Link Budgets

Signal-to-Noise Ratio

As introduced in the notes on noise, ultimately the performance of a communications system is ultimately limited by the achievable *signal-to-noise ratio (SNR)* at the receiver. Generally, there is a threshold below the performance of the communication system is unacceptable. In digital communication systems, the bit error rate of the system often becomes unacceptably high (according to the promised performance by a communication system) below a certain SNR. We have employed *link budgets* to predict the received power in a communication system. A natural evolution to a link budget to adapt it to determine the received SNR.

In this course we have focused on narrowband radio systems where a sinusoidal signal is assumed. In practise, the sinusoid acts as a carrier for the information signal, which is the true "signal". Hence, strictly speaking, the SNR refers to this power of the recovered signal power to noise power. We will use the term *carrier-to-noise ratio (CNR)* to refer to the received carrier power. Here, we will use the symbol c to refer to the received carrier power and n to the noise power.

Friis' formula can be written as

$$C = EIRP\left(\frac{\lambda}{4\pi r}\right)^2 \frac{G_r}{l}$$

where l is other losses over and above the free-space loss, and EIRP has been defined previously as the product of the transmit power and transmit gain (effective radiated isotropic power). It could be polarization loss factor, impedance mismatch loss, diffraction loss, plane-earth reflection loss, etc. including a combination of these effects.

The carrier-to-noise power ratio is found by setting $N = kT_S B$:

$$\frac{C}{N} = EIRP\left(\frac{\lambda}{4\pi r}\right)^2 \frac{G_r}{lkT_S B}$$

It is common to represent the CNR over 1 Hz of signal bandwidth ($B = 1$ Hz), so that the resulting expression can simply divided by the bandwidth to get the ratio:

$$\frac{C}{N_0} = EIRP\left(\frac{\lambda}{4\pi r}\right)^2 \frac{1}{lk}\frac{G_r}{T_S}$$

In dB, this expression becomes

$$\left[\frac{C}{N_0}\right]_{\text{dB}} = EIRP - FSL - L + \left[\frac{G_r}{T_S}\right]_{\text{dB}} + 228.6 \qquad \text{(units: dB-Hz)}$$

where $10\log(1/k) = 228.6$ dBW/K-Hz. Note that receive antenna's gain and the receiver temperature are grouped together as a ratio that is often called the *receiver figure of merit*. This per-Hz form of the CNR is useful since the CNR can be found for any signal bandwidth by simply subtracting $10 \log B$:

$$\left[\frac{C}{N}\right]_{\text{dB}} = EIRP - FSL - L + \left[\frac{G_r}{T_S}\right]_{\text{dB}} + 228.6 - 10\log(B) \qquad \text{(units: dB)}$$

Hence, a link budget is obtained by "accounting" for each of these terms in a budget in dB units, where losses are "negative" and gains are "positive". Usually, L must be expanded into a larger summation of terms to account for each of the loss effects that we have studied in detail in this course.

Link Margin

As discussed in class, some additional margin is usually provided for in the implementation of the system so that it can deal with worst-case fading caused by the atmosphere and other effects. The margin is usually introduced by increasing a combination of the transmit power, transmit antenna gain, and receive antenna gain. Often, it is the margin that is of most interest in the budget, since it tells you how much room is built into the link budget. If the minimum required CNR CNR_{req} is known, the margin is simply the difference in dB between the actual CNR and the required CNR:

$$M = EIRP - FSL - L + \left[\frac{G_r}{T_S}\right]_{\text{dB}} + 228.6 - 10\log(B) - \left[\frac{C}{N}\right]_{req,\text{dB}}$$

A nice example link budget for a satellite system is taken from page 229 of Sklar, B., "Digital Communications: Fundamentals and Applications", Prentice-Hall, 1998, and is shown in Table 1. It is an uplink budget (from the earth terminal to the satellite) at 8 GHz, covering a distance of 40,721 km. The bandwidth of the satellite signal is 2 MHz.

Note that the losses L appear multiple times in the table, alluding to the fact that all these terms must be summed to yield the total losses in the system. These losses total 13.5 dB and include:

- Fade allowance (6) refers to extra margin added to compensate for fading introduced by atmospheric and/or rain attenuation.
- Other losses (7) could include polarization loss, and propagation-related losses not modelled by free-space loss calculations.
- Edge of coverage loss (10) refers to the losses seen user at the edge of the coverage pattern, where the gain of the antenna (pattern) is lower and the signal also has a larger range to cover. Choosing the edge of the coverage pattern makes the budget conservative by assuming a worse-cast scenario.
- Implementation loss (17) refers to implementation losses in the receiver (e.g. detector efficiency)

	Description	Symbol	Value	Notes
1.	Transmit power	W_t	**20.0 dBW**	100.0 W
2.	Transmit circuit loss	$-L_t$	-2.0 dB	
3.	Transmitter antenna gain	G_t	51.6 dBi	20 ft dia. dish, 55.1% efficiency
4.	Terminal EIRP	$EIRP$	**69.6 dBW**	
5.	Free space path loss	$-FSL$	-202.7 dB	
6.	Fade allowance	$-L$	-4.0 dB	Rain fade allowance
7.	Other losses	$-L$	-6.0 dB	Other losses
8.	Received isotropic power	W_r/G_r	**-143.1 dBW**	Received power before gain
9.	Receiver antenna gain	G_r	35.1 dBi	3 ft dia. dish 55.1% efficiency
10.	Edge of coverage loss	$-L$	-2.0 dB	
11.	Received signal power	W_r	**-110.0 dBW**	
12.	Noise PSD	N_0	-192.5 dBW/Hz	$N_0 = kT_S$, $T_S = 4106$ K
13.	Received W_r/N_0	W_r/N_0	**82.5 dB-Hz**	
14.	Bandwidth	$-B$	-63.0 dB-Hz	$10\log(2$ MHz$)$
15.	Received CNR	CNR	**19.5 dB**	
16.	Implementation loss	$-L$	-1.5 dB	e.g. detector efficiency
17.	Required CNR	$-CNR_{req}$	-10.0 dB	
18.	Link margin	M	**8.0 dB**	

Table 1: Example Link Budget showing Receive Antenna Gain

Transmitter loss is treated separately since it affects the EIRP directly.

The system temperature was obtained known that the antenna temperature was 300 K, the receiver equivalent temperature was 3806 K, and the noise figure of the receiver was 11.5 dB. Hence, the system temperature is 4106 K or 36.1 dB-K.

In Table 1, the budgeting is similar to have we have handled link budgets in the past: receive antenna gain is accounted for directly and the signal-to-noise ratio calculated directly by computing the noise power kT. Hence, to calculate the received W_r/N_0 ratio, you simply divide the received isotropic power by kT or subtract 192.5 dBW/Hz in the budget.

You can also compute the link budget using the receiver figure of merit as defined earlier. Obviously, using either technique you should get the same result. The link budget employing the receiver figure of merit is shown in Table 2.

In equation form, the link margin is calculated as follows:

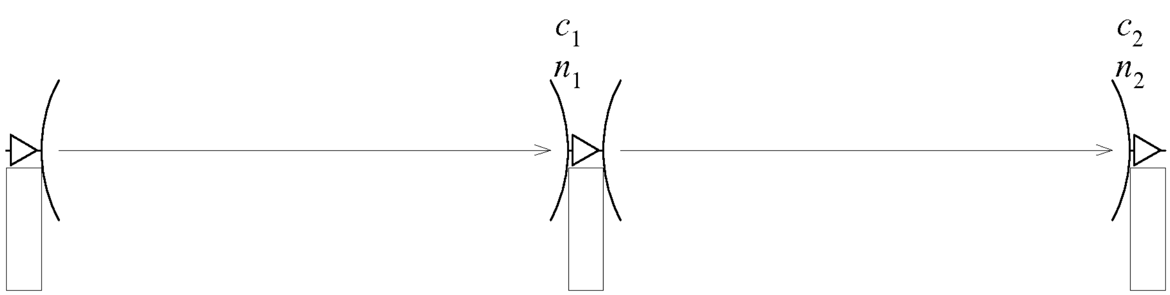
$$
\begin{aligned}
M &= EIRP - FSL - L + \left[\frac{G_r}{T_S}\right]_{\text{dB}} + 228.6 - 10\log(B) - \left[\frac{C}{N_0}\right]_{req,\text{dB}} \\
&= 69.6 \text{ dBW} - 202.7 \text{ dB} - 13.5 \text{ dB} + (-1.0 \text{ dB}) + 228.6 \text{ dBW/K-Hz} \\
&\quad -10\log(2 \text{ MHz}) - 10.0 \text{ dB} \\
&= 8.0 \text{ dB}
\end{aligned}
$$

	Description	Symbol	Value	Notes
1.	Transmit power	W_t	**20.0 dBW**	100.0 W
2.	Transmit circuit loss	$-L_t$	-2.0 dB	
3.	Transmitter antenna gain	G_t	51.6 dBi	20 ft dia. dish, 55.1% efficiency
4.	Terminal EIRP	$EIRP$	**69.6 dBW**	
5.	Free space path loss	$-FSL$	-202.7 dB	
6.	Fade allowance	$-L$	-4.0 dB	Rain fade allowance
7.	Other losses	$-L$	-6.0 dB	Other losses
8.	Received isotropic power	W_r/G_r	**-143.1 dBW**	Received power before gain
9.	Edge of coverage loss	$-L$	-2.0 dB	
10.	Receiver figure of merit	G_r/T_S	-1.0 dB	35.1 dB - $10 \log T_S$
11.	Boltzmann's constant	k	228.6 dBW/K-Hz	
12.	Received W_r/N_0	W_r/N_0	**82.5 dB-Hz**	
13.	Bandwidth	$-B$	-63.0 dB-Hz	$10 \log(2$ MHz$)$
14.	Received CNR	CNR	**19.5 dB**	
15.	Implementation loss	$-L$	-1.5 dB	e.g. detector efficiency
16.	Required CNR	$-CNR_{req}$	-10.0 dB	
17.	Link margin	M	**8.0 dB**	

Table 2: Link Budget using G_r/T_S

Multi-Hop Radio Links

Multi-hop links are used for sending microwave signals over long distances using intermediate transponders, which can be particularly useful for creating over-the-horizon links. The analysis of the resulting CNR in a multi-hop link is similar to the analysis of cascaded networks when we studied noise figure earlier in the course. Consider a two hope radio link as shown in the notes.



C_1 is the carrier power at the output of the first link. It is amplified by an amplifier, then undergoes gains/losses associated with a standard radio link to the next hop. The cumulative gain between the links is defined as α, so that the output signal power is $C_2 = \alpha C_1$.

The noise power at the output of the link is not simply αN_1 since the second link may introduce noise as well (either externally or internally generated by components on that link). Hence,

$$N = \alpha N_1 + N_2,$$

which is similar to the noise power at the output of a network with gain α: the input noise is scaled by α, and the network adds a noise of its own at the output. The resulting ratio of the overall noise to the final received carrier power is

$$\frac{N_T}{C_2} = \frac{N_2}{C_2} + \frac{\alpha N_1}{C_2} = \frac{N_2}{C_2} + \frac{\alpha N_1}{\alpha C_1} = \frac{N_2}{C_2} + \frac{N_1}{C_1}.$$

The CNR of the link is

$$\frac{C}{N} = \left[\left(\frac{C_1}{N_1} \right)^{-1} + \left(\frac{C_2}{N_2} \right)^{-1} \right]^{-1}.$$

This is the result for $M = 2$ link segments. We can generalize for M link segments, which results in

$$\frac{C}{N} = \left[\sum_{i=1}^{M} \left(\frac{C_i}{N_i} \right)^{-1} \right]^{-1}.$$