

ECE4634

Digital Communications

Fall 2007

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Lecture #33: Link Budgets



Analog and Digital Communications

Motivation for Link Budgets



Analog and Digital Communications

- We have seen that the performance of digital communications systems is dependent on the received E_b/N_o
- We must determine received E_b/N_o based on *received power*, *data rate* and the *thermal noise* at the receiver
- The received signal power is dependent on:
 - transmit power
 - transmit antenna gain
 - attenuation due to the channel (path loss and possibly fading)
 - receive antenna gain
- The thermal noise power is dependent on:
 - physics (devices above zero Kelvin generate non-zero voltage)
 - quality of the receiver (translates to *noise temperature*)

Motivation for Link Budgets



Analog and Digital Communications

- Listing all of the factors which affect the final E_b/N_o in a single table is called a *Link Budget*
- Link budget is a trade-off between
 - transmit power
 - antenna sizes/directionality
 - receiver quality
 - data rate
 - distance between transmitter and receiver (coverage)
 - Bandwidth (through the modulation scheme used)
- Received power is directly proportional to
 - transmit power
 - antenna gain (at both transmitter and receiver)
- Received power is inversely proportional to
 - distance between transmitter and receiver (path length)

Link Budgets



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- Friis Transmission Equation:

$$P_T G_{AT} = EIRP$$

$$P_R = \frac{P_T G_{AT} G_{AR}}{L_p}$$

- where

- P_T - transmit power
- P_R - received signal power
- G_{AT} - antenna gain at transmitter
- G_{AR} - antenna gain at receiver
- L_p - path loss at receiver



Link Budgets

- Analog vs. Digital System Requirements
 - analog requirement - signal-to-noise ratio for desired quality

$$\frac{S}{N} = \frac{P_R}{N_o B}$$

- digital requirement - probability of bit error for desired quality -
 - translates directly to E_b/N_o
 - E_b/N_o is calculated from signal-to-noise ratio

$$\frac{E_b}{N_o} = \frac{P_R T_b}{N_o} = \frac{S}{N} \frac{B}{R_b}$$



Link Budgets - decibels

- It is often convenient to express the link budget in decibels
 - We can actually compute the E_b/N_0 from such a link budget

$$\frac{E_b}{N_o} (dB) = P_T + \underbrace{G_{AT} + G_{AR} - L_p}_{P_R} - N_o - R_b$$

- N_0 power spectral density of noise at front end of receiver
- R_b data rate

Noise

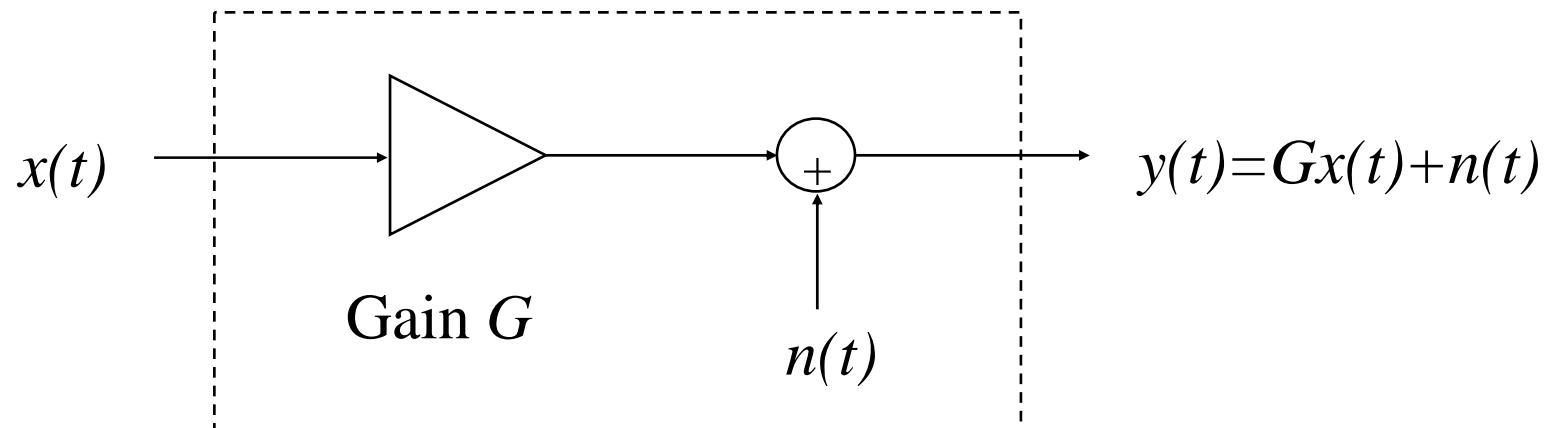


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- In many systems, the primary source of noise is thermal noise at the receiver front end
 - Caused by random voltages in the receiver
 - Can be modeled as AWGN
- Model for magnitude of noise:
 - $N_o = kT_{sys}$
 - Boltzmann's constant $k = 1.38 \times 10^{-23} \frac{\text{W}}{\text{Hz} \cdot \text{K}} = -228.6 \text{ dB}$
 - Noise Temperature of system: T_{sys}
 - Good receivers will have a noise temperature close to room temperature (~290K)

Noise Figure

- The noise figure is a figure of merit which tells us how much additional noise is introduced by a device



Model of noisy linear device

- Let $x(t)$ be a noise source with PSD $N_o = kT_o$ and P_o = average power over bandwidth B of signal $y(t)$
- Then, the noise figure F is

$$F = \frac{P_o}{kT_o BG}$$



Noise Temperature

- The system noise temperature depends on the antenna noise temperature (due to earth blackbody radiation and sky noise) and the receiver noise temperature

$$T_{sys} = T_{AR} + T_e$$

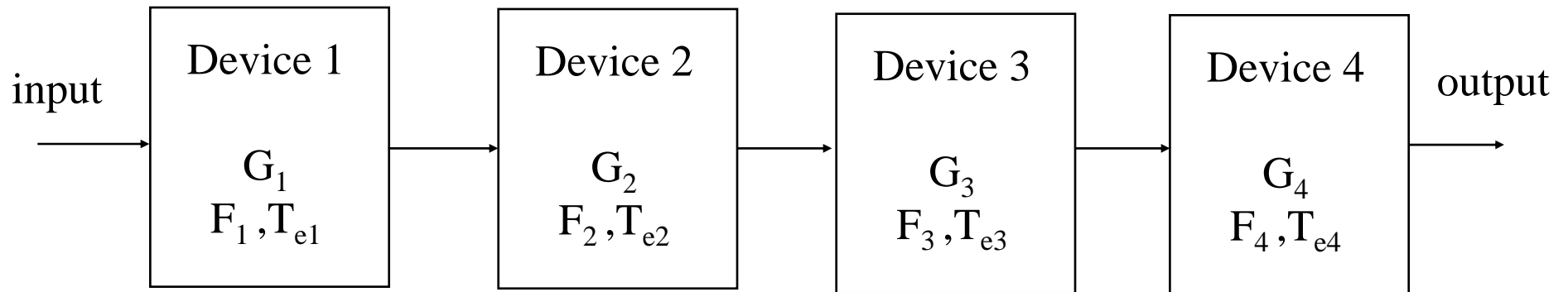
- T_{AR} is dependent on what the receive antenna sees (earth is “hot” while space is “cold”)
- T_e is the equivalent noise temperature of the receiver
 - The equivalent noise temperature tells us how much noise is added by the receiver
 - T_e is related to the noise figure of the receiver by

$$T_e = T_o (F - 1)$$

- where $T_o = 290\text{K}$



Cascaded Linear Devices



Overall noise figure and noise temperature

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3}$$

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \frac{T_{e4}}{G_1 G_2 G_3}$$

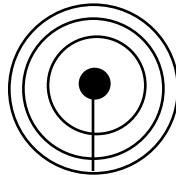
The first device is the most important and is usually a *low-noise amplifier*.

Antenna Gain

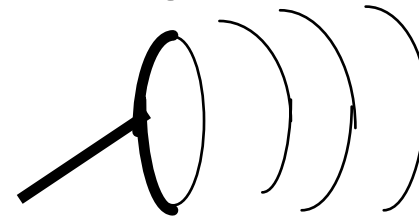


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- The simplest model for an antenna might be an isotropic antenna which radiates equally in all directions:



- The signal can be concentrated by pointing the antenna in one direction to focus the beam:



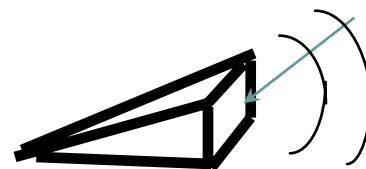
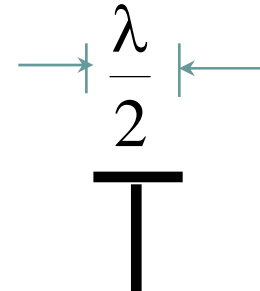
- This results in “antenna gain”
- Antenna now must be pointed in correct direction
- Antenna gain can be obtained at both the transmitter and receiver

Common Types of Antennas



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- Monopole
 - approximates isotropic
 - Gain: $1 = 0$ dB
- Half-Wave Dipole
 - Gain = $1.64 = 2.2$ dB
 - Can be used in small terminals or handsets
- Horn
 - Gain = $10A/\lambda^2$
 - Typical Gains are on the order of 5-15 dB



Area A

Common Types of Antennas



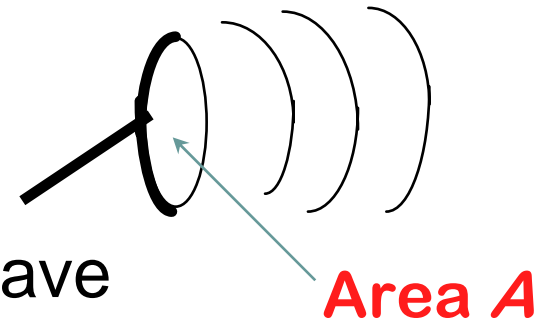
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- Parabolic Dish

- Typical Gain = $7A/\lambda^2$

- Large (up to 10 m) dishes can have gains on the order of 30-40 dB

- Used for satellite links, microwave relays



- Antenna Matching

- The impedance of the antenna must be carefully matched to the circuitry leading to the antenna

- Antenna mismatches can result in losses of 5-15 dB

Path Loss



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- Received signal attenuates from transmitter to receiver

$$L_p = \left(\frac{4\pi d}{\lambda} \right)^2$$

$$L_p (dB) = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right)$$

Note: Frequency dependency actually is an antenna effect, but we include it in the path loss. There is nothing about frequency that increases path loss.

- λ - wavelength, $f \cdot \lambda = c$
 - d - distance separating transmitter and receiver
 - 2 - path loss exponent
-
- This assumes free space. In mobile or other non-line-of-sight environments, the power decay with distance is greater than d^2 . In fact it can be proportional to d^3 or d^4

Other Factors in Link Budgets



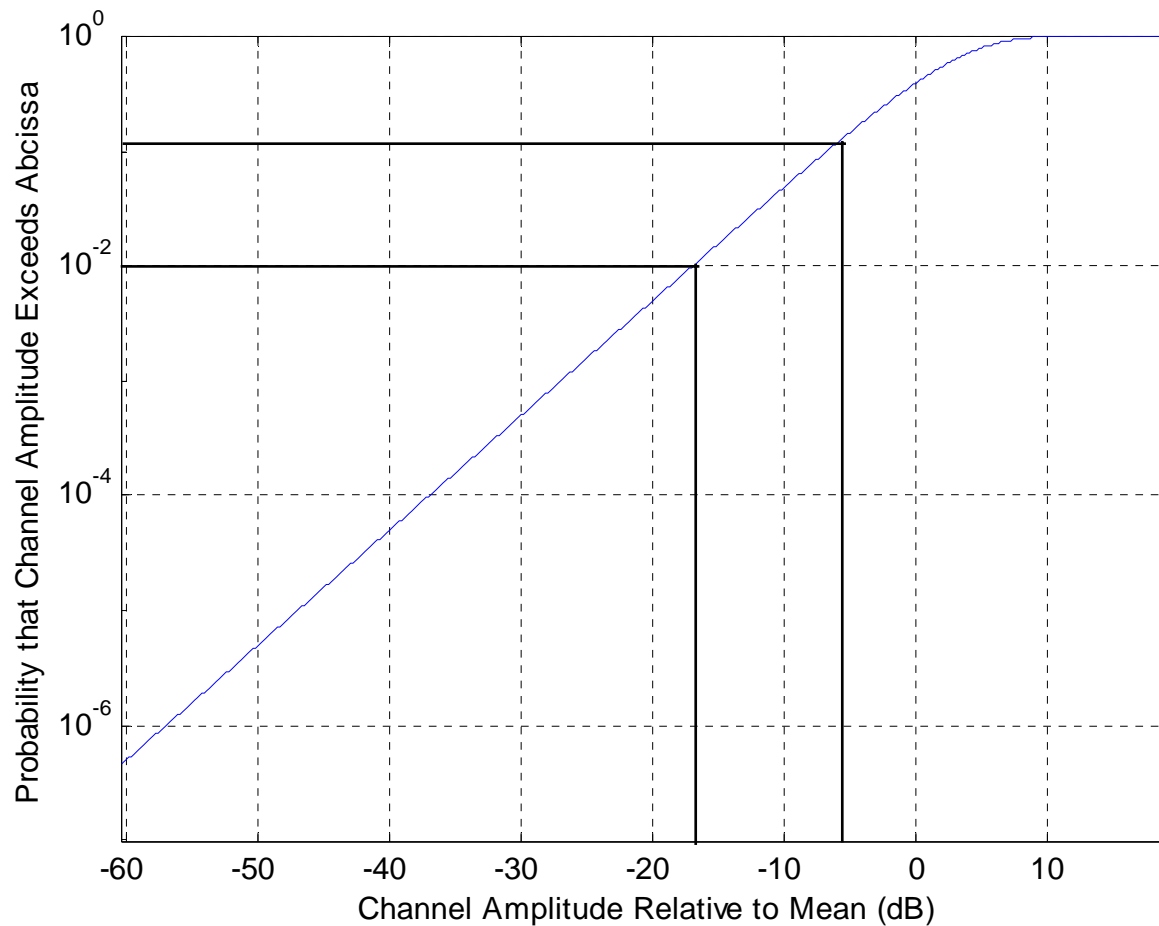
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- Other values are sometimes included in link budget
 - Receiver implementation losses
 - Antenna mismatch losses
 - Coding gain
 - gain due to error correction coding
 - Fading margin
 - We must build in a margin to account for the fact that fading will occur.
 - This is considered 'head-room' to ensure that we achieve our desired S/N or E_b/N_o some percentage of the time
 - log-normal shadowing (fading due to buildings or mountains)
 - Rayleigh fading (fading due to multipath)

Fade Margin



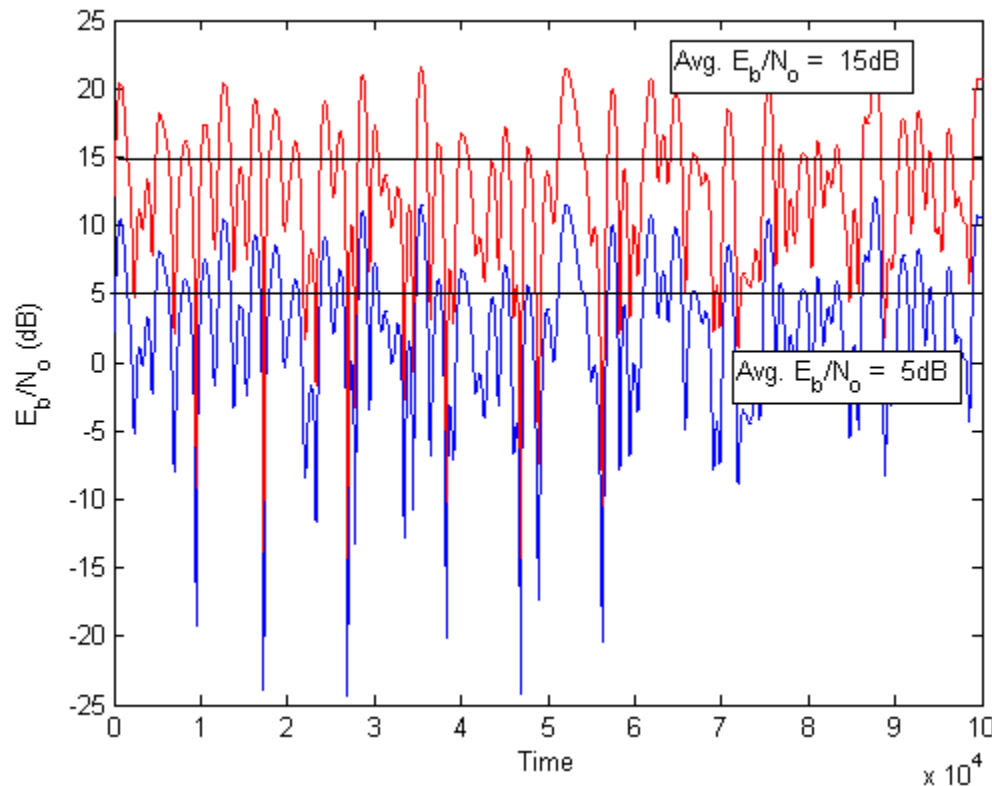
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To guarantee desired E_b/N_0 99% of time must include 17dB of fade margin. For 90% reliability we must include approximately 7dB of margin.



Fading Margin



Note that red curve (with 10dB extra avg. E_b/N_0 , is less likely to go below 0dB

- Increasing the average E_b/N_0 value decreases the probability that the instantaneous E_b/N_0 will go below a certain level
- We call this extra average E_b/N_0 margin



Example (mobile radio link)

- Find the fade margin available for a 10Mbps link with required $E_b/N_o = 9.3\text{dB}$ at 1km
 - Antenna Gains = 2.1dB
 - $P_t = 1\text{W}$
 - Frequency = 2GHz
 - Path loss exponent = 2.5
 - Coding gain = 5dB
 - $T_s = 288\text{K}$
- Compare with the fade margin available for a 100kbps link with required $E_b/N_o = 9.3\text{dB}$ at 10km



Example (cont.)

- Transmit Power = 0dBW
- Noise Spectral Density

$$\begin{aligned} N_o &= -228.6 \text{dBW/Hz/K} + 10 \log_{10}(288) \\ &= -204 \text{dBW/Hz} \end{aligned}$$

- Path Loss at 1km

$$\begin{aligned} PL &= 10n \log_{10} \left(\frac{4\pi d}{\lambda} \right) \\ &= 123 \text{dB} \end{aligned}$$

- Path Loss at 10km

$$\begin{aligned} PL &= 10n \log_{10} \left(\frac{4\pi d}{\lambda} \right) \\ &= 148.1 \text{dB} \end{aligned}$$

Example Path Loss for Mobile to Mobile Radio Link



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	10 Mb/sec @ 1 km	100 kb/sec @ 10 km
Transmitted Power	0 dBW	0 dBW
Transmit Antenna Gain	2.1 dB	2.1 dB
Path Loss	123 dB	148 dB
Receive Antenna Gain	2.1 dB	2.1 dB
Receive Signal Power	-118.8 dBW	-143.8 dBW
Energy per bit E_b	-188.8 dB J $(-118.8 - 10\log_{10}(10^7))$	-193.3 dB J
Receiver Noise $N_o = kT$	-204 dB W/Hz	-204 dBW/Hz
Received E_b/N_o	15.2 dB	10.2 dB
Required E_b/N_o	9.3 dB	9.3 dB
Coding gain	5 dB	5 dB
Required E_b/N_o after Coding Gain	4.3 dB	4.3 dB
Required Fade Margin	10 dB	10 dB
Actual Fade Margin	10.9 dB $(15.2\text{dB} - 4.3\text{dB})$	5.9 dB $(10.2\text{dB} - 4.3\text{dB})$

Distance has more impact than data rate



Summary

- The performance of digital communications is dependent on the E_b/N_o value at the receiver
- Today we have reviewed a concept for determining the E_b/N_o value at the receiver known as a *link budget*
- The link budget includes transmit power, path loss, antenna gains, noise power, receiver noise figure, data rate and fading margin.
- Path loss tends to be a dominating factor in the link budget