Santa Clara University

MECH/ENGR 371
Space Systems Design and Engineering

Communications Systems - Link Budget

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Overview

- Introduction
- Derivation of the Link Equation
- Details on Specific Parameters
  - Antennae Gains and Errors
  - Atmospheric Losses
  - System Temperature
- Computing a Link Budget
- References

Link Budget Objectives

- The "Link Budget" allows us to characterize the quality of the satellite's wireless communications link in a quantitative fashion
- Used in the design process to "size" parameters and components in the satellite's communications system and in the ground segment communications systems
  - What should the broadcast power be?
  - How big should my antennae be (or which antenna at my disposal should I use)?
  - How fast can I send data?
  - If I use an error detection and correction encoding technique, can I get away with a "noisier" link and therefore save resources elsewhere?
- Used in the operations process to predict link performance given the operational equipment and parameters
  - At what elevation should I expect to get good communications?
  - Can I improve performance by moving to a different antenna, by changing a power setting, by modifying my data rate, or by varying another parameter?
  - How well do I have to be able to point my antenna?

Link Budget Concept

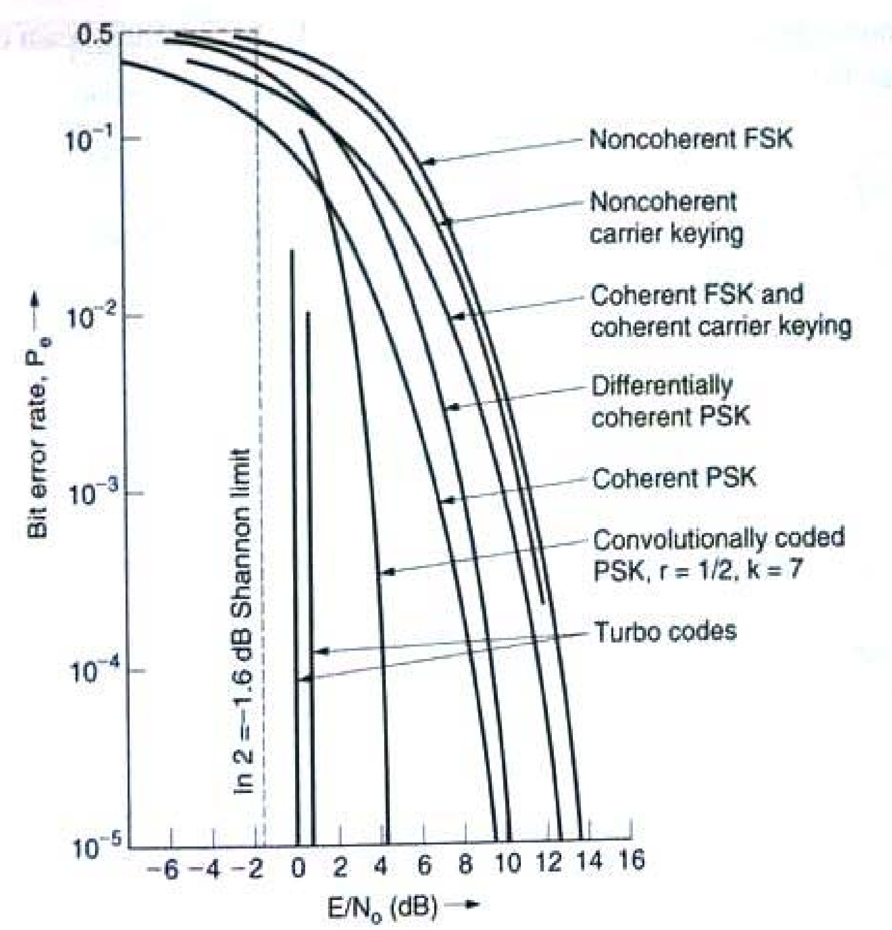
- The budget is an equation that includes the effect of:
  - Transmit Power (more power is better since it provides a stronger signal)
  - Antenna Gain (more gain is better since it means the more of the radiated power is being sent to or received by the recipient)
  - Antenna Pointing Losses due to antenna pointing error (if you have gain, you are focusing your communication beam, and if that is pointed the wrong direction, you receive less energy from the signal)
  - Distance (Path) Losses due to being far away (as the distance to the recipient increases, the energy in the transmit beam is spread out over a larger and larger area, reducing the amount of energy that is received)
  - Atmospheric Losses due to atmospheric absorption, etc.
  - Data Rate effects (power is energy per time, and "signal to noise" considers the amount of energy per bit of the signal; so, higher data rate means more bits per sec, which means that there is less energy in any one bit for a constant level of power)
  - And so on…

Link Budget Concept

- The equation quantifies performance in the form of a "Signal to Noise" ratio, with a higher value being better
- Some effects are directly computed, some are looked up, etc.
- Caution: Some seemingly simple issues can effect more than one parameter and therefore lead to non-intuitive results
  - Example: Antenna dish size – a bigger dish means a larger gain, which is good. However it also means a tighter beam, so a nominal pointing error will lead to a greater loss.
- The equation is typically written in either of 2 equivalent ways:
  - A ratio with various multiplicative parameters in the numerator or denominator
  - The log of that equation, which turns the expression into a sum of parameters
- The equation is often computed in a spreadsheet

Link Budget Concept

- Computing the Link Equation results in a "signal to noise" ratio in dB
- So what? How many dB is necessary for a "good" link
- To determine this, you consider the acceptable Bit Error Rate (BER) and your error encoding and modulation choice
  - For a given BER, a more capable encoding/modulation choice results in a lower required E_b/N ratio
  - For a given encoding/modulation choice, achieving a better BER requires a better E_b/N ratio
- The "link margin" is the number of dB you have above this required level. Comm link requirements often specify a link margin.



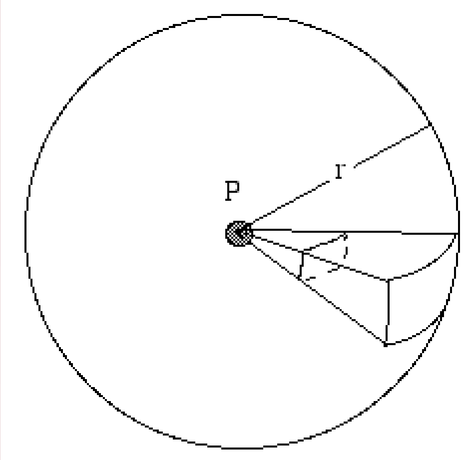
Link Equation

Derivation

Link Equation Derivation

- Consider a point source transmitter radiating an electromagnetic wave with power P_t in Watts (W)
- The wave front is spherically symmetric, so the power is "spread out" over the surface of the sphere (and so is subject to the inverse square law) :

$$flux\ density = \frac{P_t}{4\pi R^2} \quad \text{in W/m}^2$$



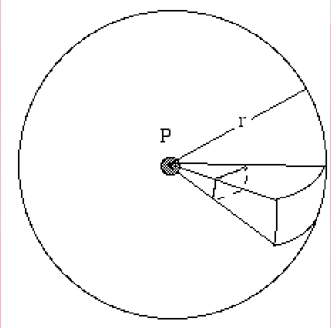
- A receiving aperture of effective area A_e intercepts a fraction of the total power:

$$P_r = \frac{P_t A_e}{4\pi R^2} \quad \text{in Watts}$$

P_t=Power transmitted
P_r=Power received
R=distance btw transmitter & receiver
A_e=area of receive antenna

Link Equation Derivation

- Now, considering a transmit antenna Gain G_t so that the power is focused:



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

- The receiver antenna Effective Area is related to the gain by:

$$G_r = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi A_e f^2}{c^2} \qquad \text{given}: \ \lambda = \frac{c}{f} \qquad \text{so}: \ A_e = \frac{G_r c^2}{4\pi f^2}$$

- Replacing A_e in the first equation:

$$P_r = \frac{P_t G_t G_r c^2}{4\pi R^2 \, 4\pi f^2} = \frac{P_t G_t G_r c^2}{(4\pi R)^2 \, f^2}$$

Link Equation Derivation

- Substituting in the definition of "Path Loss":

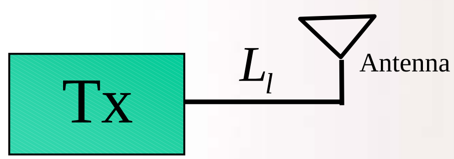
$$P_r = \frac{P_t G_t G_r c^2}{(4\pi R)^2 f^2}$$

L_s = Path Loss

(function of distance and frequency)

$$P_r = P_t G_t G_r L_s$$

- Add $L_{\theta t}$ and $L_{\theta r}$, antenna pointing losses $\quad P_r = P_t G_t G_r L_s L_{\theta t} L_{\theta r}$
- Add L_a, loss due to Atmospheric absorption $\quad P_r = P_t G_t G_r L_s L_{\theta t} L_{\theta r} L_a$
- Add L_l, loss due to signal loss in cabling $\quad P_r = P_t G_t G_r L_s L_{\theta t} L_{\theta r} L_a L_l$



Cable type, length, connectors, fnc(freq)

Link Equation Derivation

- We are interested in the "signal-to-noise ratio" at the receiver. For digital systems, this is the ratio of Bit Energy to Noise Density (E_b/N_0)
  - Bit Energy: $E_b = P_r \times [bit\ duration] = \frac{P_r}{R}$ where $R = data\ rate\,[bps]$
  - Noise is considered to be "White Noise" and proportional to temperature

$$N_o = kT_s \quad \text{where } k : \text{Boltzmann's constant} = 1.38\text{x}10^{-23}\ \text{m}^2 kg / s^2 K$$
$$T_s : \text{System Temperature}$$

  - Therefore: $$\frac{E_b}{N_o} = \frac{P_r}{kT_s R} = \frac{P_t G_t G_r L_s L_{\theta t} L_{\theta r} L_a L_l}{kT_s R}$$

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Link Equation Derivation

- For convenience, it's often expressed in decibels (dB):

$$decibels = 10\log_{10}(power\ ratio)$$

- So:

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r L_s L_{\theta t} L_{\theta r} L_a L_l}{kT_s R}$$

- Becomes:

$$\left.\frac{E_b}{N_o}\right|_{dB} = P_t + G_t + G_r + L_s + L_{\theta t} + L_{\theta r} + L_a + L_l + 228.6 - 10\log_{10} T_s - 10\log_{10} R$$

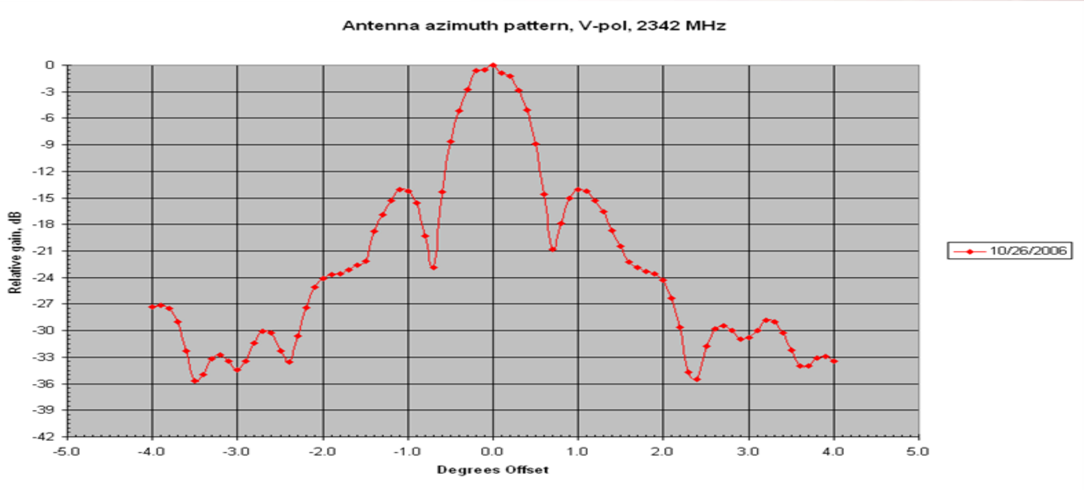
- Note: The equation may be used without considering all terms (e.g., pointing angles, etc.), and sometimes additional terms are used as appropriate (e.g., additional amplifiers, etc.).

Link Equation

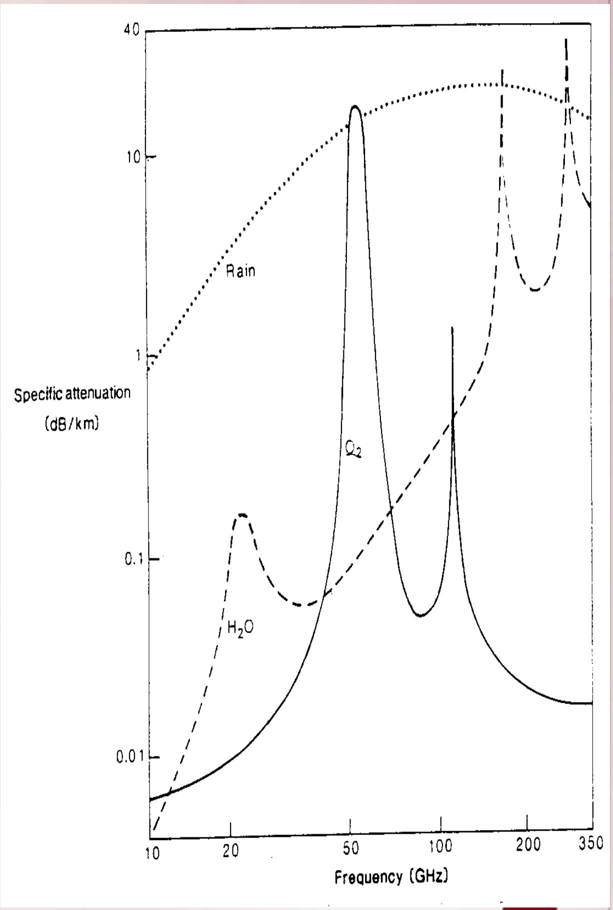
Details

Link Equation Details

- Antenna parameters
  - EIRP (Effective Isotropic Radiated Power) = $P_t L_l G_t$
  - A_e = (aperture size) x (efficiency)
    $= \pi D^2 \eta / 4$ [where efficiency typically 0.55-0.6]
  - $G_r = A_e$/(area of isotropic antenna)
    $= A_e/(\lambda^2/4\pi) = 4\pi A_e/\lambda^2$
- Antenna Pointing Error



- Atmospheric Loss

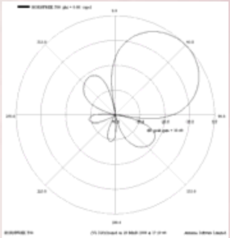


Link Equation Details

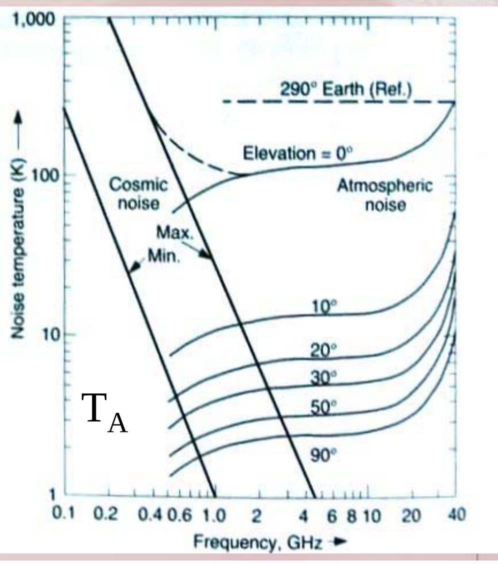
- Noise:
  - Objects at non-zero temp radiate energy → comm system noise
  - <u>Example</u>: a satellite antenna sees the noise of the Earth at ~290 °K
  - <u>Boltzmann's constant</u>: kinetic energy (of particles) per °K (of the aggregate object)
- System Temperature (measure of noise): $T_s = T_A + T_L + T_R$
  - <u>Received noise</u> (antenna noise, T_A): galactic, solar, Earth, man-made sources, objects blocking the antenna FOV,etc
    - This temperature depends on gain pattern and temperature distribution in every direction around the antenna
    - Weighted (by gain) average temperature around the antenna

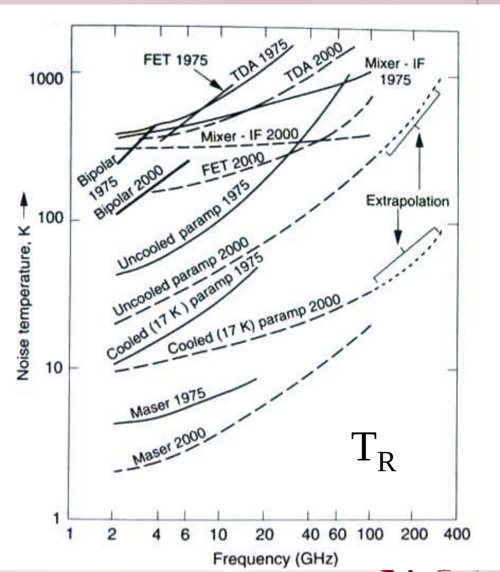
$$T_A \approx a_1 G_1 T_1 + a_2 G_2 T_2 + a_3 G_3 T_3 + \ldots$$

$$a_1 + a_2 + a_3 + \ldots = 1$$



  - <u>Internal noise</u>: sources btw antenna & receiver output
    - T_L,= line temp (35 °K typical), T_R = receiver/amplifier temp
    - Depends on the technology and the temperature
    - Receivers often specify their "noise figure": $T_r = 290(10^{\frac{NF[dB]}{10}} - 1)$





Link Equation

Computation in Spreadsheet Form

Link Budget and Mission Design

GeneSat-1 2.4GHz DownLink Budget						
Item	**Units**	**Source**	**DL**	**DL**	**DL**	**DL**
Orbit Altitude (km)	km		**410**	410	410	410
Elevation Angle	deg		**0**	**10**	**45**	**90**
Frequency	GHz	Input parameter	**2.4**	2.4	2.4	2.4
Transmitter Power	Watts	Input parameter	**1**	1	1	1
Transmitter Power	dBW	10log(P)	0	0	0	0
Transmitter Line Loss	dBW	Input parameter	-1	-1	-1	-1
Avg Transmit Antenna Gain	dBi	Input parameter	**1.0**	**1.0**	**1.0**	**1.0**
Transmit Total Gain	dB	Gpt+Lpt	0.0	0.0	0.0	0.0
Eq. Isotropic Radiated Power	dBW	P+Ll+Gpt	0.00	0.00	0.00	0.00
Propagation Path Length	km	From Alt. and El.	**2323.373**	**1466.317**	**563.287**	**410.000**
Space Loss	dB	Eq (13-23b)	-167.4	-163.4	-155.1	-152.3
Propagation and Polarization Loss	dB	Fig. 13-10	-3	-3	-3	-3
Receive Antenna Diameter	M	Input parameter	**10**	10	10	10
Receive Antenna Eff		Input parameter	0.55	0.55	0.55	0.55
Peak Receive Antenna Gain	dBi	Eq (13-18a)	45.42	45.42	45.42	45.42
Receive Antenna Line Loss	dB	Input parameter	-0.5	-0.5	-0.5	-0.5
Receive Antenna Beamwidth*	deg	Eq (13-19)	0.88	0.88	0.88	0.88
Receive Antenna Pointing Error	deg	Input parameter	**0.33**	0.33	0.33	0.33
RX Antenna Pointing Error Loss	dB	Eq (13-21)	-1.68	-1.68	-1.68	-1.68
Receive Antenna Gain with pointing error	dB	Grp+Lpr+L_theta	43.2	43.2	43.2	43.2
System Noise Temperature **	K	Table 13-10	585	585	585	585
Data Rate	bps	Input parameter	**172000**	**172000**	**172000**	**172000**
Eb/No (1)	dB	Eq (13-13)	21.4	25.4	33.7	36.5
Bit Error Rate		Input parameter	10-5	10-5	10-5	10-5
Required Eb/No (2)	dB-Hz	Fig. 13-9	**13.5**	13.5	13.5	13.5
Implementation Loss (3)	dB	Estimated	-1	-1	-2	-1
Margin	dB	(1)-(2)+(3)	**6.9**	**10.9**	**18.2**	**22.0**

References:

- Fundamental of Space Systems (2nd Edition) V. Pisacane
- Space Mission Analysis and Design, (3rd edition) Microcosm/Kluwer 1999, by Wiley J. Larson and James R. Wertz (editors)
- International Amateur Radio Union Link Budget http://www.amsat.org.uk/iaru/spreadsheet1.asp

The End

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