WHAT THE SYSTEM LINK BUDGET TELLS THE SYSTEM ENGINEER
OR
HOW I LEARNED TO COUNT IN DECIBELS

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ABSTRACT

Because it is analytically straightforward, link budget analysis often takes a back seat in engineering curricula, yet this technique represents one of the most important tools available to communications engineers and managers. This paper presents a tutorial examination of link budget development, with an emphasis on satellite communications systems, and catalogues the typical sources of loss and noise. In addition, it treats the concepts of the range equation, free space, antenna gain and effective area, system temperature, and digital versus analog parameters. This paper also illustrates a typical budget and tradeoffs using a communication satellite example.

I. SOME BASICS

Usefulness of the Link Budget

The communications system link budget is a balance sheet of gains and losses. It is comprised of the detailed apportionment of transmission and reception resources, noise sources, and signal attenuators measured from the modulator and transmitter, through the channel, up to and including the receiver and demodulator. The budget is mainly derived from the calculation of received useful power. Some of the budget parameters are statistical with large variances, e. g. , radio frequency (rf) propagation fades due to meteorological events. Link budget analysis is therefore an estimation technique for evaluating communications system performance and, as such, ranks as one of the most important tools available to the system engineer or program manager. Link budgets:

a) Are useful for rapidly determining top level resource allocations
b) Indicate hardware constraints
c) Help to predict system performance, weight, size, and cost
d) Allow recognition of the design ground rules and of system design flaws
e) Highlight reasonable design tradeoffs
f) Illustrate areas of system dependence

g) Help to predict system availability
h) Highlight system nuances
i) Facilitate changing configurations
j) Can serve as the basis for an optimal design search

Where Is the Link?

The link can best be established as that transmission path encompassing everything from the modulator and transmitter, through the channel, up to and including the receiver and demodulator. Figure 1 illustrates a block diagram for a typical satellite system transmitter-to-receiver link. The source data is first formatted and processed by a sequence of transformations within the modem (modulator/demodulator). The essential processing step here is modulation. In the case of a digital transmission system, modulation changes the bit stream to an information-bearing waveform prior to transmission. The figure illustrates the reciprocal aspect of the procedure; whatever signal processing steps take place in the transmitting chain must be reversed in the receiving chain. The modem can be thought of as the "brains" of the system(1). The transmitter, receiver, and antennas comprise the radio and are considered the "muscle."

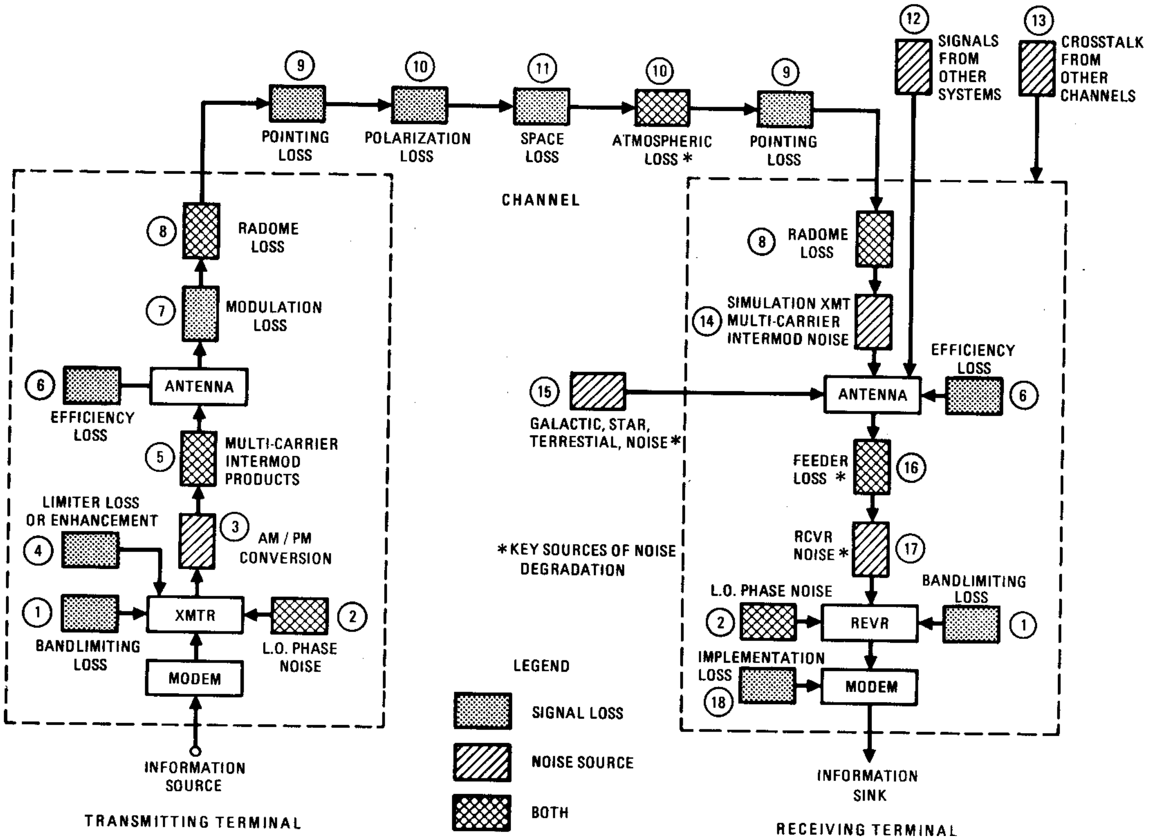

Figure 1. Satellite Communication Xmtr-to-Rcvr Link with Typical Loss and Noise Sources

The Channel

The propagating medium or electromagnetic path connecting the transmitter and receiver is called the channel. The concept of free space assumes a channel region free of all objects that might affect rf propagation by absorption, reflection, or refraction. It further assumes that the atmosphere in the channel is perfectly uniform and nonabsorbing and that the earth is infinitely far away or its reflection coefficient is negligible. The rf energy arriving at the receiver is assumed to be a function of distance from the transmitter (simply following the inverse square law of optics). In practice, of course, propagation in the atmosphere and near the ground results in refraction, reflection, and absorption, which modify the free space transmission.

A Catalog of Loss and Noise Sources

We shall restrict our discussion to those links distorted by the mechanism of additive white Gaussian noise (AWGN) only. The time waveform received at the receiver can be stated as

$$r(t) = a(t)\, s(t) + n(t)$$

where $r(t)$ = received waveform
$s(t)$ = transmitted desired waveform
$a(t)$ = attenuation (loss)
$n(t)$ = interfering waveform (noise)

Additive noise is a very useful model for the overall effects of distortion in a large class of communications systems (e. g., a satellite communication system).

Signal-to-noise ratio (SNR) is a convenient measure of performance at various points in the link. SNR is defined as

$$\text{SNR} = \frac{\text{power in desired waveform}}{\text{power in interfering waveform}}$$

The desired waveform can be an information signal, a baseband waveform, or a modulated carrier. Such a communications system primarily degrades in one of two ways: through the attenuation of desired waveform power relative to interfering waveform power, or to the increase of interfering waveform power relative to desired waveform power. These degradations are termed “loss” and “noise” respectively. Losses occur when, by some mechanism, a portion of the signal is diverted, scattered, or reflected from its intended route. Noise occurs when unwanted signal energy is injected into the link, or thermal noise is generated within the link. Thermal noise results from random motion of a conductor's free electrons caused by thermal agitation - a dissipative process.

Figure 1 represents a catalog of the most prominent sources of loss and noise in a satellite communications link. The legend utilizes a dot matrix for a loss, a crosshatch for a noise source, and a criss-crosshatch for a mechanism that might involve either (or both) loss or noise. Industry usage of the terms loss and noise frequently confuses the underlying degradation mechanisms of a particular source. For instance, sometimes a loss which is also a noise source has been called a "loss" (e. g. , atmospheric loss, line loss, radome loss). Occasionally, too, a noise source which might also manifest loss has been called "noise" (e. g. , phase noise, intermodulation noise). Since losses and noise sources are all eventually summed together, it is not essential that a precise distinction between these terms be maintained. The link budget sometimes has a single entry termed "other losses, " which allows for a large assortment of losses and noise sources.

The space loss accounts for the largest loss of signal power in a typical communications system. In satellite systems the space loss for a C-band (6-Ghz) link to a synchronous satellite is typically 200 dB, where

$$dB = 10 \log_{10} (P_1/P_2)$$

The key sources of satellite system noise degradation are the noise of the receiver amplifier and feeder line in conjunction with the noise of the receiving antenna.

II. LINK BUDGET ANALYSIS

Link Power Calculation (the Range Equation)

Figure 2 represents an omnidirectional rf source transmitting uniformly over 4 π sterad. The power density on a hypothetical sphere at a distance R from the source is related to the transmitter power P_t by

$$p(R) = P_t/4 \pi R^2$$

The power extracted with the receiving antenna can be written

$$P_r = p(R) \ A_{er}$$

$$P_r = P_t A_{er}/4 \pi R^2$$

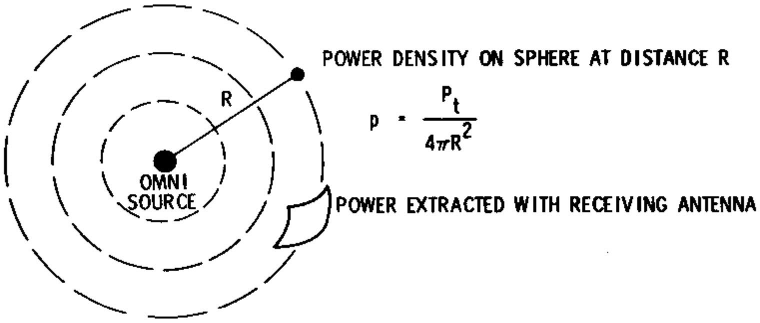

Figure 2. Power Density on Hypothetical Sphere at Distance R from Omni Source

where A_{er} is the absorption cross section of the antenna and is defined by

$$A_{er} = \frac{\text{total power absorbed}}{\text{incident power flux density}}$$

The receiving antenna's effective area and physical area are related by the efficiency η

$$A_{er} = \eta A_{pr} \tag{1}$$

which accounts for the fact that the total power is not absorbed; some of it is lost through reradiation, scattering, or spillover. Typical values for η are 0.55 for a dish antenna and 0.75 for a horn.

A common antenna parameter that measures the power output (or input) relative to the isotropic power is the antenna gain G, where

$$G = \frac{\text{maximum power intensity in some fixed direction}}{\text{average power intensity over } 4\pi \text{ sterad}}$$

Antenna gain, unlike that of an electronic amplifier, is the result of concentrating the rf flux in some restricted region less than 4 π sterad; therefore, the received power gain represents the increase in power over that calculated for an ideal omnidirectional antenna, or simply the gain referenced to isotropic. The relationship between gain and effective area is

$$G = 4\pi A_e / \lambda^2 \qquad (\text{for } A_e \gg \lambda^2) \tag{2}$$

where λ is the wavelength of the radiation. Similar expressions apply at the transmitter and receiver antennas, by the reciprocity theorem. (2) For the case in which the transmitting source manifests antenna gain over isotropic, received power is written as

$$P_r = P_t G_t A_{er} / 4\pi R^2$$

Since the effect of an antenna can be expressed as gain or area, received power can also be expressed in the following ways

$$P_r = P_t A_{et} A_{er} / \lambda^2 R^2$$
$$P_r = P_t A_{et} G_r / 4\pi R^2 \qquad (3)$$
$$P_r = P_t G_t G_r \lambda^2 / (4\pi R)^2$$

Thermal Noise

Noise, the basic system constraint, is assumed to be thermal (this is not always accurate), and its power spectral density is assumed to be flat up through the gigahertz range. AWGN is a good statistical model for thermal noise; it is also a very useful model for the overall effects of distortion in a large class of communications systems (including satellite communication systems). A common model for the thermal noise generator and its coupling into a receiving amplifier is shown in Figure 3.

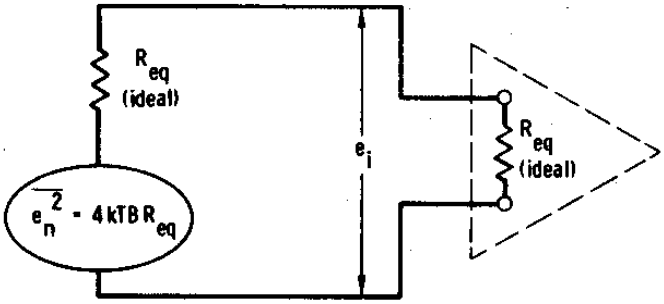

Figure 3. Electrical Model of Maximum Available Thermal Noise at Amplifier Input

The mean squared noise value is expressed as

$$\overline{e_n^2} = 4kTBR$$

where: T = temperature, K
B = bandwidth, Hz
R = resistance, ohms 3
k = Boltzmann's constant (1.38×10^{-23} Joule/K)

This represents Johnson noise, or thermal noise generated in the source resistor. (3) Let us replace the resistor R with an ideal noiseless resistor R_{eq} in series with the noise source produced by R. Let us also assume that the input impedance of the amplifier is matched to R_{eq} and is also an ideal noiseless resistor. Such matching results in the maximum available noise power coupled from the generator into the front end of the amplifier

$$N_i = e_i^2/R_{eq}$$

$$N_i = \frac{\left(\sqrt{\overline{e_n^2}}/2\right)^2}{R_{eq}} = \frac{\overline{e_n^2}}{4R_{eq}} \qquad (4($$

$$N_i = kTB$$

Back to the Range Equation

In evaluating system performance, the quantity of greatest interest is not the received power P_r, but is the SNR. This is because the basic system constraint is our ability to detect the signal, with an acceptable probability of error (P∊), in the presence of noise. (Since the desired signal here is a modulated carrier waveform, we often speak of the average carrier power-to-noise ratio (P_r/N) instead of the SNR.)

From Eq. 3 we can write

$$P_r/N = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2 \, kTBL} \qquad (5)$$

where the effective system temperature T is a function of receiver temperature, transmission line temperature, and antenna temperature (see Section III). In the above equation for P_r/N, we have introduced a term L to represent all degradation factors due to the various losses and noise sources; this term L, which represents all sources not specifically addressed by the other terms of Eq. (5) is written as

$$L = \prod_j L_j$$

where L_j is the loss or noise due to the jth degradation factor; such factors have been enumerated in Section I and Figure 1.

A quantity of great interest is the transmitter power required. We can therefore rearrange Eq. (5) and write it as

$$P_t = \frac{(P_r/N)\ kTB\ \left(\frac{4\pi R}{\lambda}\right)^2 L}{G_t G_r} \tag{6}$$

The term $(4\pi R/\lambda)^2$ in Eq. (6) is referred to as the path loss or space loss, which cannot be measured since it represents the loss due to the inverse square of the range predicated on a hypothetical isotropic receive antenna.

When Eq. (6) is expressed in decibels, the transmitted signal and noise powers are in decibel-watts (dBW), and all other terms are in decibels

P_t (dBW) = P_r /N (dB) + kTB (dBW) + space loss (dB) + L (dB) -G_t (dB) - G_r (dB)

where dBW = $10 \log_{10} \left[P_1 \text{ (W)}/1 \text{ (W)}\right]$.

Digital Communication Links

The preceding equations apply to any one-way satellite rf link. In analog systems, noise bandwidth is generally greater than signal bandwidth, and P_r/N is the main parameter for measuring signal detectability and performance quality. In digital receivers, however, matched filters or correlators, where signal bandwidth is taken to be equal to noise bandwidth, are usually used. Rather than consider input noise power, a common formulation for digital links is to replace noise power with noise density, thus eliminating the transmission bandwidth term entirely

$$N_0 = N_i/B = kT \ \text{(W/Hz)} \tag{7}$$

Then, combining Eqs. (6) and (7), we can write

$$P_t = \frac{P_r/N_0\ \ kT\ \left(\frac{4\pi R}{\lambda}\right)^2 L}{G_t G_r} \tag{8}$$

For digital systems with AWGN, the key performance parameter is E_b/N_0 instead of P_r/N_0

$$P_r/N_0 = P_r/N_0 \ (T_b R_b)$$

where T_b is the bit duration and R_b is the bit rate. As a result

$$P_r/N_0 = R_b \ (E_b/N_0)$$

Also, received or available $(E_b/N_0)_r$ can be replaced with M $(E_b/N_0)_{reqd}$, the E_b/N_0 required to meet some specified P_ϵ. The link margin M is a safety factor over $(E_b/N_0)_{reqd}$; therefore, Eq. (6) can be expressed as

$$P_t = \frac{(E_b/N_0)_{reqd}\ R_b kT \left(\frac{4\pi R}{\lambda}\right)^2 LM}{G_t G_r} \tag{9}$$

Figure 4 illustrates the basic shape of the error probability P_ϵ versus $(E_b/N_0)_{reqd}$ curve for a digital communications system. Normally, the system requirement is for some upper bound P_0 on error probability, imposing a lower bound x_0 on $(E_b/N_0)_{reqd}$. As shown in the Figure, $P\epsilon \leq P_0$ for $(E_b/N_0)_{reqd} \geq x_0$. The parameter $(E_b/N_0)_{reqd}$ reflects the differences from one system to another; these differences might be specified error rates or different modulation and coding schemes. The parameter $(E_b/N_0)_{reqd}$ also reflects the fact that the signal and noise bandwidths may not be equal for some system configurations.

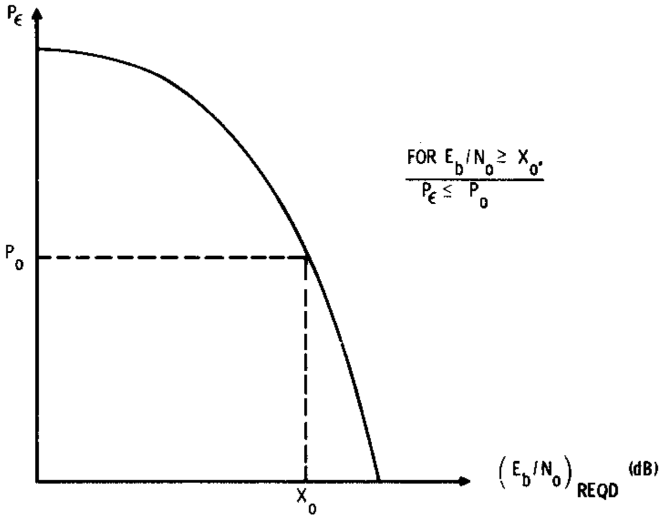

Figure 4. General Shape of the P_ϵ Versus E_b/N_0 Curve

The system link margin M is expressed by rearranging Eq. (9) as follows

$$M = \frac{EIRP_t\ G_r}{\left(\frac{4\pi R}{\lambda}\right)^2 L\ kT\ R_b\ (E_b/N_0)_{reqd}} \tag{10}$$

where $EIRP_t$ is effective radiated power (with reference to isotropic)

$$EIRP_t = P_t G_t$$

Another way of arriving at the same expression is: M = available E_b/N_0 (dB) - required E_b/N_0 (dB), which can be written as

$$M = \left[\frac{\text{Available } P_r/N_0}{R_b} \right] (\text{dB}) - (E_b/N_0)_{\text{reqd}} (\text{dB}) \tag{11}$$

Using Eqs. (5), (7), and (11), we again obtain Eq. (10).

III. NOISE FIGURE, NOISE TEMPERATURE, AND SYSTEM TEMPERATURE

Amplifier Noise and Line Losses

The noise figure F is defined as

$$F = \frac{(\text{SNR})_i}{(\text{SNR})_o} = \frac{S_i/N_i}{GS_i/G\,(N_i + N_{ai})} \tag{12}$$

where $(\text{SNR})_i$ = SNR at the amplifier input
$(\text{SNR})_0$ = SNR at the amplifier output
S_i = signal power at the amplifier input
N_i = noise power at the amplifier input
N_{ai} = amplifier noise, referred to the amplifier input
G = amplifier gain

Equation (12) can be simplified as

$$F = (N_i + N_{ai})/N_i = 1 + (N_{ai}/N_i) \tag{13}$$

The noise figure of an amplifier tells us how much noisier the amplifier is than its source, but it does not provide us with an absolute measure of the amplifier's noise. For an ideal noiseless amplifier, F = 1 (or 0 dB); note that noise figure can be made to appear small by simply using a large source resistor when taking measurements. Solving Eq. (13) for N_{ai}, we get

$$N_{ai} = (F - 1)\, N_i \tag{14}$$

The concept of receiver noise temperature equates internal receiver noise to an input resistive source at an effective temperature T_R. That is, the receiver is replaced by an ideal noiseless receiver and an input noise source kT_RB, such that the receiver output noise is equivalent to that of the original receiver. Since the receiver noise figure relates how much noisier the receiver is than its source, noise temperature can be expressed in terms of noise figure and source temperature T_0. The standard IEEE value for T_0 is 290 K.

From Eq. (4), we can write

$$N_i = k\,T_0\,B \tag{15}$$

$$N_{ai} = k\,T_R\,B \tag{16}$$

where T_0 = 290 K (room temperature reference) and T_R = receiver or amplifier equivalent noise temperature. Substituting Eqs. (15) and (16) into Eq. (14) yields

$$k\,T_R\,B = (F - 1)\,k\,T_0\,B$$

$$T_R = (F - 1)\,T_0$$

$$T_R = (F - 1)\,290\ (K) \tag{17}$$

The same technique can be used to solve for the effective temperature of the lossy line T_L (between the antenna and the receiver)

$$T_L = (L - 1)\,290\ (K) \tag{18}$$

where L, the attenuation of the line, is also the noise figure of the line if it is at room temperature. Note that even small line losses, between the antenna and a low-noise amplifier, can have drastic effects on system performance. (4)

Composite Noise Temperature

In general, a composite noise figure F_{1+2} for two tandem amplifiers with individual noise figures F_1 and F_2 and gains G_1 and G_2 can be written as

$$F_{1+2} = F_1 + (F_2 - 1)/G_1$$

Similarly, a line and amplifier in tandem have a composite noise figure as follows

$$F_{comp} = L + L(F - 1) = LF \tag{19}$$

By analogy, we can write from Eqs. (17) and (18)

$$T_{comp} = (LF - 1)\,290\ (K) \tag{20}$$

Antenna Temperature

The ideal antenna is a nondissipative device. An antenna's noise temperature is a function of what the antenna "sees" rather than what it is. The source of antenna noise may originate from celestial or atmospheric sources, from the ground or nearby objects, and from manmade sources. For earth coverage satellite antennas, 290 K is generally used as the antenna temperature. For earth-based antennas looking out toward a cooler sky temperature, the antenna temperature is often much less than 290 K. It is important to note that the noise temperature of an antenna is comprised of the noise energy entering through the main beam as well as through the sidelobes.

Sky Temperature

Figure 5 illustrates the composite sky noise temperature due to galactic sources and atmospheric absorption. Below 1 GHz the galaxy noise predominates and above 10 GHz the noise due to oxygen and water vapor absorption predominates; hence, the spectral region from 1 to 10 GHz is associated with an optimum sky noise temperature (termed the microwave or space window). (5) Note that the sky temperature is also a function of elevation angle. An elevation angle of 0 deg corresponds to a longer atmospheric path than an elevation angle of 90 deg; hence 0 deg corresponds to the worst noise temperature within the family of curves in Figure 5.

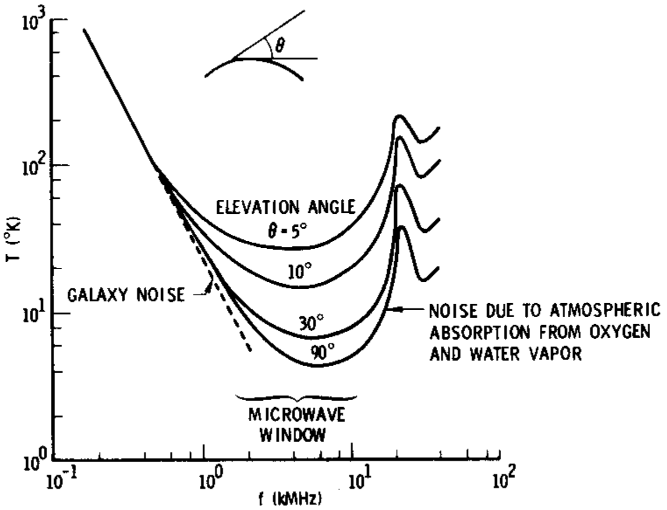

Figure 5. Sky Noise Temperature

System Effective Temperature

Figure 6 illustrates the calculation of the system effective temperature T_s, referenced to the antenna port (the input of the line)

$$T_s = T_a + T_{comp}$$

With the use of Eq. 20 we can write

$$T_s = T_a + (LF - 1)\ 290\ (K)$$

(if LF were supplied in decibels we would then write)

$$T_s = T_a + (10^{\frac{LF}{10}} - 1)\ 290\ (K)$$

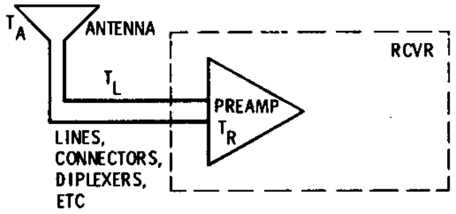

Figure 6. System Effective Temperature

IV EXAMPLE

Link Budget Example for a 4/6-Gigahertz Communication Satellite

Figure 7 shows a plot of gains, losses, and noise over the up- and downlinks for a 4/6-GHz nonregenerative communications satellite repeater (the notation 4/6 GHz means that 4 GHz is the downlink carrier frequency and 6 GHz is the uplink). Nonregenerative means that the uplink signals are not demodulated to baseband, but are simply translated in frequency and retransmitted. The sawtooth-like plot in the figure illustrates the various increases and decreases in signal and noise levels due to amplifier and antenna gains, and also due to losses and noise sources in the link.(6)

Figure 8 is a computer printout of the link budget shown in Figure 7. We shall “walk through” these up and down-links; the numbering of the following comments corresponds to the numbering on Figures 7 and 8:

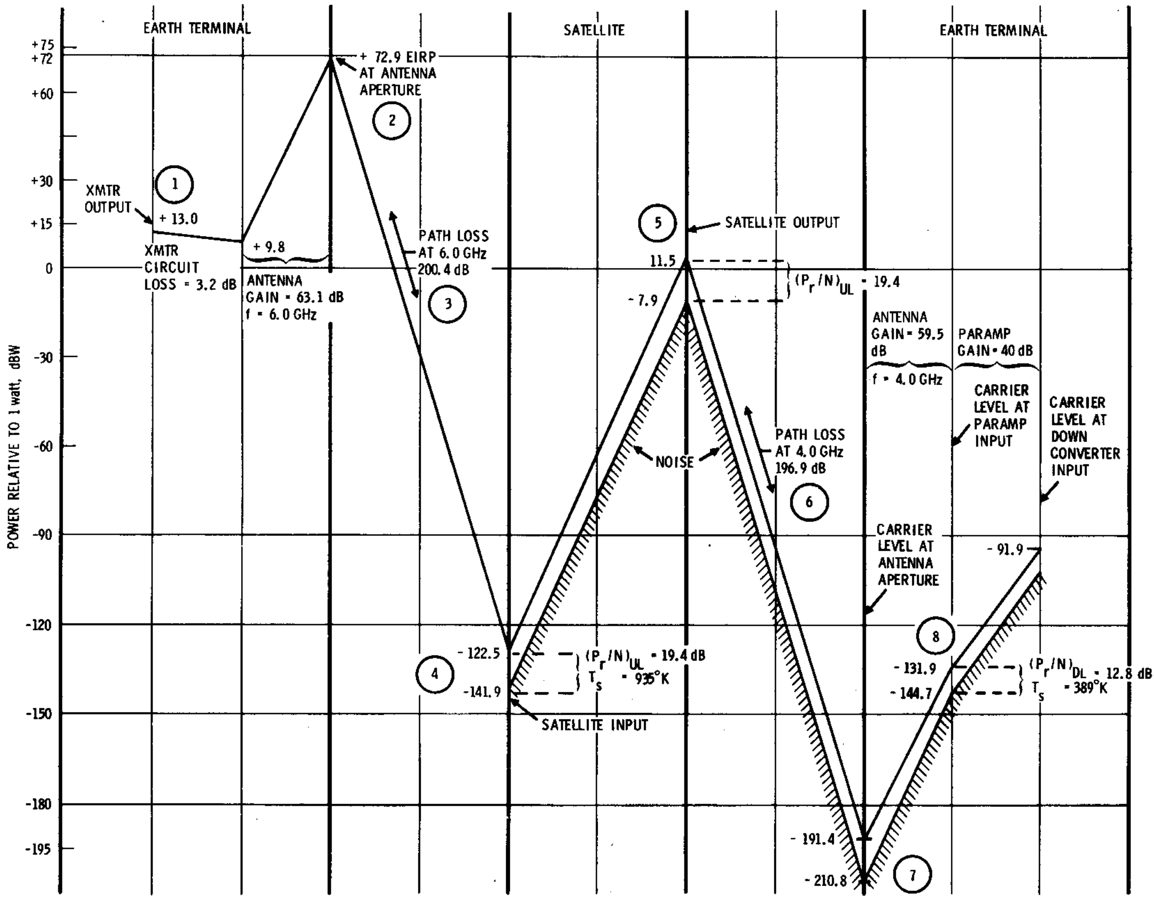

Figure 7. Gains, Losses, and Noise Over the Up- and Downlinks of a Communication Satellite System

1. The earth terminal has a 20-W transmitter (13.01 dBW). There are 3.2 dB of transmitter circuit losses, which effectively reduces the power output to 9.8 dBW.

2. The earth terminal 100-ft dish antenna at 6 GHz has a gain of 63.1 dB. The power output from the transmitting antenna is effective radiated power referenced to isotropic (EIRP) and is equal to 72.9 dBW (9.8 dBW + 63.1 dB).

3. The largest loss is the space loss of 200.4 dB, corresponding to a range of 22,500 nmi and a frequency of 6 Ghz.

3A (Figure 8 only) The received incident power (referenced to an isotropic receiving antenna) is attenuated down to -131.5 dBW. This signal is not measurable since its existence is predicated on a hypothetical isotropic antenna.

3B. (Figure 8 only) The satellite is configured with a dish antenna, 0.2 ft in diameter. At 6 GHz, its receiving gain is 9.1 dB.

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                                                         UPLINK                                        DOWNLINK

FREQUENCY (MHZ)                               6000.00                                        4000.00
RANGE (NM)                                   22500.00                                       22500.00
TRANSMITTER POWER (DBW)                                  13.01  (  20.00 W) 1                                  6.99  (   5.00 W)
XMTR CIRCUIT LOSSES (DB)                                  3.20                                                  1.00
XMTR ANT GAIN (PEAK-DB)                                  63.05                                                  5.55  5A
     DISH DIAM (FT)                            100.00                       DISH DIAM (FT)        .20
     HALF-POWER BEAMWIDTH (DEG)                   .12                                        89.81
          EIRP (DBW)                                     72.86  2                                             11.54
          PATH LOSS (DB)                                200.40  3                                            196.88  6

          XMTD SIGNAL PWR (DBW)                                                                              11.49  (  14.08 W)
          XMTD INTERF+NOISE(TH) (DBW)                                                                        ¯7.94  (    .16 W) 5

OTHER LOSSES (DB)                                         4.00                                                 6.00
          RCVD ISOTR SIGNAL PWR (DBW)                  ¯131.54  3A                                          ¯191.39  7
          RCVD ISOTR INTERF+NOISE(TH) (DBW)                                                                 ¯210.82

RCVR ANT GAIN (PEAK-DB)                                   9.07  3B                                            59.53
     DISH DIAM (FT)                               .20                       DISH DIAM (FT)     100.00
     HALF-POWER BEAMWIDTH (DEG)                 59.88                                            .18
          RCVD SIGNAL PWR (DBW)                        ¯122.48  4                                           ¯131.87  8
          RCVD INTERF+NOISE(TH) (DBW)                                                                       ¯151.29

RCVR ANT TEMP (DB-K)                                     24.89  ( 308 DEG K)                                  20.00  ( 100 DEG K)
RCVR NOISE FIGURE AT ANT PORT (DB)                        5.00                                                 3.00
RECEIVER TEMP (DB-K)                                     27.97  ( 627 DEG K)                                  24.60  ( 289 DEG K)
          SYSTEM TEMP (DB-K)                             29.71  ( 935 DEG K)                                  25.90  ( 389 DEG K)
          SYSTEM G/T (DB)                               ¯20.64  4A                                            33.63  8A

BOLTZMANN'S CONST (DBW/DEG-K/HZ)                       ¯228.60                                              ¯228.60
          THERMAL NOISE DENSITY (DBW/HZ)               ¯198.89                                              ¯202.70
SYSTEM BANDWIDTH (DB-HZ)                                 56.99  (   .50 MHZ)                                  56.99  (   .50 MHZ)
          THERMAL NOISE POWER (DBW)                    ¯141.90                                              ¯145.71

SIMULTANEOUS ACCESSES                              1

          INTERF+NOISE(TH) (TOTAL NOISE-DBW)           ¯141.90  4                                           ¯144.65
                                                                                                                       8
          PR/N (DB)                                      19.43                                                12.79
          LIMITER ENHANCEMENT (DB)                         .00
          PR/N LIMITER OUTPUT (DB)                       19.43  5

          PR/NO (DB-HZ)                                                                                       69.78  9
DATA RATE (DB-HZ)                                                                                             50.00  (100000 BPS)
          AVAILABLE EB/NO (DB)                                                                                19.78

REQUIRED THERMAL EB/NO (DB)                                                                                   15.00

NOTE:                                                                        NOISE MARGIN (DB)                 4.78       10
'INTERF' IS DEFINED AS NOISE CAUSED BY OTHER USERS.
'NOISE(TH)' STANDS FOR THERMAL NOISE.
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Figure 8. 4/6-GHz Satellite (Linear) Nonregenerative-Repeater Link Calculations

4. The measurable received signal power (increased over incident power by the satellite antenna gain) is -122.5 dBW. The noise at the satellite is comprised of receiver and line noise (627 K), antenna noise (308 K), and interference from other users (zero for now). The total satellite system noise temperature is 935 K (29.7 dB), and the channel bandwidth is 500 kHz (57.0 dB); therefore, the total input noise power kTB is equal to: -228.6 dB + 29.7 dB + 57.0 dB = -141.9 dBW.

4A. (Figure 8 only) The satellite system G/T (-20.6 dB) is a receiver figure of merit. The numerator is the gain of the receiving antenna, and the denominator is the system effective temperature. Note that G and T need not be individually specified in order to perform the link calculations. G/T is adequate; it is usually specified like this to allow antenna gain versus receiver noise figure tradeoffs.

5. In this example, the satellite downlink maintains a constant EIRP of 11.54 dBW. In nonregenerative repeaters, the uplink carrier power-to-noise ratio $(P_r/N)_{UL}$ 19.4 dB here) dictates how much of the downlink EIRP is signal and how much is noise.(7) The downlink EIRP is then divided accordingly into 11.5 dBW of signal power and -7.9 dBW of noise power.

5A. (Figure 8 only) The satellite antenna is described in item 3B (0.2-ft-diameter dish). This same antenna is simultaneously employed for transmitting the downlink as well as receiving the uplink. At the 4-GHz downlink frequency, the transmitting antenna gain is 5.6 dB (3.5 dB less than its receiving gain).

6. The downlink, like the uplink, suffers its worst loss as space loss. Here it is 196.9 dB (different from the uplink because of frequency translation).

7. The carrier level at the antenna aperture (the incident signal power referenced to isotropic) is -191.4 dBW. The incident noise is -210.8 dBW. As mentioned earlier, this is not generally a measurable quantity.

8. The earth terminal antenna is described in item 2 (100-ft-diameter dish). This same antenna is simultaneously employed for receiving the downlink as well as transmitting the uplink. At the 4-GHz downlink frequency, the receiving gain is 59.5 dB; the received signal power is -131.9 dBW. The noise here is comprised of the noise transmitted on the uplink plus the usual downlink considerations of receiver, line, and antenna noise. The earth terminal antenna is looking at a cooler temperature (100 K) than is the satellite receiving antenna; the terminal system temperature is 389 K and the total noise is -144.7 dBW. The carrier-to-noise ratio on the downlink $(P_r /N)_{DL}$ is 12.8 dB.

8A. (Figure 8 only) Here the earth terminal G/T of 33.6 dB (as compared to -20.6 for the satellite receiver) reflects the fact that the 100-ft earth dish has a much larger gain than the 0.2-ft satellite dish and also the fact that the 389 K effective earth terminal temperature is less than the 935 K temperature for the satellite system.

9. (Figure 8 only) The P_r/N_0 of 69.8 dB is obtained by adding the 57.0-dB bandwidth to the 12.8-dB P_r/N.

10. (Figure 8 only) The available E_b/N_0 (19.8 dB) is obtained by subtracting the data rate (50.0 dB) from the available P_r/N_0 69.8 dB). The margin (4.8 dB) is obtained by subtracting the $(E_b/N_0)_{reqd}$ of 15.0 dB from the available $(E_b/N_0)_r$.

Figure 8 is a typical link budget indicating expected performance at various key locations in the system. There is one important compromise in the figure, made for the sake of compactness. The item labelled “other losses” (near items No. 3A and No. 7) implies that the various losses in this category exist just prior to the point of incident power. This is not accurate. If the losses were placed in their actual locations, some of the intermediate numbers would change. The important results (e. g. , SNR and margin) would remain the same.

V. SYSTEM TRADEOFFS

A Decibel is a Decibel is a Decibel

Figure 8 indicates that, assuming all losses and noise estimates are realistic, we can expect the channel capacity to exceed 100 kbps, with a link margin of 4.8 dB. Another way of describing the 4.8-dB link margin is as follows: The 15.0-dB $(E_b/N_0)_{reqd}$ number comes from curves (similar to Figure 4) dependent on modulation, coding, and other detection parameters. It corresponds to a particular operating point on the curve, e. g. $P_\epsilon = 10^{-3}$. A margin of 4 8 dB simply says that the system will handle 100 kbps with an error rate of less than 10^{-3} (the exact error rate can be found by going back into the P_ϵ versus $(E_b/N_0)_{reqd}$ curve with a value of 19.8 dB (15.0 dB + 4.8 dB) and reading out the actual P_ϵ, e. g. , 10^{-6}. For this contrived example then, the 4.8-dB link margin means that, for safety reasons, the system is actually being designed to handle 100 kbps with a $P_\epsilon = 10^{-6}$.

Assuming that this is a desirable design goal, the system engineer can next examine all the gains, losses, and noise that brought about this link margin and consider some tradeoffs. For example (see Figure 8), he may decide that a 100-ft-diameter dish is too large or costly for the earth terminal. He may, if he has the capability of providing larger transmitter power, consider the following tradeoff: Assume that he can provide as much as 1000 W (30 dBW) of earth terminal transmitter output power. Such a signal power increase (17 dB) can be used to reduce the antenna size. This antenna is used twice in the link budget; hence, its gain can be reduced by 8.5 dB in each place. Using Eqs. (1) and (2) with $\eta = 0.55$, a decrease of 8.5 dB in antenna gain allows a decrease in dish diameter to 37.6 ft. As far as the overall performance is concerned, it will be the same as before. A transmitter power output decibel is just as good as an antenna gain decibel.

Trading Link Margin with Satellite Receiver Noise Temperature

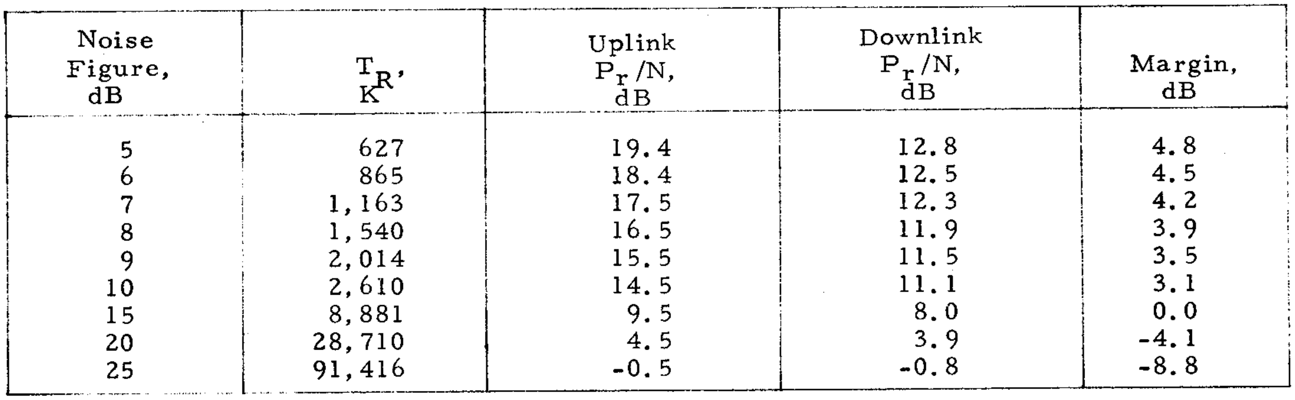
The question of how much link margin should be designed into the system is frequently asked. The answer is that if all sources of gain, loss, and noise have been rigorously detailed, and if link parameters with large variances (e. g., fades due to weather) match the statistical requirements for link availability, very little margin is needed. For satellite communications at C-band, where the parameters are known and fairly well-behaved, it should be possible to design a system with only 1 dB of link margin. Receive-only television stations operating with 16-ft-diameter dishes at C-band are frequently designed with only a fraction of a decibel of margin. However, telephone communications via satellite using standards of 99.9 percent availability use considerably more margin; some of the Intelsat systems have 4 or 5 dB of margin. Higher frequency designs (e.g., 12/14 GHz) generally call for larger margins since atmospheric losses increase with frequency and are highly variable. It should be noted that a by-product of the attenuation due to atmospheric loss is greater antenna noise. When extra margin is allowed for weather loss, additional margin should simultaneously be added to compensate for the increase in antenna temperature. With low-noise amplifiers, small weather changes can result in 40 to 50 K increases in antenna temperature.[*]

Returning to the example used in Section IV, suppose the system engineer feels that 4.8 dB of margin is excessive and would like to trade some of it for the ability to procure a satellite receiver with noise temperature greater than 627 K. The system engineer may decide that 3 dB is an adequate link margin. Table I illustrates various link features (e.g., P_r/N on the up- and downlinks and margin as a function of receiver noise figure). Examination of this table reveals that the system performs with a 3-dB margin even when the receiver noise figure (including the line) degrades to 10 dB (2610 K).

Downlink P_r/N as a Function of Uplink P_r/N in Nonregenerative Satellite Repeaters

For nonregenerative repeaters, the uplink carrier power-to-noise ratio $(P_r/N)_{UL}$ dictates how the downlink EIRP will be apportioned between signal power and noise power. For large $(P_r/N)_{UL}$, the downlink carrier-to-noise ratio $(P_r/N)_{DL}$ is essentially constrained by the loss and noise sources on the downlink alone (downlink-limited), For small $(P_r/N)_{UL}$, the $(P_r/N)_{DL}$ approximately equals the $(P_r/N)_{UL}$ (uplink-limited). (7) This can be seen by examining Table I. For all entries in the table, the $(P_r/N)_{UL}$ degrades at about the same rate as the satellite receiver noise figure. The $(P_r/N)_{DL}$, however only degrades about 0.3 dB for every decibel increase in noise figure when the $(P_r/N)_{UL}$ is large. For $(P_r/N)_{UL}$ below 9.5 dB, the $(P_r/N)_{DL}$ starts degrading faster than 0.3 dB per uplink decibel. The last two rows of the table show the $(P_r/N)_{DL}$ following the $(P_r/N)_{UL}$.

Table I. Link Features Versus Receiver Noise Figure



Noise Figure, dB	T_R, K	Uplink P_r/N, dB	Downlink P_r/N, dB	Margin, dB
5	627	19.4	12.8	4.8
6	865	18.4	12.5	4.5
7	1,163	17.5	12.3	4.2
8	1,540	16.5	11.9	3.9
9	2,014	15.5	11.5	3.5
10	2,610	14.5	11.1	3.1
15	8,881	9.5	8.0	0.0
20	28,710	4.5	3.9	-4.1
25	91,416	-0.5	-0.8	-8.8

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[*] Private communications (August 1979) with W. L. Pritchard, Satellite Systems Engineering Inc., Washington, D. C. and S. E. Levine, The Aerospace Corporation.

The link budget, then, can be used to assist the system engineer in designing an operating region to not only meet the margin requirements but also other requirements (e. g., uplink and downlink P_r/N).

Capacity as a Function of Number of Accesses

Multiple access pertains to the simultaneous utilization of a link by multiple users. There are three basic multiple access schemes for utilizing the channel resources: frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). For the first two, the multiple users' signals can generally be considered orthogonal to one another, and capacity per user can be traded off for quantity of users. Another way of saying this is that we can apportion the time-frequency resource, either in the spectral domain or the time domain, any way we like without experiencing performance or capacity degradation.

However, with CDMA, an equitable trade of simultaneous users versus capacity cannot generally be accomplished. In CDMA each link occupies the full channel bandwidth, with signal structures chosen to minimize interference between users. However, mutual interference exists between users because the signal sets are not orthogonal to each other. System capacity is limited by this mutual interference.

The total noise at the satellite receiver can be expressed as the sum of thermal noise and the interference due to the other users

$$N = N_{th} + N_{interf}$$

where N_{th} is thermal noise, It is assumed that each user's transmission is characterized by the same incident power at the satellite (affected by user protocol); therefore, N_{interf} for each user is the sum of the received power from all other users

$$N_{interf} = (Q - 1)\, P_r$$

where Q is the total number of accesses and P_r is the power received at the satellite from each user.

In the limit, as Q approaches infinity

$$N = N_{interf} = Q.P_r$$

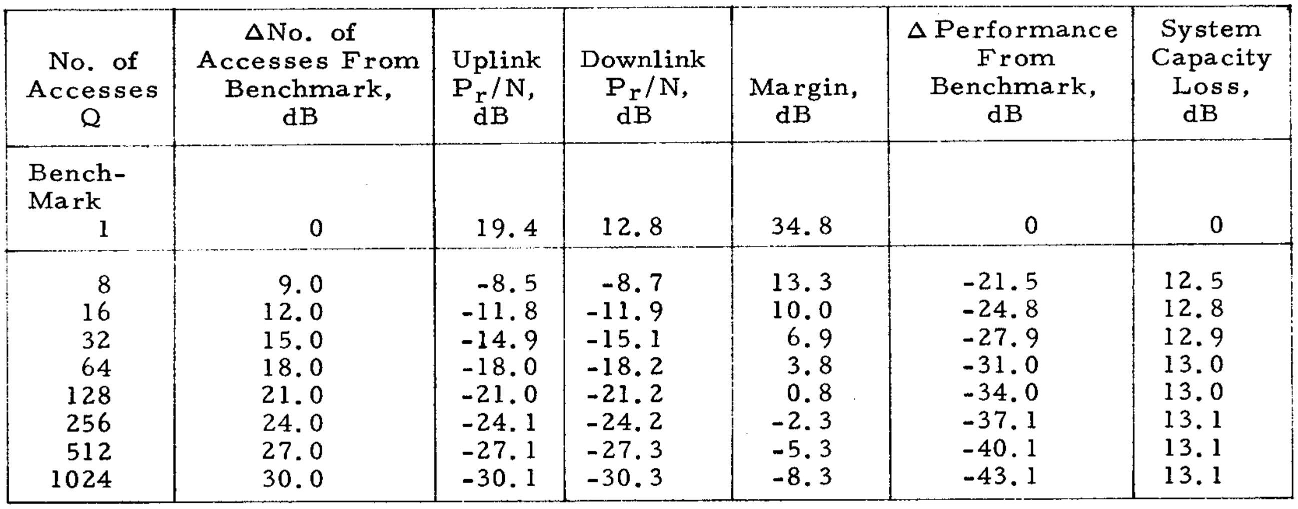
$$(P_r/N)_{UL} = P_r/Q\ P_r = 1/Q$$

$$(P_r/N)_{UL}\ (dB) = -Q\ (dB) \tag{21}$$

In the limit, then, as Q approaches infinity, P_r/N approaches the ratio of one user's signal to Q users' signals. With equal signal strength per user, this is simply 1/Q.

Table II verifies the behavior of the link according to Eq. (21). This can be seen by comparing columns 2 and 3 for $Q \geq 16$. Table II illustrates link behavior as a function of number of users for a CDM access scheme. The bit rate is 100 bps, a reduction of 30 dB from the single user example in Section IV. For other access schemes, one could expect an equitable trade of data rate versus users. Here, with 64 users, the margin is 1 dB less than our Section IV example, and the data rate is 30 dB less; therefore, the performance has degraded 31 dB. For other access schemes involving no mutual interference we would expect to serve 31 dB (1259) users, but here we are serving only 18 dB (64) users, a loss of 13 dB in system capacity.

Table II. Link Features Versus Number of Users for CDMA, 100-bps Data Rate per User



No. of Accesses Q	ΔNo. of Accesses From Benchmark, dB	Uplink P_r/N, dB	Downlink P_r/N, dB	Margin, dB	Δ Performance From Benchmark, dB	System Capacity Loss, dB
Bench-Mark 1	0	19.4	12.8	34.8	0	0
8	9.0	-8.5	-8.7	13.3	-21.5	12.5
16	12.0	-11.8	-11.9	10.0	-24.8	12.8
32	15.0	-14.9	-15.1	6.9	-27.9	12.9
64	18.0	-18.0	-18.2	3.8	-31.0	13.0
128	21.0	-21.0	-21.2	0.8	-34.0	13.0
256	24.0	-24.1	-24.2	-2.3	-37.1	13.1
512	27.0	-27.1	-27.3	-5.3	-40.1	13.1
1024	30.0	-30.1	-30.3	-8.3	-43.1	13.1

This type of loss is fundamental to CDMA, and is illustrated in Table II, column 7. The change in system capacity is obtained by summing columns 2 and 6. There is a system capacity loss of 12.5 dB that grows to 13.1 dB with increasing Q.

The advantages of CDMA are operational flexibility for low duty cycle users and potential resistance to narrowband interference and multipath. (8) The link budget allows the system engineer to make resource allocations, such as the choice of multiple access schemes. Is he willing to pay the price (13 dB in this example) for the improved flexibility? Where shall he attempt to compensate for the lost decibels, assuming they are not present as excess margin?

The Usefulness of a Link Budget

The multiple access example illustrates the use of link budgets in allocating resources and also illustrates areas of system dependence. The multiple access scheme must be chosen to accommodate the required number of users and retain the required capacity. Table II verifies that for a nonregenerative repeater $(P_r/N)_{DL}$ is downlink-limited until the $(P_r/N)_{UL}$ degrades, at which time it becomes uplink-limited.

By scanning the link budget one can methodically search the system design for over- or under-designed areas. Any of the budget parameters are candidates for tradeoff: antenna gain versus noise figure, margin versus data rate, quantity of simultaneous users versus power, coding gain versus atmospheric loss, etc.

The link budget is valuable for highlighting hardware constraints. If a power output stage shows up with an unrealizable wattage or an antenna with unrealistic dimensions, it can be readily seen. The budget allows the recognition of system nuances. Its tabular format provides a checklist for verifying the gains, losses, and noise sources at each important juncture. It also allows one to easily evaluate system performance for edge-of-coverage users or those with other constraints (e. g., users in volatile weather zones or users with a need to remain covert). Performance as a function of terminal location can be evaluated. For satellite systems, this means the effects of increased range, reduced elevation angle to the satellite, or increased rain.

The link budget allows the system engineer to determine what ground rules were used in detailing the input data. He can tell whether the losses have been methodically detailed or whether they were guessed at with “broad brush” approximations. He can check that the weather loss corresponds to the users’ outage requirements and can decide whether the margin ought to be 0.5 dB, 3 dB, or 6 dB. Once the design has been configured, he can, using weather models, predict system availability as a function of location.

In conjunction with size, weight, and cost models, one can predict the mass properties and cost of a particular communications system design. The link budget facilitates making configuration changes to satisfy changing requirements; it can also serve as the basis for an optimal design search. With the help of a computer, the system engineer enumerates all the interesting and useful tradeoffs. Keeping performance fixed, a parametric search can be undertaken for some minimization (e. g., weight, size, cost, or risk).

VI. CONCLUSION

The key sources of rf loss and noise have been catalogued. Link budget analysis has been developed, including the concepts of the range equation, free space, antenna gain and effective area, and effective system temperature. The emphasis has been on digital communication systems, particularly with the use of satellites. A typical link was described with a 4/6-GHz communications satellite example. The same example was also used to describe tradeoffs and resource allocation. In short, the paper has addressed the issue of what the system link budget tells the system engineer.

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