Spacecraft Communications

- Antennas
- Orbits
- Modulation
- Noise
- Link Budgets
The Problem

Satellite transmitter-to-receiver link with typical loss and noise sources
Antennas

- Receive & transmit RF (radio frequency) energy
- Size/type selected directly related to frequency/required gain

Gain Pattern

Omni Antenna (idealized)

Directional (Hi-Gain) Antenna

Gain is relative to isotropic with units of dBi

-3 dB Beamwidth

Boresight

Side Lobes

Peak Gain = X dBi

Omni Antenna (typical)
Orbit Considerations
Ground Station Coverage
Ground Station Coverage

Florida ground station with spacecraft altitudes 400, 800, and 1200 km
Ground Station Coverage

Ground station elevation angles of 0, 10, and 20 degrees

Spacecraft altitude of 1200 km
Ground Station Coverage

Effects of terrain and antenna limitations

Another antenna

Building

Antenna limits

Spacecraft altitude 1200 km

Spacecraft Communications
Principles of Space Systems Design
Ground Station Coverage

Hawaii (HAW3), Alaska (AGIS), Wallops Island (WPSA), Svalbard (SGIS), McMurdo (MCMS)
Frequency Bands

- **S-Band — 2-3 GHz**
  - Space operation, Earth exploration, Space research
- **X-Band — 7-8 GHz**
  - Earth exploration, Space research
- **Ku-Band — 13-15 GHz**
  - Space research
  - Loss from rain
- **Ka-Band — 23-28 GHz**
  - Inter-satellite, Earth exploration
Types of Modulation

• **Amplitude Modulation**
  - \( s(t) = A [1 + m(t)] \cos(2\pi f_c t) \)
  - Easy to implement
  - Poor noise performance

• **Frequency Modulation**
  - \( x(t) = A \cos[2\pi \int_{0}^{t} (f_c + f_{\Delta m}(\tau))d\tau] \)
  - Requires frequency lock loop

• **Polarization Modulation**
  - \( s(t) = A \cos[2\pi f_c t + \beta m(t)] \)
  - Requires phase lock loop
  - Most digital modulation techniques involve PM
Polarization

- Orientation of electric field vector
- Shape traced by the end of the vector at a fixed location, as observed along the direction of propagation
- Some confusion over left hand/right hand conventions

Linear Polarization
- Vertical (a)
- Horizontal (b)

Circular Polarization
- Left hand (c)
- Right hand (d)
Digital Modulation Techniques

- On-Off Keying (OOK)
- Frequency Shift Keying (FSK)
- Bi-Phase Shift Keying (BPSK)
- Quadrature Phase Shift Keying (QPSK)
Noise

• Any signal that isn’t part of the information sent
• Signal noise
  - Amplitude noise - error in the magnitude of a signal
  - Phase noise - error in the frequency / phase modulation
• System Noise
  - Component passive noise
  - Component active noise (amplifiers, mixers, etc...)
• Environmental Noise
  - Atmospheric noise
  - Galactic noise
  - Precipitation
Signal Noise

Amplitude Noise

Phase Noise

Constellation
System Noise

- All real components generate "thermal noise" due to the random motion of atoms.
- Passive devices' thermal noise is directly related to the temperature of the device, its bandwidth, and the frequency of operation.
- Noise is generated by thermal vibration of bound charges.
- A moving charge generates an electromagnetic signal.
- Passive components include:
  - Resistive loads (power loads)
  - Cables & other such things (like waveguides)
Environmental Noise

- Rain loss, particularly in the Ku band
- Snow is not a problem
- Lightning
- Stars, galaxies, planets
- Human interference
Noise Temperature

- Noise temperature provides a way of determining how much thermal noise is generated in the receiving system.
  - The physical noise temperature of a device, $T_n$, results in a noise power of $P_n = K T_n B$
    - $K = \text{Boltzmann’s constant} = 1.38 \times 10^{-23} \text{ J/K}$; $K$ in $\text{dBW} = -228.6 \text{ dBW/K}$
    - $T_n = \text{Noise temperature of source in Kelvins}$
    - $B = \text{Bandwidth of power measurement device in hertz}$

- Satellite communications systems work with weak signals, so reduce the noise in the receiver as far as possible.
  - Generally the receiver bandwidth is just large enough to pass the signal.
  - Liquid helium can hold the physical temperature down.
S/N and NF

- **Signal to Noise Ratio**
  - Most common description of the quantity of noise in a transmission

- **Noise Figure**
  - $S/N$ of input divided by $S/N$ of output for a given device (or devices) in a communications system
  - Related to the noise temperature of a device:
    
    \[ T_d = T_0(NF - 1) \]
    
    \[ T_0 = \text{reference temperature, usually 290 K} \]
Example 1:

Gain = 0 dbi

$T_{sky} = 50^\circ$  
Loss = $L = \frac{1}{1.585}$  
$L = \frac{1}{10^{3.3/10}} = 0.5$

System Noise Temperature $= T_s \, ^\circ K$

$T_s = T_{sky} + \frac{(1-\varepsilon)T_o}{\varepsilon} + \frac{(NF_{LNA} - 1)T_o}{\varepsilon G_{LNA}} + \frac{(NF_{PC} - 1)T_o}{\varepsilon G_{LNA} G_{DC}} + \ldots$

$T_s = 50^\circ + 290^\circ + 2*0.585*290^\circ + (2*10*290^\circ/3162.3) * (1 + 1/1,000 + 1/1,000,000)$

$T_s = 681.136^\circ K = 28.33 \, dB$
System Noise Temperature

Example 2:

\[ T_s = T_{sky} + (1 - \epsilon)T_o + \frac{(NF_{LNA} - 1)T_o}{G_{LNA}} + \frac{(NF_{IF} - 1)T_o}{G_{LNA}G_{DC}} + \ldots \]

\[ T_s = 50^\circ + 290^\circ + 2 \times 0.585 \times 290^\circ + \left(2 \times 10 \times 290^\circ / 3162.3\right) \times \left(1 + 1/1,000 + 1/1,000,000\right) \]

\[ T_s = 340.56^\circ K = 25.33 \text{ dB} \]
G/T Figure of Merit

• Gain at a reference point, divided by the system noise temperature at that reference point

• Example 1:
  0 dB gain - 28.33 dBK = -28.33 dB

• Example 2:
  -3 dB gain - 25.33 dBK = -28.33 dB

• Higher G/T = better Earth station
  (This one isn’t very good)
BER and $E_b/N_o$

- The rate at which bits are corrupted beyond the capacity to reconstruct them is called the BER (Bit Error Rate).
  - A BER of less than 1 in 100,000 bits (a BER of $10^{-5}$) is generally desired for an average satellite communications channel.
  - For some types of data, an even smaller BER is desired ($10^{-7}$).
- The BER is directly dependent on the $E_b/N_o$, which is the ratio of Bit Energy to Noise Density.
  - Since noise density is difficult to control, this means that BER can be reduced by using a higher power signal, or by controlling other parameters to increase the energy transmitted per bit.
- The BER will decrease (fewer errors) if the $E_b/N_o$ increases.
Link Margin

- Received $E_b/N_0$ minus required $E_b/N_0$ (in dB)
- Required $E_b/N_0$ found by adding losses to the expected $E_b/N_0$ for the BER (which varies with encoding scheme used)

\[
\left( \frac{E_b}{N_0} \right)_{\text{req\,dB}} = \left( \frac{E_b}{N_0} \right)_{\text{theoretical\,for\,BER}} + \sum \text{Other System Losses}_{dB}
\]

Margin = \left( \frac{E_b}{N_0} \right)_{\text{received\,dB}} - \left( \frac{E_b}{N_0} \right)_{\text{req\,dB}}
### Link Budget Example

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#### ***Downlink Margin Calculation***

**GSFC C.L.A.S. Analysis #1**  
**Date & Time:** 10/26/4  8:39:23  
**Performed by:** R. Brockdorff

- **LinkID:** S-BAND 100 Kbps Downlink
- **Frequency:** 2250.0 MHz  
- **Range:** 2078.0 km

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>01. User Spacecraft Transmitter Power - dB</td>
<td>6.99</td>
<td>Note A: 5.0 Watts</td>
</tr>
<tr>
<td>02. User Spacecraft Passive Loss - dB</td>
<td>2.00</td>
<td>Note A</td>
</tr>
<tr>
<td>03. User Spacecraft Antenna Gain - dBi</td>
<td>-3.00</td>
<td>Note A</td>
</tr>
<tr>
<td>04. User Spacecraft Pointing Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>05. User Spacecraft EIRP - dBiW</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>06. Polarization Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>07. Free Space Loss - dB</td>
<td>16.84</td>
<td>Note B: ALT: 500.0 km, EL: 5.0 deg</td>
</tr>
<tr>
<td>08. Atmospheric Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>09. Rain Attenuation - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>10. Multipath Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>11. Ground Station Antenna Gain - dB</td>
<td>44.00</td>
<td>Note A</td>
</tr>
<tr>
<td>12. Ground Station Passive Loss - dB</td>
<td>1.50</td>
<td>Note A</td>
</tr>
<tr>
<td>13. Ground Station Pointing Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>14. Power Received at Ground Station - dB</td>
<td>-121.34</td>
<td>5 - 6 -7 -8 -9 -10 +11 -12 -13</td>
</tr>
<tr>
<td>15. System Noise Temperature - dB/degrees-K</td>
<td>25.39</td>
<td>Note A</td>
</tr>
<tr>
<td>16. Ground Station G/T - dB/degrees-K</td>
<td>17.11</td>
<td>11 - 12 - 13 - 15</td>
</tr>
<tr>
<td>17. Boltzmann's Constant - dB/K*K</td>
<td>-228.60</td>
<td>CONSTANT</td>
</tr>
<tr>
<td>18. Received Carrier to Noise Density - dB/Hz</td>
<td>81.86</td>
<td>14 - 15 - 17</td>
</tr>
<tr>
<td>19. Modulation Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>20. Data Rate - bps</td>
<td>50.00</td>
<td>Note A</td>
</tr>
<tr>
<td>21. Differential Encoding/Decoding Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>22. User Constraint Loss - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>23. Received Eb/No - dB</td>
<td>31.86</td>
<td>18 - 19 - 20 - 21 - 22</td>
</tr>
<tr>
<td>24. Implementation Loss - dB</td>
<td>2.00</td>
<td>Note A</td>
</tr>
<tr>
<td>25. Theor. Required Eb/No - dB</td>
<td>9.60</td>
<td>Note B</td>
</tr>
<tr>
<td>26. Required Eb/No - dB</td>
<td>11.60</td>
<td>24 + 25</td>
</tr>
<tr>
<td>27. Required Performance Margin - dB</td>
<td>0.00</td>
<td>Note A</td>
</tr>
</tbody>
</table>

**Note A:** Parameter Value from user project - subject to change  
**Note B:** From class analysis if computed
### Downlink Margin Calculation

**GSFC C.L.A.S.S. Analysis #1**

**Date & Time:** 4/1/99 10:13:39  **Performed by:** Y. Wong

**LinkID:** EOS-AM/SGS

**Frequency:** 8212.5 MHz  **Range:** 2575.0 km

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>01. User Spacecraft Transmitter Power - dbW</td>
<td>11.60</td>
<td>Note A: EDL</td>
</tr>
<tr>
<td>02. User Spacecraft Passive Loss - db</td>
<td>1.13</td>
<td>Note A</td>
</tr>
<tr>
<td>03. User Spacecraft Antenna Gain - db</td>
<td>4.84</td>
<td>Note A include multipath loss</td>
</tr>
<tr>
<td>04. User Spacecraft Pointing Loss - db</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>05. User Spacecraft EIRP - dbW</td>
<td>16.31</td>
<td>Note A</td>
</tr>
<tr>
<td>06. Polarization Loss - db</td>
<td>0.67</td>
<td>Note A</td>
</tr>
<tr>
<td>07. Free Space Loss - db</td>
<td>178.95</td>
<td>Note B</td>
</tr>
<tr>
<td>08. Atmospheric Loss - db</td>
<td>0.45</td>
<td>Note B; EL: 5.0 DEG</td>
</tr>
<tr>
<td>09. Rain Attenuation - db</td>
<td>1.20</td>
<td>Include scintillation loss 1.1 db</td>
</tr>
<tr>
<td>10. Multipath Loss - db</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>11. Ground Station G/T - db/DEGREES-K</td>
<td>33.30</td>
<td>G/T with rain at 5 degrees</td>
</tr>
<tr>
<td>12. Boltzmann’s Constant - dbW/(Hz*K)</td>
<td>-228.60</td>
<td>CONSTANT</td>
</tr>
<tr>
<td>13. Received Carrier to Noise Density - db/Hz</td>
<td>95.95</td>
<td>5 - 6 - 7 - 8 - 9 - 10 + 11 - 12</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>I Channel</td>
<td>3.01</td>
<td>Note B; 1.00 TO 1.00</td>
</tr>
<tr>
<td>Q Channel</td>
<td>3.01</td>
<td></td>
</tr>
<tr>
<td>14. I-Q Channel Power Split Loss - db</td>
<td>0.00</td>
<td>Note A</td>
</tr>
<tr>
<td>15. Data Rate - db/bps</td>
<td>78.75</td>
<td>Note A</td>
</tr>
<tr>
<td>16. Data Rate - db =bps</td>
<td>78.75</td>
<td>Note A</td>
</tr>
<tr>
<td>17. Differential Encoding/Decoding Loss - db</td>
<td>0.20</td>
<td>Note A</td>
</tr>
<tr>
<td>18. User Constraint Loss - db</td>
<td>1.60</td>
<td>Note A include diff encoding and modulation losses</td>
</tr>
<tr>
<td>19. Received Eb/No - db</td>
<td>12.19</td>
<td>Note B; 12.19 13 - 14 - 15 - 16 - 17 - 18</td>
</tr>
<tr>
<td>20. Implementation Loss - db</td>
<td>2.00</td>
<td>Note B; 2.00</td>
</tr>
<tr>
<td>21. Theor Required Eb/No - db</td>
<td>4.25</td>
<td>Note B; 4.25</td>
</tr>
<tr>
<td>22. Required Eb/No - db</td>
<td>6.25</td>
<td>Note B; 20 + 21</td>
</tr>
<tr>
<td>23. Required Performance Margin - db</td>
<td>3.00</td>
<td>Note A</td>
</tr>
<tr>
<td>24. Margin - db</td>
<td>2.94</td>
<td>Note A</td>
</tr>
</tbody>
</table>

**Note A:** Parameter value from user project - subject to change

**Note B:** From class analysis if computed
Diagram of the Budgeted Link

I = 75 MBPS
Q = 75 MBPS

Encoder & Transmitter

Loss = 1.13 dB

Gain = 4.84 dBi

11.6 dBW
10.49 dBW
15.31 dBW

SPACE

11m Ground Antenna

LNA

G/T = 33.3 dB/K

C
N_o
= 95.95 dBHz

(\frac{E_b}{N_o})_r = 12.19 dB

(\frac{E_b}{N_o})_{REQ’D} = 4.25 dB

Implementation Loss = 2.0 dB

MARGIN = 5.94 dB

Decoded Data

Decoder

I
Q

Data

Receiver

Alaska SAR Facility
11 meter antenna

Σ Losses = 0.67 dB
178.95 dB
0.45 dB
1.2 dB

Polarization loss
space loss @ 2575 KM and 5° elevation
atmospheric loss
rain loss

8212.5 MHz

QPSK