6 A ground-to-satellite communication link is operating at 15 GHz. The satellite is located in the LEO at a distance of 2000 km from the ground station. Quadriphase shift keying (QPSK) modulation is used to transmit a data rate of 10 Mbits/sec, which is equivalent to a 5-MHz bandwidth. The satellite receiver has a noise figure of 8 dB, an antenna gain of 41 dB, and an antenna pointing error loss of 0.5 dB. The ground transmitter has an output power of 82 W, an antenna gain of 38 dB, and an antenna pointing error loss of 0.5 dB. The atmospheric loss in fair weather is 3 dB; polarization loss is 1 dB. A margin of 5 dB is used. (a) Set up a link budget table and calculate the received power. (b) Calculate the receiver output SNR ratio. (c) What is the receiver output SNR ratio if the atmospheric loss is 20 dB in a thunderstorm?

8.7 A communication link has the link budget shown below. The distance of communication is 50 km. The operating frequency is 3 GHz. The receiver has a noise figure of 5 dB, a bandwidth of 10 MHz, and an operating temperature of 290 K. Calculate (a) the space loss in decibels, (b) the received power in watts, (c) the received carrier-to-noise power ratio in decibels (at the receiver output), and (d) the EIRP in watts. (e) What is the transmit power in watts if the transmit antenna is a dipole antenna with a gain of 2 dB and we want to maintain the same EIRP and received power?

Transmitting power (100 W)	___dBW
Feed loss	−1 dB
Transmitting antenna gain	40 dB
Antenna pointing error	−1 dB
Space loss	___dB
Atmospheric loss	−2 dB
Polarization loss	−0.5 dB
Receiving feed loss	−1 dB
Receiving antenna gain	20 dB
Receiving antenna pointing error	+) −1 dB

8.8 A microwave link is set up to communicate from a city to a nearby mountain top, as shown in Fig. P8.8. The distance is 100 km, and the operating frequency is 10 GHz. The receiver has a noise figure of 6 dB, a bandwidth of 30 MHz, and an operating temperatuare of 290 K. Calculate (a) the received power in watts and (b) the received carrier-to-noise power ratio in decibels at the receiver output port. (c) Repeat (b) if there is a thunderstorm that gives an additional loss of 5 dB/km for a region of 5 km long between the transmitter and receiver.

Transmitting power (1000 W)	___dBW
Feed loss	−1.5 dB
Transmitting antenna gain	45 dB
Antenna pointing error	−1 dB
Space loss	___dB
Atmospheric loss	−2 dB
Polarization loss	−0.5 dB
Receiving feed loss	−1.5 dB
Receiving antenna gain	45 dB
Receiving antenna pointing error	+) −2 dB

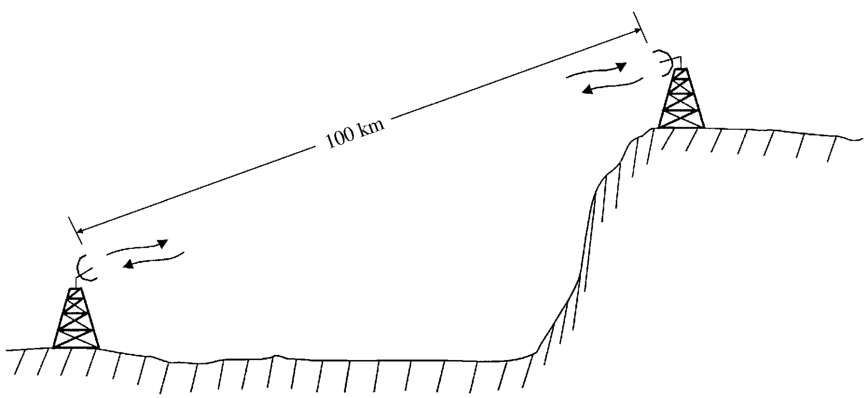

FIGURE P8.8

8.9 A microwave link is used to connect two communication towers, as shown in Fig. P8.9. The distance is 100 km, and the operating frequency is 10 GHz. The receiver has a noise figure of 5 dB and a bandwidth of 10 MHz and operates at room temperature (290 K). Calculate (a) the received power in watts, (b) the received carrier-to-noise power ratio in decibels at the input of the receiver, (c) the received carrier-to-noise ratio in decibels at the output of the receiver, (d) the transmitter EIRP in watts, and (e) the receiver output SNR ratio if a low-gain dipole antenna (gain = 2 dB) is used in the receiver.

Transmitting power (100 W)	___dBW
Feed loss	−1 dB
Transmitting antenna gain	35 dB
Antenna pointing error	−1 dB
Space loss	___dB
Atmospheric loss	−2 dB
Polarization loss	−1 dB
Receiving feed loss	−2 dB
Receiving antenna gain	35 dB
Receiving antenna pointing error	+) −1 dB

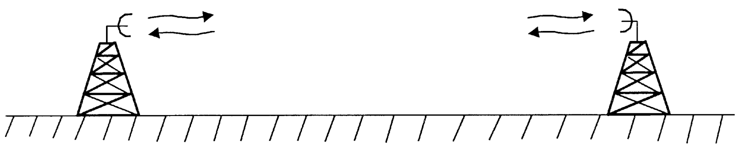

FIGURE P8.9

REFERENCES

1. E. A. Wolff and R. Kaul, *Microwave Engineering and Systems Applications*, John Wiley & Sons, New York, 1988.
2. J. R. Pierce and R. Kumpfner, "Transoceanic Communication by Means of Satellites," *Proc. IRE*, Vol. 47, pp. 372–380, March 1959.
3. G. D. Gordon and W. L. Morgan, *Principles of Communications Satellites*, John Wiley & Sons, New York, 1993.
4. W. L. Morgan and G. D. Gordon, *Communications Satellite Handbook*, John Wiley & Sons, New York, 1989.
5. M. Richharia, *Satellite Communication Systems*, McGraw-Hill, New York, 1995.
6. F. Losee, *RF Systems, Components, and Circuits Handbook*, Artech House, Boston, 1997.
7. F. Ali and J. B. Horton, "Introduction to Special Issue on Emerging Commercial and Consumer Circuits, Systems, and Their Applications," *IEEE Trans. Microwave Theory Tech.*, Vol. 43, No. 7, pp. 1633–1637, 1995.
8. B. Z. Kobb, "Personal Wireless," *IEEE Spectrum*, pp. 20–25, June 1993.