Satellite Link design.

Objective of the link design - determine properties of the satellite equipment required for successful communication.
* Antenna systems
* Amplification systems
* Filtering
* Signal processing (modulation, demodulation, coding)
* System reliability and probability of outage.

Link design - principle task in front of satellite RF engineer.

Satellite link design - two links: uplink & downlink.
* Performance depends on both links.
* Links usually work in different frequency bands (separate link design).

Examples:

Uplink

HUB/Earth station

Hub/Earth station

2 links in this case - one way communication.

Hub/Earth station

or customer end equipment

HUB/Earth station

Mobile platform

Note: Each link may be at a different frequency.

There are 4 links, 2 links per each direct link in satellite communications.
Elements of a satellite communication link

1) TX chain (amplifiers, filters and associated wave guides)
2) TX antenna system (antenna gain, pattern, polarization)
3) path loss
   * free space
   * environmental losses
   * various system losses
4) RX antenna (gain, pattern)
5) RX chain
   * noise temperature
   * Receive Operating Curve ROC (Rx Sensitivity, S/N vs. BER, ...)
6) Design margins required to guarantee proper reliability against variable parts of the link budget elements.

Typically in link budget analysis one creates a spreadsheet that takes all the elements in the account - very similar to money budgeting spreadsheet.

Principal outputs of the spreadsheet
+ Link margin
+ Reliability of the link
+ Values for all of the components in the link chain
+ Noise temperature calculations, etc.

Note: Satellite signals are very weak ⇒ careful link budget analysis
Basis of free space TX theory.

In the first approximation, a satellite link is in the free space.

\[ W = |E \times H| \]

Power flux density of the EM wave.

\[ N(\theta, \phi) = |E \times H| = \frac{P_t \cdot G_t(\theta, \phi)}{4\pi R^2} \]

- \( P_t \) - power of the signal delivered to the antenna terminal
- \( G_t(\theta, \phi) \) - gain of the TX antenna in a given direction (\( \theta, \phi \))
- \( R \) - distance between the TX antenna and a point on the EM wavefront

The received power.

\[ P_r = W \cdot A_e = W \cdot A_c(\lambda) \]

\( \lambda \) - wavelength of the communication, \( \lambda = c/f \)

- \( A_c \) - effective aperture of the antenna

\[ A_e = 2\pi \cdot A_r \quad \text{where} \quad (2\pi = 50-75\% \text{ for Cassegrain antennas}) \]

\[ 2\pi \text{ - antenna's efficiency} \]

\[ A_r \text{ - physical size of the antenna} \]
Also, the relationship between antenna's gain and its effective aperture

\[ A = \frac{4\pi}{\lambda^2} \cdot G(\theta_0, \phi_0) \]

Therefore,

\[ P_r = \frac{4\pi}{\lambda^2} \cdot G(\theta_0, \phi_0) \cdot G_r(\theta_0, \phi_0) \cdot P_t \frac{G_t \cdot G_r}{4\pi^2} \cdot P_t \frac{(4\pi/d^2)^2}{4\pi^2} \]

Expressing everything in log units with reference power of 1W

\[ P_r [\text{dBW}] = G_t [\text{dB}] + G_r [\text{dB}] + P_t [\text{W}] - 10 \log \left( \frac{(4\pi/d^2)^2}{4\pi^2} \right) \text{ in dB} \]

More commonly:

\[ P_r [\text{dBW}] + G_t [\text{dB}] = E_{\text{RP}} [\text{dBW}] \]

\[ 10 \log \left( \frac{(4\pi/d)^2}{4\pi^2} \right) = L_p \text{ in dB} \]

Therefore:

\[ P_r [\text{dBW}] = E_{\text{RP}} [\text{dBW}] + G_t [\text{dB}] - L_p [\text{dB}] \quad (\star) \]

Equation (\star) - fundamental link budget equation.

Note: If there is some doubt about using dBs, students should consult appendices A or the textbook or the appropriate lecture/video of the RF propagation class.

Note 2: In satellite communication, 1W is used as a reference quantity.

Recall:

\[ P[\text{dBW}] = P[\text{dBm}] - 30 \]

Example:

3 dBW = 23 dBm (or 2 W = 2000 mW).
Equations for free space path loss

\[ \text{FSPL [dB]} = 10 \log \left( \frac{4\pi R}{\lambda} \right)^2 \]

More common form of the FSPL equation

\[ \text{FSPL [dB]} = 92.44 + 20 \log R \text{[km]} + 20 \log f \text{[MHz]} \]  

\[ \text{FSPL [dB]} = 96.5 + 20 \log R \text{[m]} + 20 \log f \text{[MHz]} \]  

**Example:** Consider a GEO satellite operating at 60 GHz. The FSPL may be calculated as follows.

\[ R = 42134 \text{ km} \]

\[ \text{FSPL} = 92.44 + 20 \log \left( \frac{42134 \text{ km}}{\lambda} \right) + 20 \log \left( \frac{6 \text{ GHz}}{\lambda} \right) = 200.5 \text{ dB} \]

\[ \text{FSPL} = 200 \text{ dB} \Rightarrow \text{huge losses!! (}200 \text{ dB} \sim 10^{20}\) \]

Additional losses (beyond free space) may be attributed to

1. Misalignment of the antennas
2. Environmental losses (atmosphere)
3. Mismatch of the components (reflection coefficients, polarization, ...)

**Modified Friis formula**

\[ \frac{P_t}{P_r} = G_t(\theta_t, \phi_t)G_r(\theta_r, \phi_r) \left( \frac{\lambda}{4\pi R_r} \right)^2 \left( 1 - |\eta|^2 \right) \left( 1 - |\eta|^2 \right) \text{ E}^{-\alpha R} \]

where
|Pr1| - magnitude of the reflection coefficient at the RX antenna
|Pr1| - magnitude of the reflection coefficient at the TX antenna
\( \vec{e}, \vec{v} \) - polarization vectors of the TX and RX waves
\( \alpha \) - attenuation of the medium where the wave propagates

In satellite communication, (*) is rarely used as one estimate. Instead, link budget analysis is performed to account for all gains and losses.

**Spectral Efficiency:** (Not in the textbook)

Satellite channel - largely AWGN Channel

**Shannon formula for Gaussian channel**

\[
C = B \cdot \log_2 (1 + S/N)
\]

- \( C \) - capacity of the channel in bps/Hz
- \( B \) - bandwidth of the channel in Hz
- \( S/N \) - signal to noise ratio in linear domain

Define \( \gamma = R/B \) - spectral efficiency of the system

Obviously, \( \gamma \leq S/B = \log_2 \left( 1 + \frac{E_b}{N_0} \cdot \frac{R}{B} \right) \)

or \( \gamma \leq \log_2 \left( 1 + \frac{S}{B} \cdot \frac{E_b}{N_0} \right) \)

Expressing \( E_b/N_0 \) as a function of \( \gamma \), one obtains

\[
E_b/N_0 \geq \min \left\{ \frac{E_b}{N_0} \right\} = \frac{2^{\gamma} - 1}{\gamma}
\]

- \( E_b/N_0 \) required link performance for a given spectral efficiency
In power limited region small increases in power give significant increase in spectral efficiency.

In bandwidth limited region even small improvements in spectral efficiency result in large increase in signal power.

Contemporary systems work with γ ≈ 3.7 dB.

Given limited spectrum and ever growing need to send more data, the only practical way to improve efficiency is through spectral reuse.

Example 4.2.1. Consider a satellite at $R = 40,000$ km. $P_t = 10$ W into $G_t = 17$ dB. Find the power flux density on the Earth's surface and power received by an antenna with $A_e = 10$ m².

$$ W = \frac{P_t G_t}{4 \pi R^2} = \frac{10 \text{ W} \cdot 10^{17/10}}{4 \pi (40,000 \times 10^3 \text{ m})^2} = 2.49 \times 10^{-14} \text{ W/m}^2 $$

$$ P_r = W \cdot A_e = 2.49 \times 10^{-14} \text{ W/m}^2 \times 10 \text{ m}^2 = 2.49 \times 10^{-12} \text{ W} $$

$$ P_r [\text{dBW}] = -126.03 \text{ dBW} = -96.03 \text{ dBW} $$

Example 4.2.2. The satellite in Example 4.2.1 operates at 11 GHz. The Rx antenna gain is 52.3 dB. Find the Rx power.

$$ P_{\text{Rx}} [\text{dBW}] = 10 \text{ dBW} + 17 \text{ dB} = 27 \text{ dBW} $$
\[ PL_{[\text{dBJ]} = 92.44 + 20 \log (40000) + 20 \log (11) = 205.3 \text{ dB}. \]

\[ P_r = E_{[\text{dBW]} + G_{[\text{dBJ]} - PL_{[\text{dBJ]} \]

\[ = 27 \text{ dBW} + 52.3 \text{ dB} - 205.3 \text{ dB} = -126 \text{ dBW} \]