ECE4634
Digital Communications
Fall 2007

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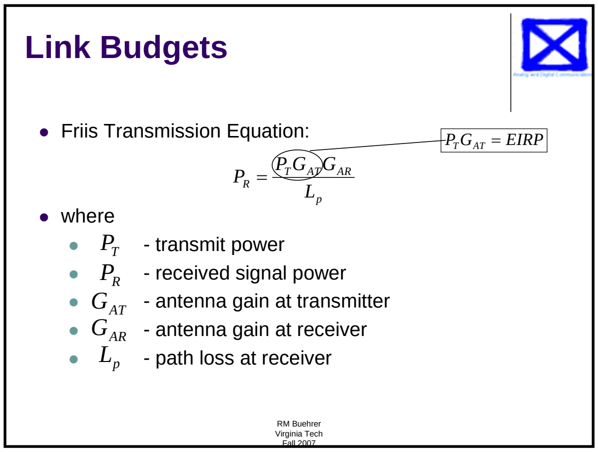
Lecture #33: Link Budgets

Motivation for Link Budgets

- 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

- 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)



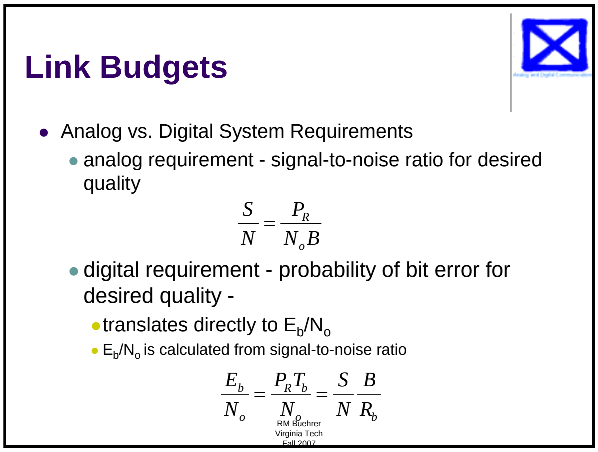
Link Budgets

- Friis Transmission Equation:

$$\boxed{P_T G_{AT} = EIRP}$$

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

- 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



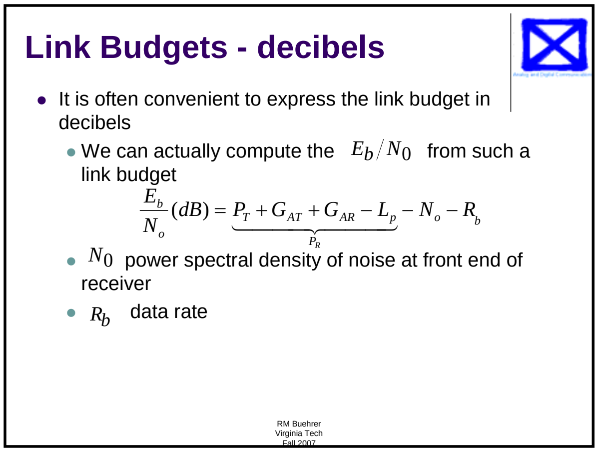
Link Budgets

- 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

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

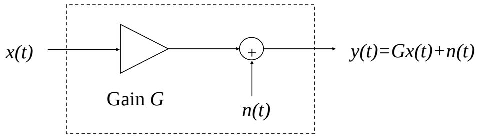
  - N_0 power spectral density of noise at front end of receiver
  - R_b data rate

Noise

- 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 $k = 1.38 \times 10^{-23} \frac{\mathrm{W}}{\mathrm{Hz} \cdot \mathrm{K}} = -228.6 \text{ dB}$
  - 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 $\boxed{F=\frac{P_o}{kT_oBG}}$

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

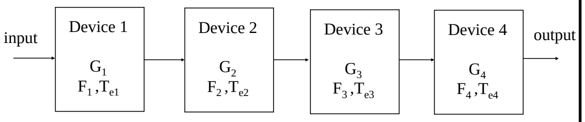
$$T_{sys} = T_{AR} + T_e$$

- 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 = 290K

Cascaded Linear Devices



Overall noise figure and noise temperature

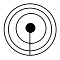
$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3}$$

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

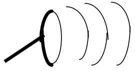
The first device is the most important and is usually a *low-noise amplifier.*

Antenna Gain

- 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:

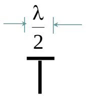


  - This results in “antenna gain”
  - Antenna now must be pointed in correct direction
  - Antenna gain can be obtained at both the transmitter and receiver

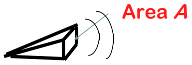
Common Types of Antennas

- Monopole
  - approximates isotropic
  - Gain: 1 = 0 dB

- Half-Wave Dipole
  - Gain = 1.64 = 2.2 dB
  - Can be used in small terminals or handsets

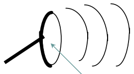


- Horn
  - Gain = $10A/\lambda^2$
  - Typical Gains are on the order of 5-15 dB



Common Types of Antennas

- 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

- 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.

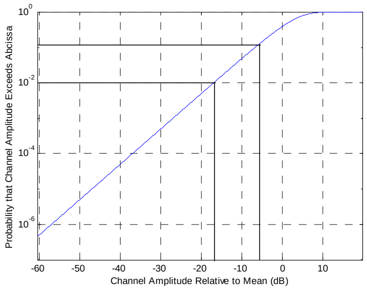
  - λ - wavelength, $f \cdot \lambda = c$
  - d - distance separating transmitter and receiver
  - 2 - path loss exponent

- 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

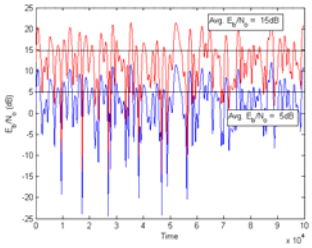
- Other values are sometimes included in link budget
  - Receiver implementation losses
  - Antenna mismatch losses
  - Coding gain
    - gain due to error correction coding
  - Fading margin
    - We must build in a margin to account for the fact that fading will occur.
    - This is considered 'head-room' 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



To guarantee desired E_b/N_o 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_o, is less likely to go below 0dB

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

Example (mobile radio link)

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

Example (cont.)

- Transmit Power = 0dBW
- Noise Spectral Density

$$N_o = -228.6 dBW/Hz/K + 10\log_{10}(288)$$
$$= -204 dBW/Hz$$

- Path Loss at 1km

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

- Path Loss at 10km

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

Example Path Loss for Mobile to Mobile Radio Link

	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 – 10log$_{10}$(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** *(15.2dB – 4.3dB)*	**5.9 dB** *(10.2dB – 4.3dB)*

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