CHAPTER 4

SATELLITE LINK DESIGN

The design of a satellite communication system is a complex process requiring compromises between many factors to achieve the best performance at an acceptable cost. We will first consider geostationary satellite systems, since GEO satellites carry the vast majority of the world's satellite traffic.

INTRODUCTION

Figure 2.17 of Chapter 2 shows that the cost to build and launch a GEO satellite is about $25,000 per kg. Weight is the most critical factor in the design of any satellite, since the heavier the satellite the higher the cost, and the capital cost of the satellite must be recovered over its lifetime by selling communication services. The overall dimensions of the satellite are critical because the spacecraft must fit within the confines of the launch vehicle. When stowed for launch, the diameter of the spacecraft typically must be less than 3.5 m. Most large GEO satellites use deployable solar panels and antennas, but the antenna reflectors require accurate surfaces and are not folded for launch. This limits the maximum aperture dimension to about 3.5 m. As in most radio systems, antennas are a limiting factor in the capacity and performance of the communication system.

The weight of a satellite is driven by two factors: the number and output power of the transponders on the satellite and the weight of station-keeping fuel. As much as half the total weight of satellites intended to remain in service for 15 years may be fuel. High power transponders require lots of electrical power, which can only be generated by solar cells. Increasing the total output power of the transponders raises the demand for electrical power and the dimensions of the solar cells, adding more weight to the satellite.

Three other factors influence system design: the choice of frequency band, atmospheric propagation effects, and multiple access technique. These factors are all related, with the frequency band often being determined by what is available. Tables 4.1 and 4.2 tabulate

Regions I, II, and III are regions of the earth's surface defined in the International Telecommunication Union's Radio Regulations. Region I covers Europe, Africa, and northern Asia. Region II covers North and South America, and Region III covers the remainder of Asia.

TABLE 4.1 Major Frequency Allocations for Fixed Satellite Service and Broadcasting Satellites

Frequency	Fixed satellite service	Broadcasting satellites
2320–2345 MHz		Radio broadcasting
2500–2535		Down region III
2500–2655	Down region II	Down region II
2655–2690	Down region II	Down region II Up region II, III
3400–3700	Down	
3700–4200	Down	
4500–4800	Down, up	
5725–5850	Up region I	
5850–5925	Up region I	
5925–7075	Up	
7250–7450	Down, government	
7450–7550	Down, government	
7550–7750	Down, government	
8215–8400	Up, government	
10.7–11.7 GHz	Down	Up region I
11.7–12.2	Down region II	Down regions I and III
12.2–12.7		Down regions I and II, U.S. Direct Broadcast Satellite T
12.50–12.75	Up region I and II, down region I	
12.75–13.25		Up
14.00–14.25	Up	
14.25–14.50	Up	
14.5–14.8		Up
17.3–17.7		Up
17.7–18.6	Down	
17.7–18.6	Down	
18.1–18.6	Down	
18.6–18.8	Down regions I and III	
18.8–19.7	Down	
27.0–27.5	Up regions II and III	
27.5–29.5	Up	
30.0–31.0	Up	
37.5–39.5	Down	
39.5–40.5	Down	
40.5–42.5	Down	
42.5–43.5	Up	
47.2–50.2	Up	
50.4–51.4	Up	
71.0–75.5	Up	
81–84	Down	
84–86	Down	
92–95	Up	
102–105	Down	
149–164	Down	
202–217	Up	
231–241	Down	
265–275	Up	

TABLE 4.2 Major Frequency Allocations for Mobile Satellite Services

Frequency	Aeronautical mobile	Maritime mobile	Land mobile and other services
137–138 MHz			Down, shared
148–149.9			Up, shared
149.9–150.05			Up, shared
399.9–400.05			Up
400.15–401			Down, shared
406–406.1			Emergency beacons
890–896			Region II (limited use) Shared with cellular radio
1559–1610			Navigation satellite, down
1530–1535		Down	Down region I only
1535–1544		Down	
1544–1545		Down	
1545–1555	Down		
1555–1559			Down
1559–1610			Navigation satellite, down
1610–1625.5			Navigation satellite, up
1625.5–1631.5		Up	
1631.5–1634.5			Up
1634.5–1645.5		Up	Shared
1645.5–1646.5	Up	Up	Up
1646.5–1656.5	Up		
1656.5–1660			Up
1660.0–1660.5			Up
1660.0–1660.5			Up
2483.5–2500	Down	Down	Down
5.00–5.25 GHz	Up	Up	Up
7.30–7.75	Up, government	Up, government	Up, government
15.4–15.7	Down	Down	Down
20.2–21.2	Down	Down	Down
29.5–31.0	Up	Up	Up
39.5–40.5	Down	Down	Down
43.5–45.5	Up, government	Up, government	Up, government
45.5–47.0	Up	Up	Up
66.0–71.0	Down	Down	Down
71.0–74.0	Up	Up	Down
81.0–84.0	Down	Down	Down
95.0–100			
134–142			
190–200			
252–265			

Regions I, II, and III are regions of the earth's surface defined by the International Telecommunications Union. (See Table 4.1 for an explanation of their geographic locations.)

the most important frequencies allocated for satellite communications. The major bands are the 6/4 GHz, 14/11 GHz, and 30/20 GHz bands. (The uplink frequency is quoted first, by convention.) However, over much of the geostationary orbit there is already a satellite using both 6/4 GHz and 14/11 GHz every 2°. This is the minimum spacing used for satellites in GEO to avoid interference from uplink earth stations. Additional satellites can only be accommodated if they use another frequency band, such as 30/20 GHz. Rain in the atmosphere attenuates radio signals. The effect is more severe as the frequency increases, with little attenuation at 4 and 6 GHz, but significant attenuation above 10 GHz. Attenuation through rain (in decibels) increases roughly as the square of frequency, so a satellite uplink operating at 30 GHz suffers four times as much attenuation as an uplink at 14 GHz.

Low earth orbit (LEO) and medium earth orbit (MEO) satellite systems have similar constraints to GEO satellite systems, but require more satellites which each serve a smaller area of the earth's surface. Although the satellites are much closer to the earth than GEO satellites and therefore produce stronger signals, this advantage is usually lost since the earth terminals need low gain omnidirectional antennas because the position of the satellite is continually changing. LEO and MEO satellites use multiple beam antennas to increase the gain of the satellite antenna beams, and also to provide frequency reuse.

Mobile satellite terminals must operate with low gain antennas at the mobile unit, and at as low a RF frequency as can be obtained. The link between the satellite and the major earth station (often called a *hub station*) is usually in a different frequency band as it is a fixed link. Figure 4.1 shows an illustration of a maritime satellite communication system using a GEO satellite and L-band links to mobiles, with C-band links to a fixed hub station.

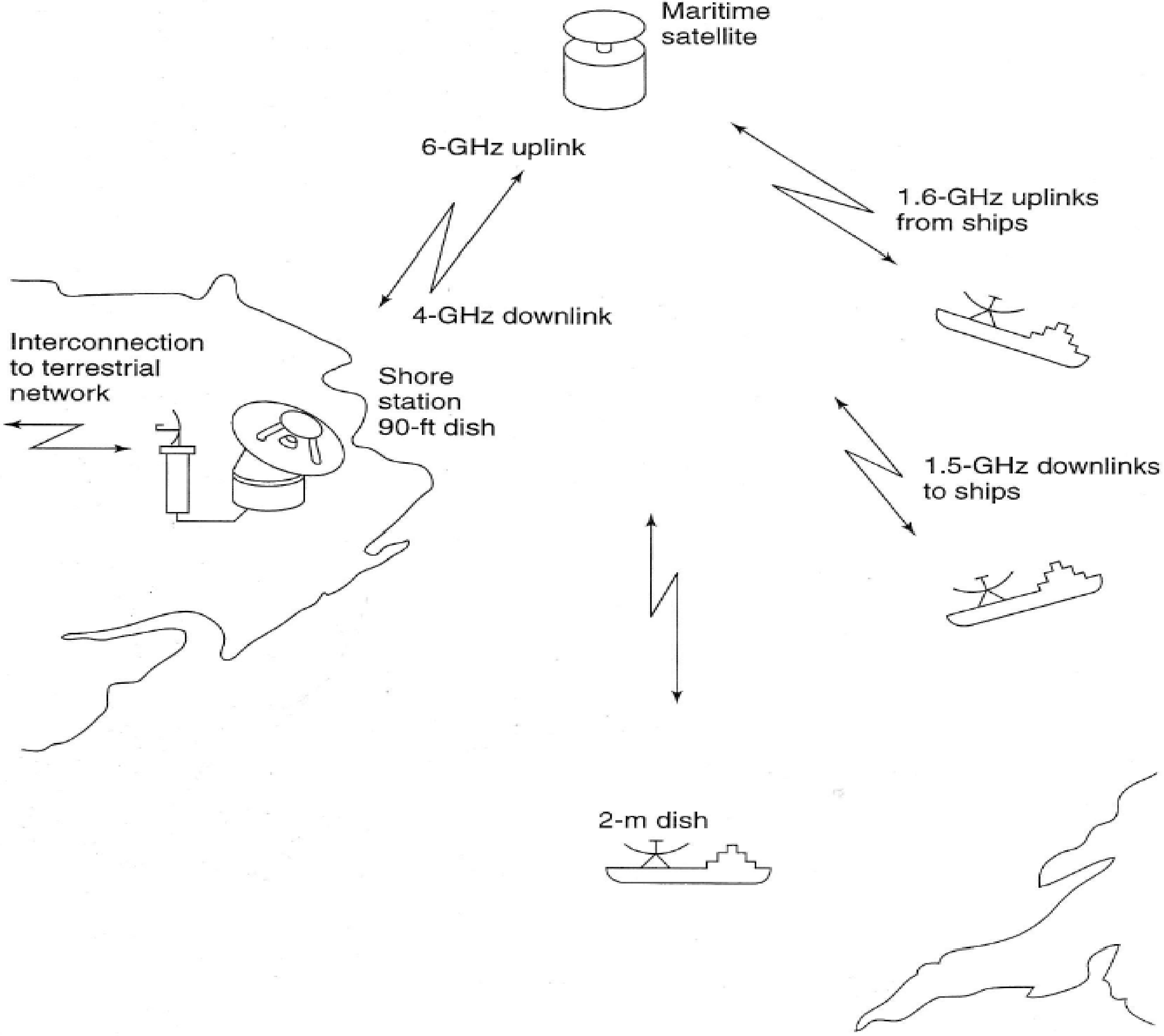
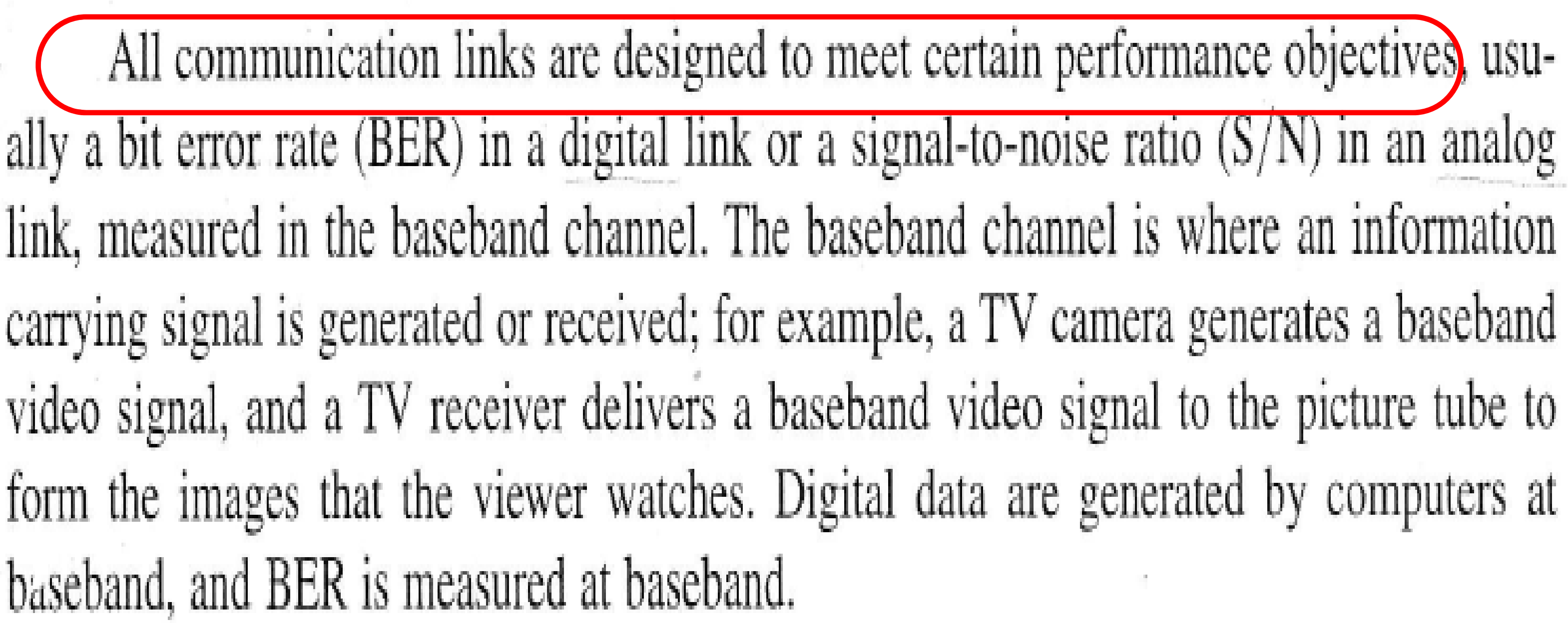
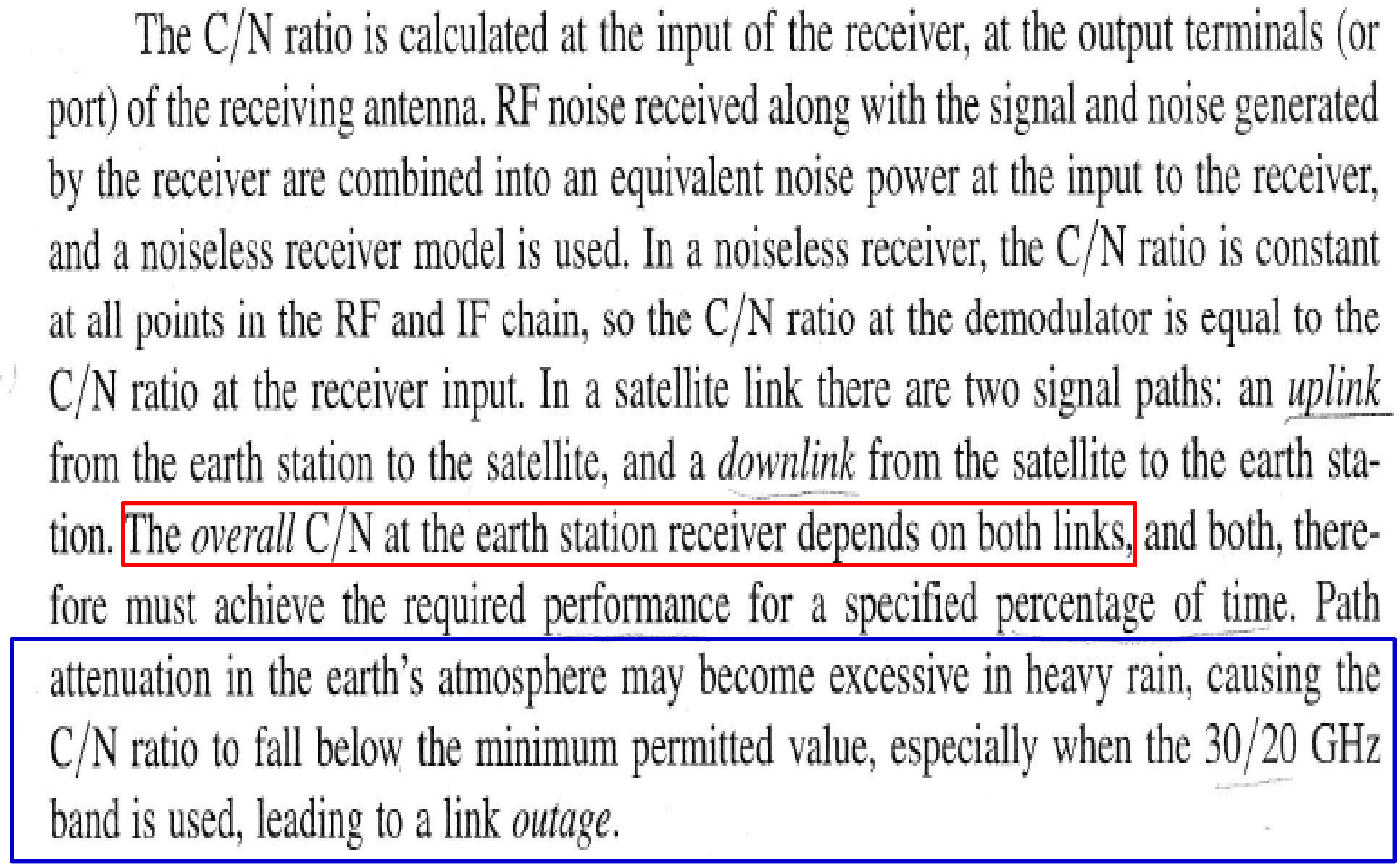


FIGURE 4.1 A maritime satellite communication system.

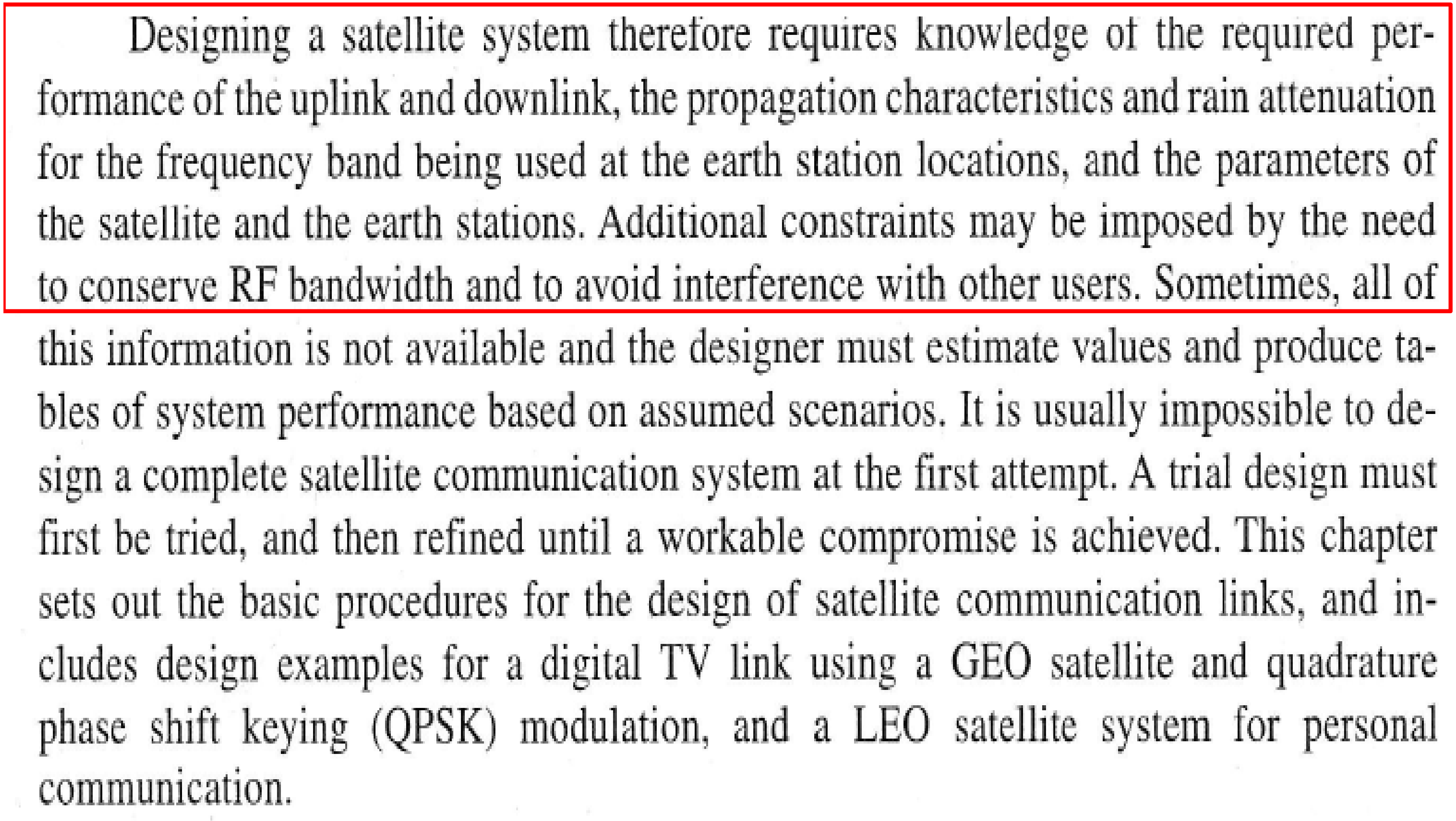


All communication links are designed to meet certain performance objectives, usually a bit error rate (BER) in a digital link or a signal-to-noise ratio (S/N) in an analog link, measured in the baseband channel. The baseband channel is where an information carrying signal is generated or received; for example, a TV camera generates a baseband video signal, and a TV receiver delivers a baseband video signal to the picture tube to form the images that the viewer watches. Digital data are generated by computers at baseband, and BER is measured at baseband.

The baseband channel BER or S/N ratio is determined by the carrier-to-noise ratio (C/N) at the input to the demodulator in the receiver. In most satellite communications applications, the C/N ratio at the demodulator input must be greater than 6 dB for the BER or S/N objective to be achieved. Digital links operating at C/N ratios below 10 dB must use error correction techniques to improve the BER delivered to the user. Analog links using frequency modulation (FM) require wideband FM to achieve a large improvement in S/N ratio relative to C/N ratio.



The C/N ratio is calculated at the input of the receiver, at the output terminals (or port) of the receiving antenna. RF noise received along with the signal and noise generated by the receiver are combined into an equivalent noise power at the input to the receiver, and a noiseless receiver model is used. In a noiseless receiver, the C/N ratio is constant at all points in the RF and IF chain, so the C/N ratio at the demodulator is equal to the C/N ratio at the receiver input. In a satellite link there are two signal paths: an *uplink* from the earth station to the satellite, and a *downlink* from the satellite to the earth station. The *overall* C/N at the earth station receiver depends on both links, and both, therefore must achieve the required performance for a specified percentage of time. Path attenuation in the earth's atmosphere may become excessive in heavy rain, causing the C/N ratio to fall below the minimum permitted value, especially when the 30/20 GHz band is used, leading to a link *outage*.



Designing a satellite system therefore requires knowledge of the required performance of the uplink and downlink, the propagation characteristics and rain attenuation for the frequency band being used at the earth station locations, and the parameters of the satellite and the earth stations. Additional constraints may be imposed by the need to conserve RF bandwidth and to avoid interference with other users. Sometimes, all of this information is not available and the designer must estimate values and produce tables of system performance based on assumed scenarios. It is usually impossible to design a complete satellite communication system at the first attempt. A trial design must first be tried, and then refined until a workable compromise is achieved. This chapter sets out the basic procedures for the design of satellite communication links, and includes design examples for a digital TV link using a GEO satellite and quadrature phase shift keying (QPSK) modulation, and a LEO satellite system for personal communication.

4.2 BASIC TRANSMISSION THEORY

The calculation of the power received by an earth station from a satellite transmitter is fundamental to the understanding of satellite communications. In this section, we discuss two approaches to this calculation: the use of flux density and the *link equation*.

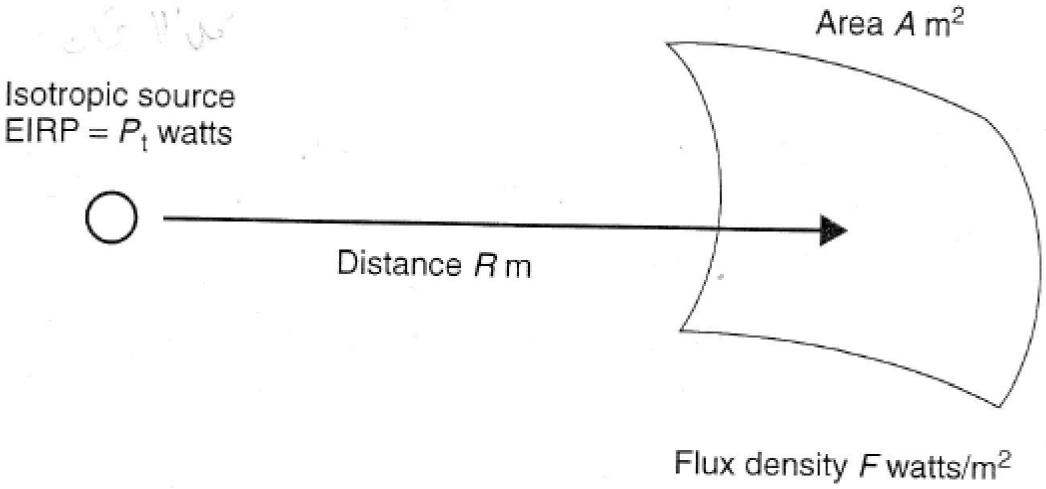


FIGURE 4.2 Flux density produced by an isotropic source.

Consider a transmitting source, in free space, radiating a total power P_t watts uniformly in all directions as shown in Figure 4.2. Such a source is called isotropic; it is an idealization that cannot be realized physically because it could not create transverse electromagnetic waves. At a distance R meters from the hypothetical isotropic source transmitting RF power P_t watts, the flux density crossing the surface of a sphere with radius R is given by

$$\boxed{F = \frac{P_t}{4\pi R^2} \text{ W/m}^2}$$

All real antennas are directional and radiate more power in some directions than in others. Any real antenna has a gain $G(\theta)$, defined as the ratio of power per unit solid angle radiated in a direction θ to the average power radiated per unit solid angle

$$\boxed{G(\theta) = \frac{P(\theta)}{P_0/4\pi}}$$

where

$P(\theta)$ is the power radiated per unit solid angle by the antenna

P_0 is the total power radiated by the antenna

$G(\theta)$ is the gain of the antenna at an angle θ [1]

The reference for the angle θ is usually taken to be the direction in which maximum power is radiated, often called the boresight direction of the antenna. The gain of the antenna is then the value of $G(\theta)$ at angle $\theta = 0°$, and is a measure of the increase in flux density radiated by the antenna over that from an ideal isotropic antenna radiating the same total power. For a transmitter with output P_t watts driving a lossless antenna with gain G_t, the flux density in the direction of the antenna boresight at distance R meters is

$$F = \frac{P_t G_t}{4\pi R^2} \ \mathrm{W/m^2}$$

The product $P_t G_t$ is often called the *effective isotropically radiated power* or EIRP, and it describes the combination of transmitter power and antenna gain in terms of an equivalent isotropic source with power $P_t G_t$ watts, radiating uniformly in all directions.

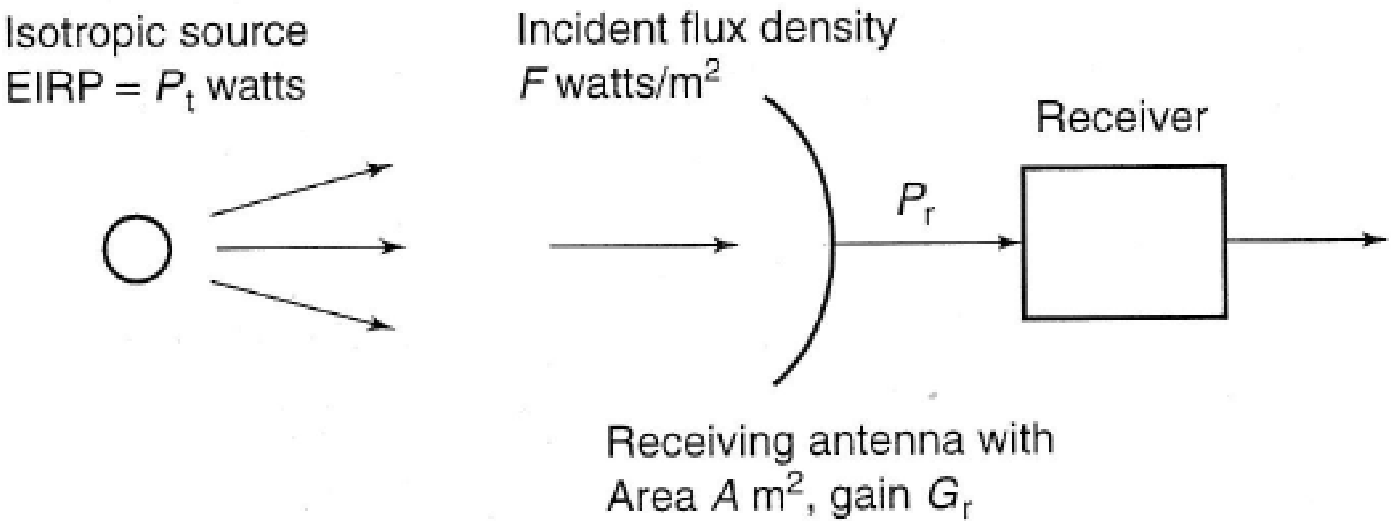


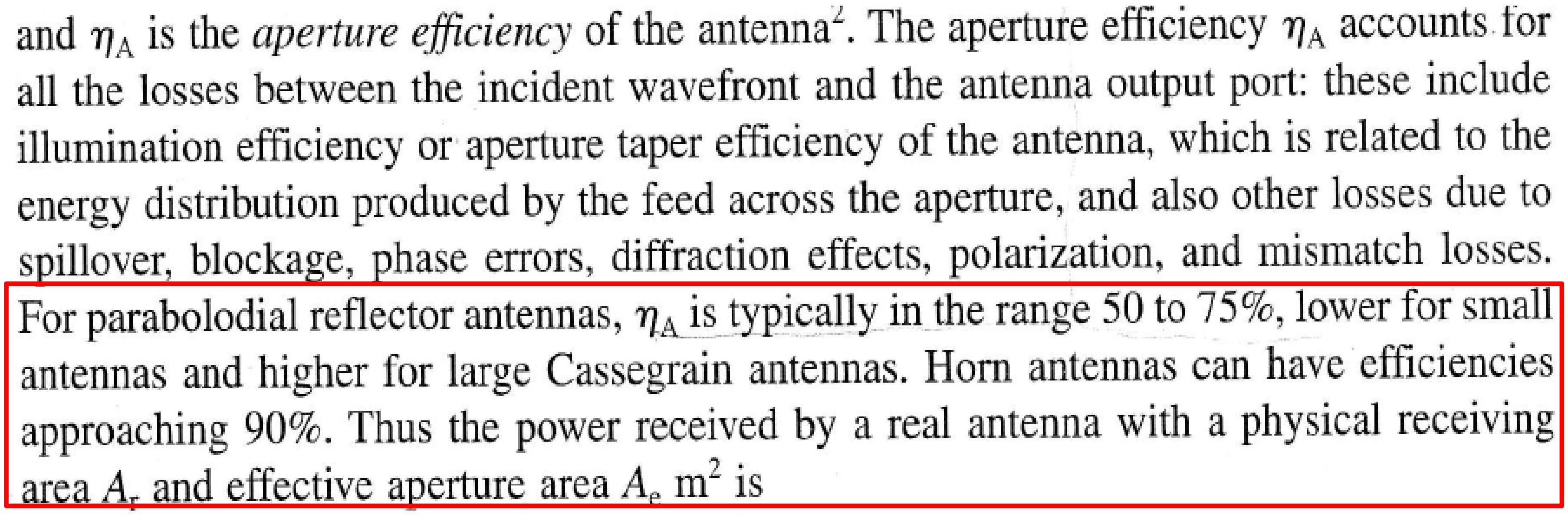
FIGURE 4.3 Power received by an ideal antenna with area A m^2. Incident flux density is $F = P_t/4\pi R^2$ W/m^2. Received power is $P_r = F \times A = P_t A/4\pi R^2$ W.

If we had an ideal receiving antenna with an aperture area of A m^2, as shown in Figure 4.3, we would collect power P_r watts given by

$$\boxed{P_r = F \times A \text{ watts}}$$

A practical antenna with a physical aperture area of A_r m^2 will not deliver the power given in Eq. (4.4). Some of the energy incident on the aperture is reflected away from the antenna, and some is absorbed by lossy components. This reduction in efficiency is described by using an *effective aperture* A_e where

$$\boxed{A_e = \eta_A A_r}$$



and η_A is the *aperture efficiency* of the antenna[2]. The aperture efficiency η_A accounts for all the losses between the incident wavefront and the antenna output port: these include illumination efficiency or aperture taper efficiency of the antenna, which is related to the energy distribution produced by the feed across the aperture, and also other losses due to spillover, blockage, phase errors, diffraction effects, polarization, and mismatch losses. For parabolodial reflector antennas, η_A is typically in the range 50 to 75%, lower for small antennas and higher for large Cassegrain antennas. Horn antennas can have efficiencies approaching 90%. Thus the power received by a real antenna with a physical receiving area A_r and effective aperture area A_e m^2 is

$$P_r = \frac{P_t G_t A_e}{4\pi R^2} \text{ watts}$$

Note that this equation is essentially independent of frequency if G_t and A_e are constant within a given band; the power received at an earth station depends only on the EIRP of the satellite, the effective area of the earth station antenna, and the distance R.

A fundamental relationship in antenna theory[2] is that the gain and area of an antenna are related by

$$\boxed{G = 4\pi A_e/\lambda^2} \qquad (4.7)$$

where λ is the wavelength (in meters) at the frequency of operation.

Substituting for A_e in Eq. (4.6) gives

$$\boxed{P_r = \frac{P_t G_t G_r}{(4\pi R/\lambda)^2} \text{ watts}} \qquad (4.8)$$

This expression is known as the *link equation*, and it is essential in the calculation of power received in any radio link. The frequency (as wavelength, λ) appears in this equation for received power because we have used the receiving antenna gain, instead of effective area. The term $[4\pi R/\lambda]^2$ is known as the *path loss*, L_p. It is not a loss in the sense of power being absorbed; it accounts for the way energy spreads out as an electromagnetic wave travels away from a transmitting source in three-dimensional space.

Collecting the various factors, we can write

$$\boxed{\text{Power received} = \frac{\text{EIRP} \times \text{Receiving antenna gain}}{\text{Path loss}} \text{ watts}} \tag{4.9}$$

In communication systems, decibel quantities are commonly used to simplify equations like Eq. (4.9). In decibel terms, we have

$$\boxed{P_r = \text{EIRP} + G_r - L_p \text{ dBW}} \tag{4.10}$$

where

$$\text{EIRP} = 10 \log_{10}(P_t G_t) \text{ dBW}$$

$$G_r = 10 \log_{10}(4\pi A_e/\lambda^2) \text{ dB}$$

$$\text{Path loss } L_p = 10 \log_{10}[(4\pi R/\lambda)^2] = 20 \log_{10}(4\pi R/\lambda) \text{ dB}$$

Equation (4.10) represents an idealized case, in which there are no additional losses in the link. It describes transmission between two ideal antennas in otherwise empty space. In practice, we will need to take account of a more complex situation in which we have losses in the atmosphere due to attenuation by oxygen, water vapor, and rain, losses in the antennas at each end of the link, and possible reduction in antenna gain due to mispointing. All of these factors are taken into account by the *system margin* but need to be calculated to ensure that the margin allowed is adequate. More generally, Eq. (4.10) can be written

$$\boxed{P_r = \mathrm{EIRP} + G_r - L_p - L_a - L_{ta} - L_{ra}\ \mathrm{dBW}} \tag{4.11}$$

where

L_a = attenuation in the atmosphere

L_{ta} = losses associated with the transmitting antenna

L_{ra} = losses associated with the receiving antenna

The conditions in Eq. (4.11) are illustrated in Figure 4.4. The expression dBW means decibels greater or less than 1 W (0 dBW). The units dBW and dBm (dB greater or less than 1 W and 1 mW) are widely used in communications engineering. EIRP, being the product of transmitter power and antenna gain is often quoted in dBW.

Note that once a value has been calculated in decibels, it can readily be scaled if one parameter is changed. For example, if we calculated G_r for an antenna to be 48 dB, at a frequency of 4 GHz, and wanted to know the gain at 6 GHz, we can multiply G_r by $(6/4)^2$. Using decibels, we simply add $20 \log(6/4)$ or $20 \log(3) - 20 \log(2) = 9.5 - 6 = 3.5$ dB. Thus the gain of our antenna at 6 GHz is 51.3 dB.

Appendix A gives more information on the use of decibels in communications engineering.

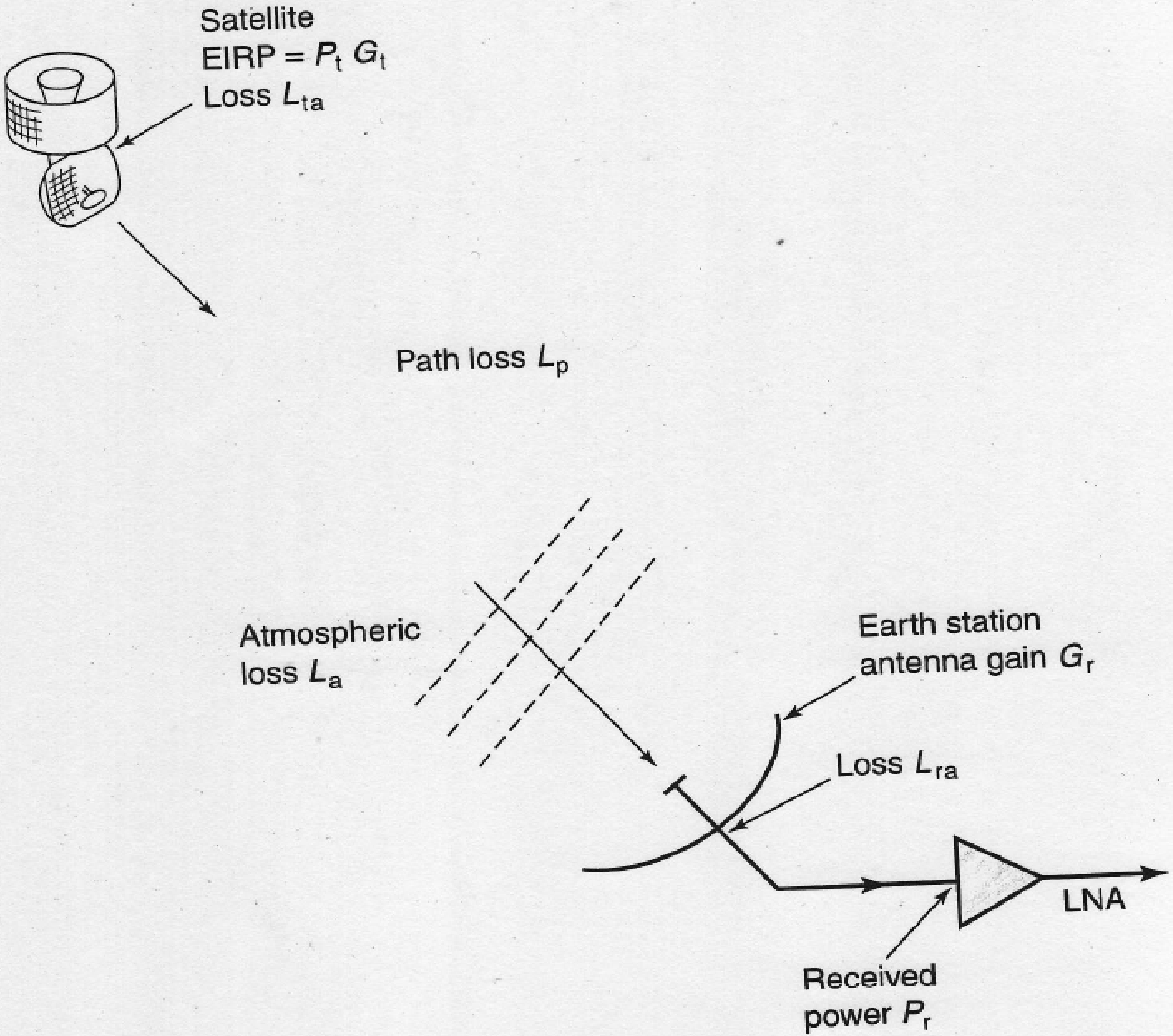
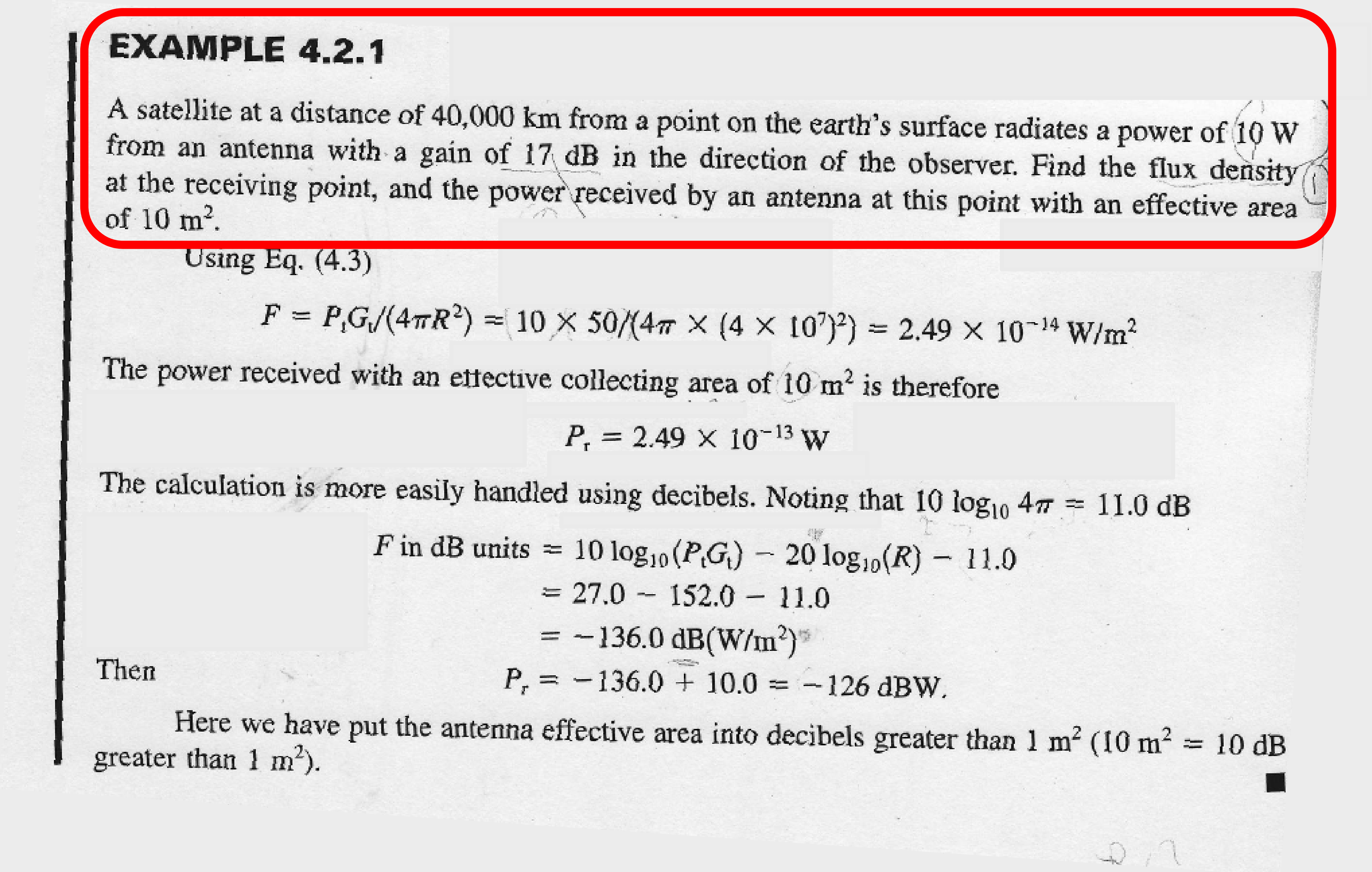


FIGURE 4.4 A satellite link. LNA, low noise amplifier.



EXAMPLE 4.2.1

A satellite at a distance of 40,000 km from a point on the earth's surface radiates a power of 10 W from an antenna with a gain of 17 dB in the direction of the observer. Find the flux density at the receiving point, and the power received by an antenna at this point with an effective area of 10 m^2.

Using Eq. (4.3)

$$F = P_t G_t/(4\pi R^2) = 10 \times 50/(4\pi \times (4 \times 10^7)^2) = 2.49 \times 10^{-14}\ \text{W/m}^2$$

The power received with an effective collecting area of 10 m^2 is therefore

$$P_r = 2.49 \times 10^{-13}\ \text{W}$$

The calculation is more easily handled using decibels. Noting that $10 \log_{10} 4\pi = 11.0$ dB

$$\begin{aligned} F \text{ in dB units} &= 10 \log_{10}(P_t G_t) - 20 \log_{10}(R) - 11.0 \\ &= 27.0 - 152.0 - 11.0 \\ &= -136.0\ \text{dB(W/m}^2) \end{aligned}$$

Then

$$P_r = -136.0 + 10.0 = -126\ \text{dBW}.$$

Here we have put the antenna effective area into decibels greater than 1 m^2 (10 m^2 = 10 dB greater than 1 m^2). ■

EXAMPLE 4.2.2

The satellite in Example 4.2.1 operates at a frequency of 11 GHz. The receiving antenna has a gain of 52.3 dB. Find the received power.

Using Eq. (4.10) and working in decibels

$$P_r = \mathrm{EIRP} + G_r - L_p \ \mathrm{dBW} \tag{4.10}$$

$$\mathrm{EIRP} = 27.0 \ \mathrm{dBW}$$

$$G_r = 52.3 \ \mathrm{dB}$$

$$\text{Path loss} = (4\pi R/\lambda)^2 = 20 \log_{10}(4\pi R/\lambda) \ \mathrm{dB}$$

$$= 20 \log_{10}[(4\pi \times 4 \times 10^7)/(2.727 \times 10^{-2})] \ \mathrm{dB} = 205.3 \ \mathrm{dB}$$

$$P_r = 27.0 + 52.3 - 205.3 = -126.0 \ \mathrm{dBW}$$

We have the same answer as in Example 4.2.1 because the figure of 52.3 dB is the gain of a 10 m^2 aperture at a frequency of 11 GHz. ■

Equation (4.10), with other parameters for antenna and propagation losses, is commonly used for calculation of received power in a microwave link and is set out as a link power budget in tabular form using decibels. This allows the system designer to adjust parameters such as transmitter power or antenna gain and quickly recalculate the received power.

The received power, P_r, calculated by Eqs. (4.6) and (4.8) is commonly referred to as carrier power, C. This is because most satellite links use either frequency modulation for analog transmission or phase modulation for digital transmission. In both of these modulation systems, the amplitude of the carrier is not changed when the data are modulated onto the carrier, so received carrier power C is always equal to received power P_r.