Terrestrial Link Budgets for Digital Communications

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Scope

The purpose of this paper is to provide a basic understanding of how to prepare a link budget for the purpose of verifying proper data transfer, at least at acceptable error rates, of a digital RF communication system. Although some of the issues discussed may be outside those normally encountered at amateur radio bands, their discussion may provide some useful background information for the reader. Basis equations are provided.

The Basics

Probably most amateur radio operators are familiar with the term signal to noise ratio (SNR or S/N) as a parameter applied to voice communications. The higher the signal (S) and / or the lower the noise (N), the higher the likelihood of being understood over the radio. The digital equivalent of S/N is energy per bit (E_b) over noise power density (N_o). This is the energy in a single bit over the noise in a one Hertz bandwidth, is designated as E_b/N_o, and is measured in dB. A link budget is a concise way of determining if communications is possible with the given set of equipment and channel parameters (ie, path losses). The equation is as follows:

$$Eb/No = EIRP - L + G/T - k - R \qquad \text{Eq 1}$$

Where E_b/N_o = received energy per bit over noise power density, in dB
EIRP = transmitter Effective Isotropic Radiated Power, in dBW
L = sum of all path losses, in dB
G/T = receiver figure of merit, in dB/K (dBK^{-1})
K = 10 Log (Boltzmann's constant) = -228.6 dB
R = 10 Log (Data Rate, in bits per second)

Once the received E_b/N_o is known it can be compared to a bit error rate (BER) vs E_b/N_o graph for the type of digital modulation in service. Figure 1 illustrates such a graph for BPSK modulation. The received Eb/No is found on the horizontal axis and a vertical line is drawn from that point up till it intersects the curve. From that point, a horizontal line is drawn to the left to find the associated BER. As a general rule, a BER of at least 10^{-5} is desirable for reasonable link closure of digital RF systems. It should be noted that Figure 1 provides theoretical values. Actual modem designs may have additional implementation losses.

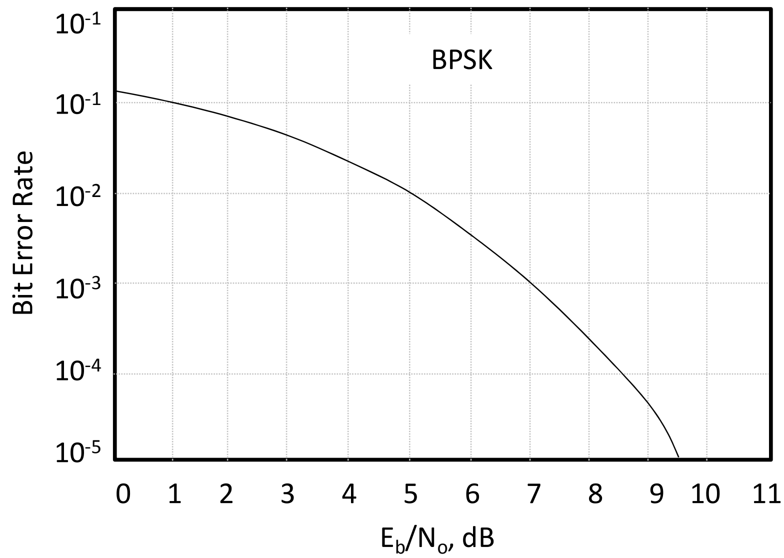

Figure 1: BPSK BER vs E_b/N_o

The Devil Is In the Details

Simple enough, but the devil is in the details.

EIRP is the transmitter power out minus the losses between the transmitter and the antenna (e.g., cable losses, RF duplexers, etc) plus the antenna gain. In simple terms, the G/T is the receiver antenna gain divided by the receiver system noise temperature. The latter is a measure of how much noise is contributed by the receiver itself but should also include the impact of the sky temperature, and reflected ground temperature, if any, as seen by the receiving antenna. Determining G/T is a bit more of a difficult task and is beyond the scope of this paper. For purposes of this paper, we will assume that EIRP and G/T are already known.

A lot of factors can play into the RF path losses and we will mention a few of them now. The first loss to consider is free space loss or spreading loss. This is the reduction in signal strength as the RF wave travels away from the transmitting source. It is a function of frequency and distance between the transmitter and receiver. An equation for free space loss is shown below:

$$L_{fs} = 32.4 + 20 \text{ Log } F + 20 \text{ Log } D \qquad \text{Eq 2}$$

Where L_{fs} = free space loss, in dB

F = frequency, in MHz

D = distance between transmitter and receiver, in km

Rain attenuation is another concern, particularly at microwave frequencies. A simple approach uses readily available graphs of dB/km loss vs frequency at various rain fall rates. The designer determines the rain fall rate the link will be subjected to and looks up the rain loss, in dB/km, from the appropriate graph. Once the dB/km rain attenuation is known, simply multiply this value by the path length, in km, to get the total rain fall attenuation for the link. This will yield a very conservative and often overly constraining rain loss. It assumes a uniform rate of rainfall across the entire path which is generally not encountered in nature. More realistic estimates of rain fall attenuation are available from different models. One that comes to mind is the two-component Crane rain model [4]. Gaseous attenuation from oxygen molecules and water vapor in the atmosphere can also be an issue at microwave frequencies. The Rice gas model can be used to estimate this loss [5]. Terrain effects must be taken into account for point to point links at microwave frequencies. Such links may experience refraction, diffraction, or reflection. Refraction is the bending of the RF ray caused by changes in the refractive index of the medium through which it travels. This accounts for the well know 4/3 effective earth's radius (caused by refraction through a "typical" atmosphere). Diffraction is the bending of the RF ray around obstacles in its path. The amount of bending – and associated loss of the signal at the receive antenna – is a function of the type of terrain. Sharp edges, such as a building, result in less loss than a smooth, spherical surface such as a large, gently sloping hill. Reflected signals can arrive at the receive antenna in phase with the direct ray from the transmitter, out of phase, or any where in between. If they arrive in phase, they add to the direct ray and actually increase the received signal at the receive antenna. If they arrive out of phase, they cancel the direct ray resulting in deep fades at the receive antenna. Terrain loss is affected by the topography, type of soil, antenna height, and earth's curvature. Antenna heights and site selection must provide adequate clearance along the RF path from transmitter to receiver. A good rule of thumb is to maintain a line of sight clearance at least 60% of the first Fresnel zone radius. Due to curvature of the RF ray, communications may be possible even if this clearance criterion isn't met, but higher terrain losses will be incurred. These are complex loss mechanisms and are best left to computer models. A good one, free of charge, is "RF Signal Propagation Loss and Terrain" (SPLAT). Search for it on the internet for free downloads and instructions. Reference [5] provides a detailed discussion of the issues discussed above. A source of severe, time varying fades is hot, stagnant air sometimes encountered in the early morning or evening in coastal areas. Such atmosphere anomalies can cause severe refraction and / or reflection resulting in deep fades (tens of dB) lasting for several minutes. ITU P.530 [6] provides a model for estimating such losses. Foliage is another issue. At some radio frequencies, the attenuation due to foliage is in the dB's per *meter*. The best way to mitigate this is to be clear of foliage, either by antenna height or site selection.

This concludes our discussion on link budget topics. This has not been an exhaustive discussion of the topic and the reader is encouraged to delve deeper. Obviously, a link budget will only be as accurate the detail one puts into identifying and correctly quantifying all the parameters in equation 1, with particular attention to the path losses.

An Example

Consider a fictitious link operating in the 23 cm amateur band at 1240 MHz. The radio parameters used in this example do not represent any specific class of radio but are intended for illustrative purposes only. Assume a smooth earth, path length of 18.94 miles, with antennas 20 feet high at both ends. EIRP and G/T are as shown. Assume a data rate of 1 Mbps with BPSK modulation. The link budget, per equation 1, is shown in Table 1 below. Note the high terrain loss. This is caused by inadequate clearance over the earth's curvature in this simple example.

Frequency, GHz	1.24	
EIRP, dBW	12	12
Path Length, miles	18.94	
Path, km	30.304	
Free Space Loss, dB	123.90	
Terrain Loss, dB	47.2	
Rain, dB	0.07	
Gas, dB	0.18	
Total Losses, dB	171.34	171.34
G/T, dBk^{-1}	-8	-8
Boltzmann's constant, J/K	1.38E-23	
K, dB	-228.60	-228.60
Data Rate, bps	100000	
R, dB	50	50
	E_b/N_o, dB	11.26

Table 1: Example Link Budget

Compare the resulting E_b/N_o of 11.26 dB to the BER vs E_b/N_o curve of figure 1. The 11.26 dB is greater than the ~ 9.5 dB required for a BER of 10^{-5}. Thus, the link should provide reasonable service.

Conclusion

This paper has provided a brief overview of terrestrial link budgets for digital communications with a fictitious example in the 23 cm amateur band. Various issues associated with RF path losses were also discussed and the reader was introduced to various models that can be useful in completing link budgets.

References

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[3] An Introduction to Satellite Communications, D.I. Dalgeish

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[6] Propagation data and prediction methods required for the design of terrestrial line-of-sight systems, RECOMMENDATION ITU-R P.530-9