CHAPTER 10

SPACE-COMMUNICATIONS SYSTEMS DESIGN

10.1 INTRODUCTION

10.1.1 Performance Requirements

The role of propagation phenomena in earth-space telecommunications system design is illustrated in this final chapter, and it appears desirable to include some related considerations about systems as well. The propagation loss L and system noise temperature T_{sys}, introduced in Chap. 1, appear in the link power budget equation, and reference to system design in this chapter refers primarily to link budgets. In earlier chapters, including Chap. 9, Estimation of Propagation Impairments, this handbook treats the additional topics of time and range delay, phase and Doppler frequency, and refractive bending. Also Chap. 8 is devoted to propagation effects on interference and determination of coordination area.

The system designer may have the function of meeting system requirements posed by the user, but in the process of attempting to do so it may develop that the requirements present problems and may need tobe modified. The design of a complicated system like a telecommunications system is largely an iterative process, starting with a preliminary design, rather than a true synthesis. The amount of readily available information dealing specifically with system design is limited, but a useful treatment of the subject has been provided by Ippolito, Kaul, and Wallace (1983) in the final chapter of NASA Reference Publication 1082(03) for the design of systems operating at frequencies from 10 to 100 GHz.

Some minimum signal-to-noise ratio is needed for satisfactory operation of a telecommunications system, and information must be available or a decision must be reached in some way as to what this value is. [We will use C/X generally as in Eq. (1.6) for this ratio but certain related designations may be used instead in particular cases]. Because of the characteristics of the propagation medium, C/X tends to be a random variable and, as it is usually impractical to design a system so that C/X never drops below any particular level, a specification should normally be made of the permissible percentage of time for which C/X may be below the specified level. This specification defines the signal availability, namely the percentage of time that a specified C/X ratio should be available. Alternatively, or additionally, a specification may be made concerning outage, for example the mean outage duration, the time until the next outage, etc. In some cases the statistical nature of the phenomena affecting C/X may not be known, and it may not be possible to design a system to have a specified availability or outage characteristic. In such cases, one may nevertheless need to estimate the margins that should be povided for the phenomena under consideration as best one can. For example, a margin of so many dB must be allotted in some cases to take account of ionospheric scintillation even though a satisfactory statistical description of the scintillation may not be available.

10.1.2 Digital Systems

For digital systems performance is generally measured in terms of the bit error rate (BER), and the BER is a function of the energy-per-bit to noise-power-density ratio E_b/N_o. (When referring specifically to digital systems, we will use No in place of the X. of Chap. 1 and elsewhere). The energy per bit E_b is related to carrier power C by $E_bR = C$, where R is the information rate in bits per second. Therefore

$$E_b/N_o = C/(N_oR) \qquad (10.1)$$

Also

$$\frac{E_b}{N_o}\frac{R}{B} = \frac{C}{X} \qquad (10.2)$$

Equation (10.2) shows that if bandwidth B equals bit r-ate R, E_b/N_o = C/X. The ratio R/B depends on the type of modulation and coding used. For uncoded binary phase-shift modulation (BFSK) employing phase values of O deg and 180 deg, B may be equal to R, For uncoded quadriphase modulation (QPSK) employing phase values of O, 90, 180, and 270 deg, the bandwidth B may be only half the bit rate, as for each phase there are two corresponding bits (Feher, 1983; Freeman, 1981). Coding of digital transmissions is used as a means of minimizing errors or to reduce the needed E_b/N_o ratio and therefore the power C needed for a fixed BER. Coding involves adding redundant symbols to an information symbol sequence and requires additional bandwidth beyond that of the original uncoded signal. The ratio of the number of information bearing symbols to the total number is known as the rate of the code and has values such as 3/4, 2/3, etc., with 1/3 usually being the minimum value of the rate that is used. The two principal types of error-correcting codes are block codes and convolutional codes (Feher, 1983; Pratt and Bostian, 1986). FEC (forward-error-correction) codes have application to ameliorating the effect of attenuation due to rain, for example (Ippolito, 1986). When using coding in this way, a small amount of system capacity may be held in reserve and allocated as needed for links experiencing attenuation. The link data rate remains constant when following this procedure, the additional capacity being used for coding, or additional coding. Although block codes may be used in some cases, convolutional codes have the advantages for satellite communications of ease of implementation and availability of attractive decoding schemes (Van Trees, 1979). Convolutional coding and Viterbi decoding (Heller and Jacobs, 1971) are an effective combination. The performance of a Viterbi decoder depends upon the rate R, the number K of consecutive information bits encoded (e.g. 4, 6, or 8), the levels Of quantization Q (1 to 8), and path length (e.g. 8, 16, or 32 bit). Figure 10. 1 shows illustrative plots of BER versus E_b/N_o for convolutional coding and Viterbi decoding and for no coding.

10.1.3 Analog Systems

The allowable noise in analog systems used for voice communications may be specified in pW0p, standing for noise power in picowatts (pW) at a point of zero relative level (0) with psophometric weighting (p) utilized. We consider here how the system designer, given the permissible value of pW0p, can determine the corresponding C/X ratio.

In Recommendation 353-5, the CCIR (1986a) advises that the noise power at a point of zero relative level in any telephone channel used in FDM-FM (frequency division multiplex-frequency modulation) telephony in the fixed satellite service should not exceed the following values:

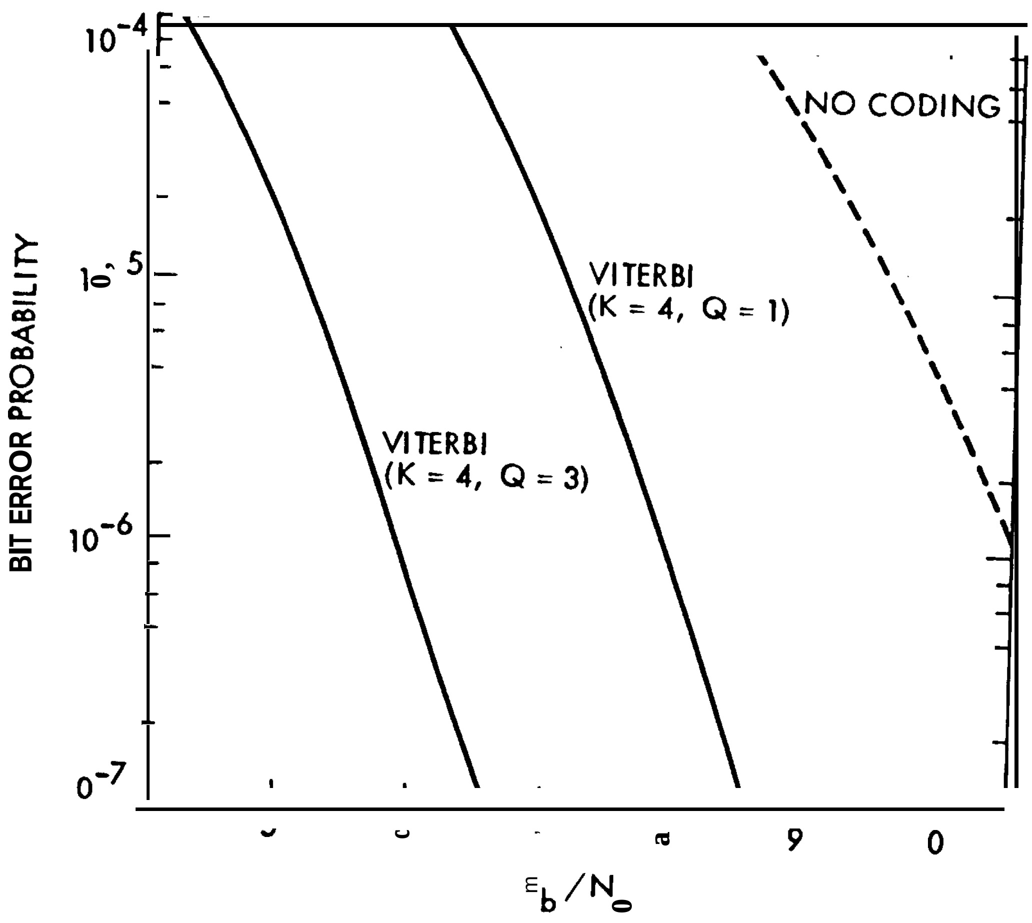

Figure 10.1. Bit error rate versus E_b/N_o (Van Trees, 1979).

10,000 pWOp for psophometrically-weighted one-minute mean power for more than 20 percent of any month

50,000 pWOp for psophometrically-weighted one-minute mean power for more than 0.3 percent of any month

1,000,000 pWO for unweighed power (with an integration time of 5 ms) for more than 0.01 percent of any year

For RF levels above the FM threshold (commonly 10 dB above the noise level), the noise expressed in pWOp can be related to carrier power by (GTE, 1972)

$$10 \log pW0p = -C_{dBm} - 48.6 + F_{dB} - 20 \log(\Delta f/f_{ch}) \quad (10.3)$$

where F is the receiver noise figure, Af is the peak frequency deviation of the charnel for a signal of O test tone level, and f_{ch} is the center frequency occupied by the channel in the baseband.

Solving for C_{dBm} and then subtracting 10 log kT = 10 log kT_o + F_{dB} = - 174 dBm + F_{dB} for To = 290 K, yields

$$(C/X_o)_{dB} = (C/kT)_{dB} = 125{,}4 - 20 \log(\Delta f/f_{ch}) - 10 \log pW0p \quad (10.4)$$

For determining C/X, use X = X_oB where B is bandwidth. Values of $20 \log(\Delta f/f_{ch})$ are given in GTE (1972) as -1.82 dB for an 120-channel system with emphasis, -9.2 for a 300-channel system with emphasis, etc.

10.1.4 Allocation of Noise and Signal-to-Noise Ratio

A communication satellite system consisting of an uplink and a downlink is subject to thermal noise generated in the uplink and downlink, to intermodulation noise generated in the satellite transpoder in an FDMA system, and to interfering signals which may be received on the uplink or downlink or both. Considering all the individual noise sources to be additive at the downlink receiver input terminal, the ratio of carrier power C to total noise power density $(X_o)_T$ is given by

$$\frac{C}{(X_o)_T} = \frac{C}{(X_o)_U + (X_o)_D + (X_o)_{IM} + (X_o)_I} \qquad (10.5)$$

where $(X_o)_D$ is generated in the downlink, $(X_o)_{IM}$ represents intermodulation noise, and $(X_o)_I$ represents interference. The quantity $(X_o)_u$ is derived from but is not equal to the noise $(X'_o)_U$ at the satellite (uplink) receiver input terminal. The relation between the two quantities is $(X_o)_u = (X'_o)_U \, g/L_t$ where g is gain of the satellite transponder and L_t is the total downlink loss factor, defined so as to be greater than unity. Starting from Eq. (10.5), it can be shown by algebraic manipulation that

$$\frac{1}{(C/X_o)_T} = \frac{1}{(C/X_o)_U} + \frac{1}{(C/X_o)_D} + \frac{1}{(C/X_o)_{IM}} + \frac{1}{(C/X_o)_I} \qquad (10.6)$$

The ratio $(C/X_o)_T$ appears at the downlink receiver input terminal; the ratio $(C/X_o)_D$ would be observed at this location if the input signal for the downlink was noiseless and interference was negligible. If one knows the values of all of the terms of Eq. (10.6) but one, that unknown quantity can be determined from Eq. (10.6).

The allowable noise of 10,000 pWOp is separated in the INTELSAT system noise budget into the three major categories shown below.

Space segment	8,000 pWOp
Earth stations	i ,000 pwop
Terrestrial interference	1,000 pwop
Total noise	10,000 pwop

Noise allotted to the space segment includes noise generated in the uplink and downlink, intermodulation noise generated in the satellite transponder, and interference other than terrestrial interference,

10.2 DIVERSITY RECEPTION

Diversity reception of several types, most prominently site diversity, space diversity, and frequency diversity, may be advantageous for particular applications. For satellite communications site diversity can be used to reduce the effect of attenuation due to rain. Site diversity takes advantage of the fact that high rain rates tend to occur only over areas of limited extent. For example, the probability that rain rates greater than 50 mm/h will occur jointly at two locations 20 km apart is reported to be about 1/15th the probability that the rate will occur at one location (Miya, 1981). Most interest in site diversity is directed to frequencies above 10 GHz for which attenuation due to rain is most severe (Ippolito, Kaul, and Wallace, 1983). For terrestrial line-of-sight paths, space and frequency diversity are used to combat fading due to atmospheric multipath and reflections from surfaces (GTE, 1972). The form of space diversity most commonly used involves vertical separation of two receiving antennas on the same tower.

The performance of a diversity system can be characterized by diversity gain and diversity advantage, which are shown in Fig. 10.2. Diversity gain is the difference, for the same percentage of time, between the attenuation exceeded on a single path and that exceeded jointly on two paths to two sites. Diversity advantage is defined as the ratio of the percentage of time that a given attenuation is exceeded on a single path to that exceeded jointly on two paths.

Site diversity to minimize the effects of attenuation due to rain may be useful for critical applications at frequencies below 10 GHz but must be weighed against the alternative of providing a margin to cover the expected attenuation. For the higher attenuations that tend to occur at higher frequencies, the advantage is more apt to be on the side of site diversity. Likewise, site diversity may be helpful on low-angle paths where atmospheric multipath or reflections from sea or land surfaces are a problem. An example of this type is provided by the Canadian arctic where, in the 6/4 GHz band, a site diversity system involving two receiving sites is expected to reduce the required propagation margin from 20 to 8 dB (Mimis and Smalley, 1982).

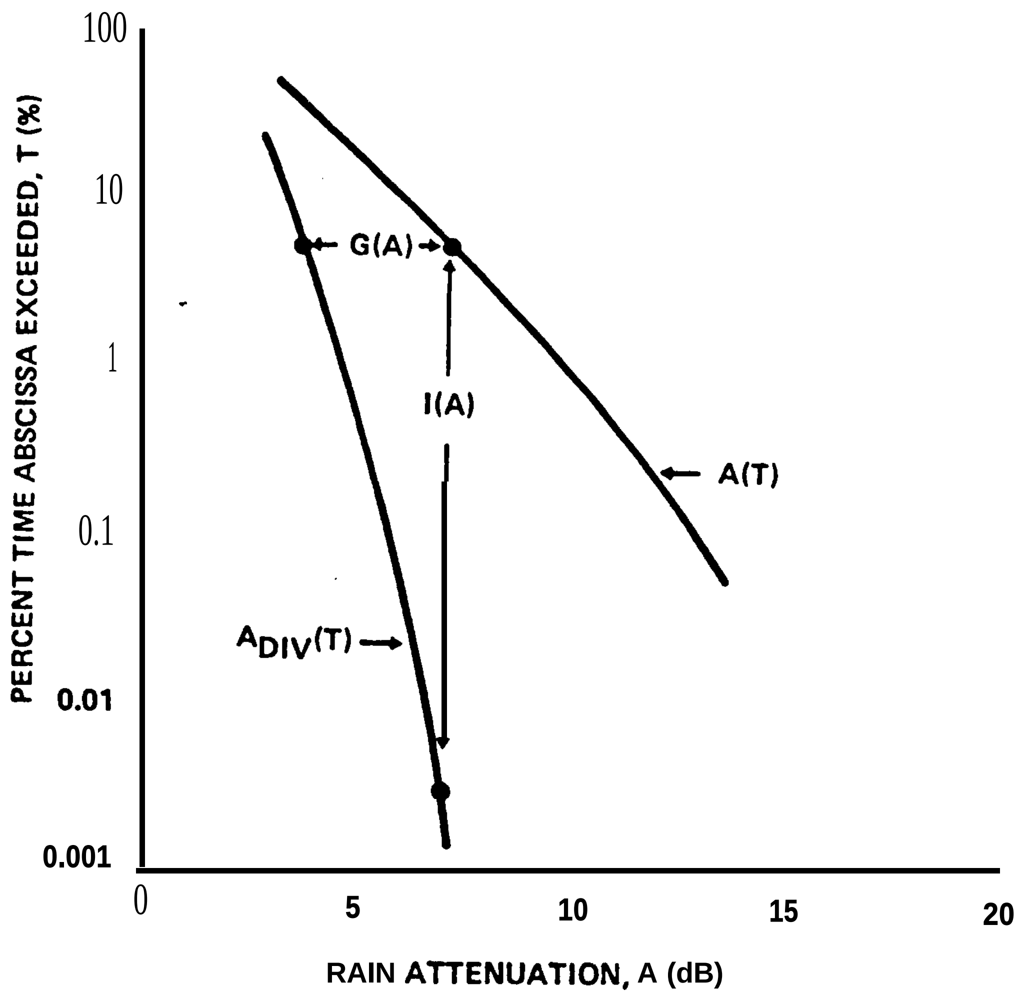

Figure 10.2. Definition of diversity gain G(A) and diversity advantage I(A). The curve A(T) represents performance when only one path is employed, while $A_{DIV}(T)$ represents performance when two paths are employed in a diversity system (Ippolito, Kaul, and Wallace, 1983).

10.3 TELECOMMUNICATION LINK BUDGETS

The link power budget equation gives the received signal-to-noise ratio in terms of all the various parameters that affect it. Two of these, loss factor L and system noise temperature T_{sys}, tend to be random variables. The object of system design is' to ensure a satisfactory signal-to-noise ratio for a specified high percentage of time. The equation can be written in terms of $C/X_o = (C/kT_{sys})$ where C is carrier power (W) and k is Boltzmann's constant (1 .38 x 10-23 J/K). This ratio C/X. is the carrier power to noise density ratio, as X. is the power per Hz. To obtain C/X from C/X_o, one can simply divide by B, the bandwidth in Hz. The quantity C/X. was introduced in Chap. 1 where it was first written in the form of

$$\frac{C}{X_o} = \frac{C}{kT_{sys}} = \frac{EIRP\ G_R}{L\, L_{FS}\, k\, T_{sys}} \qquad (10.7)$$

where EIRP stands for effective isotropic radiated power, G_R is the gain of the receiving antenna, L is a loss factor greater than unity if truly representing a loss, and L_{FS} is the free space basic transmission loss. The propagation medium plays a major role in determining L and T_{sys}. In carrying out satellite telecommunication systems design, attention must be given to both the uplink and the downlink; they both affect the C/X. ratio observed at the downlink receiver input terminal.

For applying Eq. (10.7), we separate EIRP into the product of P_T and G_T and convert to decibel values as is customary, with the result that

$$(C/X_o)_{dB} = (P_T)_{dB} + (G_T)_{dB} + (G_R)_{dB} - L_{dB} - (L_{FS})_{dB} - k_{dBW} - (T_{sys})_{dB} \qquad (10.8)$$

where for k we actually use Boltzmann's constant k times 1 K times 1 Hz to obtain a quantity in dBW. Then T_{sys} and bandwidth B when it is utilized are treated as nondimensional. But G_R and T_{sys} are often combined into one term which is considered a figure of merit. Using this combination and also reverting back to EIRP

$$(C/X_o)_{dB} = (EIRP)_{dB} + (G_R/T_{sys})_{dB} - L_{dB} - (L_{FS})_{dB} - k_{dBW} \qquad (10.9)$$

The treatment of telecommunication link power budgets here is primarily by example. The first example, 10.1, illustrates some of the basic types of calculations pertinent to link budgets, and the second example deals with a hypothetical system operating at 8.5/8.0 GHz. Following examples deal with particular systems using values quoted in the literature.

Example 10.1 System Concepts

1. System Noise Temperature, T_{Sys}

The system noise temperature T_{Sys} is a measure of noise power as X_o, the noise power per Hz, equals kT_{Sys} where k is Boltzmann's constant (i, 38 x 10-23 J/K). Also X, the total noise power, equals X_0 times bandwidth B. System noise temperature is defined at the antenna terminal of a receiving system as shown in Fig. i 0.3, which shows an antenna having a noise temperature of T_A, a lossy transmission line at the standard reference temperature To (commonly taken as 290 K), and a receiver having a noise temperature of T_R.

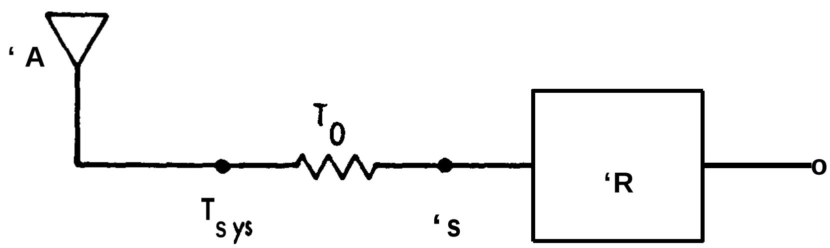

Figure 10,3. Receiving system, showing location of T_{sys}.

For the receiving system of Fig. 10.3, T_{Sys} is given by

$$T_{Sys} = T_A + (\ell_a - 1)T_o + \ell_a T_R$$

To illustrate the calculation of T_{sys}, let T_R equal 100 K and T_A = 50 K, and consider that the transmission line has a loss of 1 dB. In the expression for T_{sys}, $\ell_a = 1/g_a$ where g_a is less than unity and is the power "gain" of the transmission line, considering it as a lossy attenuator, The relation between g_a and attenuation A in dB is

$$-A_{dB} = 10 \log g_a$$

and for A = 1

$$-i = 10 \log g_a, \quad g_a = 0.794, \quad \ell_a = 1/g_a = 1.26$$

Substituting values into the expression for T_{Sys}

$$\begin{aligned} T_{sys} &= 50 + (1.26 - 1)\ 290 + 1.26\ (100) \\ &= 50 + 75.4 + 1.26 \\ &= 251.4 \text{ K} \end{aligned}$$

Note that if there were no attenuation between the antenna and receiver, g_a and ℓ_a would equal unity and T_{Sys} would equal T_A + 'R = 150 K.

The noise power density X. corresponding to T_{sys} = 251.4 K is given by

$$X_0 = kT_{sys} = (1.38 \times 10^{-23})\ (251.4) = 3047 \times 10^{-2},\ \text{W}$$

and

$$(X_o)_{dB} = 10 \log (3.47 \times 10^{-21}) = -204.6 \text{ dBW}$$

Also

$$(X_o)_{dBm} = -174.6 \text{ dBm}$$

The quantity X. is 204.6 dB below one watt (W) and 174.6 dB below one milliwatt (mW).

2. Antenna gain, G

The gain of an antema having an effective aperture area, A_{eff}, is given by

$$G = (4\pi A_{eff})/\lambda^2$$

where λ is wavelength. The effective area for the antenna aperture considered here equals the geometric area times an efficiency factor κ which generally falls between about 0.5 and 0.7 or higher, To illustrate the calculation of G consider a frequency of 3 GHz, a paraboloidal antenna having a diameter of 3 m, and an efficiency factor of 0.54. The wavelength $\lambda \simeq 3 \times 108/(3 \times 10^9) = 0.1$ m and

$$A_{eff} = (\pi d^2/4)\kappa = \pi(9/4)\ (0.54) = 3.817\ m^2$$

Thus

$$G = 4\pi\ (3.817)/0.01 = 4,797$$

$$G_{dB} = 10 \log G = 36.8$$

3. Distance and elevation angle of geostationary satellite

Consider an earth receiving station at 65 deg N and a geostationary satellite on the same meridian. The distance d betweeen the station and the satellite is given by Eq. (1. 13).

$$d^2 = r_o^2 + (h+ r_o)^2 - 2r_o(h+ r_o) \cos \theta'$$

where r. is the earth radius, h is the height of the satellite above the Earth, and θ' is latitude (65 deg in this example). Thus

$$d^2 = (6378)^2 + (35786 + 6378)^2 -2(6378)\ (35786 + 6378) \cos 65°$$

$$d = 39,889.6 \text{ km}$$

To determine the elevation angle θ, the following expression can be solved for ψ which equals the elevation angle θ plus 90 deg.

$$-- (h + r_0)^2 = d^2 + r_o^2 - 2\, r_o d \cos \psi$$

$$(42,164)^2 = (39.889.6)^2 + (6378)^2 -2(6378)(39,889.6) \cos \psi$$

$$\cos \psi = -0.2868(, \psi = 106.67^o$$

$$\theta = 106.67°-90° = 16.67^o$$

If the earth station were displaced by 10 deg from the longitude of the satellite then in place of cos θ' = cos 65 deg = 0.4226 one would use cos 65 deg cos 10 deg = 0.4162. The result would be that d = 39,932 km and θ = 16.24 deg. If the difference in longitude were 20 deg, the distance would be 40,060 km and the elevation angle would be 15.0 deg.

Example 10.2 Link Power Budget Equation for Hypothetical 8.5/8.0 GHz System

For an example of a link power budget, consider a hypothetical analog system using 8.5 GHz for the uplink and 8.0 GHz for the downlink. The system has a performance objective of 99.99 percent availability in an environment in which a rain rate of 35mm/h is exceeded for 0.01 percent of the time. The elevation angle of the path is taken as 42 deg which allows using the results of Example 9.5 for attenuation due to rain. An earth-station antenna which would be suitable for a portable system is considered.

The distance d to the satellite corresponding to the elevation angle of 42 deg can be found from Eq. (1.15), namely

$$(h + r_o)^2 = d^2 + r_o^2 - 2r_o\, d \cos \psi$$

with ψ = 42 deg + 90 deg = 132 deg, and turns out to be about 37,600 km. Ordinarily one would start with a particular location to find the value of d and then find ψ, but here we have determined a value of d consistent with an elevation angle of 42 deg. Knowing d, $(L_{FS})_{dB}$, the free space loss can be determined from

$$(L_{FS})_{dB} = 20 \log (4\pi d/\lambda)$$

and is found to be 202.55 dB for 8.5 GHz and 202.02 dB for 8.0 GHz.

To formulate a link equation, some initial assumptions must be made about the equipment to be utilized, the required C/X ratio, the bandwidth, etc. The initial assumptions may need to be modified later. We assume a minimum overall or composite C/X ratio of 10 dB, a bandwidth B of 5 MHz, a 3-m earth-station antenna having an efficiency factor of 0.54, T_{Sys} = 300 K for the earth station, and G/T_{Sys} = -10 dB for the satellite.

Allowance is made for a carrier-to-interference ratio of 18 dB, as well as for thermal noise on the uplink and downlink. The C/X ratios for the uplink and downlink could be chosen to be equal, but it is easier to supply relatively high power for the uplink so a somewhat higher C/X ratio is chosen for it. The combination of (c/x)" = 15 dB for the uplink, $(C/X)_D$ = 13 dB for the downlink, and 18 dB for C/I gives an overall or composite ratio of 10. i 1 dB, thus satisfying the requirement of 1 O dB. As ordinary numbers, the four ratios are 31.62, 19.95, 63.10, and 10.25, corresponding to 1 5, 13, 18, and 1 O. 11 dB respectively, consistent with q.(i O. 6) without a contribution for intermodulation noise. The applicable equation is

$$1/(C/X)_T = 1/(C/X)_U + 1/(C/X)_D + 1/(C/X)_I$$

Substituting numbers

$$1/10.247 = 1/31.623 + 1/19.953 + 1/63.096$$

Uplink (8.5 GHz)

Attenuation due to rain is taken to be 2.49 dB (from Example 9. S), gaseous attenuation is assumed to be 0.1 dB, and the pointing error loss is taken as 0.3 dB. The gain of the transmitting antenna is calculated from $G_T = 4\pi A_{eff}/\lambda^2$ (Example 10.1, Sec.2) to be 38,558 or 45.86 dB. At this stage the needed transmitter power P_T can be determined by rearranging Eq. (10.9) to give

$$(EIRP)_{dBW} = (C/X_o)_{dB} + (L_{FS})_{dB} + L_{dB} + \text{‘ dBw} - (G_R/T_{sys})_{dB}$$

where

$$(C/X_o)_{dB} = (C/X)_{dB} + B_{dB}$$

The bandwidth B is 5 MHz and B_{dB} = 67 dB. Thus

$$(C/X)_{dB} = 15 + 67 = 82 \text{ dB}$$

Substituting numbers into the equation for EIRP.

$$(EIRP)_{dBW} = 82 + 202.55 + 2.89 - 228.6 + 10 = 68.84 \text{ dBW}$$

where

$$(EIRP)_{dBW} = (P_T)_{dBW} + (G_T)_{dB}$$

so that

$$(P_T)_{dBW} = 68.84-45.86 = 22.98 \text{ dBW} \simeq 200 \text{ W}$$

The various system parameters are summarized in Table 10. 1.

Table 10.1A Uplink (8,5 GHz).

Transmitter Power, P_T	22.98 dBW (200 W)	
Antenna Gain. G_T	45.86 dB	
EIRP		68.84 dBW
Free Space Loss, L_{FS}		202.55 dB
Losses, L		
Attenuation from rain	2.49 dB	
Gaseous attenuation	0.1 dB	
Pointing error	0.3 dB	
Total		2.89 dB
Satellite 'R'Tsys		-10 dB
C/X		15 dB
C/X.		82 dB

Downlink (8.0 GHz)

The gain of the receiving antenna for the downlink (same antenna as for the uplink) is calculated to be 34,159 or 45.34 dB. The system noise temperature T_{sys} is taken to be 300 K or 24.77 dB above 1 K in the absence of attenuation due to rain, and the G_R/T_{sys} ratio is thus 45.34 - 24.77 = 20.57 dB. The assumed rain rate of 35 mm/h introduces an attenuation of 2.092 dB and an additional contribution to the antenna noise temperature given by

$$T_b = 280 \ (1 - e^{-\tau}) = 280 \ (1 - e^{-2.09/4.34}) = 107.1 \text{ K}$$

The total degradation in C/X due to rain is then given by

$$(C/X)_{dB} = 2.092 + 10 \log [(107.1 + 300)/300]$$
$$= 2.092 + 1,325 = 3.42 \text{ dB}$$

Gaseous attenuation of 0.1 dB and a pointing error loss of 0.3 dB are assumed. Solving for EIRP and P_T in the same way as for the uplink

$$(EIRP)_{dBW} = (C/X_o)_{dB} + B_{dB} + (L_{FS})_{dB}$$
$$+ L_{dB} + k_{dBW} - (G_R/T_{sys})_{dB}$$
$$= 13 + 67 +.202.02 + 3.82-228.6-20.57$$
$$= 36.67 \text{ dBW}$$

At this point it is necessary to have information on or to make an assumption about the gain of the transmitting antenna. Taking this gain G_T as 24 dB, the transmitter power P_T is given by

$$(P_T)_{dBW} = 36.67-24 = 12.67 \text{ dBW} \simeq 20 \text{ W}$$

System parameters are summarized in Table i O. 1B.

Table 10. 1B Downlink (8.0 GHz).

Transmitter Power, P_T	13 dBW (20 W)	
Antenna Gain, G_T	24 dB	
EIRP		37 dBW
Free Space Loss, L_{FS}		202.02 dB
Losses, L		
Attenuation due to rain	2.09 dB	
Gaseous attenuation	0.1 dB	
Pointing error	0.3 dB	
Total loss		2.49 dB

(continued on p. 10-17)

Antenna Gain, G_R	45.34 dB	
T_{Sys}	24.77 dB (300 K)	
G_R/T_{sys}		20.57 dB
Increase in noise due to rain		1.32 dB
C/X		13 dB
C/X.		80 dB

Example 10.3 Initial LMSS System

As an example in the UHF band, we consider an initial design for a Land Mobile Satellite System (LMSS) (Naderi, 1982). This system was planned for an 806-890 MHz allotment for satellite-mobile and mobile-satellite links and the S band for satellite-base station and base station-satellite links. As mentioned at the end of Sec. 1.2, the FCC authorized use of only the L band for land-mobile service in its decision of July 28, 1986, but the original design (uplink at 826 MHz and downlink at 871 MHz) nevertheless serves as an illustration of design, and we retain it in this second edition. At the time of writing, no L-band frequencies have actuallly been assigned nor have licenses for operation been issued,

For the UHF links, a design was prepared for a large (55-m) multibeam (87-beam) offset-reflector antenna on the satellite with separate beams formed by the use of 134 microstrip-patch feed elements excited in clusters of 7. The 87 beams would provide coverage of the entire conterminous 48 states of the United States. An original concept was that the satellite system would be compatible with cellular mobile radiotelephone service, but developments have not proceeded in that direction. At UHF, 95 voice channels would have been available per beam, each requiring a 10.2 kHz bandwidth with a 15 kHz channel separation and a total bandwidth per beam of 10 MHz. It was recognized, however, that the initial systems would have a much smaller number of beams and charnels. The satellite-to-mobile link, initially planned for operation at 871 MHz, is the most critical of the links, and the power budget for this link is shown in Table 10.2A.

Downlink (871 MHz)

The required total or overall C/X ratio is taken to be 10 dB, and the system must be able to function with a C/I (carrier-to-interference ratio) of 17 dB Analysis of intermodulation noise indicates that a 25 dB carrier-to-intermodulation noise ratio is expected. To initiate the link design process, a 20 dB $(C/X)_U$ ratio (carrier-to-thermal noise ratio for the uplink) is assumed. Using the relation of Eq. (10.6) but applying it to C/X = C/ (X_oB), it is determined that $(C/X)_D$ for the downlink must be 11.8 dB in order for the carrier-to-overall-noise ratio to be 1 O dB (line 1). For designing the links, the process begins with the carrier-to-noise requirement at the receiver terminal and progresses backwards to find the needed transmitter power.

A number of the losses shown in Table 10.2A are equipmental in nature or due to the fact that the system is a mobile system. For example, a 4 dB loss is shown to account for a mobile receiver not being at the center of a beam but at a point of minimum signal (line 14). Also losses of 2 dB and 1 dB represent pointing losses for the mobile and satellite antennas respectively (lines 15 and 16). The mobile antenna has a maximum gain of only 5 dB and a correspondingly large beamwidth but the antenna may not always be pointed towards the satellite-as the mobile moves uphill and downhill, etc. The satellite antenna has a pointing stability of 0,04 deg but at a point at the edge of the coverage area of a beam a pointing error of 0.04 deg could cause. a loss of 1 dB.

For system noise temperature, the use of such a large antenna beamwidth for the mobile receiver indicates a minimum antenna temperature of 290 K. In addition it is considered that the LMSS must provide satisfactory performance in suburban areas where man-made noise would be encountered. A value of antema temperature of 1.6 times 290 K or 464 K as suggested in the ITT handbook (ITT, 1968) is used for this reason (line 4). Taking into account also a receiver noise figure of 2 dB and 2.25 dB for input circuit losses gives a T_{Sys} of 991 K or about 30 dB (relative to 1 K).

For propagation losses, 'the following considerations apply. At UHF frequencies, attenuation and depolarization due to precipitation are negligible. Circular polarization is used, and Faraday rotation is not a factor, Ionospheric scintillation is most severe at equatorial and auroral latitudes, and the design is for the conterminous 48 states. Table 9.3 gives data for mid-latitude fading due to ionospheric scintillation. The smallest percentage of time shown in the table is 0.1, for which the fade depth is 1 dB for 500 MHz and 0.3 dB for 1000 MHz. Thus the 800-900 MHz range is sufficiently high that scintillation effects should not be severe, and taking into account that a two percent probability of system overload was assumed an allowance for scintillation was not not included among the losses. For service at the lower latitudes of Hawaii, for example, an allowance would probably needed. Also observations of peak-to-peak scintillations of i 8, i O, 15, and 3.5 dB at 1 36 MHz and 1.7, 4, and 14 GHz, respectively, in and around Japan (Minakoshi et al., 198 1), indicate that ionospheric scintillation may need to be taken into account in some system designs at temperate latitudes if a high grade of service is required.

Mobile observations are subject to fading due to multipath propagation involving specular reflection from the Earth's surface or structures. Also, as specular reflection decreases due to surface roughness, diffuse scatter may become important. On the basis of measurements made by use of the ATS-6 satellite, a 5 dB margin for multipath effects was utilized in the original LMSS design. However, subsequent measurements (Sec. 6.4) have indicated that shadowing due to trees is a serious effect, and emphasis has shifted from multipath effects to shadowing, A margin of at least 10 dB would be needed to ameliorate effects of shadowing by trees.

Uplink (826 MHz)

For the uplink operating at 826 MHz, many of the same considerations apply. A 20 dB $(C/X)_U$ ratio at the satellite was assumed at the outset, This ratio is achieved by using a mobile antenna gain of 5 dB and a transmitter power per channel of 2.45 W or 3.9 dBW. The system noise temperature (line 4) is 580 K rather than 991 K. A principal reason for the difference is that the mobile receiver is assumed to operate in a 464 K noise environment whereas the satellite receiver is assumed to receive radiation from the Earth at 290 K. A fading allowance of i O dB or more, rather than 5 dB, would actually be needed for shadowing, as on the downlink.

Table 10.2A LMSS Satellite-to- Mobile Link Budget.

Line	Parameter	Value	Comment
1	Downlink C/X	11.8 dB	At mobile receiver
2	IF Bandwidth, 10.2 kHz	40.1 dB	Charnel spacing 15 kHz
3	c/x.	51.9 dB	(1) + (2)
4	T_{sys} (991 K)	30.0 dB	464 K suburban noise, 2 dB receiver
5	Boltzmann's constant	-228,6 dB	
6	Misc. receiver loss	200 dB	
7	Needed received power	-147.7 dBW	(3) + (4) + (5) + (6)
8	Mobile antenna gain	5.0 dB	G/T_{sys} = -25 dB
9	Free space loss (f= 871 MHz)	182.8 dB	182.5 to 183.2 dB over U.S.
10	Transmitting antenna gain, G_T	50.0 dB	
11	Transmitting circuit losses	i dB	
12	Control signal power	1 dB	
13	Fading (multipath)	5 dB	10 dB or more with shadowing
14	Edge of coverage	4 dB	
15	Mobile pointing loss	2 dB	
16	Satellite pointing loss	1 dB	
17	Scanning loss	0.5 dB	
18	Required transmitter power per channel	-2.2 dBW (0.6 W)	(7) - (8 + 10) + (9 + 11 through 17)
19	Average transmitter power per channel	-6.2 dBW (0.24 W)	40 percent voice activity factor

Table 10.2B LMSS Mobile-to-Satellite Link Budget.

Line	Parameter	Value	Comment
1	Uplink C/X	20.0 dB	At satellite receiver
2	IF bandwidth	40.1 dB	
3	c / x .	60.1 dB	(1) + (2)
4	T_{Sys} (580 K)	27.7 dB	290 K Earth, 2 dB receiver
5	Boltzmann's constant	-228.6 dBW	
6	Misc. receiver loss	1 dB	
7	Needed received power	-139.8 dBW	(3 + (4) + (5) + (6)
8	Satellite antenna gain	49.7 dB	G/T = 22 dB
9	Free space loss (f= 826 MHz)	182.4 dB	182.0 to 182.7 over U.S.
10	Transmitting antenna gain, G_T	5 dB	
11	Transmitting circuit losses	2.5 dB	
12	Control signal power	1 dB	
13	Fading (multipath)	5 dB	10 dB or more with shadowing
14	Edge of coverage	4 dB	
15	Mobile pointing loss	2 dB	
16	Satellite pointing loss	1 dB	
17	Scanning loss	0.5 dB	
18	Required transmitter power per channel	3.9 dBW (2.45 W)	

Example 10.4 Maritime Mobile System

This example involves L-band operation for the uplink from a ship to a MARISAT satellite and C-band operation for the downlink from the satellite to a ground station, The system parameters utilized in the example and shown in Tables 10.3A and 10.4B are taken from a paper dealing with application of the MARISAT system to the transmission of seismic data at 56 kbps from a ship or seismic vessel, with losses taken into account (Calvit and Heitman, 1981). Since the date of this paper, the INMARISAT system has replaced the original MARISAT system (Sec. 6.5),

Table 10.3A Ship to Sate, lite Uplink (1.6405 GHz)

Transmitter Power, P_T	15.7 dBW	
Diplexer/Feed Loss	0,6 dB	
Antenna Gain, G_T	23.5 dB	
EIRP		38.6 dBW
Free Space Loss, L_{FS}		188.6 dB
Losses, L		
Wet Radome	0.5 dB	
Polarization Coupling	0.2 dB	
Atmospheric absorption	004 dB	
Total		1.1 dB
Satellite G_R/T_{sys}		-15.9 dB
C/N. (carrier power to noise density ratio in digital system)		61.6 dB

The values in the table are consistent with Eq. (10.9), namely

$$(EIRP)_{dBW} - (L_{FS})_{dB} - L_{dB} - k_{dBW} + (G_R/T_{sys})_{dB} = (C/X)_{dB}$$

as can be checked by numerical substitution, giving

$$38,6 - 188,6 - 1.1 - (-228.6) - 15.9 = 61.6$$

Next consider Table 10.3B for the downlink

Table 10.3B Satellite to Shore Station Downlink (4. 197 GHz).

Satellite EIRP		2 dBW
Free Space Loss, L_{FS}		196.9 dB
Losses, L		
Atmospheric Absorption	0.3 dB	
Rain Attenuation	1.2 dB	
Polarization Coupling	0.4 dB	
Total		1.2 dB
Increase in T_{Sys} Due to Rain		1.2 dB
Shore Station G_R/T_{sys}		33 dB
C/N_o		64.3 dB

Overall C/N Ratio

The overall or composite C/N_o value, neglecting interference, is found from

$$\frac{1}{(C/N_o)_T} = \frac{1}{(C/N_o)_U} + \frac{1}{(C/N_o)_D}$$

in which $(C/N_o)_U = 10^{6.16} = 1.445 \times 10^6$ and $(C/N_o)_D = 10^{6.43} = 2.96 \times 10^6$. The resulting value of $(C/N_o)_T$ is 9.333×10^5 or 59.7 dB.

The E_b/N_o ratio can then be found from $E_b/N_o = C/(N_oR)$ where R is the data rate, namely 56 kbps in this case. Carrying out the calculation in decibels, 10 log(5.6 x 104) = 47.5 dB and

$$(E_b/N_o)_{dB} = 59,7 - 47.5 = 12.2 \text{ dB}$$

which is a satisfactory value, as it was determined that a bit error rate (BER) of better than 1 x 10-5 can be acheived with an E_b/N_o ratio above 5 to 6 dB.

A film of water on antema or radome has the potential for creating a loss, and a loss of 0.5 dB was assigned for the condition of a wet radome on the uplink. A loss of 0.4 dB was assigned for atmospheric absorption on the uplink, at about 1.6 GHz. At this frequency, true absorption of this magnitude is improbable, but a reduction in signal amplitude of this magnitude associated with ionospheric scintillation could very likely occur. For the downlink at about 4.2 GHz, a generous allowance of 0.3 dB is provided for atmospheric absorption, 0.5 dB is assigned for attenuation due to rain, and 1.2 dB is assigned for the increase in noise due to rain. The basis for the rain effects is not stated but they correspond to intense rain such as might be exceeded in region D_3 of the United States for 0.0 i percent of the time (63 mm/h) or slightly higher. A greater margin would be needed at 1.6 GHz for ionospheric scintillation at equatorial latitudes, and a larger margin would probably be needed for the degradation in signal-to-noise ratio on paths at elevation angles below 10 deg. It appears that the system actually had a larger margin than that specifically assigned. A practical consideration in shipboard operations is that ships are subject to large values of pitch and roll in high seas, and these motions can result in degradation in performance unless the antenna platform is extremely well stabilized. Also, as stated in Sec. 6.5 where maritime mobile systems are considered, fading problems are likely to be encountered at low elevation angles. Ohmori and Miura (1983) "have described the use of a four-terminal hybrid combiner for use in overcoming this problem when using circular polarization and low-gain antennas which have low discrimination against specular reflection from the sea surface.

Example 10.5 Westar V

Westar V serves as an example of a C-band system, with the uplink operating at 6 GHz and the downlink operating at 4 GHz (Piraino and Scioen, 1982). Tables 10.4A and 0.4B give some of the parameters for the uplink and downlink. The system is a digital system having a bit error rate of 1 x 10^{-6} as a performance objective without encoding and 1 x 10^{-11} when rate-7/8 convolutional forward-error-correction (FEC) encoding is employed. The overall E_b/N_o required to meet these objectives is stated to be

14.5 dB. The various contributions to this ratio are 22.9 dB for the uplink, 18.6 dB for the downlink, 24.3 dB for adjacent satellite interference, 20.1 dB for cross-polarized transponders, and 23.0 dB for interference from terrestrial microwave systems. When these quantities are taken into account in a relation like that of Eq. (10.6), which is written in terms of ordinary numbers rather than decibel values, an overall E_b/N_o value of i 4.3 dB (close to 14.5 dB) is obtained. The calculation is summarized in Table 10.4A.

Table 1 O. 4A E_b/N_o Values for Westar V.

Category	dB	Numerical	Reciprocal
Uplink	22.9	194.984	0.00512861
Downlink	18.6	72.4436	0,0138038
Adjacent Sat.	24.3	269.153	0.00371535
Cress Pol.	20.1	102.329	0.00977237
Terrestrial	23.0	199.526	0.00501187
Overall (Total)	1403	26.7171	0.0374320

<u>Uplink (6 GHz)</u>

Table 10.4B 6 GHz Uplink Budget.

Earth" Station EIRP	79.0 dBW
Free Space Loss, L_{FS}	200.1 dB
Atmospheric Absorption	0.1 dB
Rain Attenuation	0.4 dB
Wind Effect on Antenna	0.3 dB
Transponder G_R/T_{sys}	-6.0 dB

m

The values of the table are consistent with Eq. (10.9), repeated below.

$$(C/N_o)_{dB} = (EIRP)_{dB} - (L_{FS})_{dB} - L_{dB} - k_{dBW} + (G_R/T_{sys})_{dB}$$

Substituting numbers

$$(C/N_o)_{dB} = 79.0 \quad -200.1 \quad -0.8- \ (-228.6) \ -6.0 \ = \ 100.7$$

Converting to $(E_b/N_o)_{dB}$ by subtracting R_{dB} with R, the bit rate being 60 Mbps,

$$(E_bN_o)_{dB} = (C/N_oR)_{dB} = \mathbf{100.7-10} \ \log \ (\mathbf{6} \times 10^7)$$

$$100.7 \ -77.8 \ = \ 22.9 \ dB$$

<u>Downlink (4 GHz)</u>

Table i 0.4C 4 GHz Downlink Budget.

Transmitter EIRP	3303 dBW
Free Space Loss, L_{FS}	196.6 dB
Atmospheric Absorption	0.1 dB
Rain Attenuation	0.1 dB
Wind Effect on Antenna	0.2 dB
Increase in T_{Sys} due to Rain	0.3 dB
Earth Station G_R/T_{sys}	31.8 dB

Substituting numbers into Eq. (1 O. () as was done following Table 10.4B,

$$(C/N_o)_{dB} = \ 33.3-196.6-0.7- \ (-228.6) \ + \ 31.8 \ = \ 96.4$$

$$(E_b/N_o)_{dB} = \ 96.4 \ -77.8 \ = \ 18.6 \ dB$$

In the numerical relation, 0.7 represents the sum of atmospheric absorption, rain attenuation, wind effect on antenna, and increase in noise due to rain.

For both the uplink and downlink, the small reasonable allowance of 0.1 dB is made for atmospheric absorption. An allowance of 0.4 dB is made for rain attenuation on the uplink at 6 GHz and 0.1 dB for rain attenuation lus 0.3 dB for noise due to rain is assigned for the downlink. f he basis for the attenuation values is not given, but the values are reasonable though less than those for the rain rate of 35 mm/h considered in Example 9.5. Effects due to rain at these frequencies are small but shoul still be included in the link equations.

1004 A GRAPHICAL MARGIN-DESIGN PROCEDURE

Insight into choosing suitable uplink and downlink margins in the presence of rain can be obtained by use of a graphical procedure described by Calo, Schiff, and Staras (1978). Consider first Fig. 10.4 in which the curve illustrates the combination of uplink and downlink C/X ratios which can provide the needed total or composite C/X ratio (10 dB in this case) in the absence of rain. Equal C/X values of 13 dB for the uplink and downlink, for example, can provide the composite value of 10 dB.

Now consider how the curve would need to be modified for the presence of rain on the uplink of a TDMA (time-division-multiple-access) system. Numerical values will be used for purposes of illustration. If 3 dB of attenuation is expected to be encountered, with a probability of p percent of being exceeded where p is consistent with performance objectives, the original curve of Fig. 10.4 can be moved to the right by 3 dB in order to provide a margin of 3 dB for the uplink. In addition the output power of the satellite repeater, which serves as the transmitter power for the downlink, will have been reduced but, because of the. nonlinear characteristic of traveling-wave tubes, by not necessarily the same amount as the reduction in input power. Assuming the reduction is 2 dB, the original curve can be moved upwards to compensate by 2 dB, corresponding to increasing the downlink power and therefore the downlink C/X ratio ly 2 dB. In Fig. 10.5, the curve of Fig. 10.4 is redrawn and labe ed A and the curve obtained by an upward movement of 2 dB and movement to the right of 3 dB is labeled as B. Next consider rain causing attenuation of 3 dB on the uplink. Whereas the receiving antenna of the uplink is commonly assumed to receive noise corresponding to 290 K from the Earth [but see Fig.

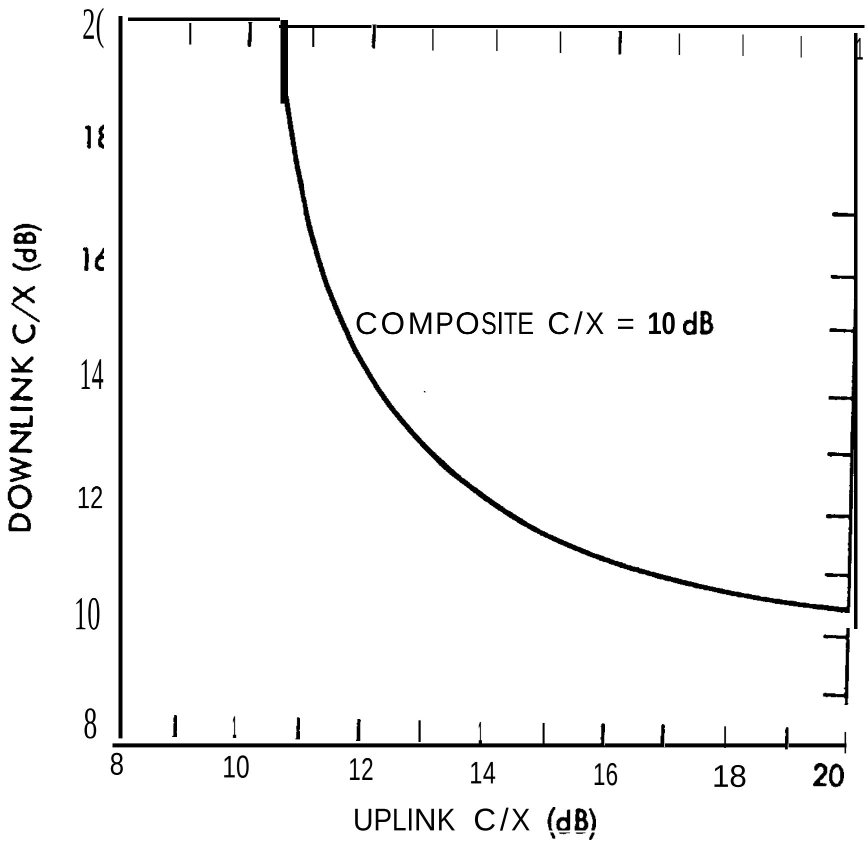

Figure 10.4. Values of downlink and uplink C/X ratios that give a composite ratio of 10 dB in the absence of attenuation.

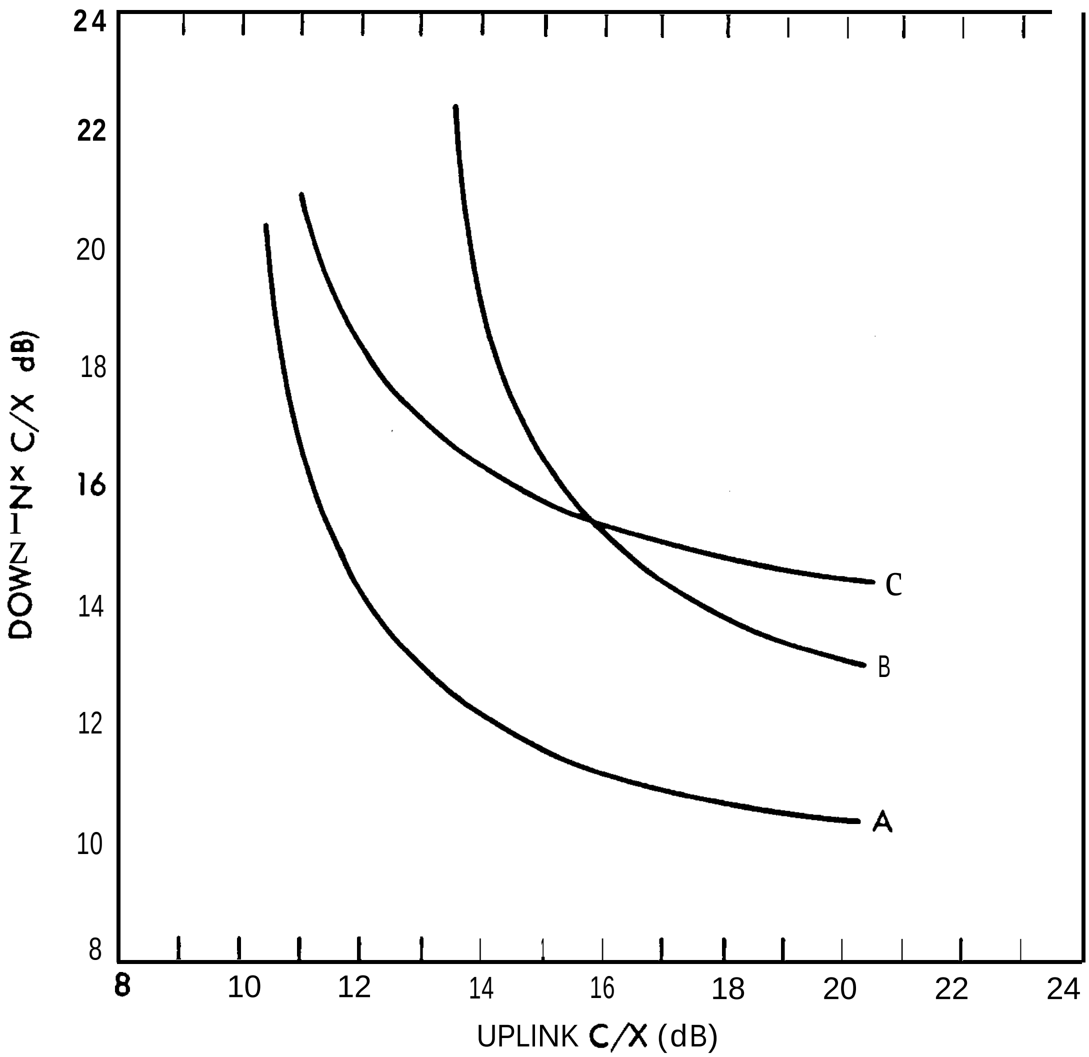

Figure 10.5. Illustration of graphical procedure for determining downlink and uplink C/X ratios such that the composite ratio will be satisfactory when propagation impairments caused by rain are encountered.

7. 1 L?), whether there is rain or not, the receiving antema of the downlink receives additional noise when there is rain along the path. Take the increase in noise to be 2 dB so that the total degradation in C/X ratio for the downlink is 4 dB. To compensate for this degradation, the original curve A can be moved upwards by 4 dB to form curve C which therefore includes a margin of 4 dB. The point where curves B and C intersect now corresponds to C/X values providing sufficient margins to accommodate simultaneous rain causing attenuations as indicated for both the uplink and downlink. Assuming the probabilities of such rain rates are independent, however, the accommodation is now for all but 2p percent of the time rather than for all but p percent. Although the point of intersection of curves B and C may give suitable C/X values for the uplink and downlink, it may be desirable to choose a point slightly to the right along curve C so that C/X for the uplink is slightly higher than previously for the uplink than for the downlink.

10.5 COVERAGE AREA

It may be necessary in system design to provide for service over a given, possibly extensive, geographical area rather than for only a particular earth station. The relation betwen the service or coverage area, A_{cov}, and system parameters, including C/X_o, is shown in Eq. (1.11), from which k and other numerical factors. were eliminated. The relation is repeated below but with k and κ_{ant}, the antenna efficieny factor, reinserted

$$A_{cov}(C/X_o) \simeq \frac{P_T A_R \kappa_{ant}}{k\, T_{Sys}\, L} \qquad (10.10)$$

The relation is still shown as only an approximation for a reason to be explained in the course of deriving the expression, To derive Eq. (10. 10) one can start with Eq. (10. 7). In this expression make the substitutions $L_{FS} = (4\pi d/\lambda)^2$, $G_R = 4\pi A_R/\lambda^2$, and $G_T = \kappa_{ant} 4\pi/\Omega_A$ where AR is the effective area of the receiving antenna and Ω_A is the solid angle of the transmitting antenna beam. Note that $4\pi/\Omega_A$, with Ω_A in rad^2 or steradians, represents antenna directivity by definition and that directivity times antenna efficiency equals gain. After making these substitutions the resulting expression for C/X. is

$$(c/xo) = \frac{{}^{\prime}TKantAR}{\Omega_A d^2 LkTsys} \quad (10.11)$$

By definition the solid angle Ω_A subtended at a Point by an area A, that is perpendicular to the line of sight from the point at a di&.ante d is given by

$$\Omega_A = \frac{{}^{\prime}\ 1}{d^2} = \frac{\int a_r \cdot dS}{d^2} \quad (10.12)$$

If A_1 is identified as A_{cov} and Ω_A of Eq. (10.11) is set equal to A_{cov}/d^2, Eq. (10. 10) is obtained. The equation is an approximation and possible a rough one because A_{cov} is not strictly perpendicular to the line of sight except in the vicinity of the subsatellite point. But if that limitation is taken into account, Eq. (1 O. 10) shows correctly that, with other parameters held constant, it takes more power to provide coverage over a large area than over a smaller area.

Contours of constant EIRP and G_R/T_{sys} for Westar IV and V are shown in Figs. 10.6 and 10.7, respectively. These satellites provide coverage over the entire United States, with an EIRP 'or downlink transmission at 4 GHz of 34 dBW for the adjacent 48 states and with smaller values of EIRP for Alaska, Hawaii, and Puerto Rico. Fig. 10.7 shows that G_R/T_{sys} for the uplink at 6 GHz has a value of -6.0 dB for the adjacent 48 states.

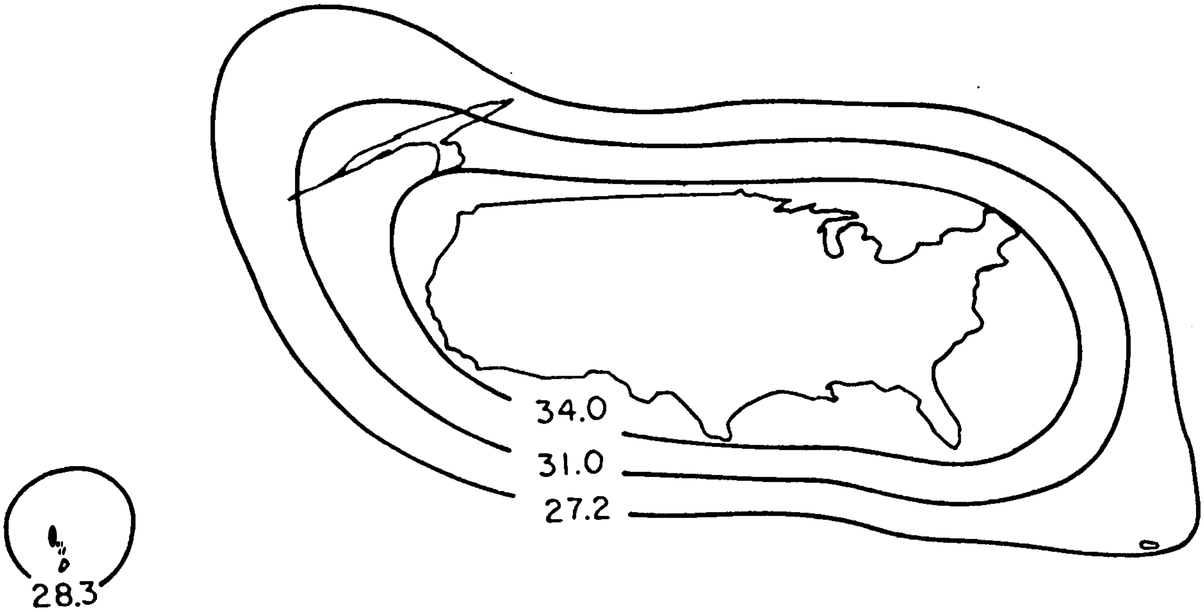

Figure 10.6. EIRP contours for Westar IV and Vat 4 GHz.

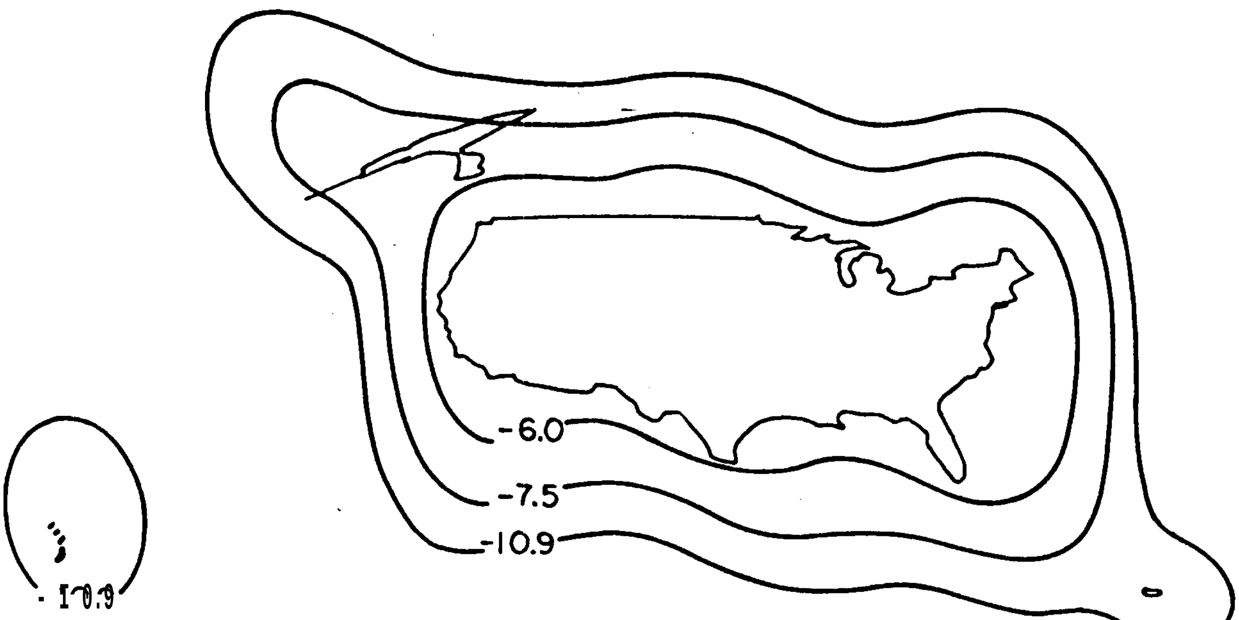

Figure 10.7. Contours of G_RT_{sys} for Westar IV and Vat 6 GHz.

10.6 COMPANDED SSB SYSTEMS

As mentioned in Sec. 6.3.3., companded single-sideband systems (SSB systems) use spectrum efficiently and have an advantage with respect to signal-to-noise ratio for analog audio signals. The interest in that section was in the use of a pilot tone for reducing the unwanted amplitude and phase modulation introduced by fading. Companded systems involve the use of a compressor at the transmitter and an expandor at the receiver. These compress and expand the dynamic range of the signal. A zero level is unaffected by the compression and expansion, but signals having greater or smaller amplitudes are affected. Compression generally reduces the dynamic range to one half of the original range, and expansion by a factor of two than restores the signal to its original range (Fig. 10.8). In a noiseless system, this would be the only effect; the receiver-output signal would simply be the same as the transmitter-input signal. In a practical noisy system, however, the signal-to-noise ratio at the receiver input is considerably less than that at the transmitter output. Assume that the noise level at the receiver input in gaps between syllables, words, and sentences is -25 dB relative to the zero reference level. After expansion, however, the corresponding noise level is -50 dB. Thus commanding produces an improvement in the subjective or apparent signal-to-noise ratio. The word "apparent" is used because the improvement cannot be measured by instruments but is apparent to the listener. It is rather difficult to decide what value to assign to this improvement. Values in the range from about 6 to 16 dB have been seriously considered, and the present trend appears to be to use values of about 10 or possibly slightly greater.

Another characteristic of the commanding process is that average power level is increased by compression with respect to that of the input audio signal. To obtain a quantitative estimate of the amount of increase, use can be made, both before and after compression, of

$$L = L_s + 0.1125\,\sigma^2 + 10 \log \tau \qquad (10.13)$$

(Bell Tel. Labs., 1971; Jonnalagadda and Schiff, 1984). In this expression L is the average talker power, σ is the standard deviation of active speech power, and t is the duty factor of speech. Ls is the mean power of a distribution of talkers. L and L_s ‘differ because the normal distribution for which L_s is the mean is a distribution in dB values, whereas L is the average of the corresponding distribution of actual power. To illustrate the increase in power let L_s = -20 dBm0 and σ = 4.8 dB at the compressor input. Also letting τ = 0.35 and L = L,

$$L_1 = -20 + 0.115\ (4.8)^2 + 10 \log 0.35$$

$$= -21.9 \text{ dBm0}$$

After compression, however, the average talker level is given by

$$L_2 = -10 + 0.115\ (2.4)^2 + 10 \log 0.35$$

$$= -13.9 \text{ dBm0}$$

Using X to stand for the increase in power level

$$x = -13.9 - (-21.9) = 8 \text{ dB}$$

Performance of such systems can be analyzed in terms of test-tone to noise-power ratio, T_T/N, for a 0-dBm0 signal at the receiver input, after transmission over a radio-frequency link. This ratio can be expressed in terms of signal-to-noise ratio S/N, the commanding improvement ratio A, and the levels L_1 and L_2 by (Jonnalagadda, 1 982)

$$T_T/N = S/N + A - (L_1 + X) = S/N + A - L_2 \tag{10.14}$$

The value of T_T/N is generally required to be 51 dB. Using 51 for T_T/N, 12 for A, and the values for L_1 and L_2 given above

$$51 = S/N + 12 - (-21.9 + 8) = S/N + 12 + 13.9$$

and the necessary S/N ratio is 25.1 dB. If a commanding advantage of 12 is truly applicable, the S/N ratio can be 12 dB less than it would otherwise need to be. To justify the above expression for T_T/N , it needs to be recognized that T_T/N must be 51 dB for a 0-dBm0 signal whereas the actual signal level of this example is -13.9 dBm0 (13,9 dB below that for a 0-dBm0 signal). Assuming the system to be satisfactory if T_T/N is 51 dB for a 0-dBm0 signal means that it is also satisfactory for S/N to be lower by 13.9 dB for a -13.9 dBm0 signal. The two factor-s of A and $-L_2$ result in a value of 25.1 dB being satisfactory for S/N.

The value of L_1 of -21.9 dBm0 used above is lower than what has been the CCIR recommended value of -15 dBm0 because recent studies of average talker level have shown the level to be lower (Jonnalagadda, 1982). If psophometric weighting is utilized a factor of w dB (with w = 2.5 dB) can be added with the result that the needed value of S/N is reduced further to 22.6 dB for A = 12. In that case the subjectively perceived signal-to-noise ratio is higher by A + w = 12 + 2.5 = 14.5 dB than S/N.

SSB satellite systems are subject to intermodulation noise, which is developed in the transmitting amplifiers of satellites. The newer solid-state power amplifiers (SSPA) are more nearly linear and thus generate less intermodulation noise than traveling-wave-tube amplifiers (TWTA). Analysis for an uplink can be carried out in terms of flux density ϕ at the satellite where

$$\phi = \frac{(EIRP)_e}{4\pi d^2} \qquad (10.15)$$

with $(EIRP)_e$ referring to the earth station EIRP and d the distance from the earth station to the satellite. A saturation flux density ϕ_{sat} (the flux density that saturates the satellite amplifier) is specified by the manufacturer but to reduce intermodulation noise the amplifier may be operated with a lower density ϕ where

$$(\phi)_{dBW/m^2} = (\phi_{sat})_{dBW/m^2} + IBO_{dB} \qquad (10.16)$$

where IBO stands for input backoff and is negative as ϕ is less than ϕ_{sat}. If the input signal is reduced below the saturation level, the output signal is also reduced. That is, the output signal is also backed off, but the amount of output backoff is not necessarily the same as the amount of input backoff. The difference between the output backoff OBO and in the input backoff IBO equals a "gain" G_a. Thus

$$(OBO)_{dB} - (IBO)_{dB} = (G_a)_{dB} \qquad (10.17)$$

An expression for S/N in an uplink channel, in terms of ϕ and considering only thermal noise, is

$$(S/N)_{dB} = \phi_{dBW/m^2} - 10 \log n + 10 \log (\lambda^2/4\pi)$$
$$+ (G_s/T_{sys})_{dB} - 10 \log b - 10 \log k \qquad (10.18)$$

The expression is similar to that of Eq. (i. 8), but here for an audio charnel we use S/N rather than C/X. Also the factor of d squared and one factor of 4π of

$$(L_{FS})_{dB} = 10 \log (4\pi d/\lambda)^2$$

have been included in ϕ, leaving a factor of 10 log ($\lambda^2/4\pi$) in the equation. For B_{dB} of Eq. (1.8) there is 10 log b where b is the bandwidth of an audio charnel, commonly 3000 Hz, Also a 10 log n term, where n is the number of channels, is included to take account of the fact that the total power included in # is distributed over n channels. The quantity Gs is the gain of the receiving antenna on the satellite. If ϕ of Eq. (1 O. 18) is recognized as being equal to $\phi_{sat} + I_{BO}$, the equation has the form of

$$(S/N)_{dB} = (\phi_{sat})_{dBW/m^2} + (I_{BO})_{dB} - \log n + 10 \log(\lambda^2/4\pi)$$
$$+ (G/T_{sys})_{dB} - 10 \log b - 10 \log k \qquad (10.19)$$

Equation (10. 19) is given by Jonnalgadda (1982) for the uplink from a gound station to a satellite. He then proceeds to consider intermodulation noise and external interference, including that from adjacent transponders of the same satellite that are designed to be cross polarized but become depolarized to a degree because of Faraday rotation or propagation though precipitation. External interference from adjacent satellites is aggravated by the fact that satellites may be spaced only 2 deg apart in the geostationary orbit. To keep such adjacent-satellite interference within bounds, earth-station uplink antenna gains must be no greater than 32 - 25 logθ with θ the angle from the center of the main beam in deg, for $\theta \geq 1$ deg. For the downlink the corresponding relation is 29 - 25 loge*

A similar analysis for a downlink results in

$$(S/N)_{dB} = (EIRP)_{dBW} + (OBO)_{dB} - 10 \log n - (L_{FS})_{dB} + (G_e/T_{sys})_{dB} - 10 \log b - 10 \log k \quad (10.20)$$

Effort has been devoted to accommodating as many as 6000 audio channels in a 36 MHz transponder by use of SSB, and a paper used in preparation of this section by Jonnalagadda (1982) was devoted to this topic. This type of application has apparently not met with success because of power limitations in 6/4 GHz service, interference considerations, etc., and this approach is understood to have been dropped. A number of the 12 companies that have applied for licenses to provide satellite land-mobile service, however, have planned to use SSB in their first-generation systems. This application appears to be practical and is a ma "or reason for treating SSB here. A change may. be made in later-generation systems, however, to digital transmission.

10.7 APPLICATIONS OF SPREAD-SPRECTRUM SYSTEMS

Some basic concepts of spread-spectrum systems were introduced in Sec. 6.3.5, and attention is given now to possible applications of such systems. Spread-spectrum systems provide a degree of immunity from interference and jamming and their low power densities in W/m^2 contribute to a low probability of intercept. For these reasons as well as relative freedom from multipath effects, spread-spectrum systems have been employed quite extensively in military applications. Considerable interest is now being shown in applications for nonmilitary purposes as well (Utlaut, 1978; CCIR, 1986b; Cooper and Nettleton, 1983; IEEE, 1983). Docket 81-413 of the Federal Communications Commission called for comments on proposed authorization for spread-spectrum systems and an IEEE Communications Society panel prepared a statement about spread-spectrum systems and some of the responses that had already been received to the docket (IEEE, 1983). The statement of the Communications Society does not promote or condemn any particular application and is a careful analysis of possible applications.

The subject of the relative spectral efficiencies of spread-spectrum and other systems is complex. Cooper and Nettleton (1978) asserted that, for cellular mobile systems employing small cells for which frequency-division multiple access (FDMA) systems and spread-spectrum systems are interference limited, spread-spectrum systems employing differential phase shift keying (DPSK) can achieve greater user densities by a considerable factor than FDMA systems. Developments regarding the relative spectral efficiencies of the various systems have reviewed by Yue (1983), using efficiency as defined by

$$\eta_m = U\ (30\ \text{kHz})/W \qquad (10.21)$$

witn η_m the efficiency of an m cell system, U the average number of users per cell, and W the bandwidth for one-way transmission. If only a single cell is considered, the efficiency of an FM system with channel spacing of 30 kHz is unity (100 percent) when defined in this way. In a multicell system, however, this efficiency must be reduced by the reuse factor (which takes into account that adjacent cells can not use the same frequency because of mutual interference considerations). Taking the reuse factor as 12, η_m for FDMA is reduced to 8.3 percent. An analysis by Yue (1982) showed a spectral efficiency of 8.4 percent for the PSK technique of Cooper and Nettleton. Goodman et al. (i 980) reported that an efficiency of 35.7 percent should be possible by use of multiple level frequency shift keying (MFSK), and Viterbi (1978) reported the possibility y of efficiencies up to 37.5 percent by use of a process ing transponder on a satellite. Use of on-board processing, although introducing some complication into a satellite, has important advantages (Pelton, 1984) and satellites of the future are expected to make considerable use of it (Evans, 1986). Signals may be reduced to baseband on a processing satellite. Yue (1983) concluded that it had not been demonstrated that FH/CDMA was more spectrally efficient than FDMA. The reverse would also seem to be true. Yue indicated that other practical considerations concerning spread-spectrum, including cost, needed to be resolved before a commercial system could be implemented.

An interesting point about the comparison between broad and narrow band charnels has been made by Costas (1959) and considered further by Utlaut (1978). Costas showed that the relative communication' capacities of broadband channels, C_B, and narrowband channels, C_N, are given by

$$C_B/C_N = 1/[\alpha (S/N)_{min}] \quad (10.22)$$

where α is the fraction of time each station is transmitting and $(S/N)_{min}$ is the minimum signal-to-noise ratio that can be tolerated. The comparison applies to the case for which the broadband users occupy an entire bandwidth whereas for narrowband operation the same bandwidth is broken into a number of narrowband channels. When α is small, C_B tends to be significant y larger than C_N. Utlaut (1978) used as an example the case for which a 3 MHz bandwidth is separated into 1000 channels of 3 kHz for narrowband operation. He considered two grades of service, one percent and seven percent, meaning that one in a hundred or one in fourteen attempts at establishing communication fail on the first attempt because all channels are occupied. The results are summarized in Table 10.5. For C_B, each user occupies the entire bandwidth.

Table 10.5 Capacities of Broad and Narrow Band Systems (C_B, C_N)

C_B or C_N	Grade of Service	Capacity (Erlangs)
C_N	1/100	10
C_B	1/100	84.1
C_N	1/14	80
C_B	1/14	98.99

This interesting example shows a clear advantage for the broadband system, but caution must be exercised in drawing broad conclusions. It does seem reasonable to conclude that the most favorable cases for employing spread-spectrum systems will be those for which α of Eq. (10.22) is small. In other words, lightly used systems appear to offer the best prospects. Applications which the IEEE panel (IEEE, 1983) looked on most favorably included low-power-density applications and multiple access systems with many low-duty-cycle users.

The Global Positioning System (GPS) uses spread spectrum for positioning (Sec. 6.7), and spread spectrum has also been used for satellite communications. Prominent in this respect is the TDRSS (Tracking and Data Relay Satellite System) which provides for transmitting commands to and receiving data from low-orbiting satellites by means of the TDRS satellites (Holmes, 1978; Goddard, 1 980). The configuration for using a TDRS satellite is shown in Fig. 10.8. Forward and return links from the ground terminal through the TDRS satellite to the user spacecraft at S band and Ku band use the direct-sequence pseudonoise spread-spectrum technique. The multiple access return link can accommodate 20 users at data rates up to 50 kbps. Return single access service at S band can provide data rates to 12 Mbps, and single access return service at Ku band can provide data rates to 300 Mbps but in this case spread spectrum is not used. An important factor in deciding to use spread spectrum was the need to keep power density levels low at the Earth's surface.

The Equatorial Communications Company (Parker, 1984) uses a combination of VSAT (Very-Small-Aperture-Terminal) and spread-spectrum technologies. Data transmission is carried out in the 6 and 4 GHz bands by using antennas 1. 2 or 0.6 m in diameter. The bread beamwidth of such small receiving antennas allows them to receive interfering signals from satellites close to the satellite that it is intended to be operating with. Signals from five satellites spaced two deg apart, for example, could be received by a 0.6 m antenna having a beamwidth fo nine deg. The use of spread spectrum employing code division multiple access, however, allows successful operation under such conditions. One hundred parties can use the same channel at the same time and, if a duty cycle of 0.01 is assumed for the users, 10,000 assignments can be made to one channel though 1,000 to 5,000 is more typical (Parker, 1 986).

Other satellite applications of spread spectrum that are reported include SAMSARS (Satellite Aided Maritime Search and Rescue System) and TATS (Tactical Transmissions System), described by Proakis (1983, pp. 594, 595). SAMSARS was described in the 1982 version of CCIR Report 761. The same report for 1986 (CCIR, 1986) has much interesting material on other systems for facilitating maritime rescue. A domestic Japanese mobile satellite system that is under development is reported to be using FH spread spectrum.

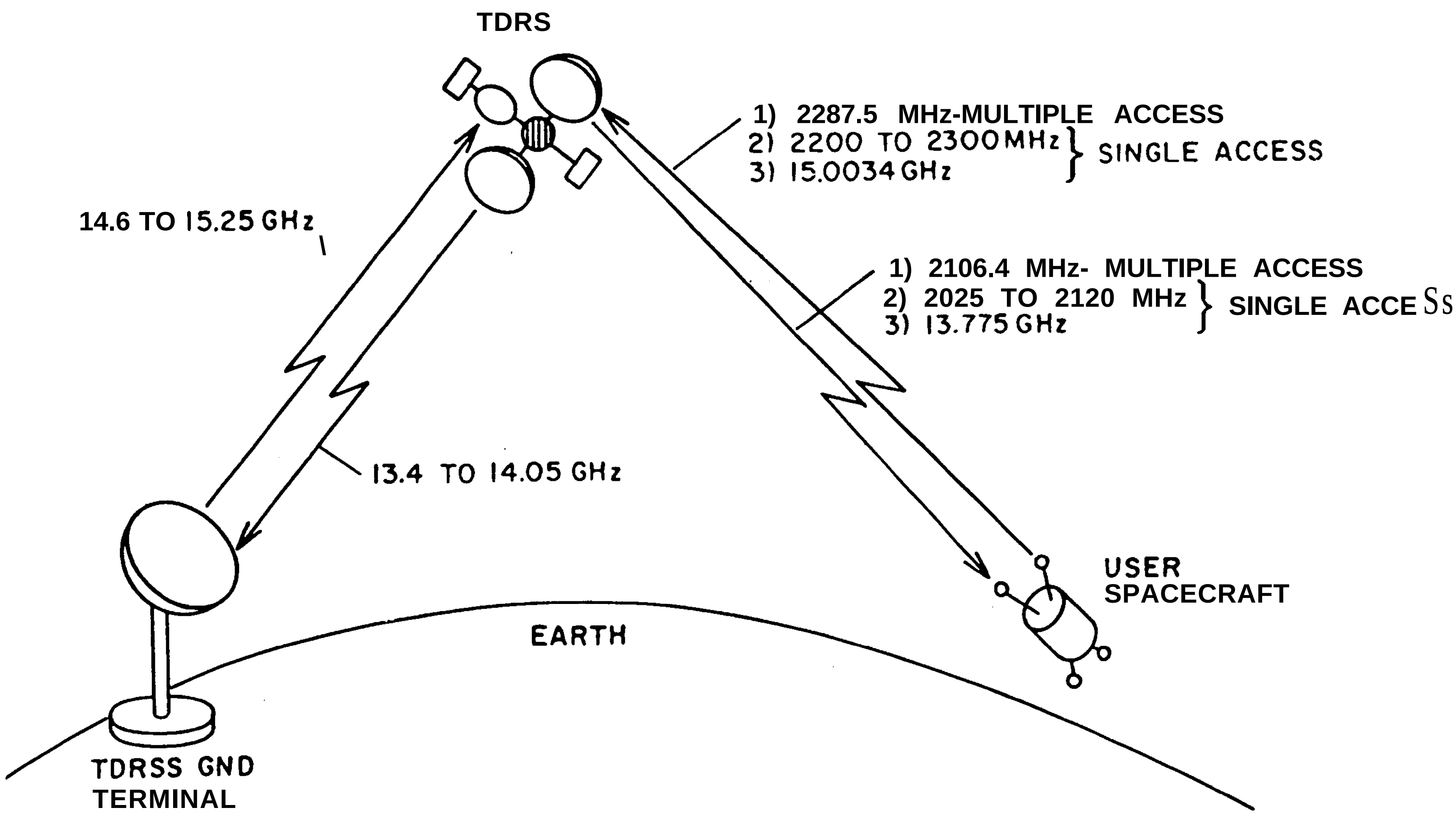

Figure 10.8. Telecommunication links of Tracking and Data Relay Satellite System (TDRSS).

10.6 CONCLUSION

The emphasis of this handbook is on propagation effects, but the intent has been to relate propagation to the closely related subject of earth-space link design rather than to treat propagation as an isolated, academic topic of its own. Some remarks on trends and potential developments in satellite communications follow. Increasing attention is likely to be given to effects at higher frequencies, up to perhaps 94 GHz, but we concentrate on the 100 MHz to 10 GHz range of this handbook. In this frequency range, the propagation effects of interest in the future may not be much different than those of today, but the associated satellite link parameters are likely to show a trend that takes account of the increasing importance of small earth stations.

During the first two decades of satellite operations. satellites had a near monoply of new long-distance telecommunication service, but fiber optics has made major advances in recent years. The view is taken here that satellite and fiber optic systems are largely complementary, but they will probably be in competition on some high-capacity point-to-point links such as those across the Atlantic. Trends in future satellite systems, taking account of the role of fiber optics, have been discussed by Evans (i 986). The INTELSAT system, presently involving about 110 countries, originally acheived interconnectivity by employing broad satellite antema beams which provided coverage over wide areas. The earth stations required for this mode of operation, however, use very large, expensive antemas. The trend in the future is expected to be to use multiple spot beams, on-board switching, and higher transmitter powers on satellites for interconnectivity. The earth stations that will used for such systems can in many cases be small and low in cost. The term VSAT, standing for Very Small Aperture Terminal, is now applied to such earth stations. Antenna diameters may be very small, like 1.2 or 0.6 m for 6/4 GHz systems. The corresponding beamwidths will be large, and the earth stations will tend to be subject to interference from, or cause interference to, satellites spaced as little as two deg from the satellite the system is designed to operate with. It was mentioned in See, 6.7 that the use of spread spectrum is one means to alleviate this problem.

Numbers of active satellite transponders used for various traffic types, as measured by the FCC in March 1986, summarized in Satellite Week, and repeated by Inglis (1986) are shown in Table 10.6. It appears unlikely that many of the transponder usages listed, other than for heavy-route voice service, will be affected very greatly by optical fibers.

Table 10.6 Estimated Usage of Active Transponders by Traffic Type

Traffic Type	C-Band	K-Band	Total
Television			
Cable TV	68	1	69
Broadcast	43	17	60
Closed Circuit	9	3	12
Radio	5	0	5
Voice			
Heavy Route	7	0	7
Light Route	37	0	37
Private Networks	39	1	40
Data (Private Networks)	72	29	101

The 1 GHz to 10 GHz range that is included in the coverage of this handbook is an ideal frequency range from the propagation and noise viewpoints, but propagation effects still need to be taken into account and may possibly be severe in some cases. Ionospheric scintillation may be serious, especially at frequencies of about 1.5 GHz and lower, within about 20 deg of the equator. Excess range delay due to the ionosphere and troposphere are important to range measurements, and increasing accuracy is demanded for geodetic applications and programs like TOPEX (Ocean Topography Experiment, Sec. 6.7). The ionospheric delay can be determined by using two transmitted frequencies (Sec. 2.3. 1) or eliminated by going to a sufficiently high frequency, but tropospheric effects tend to be more serious at high frequencies. The use of water vapor radiometers is needed to obtain the highest accuracy for the excess range delay due to the troposphere (Sec. 3.7).

Effects of rain are most intense at frequencies above 10 GHz, but attenuation, depolarization, thermal noise, and scatter as a source of interference are all significant below i O, GHz. Specular reflection and diffuse scatter may be problems for land and maritime satellite mobile systems, but shadowing by trees has become prominent as the major problem for land-mobile systems (Sec. 6.4).

It is desirable to treat the propagation impairments sadistically. This type of approach has been quite well developed for attenuation due to rain but is less well developed for other impairments. In the latter cases, it may be necessary to rely to a considerable extent on operational experience and representative values that have been reported. Some more nearly complete analyses, however, have been made. Bantin -and Lyons (19'78) in their statistical analysis of propagation effects in northern and southern Canada included rain attenuation, ionospheric scintillation, tropospheric scintillation (including multipath fading), gaseous attenuation, and pointing error due to wind. "

REFERENCES

Bantin, C.C. and R.G. Lyons, "The evaluation of satellite link availability," IEEE Trans. Commun., vol. COM-26, pp. 847-853, June 1978.

Bell Telephone Laboratories, Transmission Systems for Communications. 4th Ed. Holmdel, NJ: Bell Labs., 1971.

Calo, S.B., L. Schiff, and H. Staras, "Effects of rain on multiple access transmission of data via satellite," Record, IEEE 1978 Int. Communications Conf., Toronto, pp. 30.1.1-6.

Calvit, T.O. and L.B. Heitman, "High-speed satellite data transmission of maritime seismic data," Tech. Papers, Communication Satellite Systems Conf., 8th, Orlando, - FL, April 20-24, 1980, pp. 714-722. New York: AIAA, 1980.

CCIR, "Allowable noise power in the hypothetical reference circuit for frequency-division mulitplex telephony in the fixed satellite service," Recommendation 353-5, Vol. IV, Fixed Service Using Communication Satellites, Recommendations and Reports of the CCIR, 1986 Geneva: Int. Telecomm. Union, 1986a.

CCIR, "Spread "spectrum techniques," Report 651-2 in Vol.I, Spectrum Utilization and Monitoring, Recommendations and Reports of the CIR, 1986. Geneva: Int. Telecomm. Union, 1986b.

CCIR, "Technical and operating characteristics of distress systems in the maritime mobile-satellite service." Report 761-2 in Vol. VIII, Mobile Services, Recommendations and Reports of the CCIR, 1986. Geneva: Int. Telecomm. Union, 1986c.

Cooper, G.R. and R. W. Nettleton, "A spread-spectrum technique for high-capacity mobile communication," IEEE Trans. Veh. Technol., vol. VT-27, pp. 264-275, Nov. 1978.

Cooper, G.R. and R. W. Nettleton, "Cellular mobile technology: the great multiplier, " IEEE Spectrum, vol. 20, pp. 30-37, June 1983.

Costas, J. P., "Poisson, Shannon, and the radio amateur," Proc. IRE, vol. 47, pp. 2058-2068, Dec. 1959.

Evans, J. V., "Twenty years of international satellite communication," Radio Sci., vol. 21, pp. 647-664, July-Aug. 1986.

Feher, K., Digital Communications, Satellite/Earth Station Engineering. Englewood Cliffs, NJ: Prentice-Hall, 1983.

Freeman, R.L., Telecommunication Transmission Handbook, 2nd Ed. New York: Wily, 1981,

Goddard Space Flight Center, Tracking and Data Rely Satellite System (TDRSS) User's Guide, Revision 4, Goddard Space Flight Center, Greenbelt, MD, Jan. 1980.

Goodman, D. J., P.S. Henry, and V.K. Prabhu, "Frequency-hopped multilevel FSK for mobile radio," Bell Syst. Tech, J., vol. 59, pp. 1257-1275, Sept. 1980.

GTE Lenkurt, Engineering Considerations for Microwave Communication Systems. San Carlos, CA: GTE Lenkurt, Inc., 1972.

Heller, J.A. and I.W. Jacobs, "Viterbi decoding for satellite and space communications," IEEE Trans. Commun. Technol., vol. COM-19, pp. 835-848, Oct. 1971. Also in Van Trees (1979).

Holmes, W. M., "NASA's tracking and data relay satellite system," IEEE Commun. Mag., Sept. 1978.

IEEE (Communication Society), "Before the Federal Communications Commission, Washington, DC 20554, General Docket No. 81-413," IEEE Commun. Mag., vol. 21, p. 59-63, March 1983.

Inglis, A. F., "The United States satellite industry - an overview," Proceedings FIBRESAT 86, pp. 73-81, Vancouver, BC, Sept. 9-12, 1986,

Ippolito, L. J., R.D. Kaul, and R.G. Wallace, Propagation Effects Handbook for Satellite Systems Design, A Summary of Propagation Impairments on 10 to 100 GHz Satellite Links with Techniques for System Design, NASA Reference Pub. 1082(03). Washington, DC: NASA Headquarters, 1983.

Ippolito, L. J., RadioWave Propagation in Satellite Communications. New York: Van Nostrand Reinhold, 1986.

ITT, Reference Data for Radio Engineers, 5th Ed. Indianapolis: Howard W Sams & Co., 1968.

Jonnalagadda, "K., "Single sideband, amplitude modulated, satellite voice communication system having 6000 channels per transponder," RCA Rev., vol. 43, pp. 464-488, Sept. 1982.

Jonnalagadda, K. and L. Schiff, "Improvements in capacity of analog voice multiplex systems carried by satellite," Proc. IEEE, vol. 72, pp. 1537-1547, Nov. 1984.

Mimis, V. and A. Smalley, ."Low elevation angle site diversity satellite communications for the Canadian arctic," Record, IEEE 1982 Int. Commun. Conf., Philadelphia, PA, June 13-17, 1982, pp. 4A.4.1-5.

Minakoshi, H. et al., "Severe ionospheric scintillation associated with magnetic storm on March 22, 1979 ," J. Radio Res. Labs. (Japan), vol. 28. pp. 1-9, March/July 1981.

Miya, K. ," 'Satellite" Communications Technology. KDD Bldg. 3-2, Nishi-Shinjuku 2-chome, Shinjuku Tokyo 160, Japan, 1981.

Naderi, F. (ed.), Land Mobile Satellite Service (LMSS), Part II: Tech. Report, JPL Publ. 82-19. Pasadena, CA: Jet Propulsion Lab., 1982.

Ohmori, S. and S. Miura, "A fading reduction method for maritime satellite communications," IEEE Trans. Antennas Propagat., vol. AP-31, pp. 184-187, Jan. 1983.

Parker, E.B., "Micro earth stations as personal computer accessories," Proc. IEEE, vol. 72, pp. 1526-1531, Nov. 1984.

Parker, E. B., "Micro earth station satellite networks and economic development," Proceedings FIBRESAT 86, pp. 122-125, Vancouver, BC, Sept. 9-12, 1986.

Pelton, J. N., "Satellite telenets: a techno-economic assessment of maj"or trends for the future," Proc. IEEE, vol. 72, pp. 1445-1456, Nov. 1984.

Piraino, S.M. and A.P. Schoen, "CITISATCOM: Citicorp's digital satellite network," 82-05 i 3, Technical Papers, Communications Satellite Systems Conf., 9th, San Diego, CA, March 7-11. 1982, pp. 309-404. New York: AIAA, 1982.

Pratt, T. and C. W. Bostian, Satellite Communications. New York: Wiley, 1986.

Proakis, J.G., Digital Communications. New York: McGraw-Hill, 1983.

Utlaut, W. F., "Spread-spectrum principles and possible application to spectrum allocation," Telecomm. J., vol. 45, pp. 20-32, Jan. 1978.

Van 'Trees, H.L. (cd.), Satellite Communications. New York: IEEE Press. 1979.

Viterbi, A. J., "A processing satellite transponder for multiple access by low-rate users," Proc. Fourth Int. Conf. on Digital Satellite Communications, Montreal, Quebec, Oct. 1978.

Yue, O., "Maximum likelihood combining for noncoherent and differentially coherent frequency-hopping, multiple-access systems," IEEE Trans. Inform. Theory, vol. IT-28, pp. 631-639, July 1982.

Yue, O., "Spread spectrum mobile radio, 1977 -1982," IEEE Trans. Veh. Technol., vol. VT-32, pp. 98-105, Feb. 1983.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA RP-1108(02)	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Propagation Effects on Satellite Systems at Frequencies Below 10 GHz - A Handbook for Satellite Systems Design Second Edition		5. Report Date December 1987 6. Performing Organization Code
7. Author(s) Warren L. Flock		8. Performing Organization Report No. 10. Work Unit No.
9. Performing Organization Name and Address University of Colorado Department of Electrical Engineering Boulder, CO 80309		11. Contract or Grant No. NAS7-100; 956249 (JPL) 13. Type of Report and Period Covered Reference Publication (Second Edition)
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Frequencies below 10 GHz continue to be used for a large fraction of satellite service, and new applications, including mobile satellite service and the global positioning system, use frequencies below 10 GHz. As frequency decreases below 10 GHz, attenuation due to precipitation and gases decreases and ionospheric efforts increase. Thus the ionosphere, which can be largely neglected above 10 GHz, receives major attention in this handbook. Although attenuation and depolarization due to rain are less severe below 10 GHz than above, they are nevertheless still important and constitute another major topic. The handbook emphasizes the propagation effects on satellite communications but material that is pertinent to radio navigation and positioning systems and deep-space telecommunications is included as well. Chapter 1 through 7 describe the various propagation impairments, and Chapter 9 is devoted to the estimation or calculation of the magnitudes of these effects for use in system design. Chapter 10 covers link power budget equations and the role of propagation effects in these equations. Chapter 8 deals with the complex subject of interference between space and terrestrial systems. The second edition of this handbook supersedes the first.

17. Key Words (Suggested by Author(s)) Microwave Propagation, Slant path satellite communications systems ionosphere propagation effects, troposphere propagation effects, VHF, UHF, SHF propagation, radio noise		18. Distribution Statement Unclassified - Unlimited Subject Category 32	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 506	22. Price A22

NASA FORM 1626 OCT 86

✩ U.S. GOVERNMENT PRINTING OFFICE: 1988—526-064/61809