Link Budget Analysis: Getting Started

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Presentation Content
Link Budget Analysis: Getting Started

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2. Types of Communication Links.
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Link Budget

- Antenna Parameters
- Noise Power
- Influence of propagation medium
- Signal to Noise Ratio
- System Implications
  - Shadowing
  - Multipath Fading
Link Budget: What’s that?  
Link Budget Analysis: Getting Started

1. A Link Budget analysis determines if there is enough signal power at the receiver to recover the information transmitted to it with acceptable fidelity so the received signal can be used.
   A. The sum of gains and losses in various parts of the system has to result in satisfactory performance (typically, output S/N or BER).
2. The design of any communication link is based on:
   A. Meeting of minimum C/N ratio for a specific percentage of time.
   B. Carrying the maximum revenue earning traffic at minimum cost.
3. Link-power budget calculations take into account all the gains and losses from the transmitter, through the propagation medium to the receiver in a communication system. Also taken into the account are the attenuation of the transmitted signal due to propagation, and the loss or gain due to the antenna. Link calculations often determine the maximum distance at which a transmitter and receiver can successfully operate.
Comm Systems needing a Link Budget Analysis
Link Budget Analysis: Getting Started
Types of Communication Links

Link Budget Analysis: Getting Started

1. **Point-to-Point** Link: Radio tower relay stations.
2. **Satellite** Link: Communications payload and TT&C signals
   - A. Earth Station to Satellite.
   - B. Satellite-to-Satellite.
   - C. Satellite-to-Earth Station.
3. **Terrestrial** Link:
   - A. Cable/wire to cable/wire
   - B. Fiber optic-to-fiber optic.
4. **Maritime** Link: Ship-to-Ship
Benefits of a Link Budget Analysis

1. The overall performance of a communication system is expressed in terms of the ratio of carrier’s signal power to noise power: C/N and, ultimately, the information quality in the form of:
   - A. Message quality,
   - B. BER: Bit error rate,
   - C. Video impairment, or
   - D. Audio fidelity.

2. Done properly, link analysis can predict if the operation thresholds of the communication link are met with satisfactory quality, based on the specifications of the ground components and space components.

3. Operation thresholds in the communication link depend on:
   - A. Modulation scheme being used.
   - B. Desired communication quality.
   - C. Coding gain.
   - D. Additional overheads.
   - E. Channel Bandwidth.
   - F. Thermal Noise power.

4. Any uncertainty can be covered by providing an appropriate amount of link margin, which is over and above the C/N needed to account for propagation effects and nonlinearity in the system.
Link Budget Objectives

Link Budget Analysis: Getting Started

1. The Link Budget allows us to characterize the quality of the wireless communications link in a **quantitative fashion**.

2. Link Budget is used in the design process to define & “size” parameters and components in the wireless communication system:
   A. How much RF signal power do I need to transmit/broadcast?
   B. How big should my antenna be? Or, which antenna should I use?
   C. How fast can I send data?
   D. If I use an error detection and correction encoding technique, can I get away with a “noisier” link and therefore save system (& cost) resources elsewhere?

3. **Goals** in communication systems design:
   A. To maximize transmission bit rate, $R_{bit}$
   B. To minimize bit error rate, $BER$.
   C. To minimize required power, $E_b/N_0$.
   D. To minimize required system bandwidth, $B_w$.
   E. To maximize system utilization.
   F. To minimize systems complexity.
How Many Link Budget Analysis?
Link Budget Analysis: Getting Started

1. Two link budget analysis need to be planned:
   A. Uplink Analysis: From ground to satellite.
   B. Downlink Analysis: From satellite to ground.
2. Two-way communication requires **4 link analysis:**
   A. Example: Maritime communications.
3. One way communication require **2 link analysis:**
   A. Example: Direct-To-Home TV broadcast.
4. Two communication links often operate at different frequencies within the same frequency band.
5. Two links may not be in the same frequency band.
   A. Fixed / broadcast satellite services usually use same frequency band, like C-band or Ku-band.
   B. Mobile satellite services may use different frequency bands, like: L-band uplink & S-band downlink.
6. In some communication systems, satellite links may be combined with terrestrial returns.
Power Transfer into Free Space
Friis’ Transmission Equation

1. In any communication link, there is a transmitting antenna with directional gain: $G_{Tx}$, radiating to a receive antenna with directional gain: $G_{Rx}$, separated by a distance: $R$.
2. The **power flux density**, PFD, at any given distance: $R$ meters, from an ideal lossless isotropic antenna radiating a transmit power $P_t$ is:

$$PFD_{isotropic} = \frac{P_t}{4\pi R^2}, \text{ Watts/m}^2,$$

where the area of a sphere is: $A_{sphere} = 4\pi R^2, m^2$

3. The power flux density focused in the direction of maximum radiation by a transmit antenna having a directional gain: $G_{Tx}$ is:

$$PFD_t = PFD_{isotropic} \cdot G_{Tx} = \frac{P_t G_{Tx}}{4\pi R^2}, \text{ Watts/m}^2$$

where: $EIRP = P_t G_t$

4. The signal power received ($P_{rec}$) by an antenna having an effective aperture area: $A_{e,r}$ is:

$$P_{rec} = PFD_t \cdot A_{e,r} = \left(\frac{P_t G_{Tx}}{4\pi R^2}\right) \cdot A_{e,r} = P_t G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi R}\right)^2, \text{ Watts}$$

where: $A_{e,r} = \frac{\lambda^2}{4\pi} \cdot G_{Rx}$

5. Rearranging, one obtains Friis’ Transmission Equation:

$$P_{rec} = \frac{P_t G_{Tx} G_{Rx}}{(4\pi R / \lambda)^2}, \text{ Watts}$$

where **Free Space Path Loss**: $FSPL = \left(4\pi R / \lambda\right)^2$

Friis’ Transmission Equation with Loss

Link Budget Analysis: Getting Started

\[
\frac{P_r}{P_t} = \eta_{cdt} \eta_{cdr} (1 - |\Gamma_r|^2)(1 - |\Gamma_t|^2) \left( \frac{\lambda}{4\pi R} \right)^2 D_{gt}(\theta_t, \phi_t) D_{gr}(\theta_r, \phi_r) |\hat{\rho}_w \cdot \hat{\rho}_a|^2
\]

- Conductor and Dielectric losses in Transmit antenna
- Conductor and Dielectric losses in Receive antenna
- Reflection loss in Transmit antenna (impedance mismatch)
- Reflection loss in Receive antenna (impedance mismatch)
- Free Space Path Loss
- Directivity of Transmit antenna
- Directivity of Receive antenna
- Polarization Mismatch
Link Budget for Receive Power: $P_r$

Additional Losses to Friss’ Transmission Equation

Additional losses are experienced in any wireless communication link, and those losses can be included in Friss’ transmission equation as:

$$P_r = \frac{P_t G_{Tx} G_{Rx}}{L_p L_a L_{ta} L_{ra} L_{pol} L_{other} L_r}, \text{watts}$$

where:

A. EIRP = $P_t + G_{Tx}$, dBW (Effective Isotropic Radiated Power).
B. $P_t$: RF power delivered to the Transmitting antenna, dBW.
   1) $P_t$ = Transmit amplifier’s RF output power ($P_{out}$) minus feeder losses ($L_t$).
C. $G_{Tx}$: Directional Gain of the Transmitting antenna, dBi.
D. $G_{Rx}$: Directional Gain of the Receiving antenna, dBi.
E. Losses in the communication link:
   1) $L_p$ = **Free-Space Path Loss** (FSPL) caused by spherical spreading of the Tx RF signal.
      a) $L_p = 10 \log_{10} \left(\frac{(4\pi R)^2}{\lambda^2}\right)$; $R$ = Distance, meters; $\lambda$ = Wavelength of RF signal, meters.
   2) $L_a$ = Losses due to attenuation in Earth’s atmosphere.
   3) $L_{ta}$ = Losses associated with transmitting antenna: Ohmic & reflection losses.
   4) $L_{ra}$ = Losses associates with receiving antenna: Ohmic & reflecton losses.
   5) $L_{pol}$ = Losses due to polarization mismatch.
   6) $L_{other}$ = Any other known loss. Include as much detail as available.
   7) $L_r$ = Additional losses at receiver (after receiving antenna).
Link Power Budget Equation
Link Budget Analysis: Getting Started

1. Friss’ Transmission equation, including all additional losses, forms the **Link Power Budget equation** for the communication system, where each term can be expressed in decibel (dB) form: \(10\log_{10}(x)\) as:

\[ P_r = EIRP + G_{Rx} - Losses, dBW \]

2. The receive power: \(P_r\) is commonly referred to as **Carrier Power**: \(C\), which is measured at the input to the Receiver’s Low Noise Amplifier.

3. The major source of loss in any ground-satellite link is the free-space spreading loss (FSPL), represented by \(L_p\) in the Link Power equation.

4. **Linear form** for FSPL:

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

where:
- \(R\) = Distance between Tx and Rx.
- \(\lambda\) = Wavelength of the RF signal.

**Decibel form** for FSPL:

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

\[ FSPL = 96.5 + 20\log(d[\text{miles}]) + 20\log(f[\text{GHz}]) \]

\[ FSPL = 92.44 + 20\log(d[\text{km}]) + 20\log(f[\text{GHz}]) \]

\[ FSPL = 147.56 + 20\log(d[\text{m}]) + 20\log(f[\text{Hz}]) \]
Propagation Path Loss Models
Link Budget Analysis: Getting Started

1. Propagation path loss is a reduction in the signal’s power, which is a direct result of the distance between the transmitter and the receiver in the communication path. . . . Spreading loss.

2. There are many models used in the industry today to estimate the propagation path loss, and the most common are:
   A. Free Space Path Loss (FSPL).
   B. Hata Path Loss.
   C. Lee Path Loss.

3. Each propagation path loss model has its own requirements that need to be met in order to be utilized correctly.

4. The Free Space Path Loss (FSPL) is used as the foundation for all propagation path loss models. Used extensively for predicting Point-to-Point, fixed, propagation path loss. Typically underestimates the path loss actually experienced for mobile communications.
Free-Space Path Loss vs Distance: $R$

$$FSPL = \left( \frac{4\pi R}{\lambda} \right)^2$$
Communication System Noise
Link Budget Analysis: Getting Started

1. Noise in a communication system is caused by thermal noise sources, or can be represented as a thermal noise source:

   A. Noise sources **external** to the Receive system, such as:
      1) Transmitted noise on the communication link.
      2) Environmental noise captured by the Receive antenna:
         a) Antennas pointed at outer space, which appears cold and produces little thermal noise power (about 5°C).
         b) Onboard satellite antennas pointed towards the Earth capture thermal noise power (about 290 °K):

   B. Noise sources **internal** to the Receive system, such as:
      1) Feed-line losses located before the LNA.
      2) Noise from the Receiver’s Low-Noise Amplifier (LNA).

2. Different noise sources have different origins but a similar power spectral density, so they can all be **treated as thermal noise**.
N: Noise Power & \( N_0 \): Noise Spectral Density

Link Budget Analysis: Getting Started

1. The power available from thermal noise is:

\[
N = kT_s B_w \text{, watts}
\]

where:

- \( k \) = Boltzmann’s constant.
  - \( = 1.38 \times 10^{-23} \text{ Joules/Kelvin} \) \( (= -228.6 \text{ dBW/K/Hz}) \)
- \( T_s \) = Effective system noise temperature, °Kelvin.
- \( B_w \) = Effective Rx system bandwidth, Hertz.

2. Recall: °Kelvin = °Celsius + 273°.

3. The noise spectral density (density of noise power in a 1 hertz bandwidth) is:

\[
N_0 = \frac{N}{B_w} = \frac{(kT_s B_w)}{B_w} = kT_s \text{, watts/Hz}
\]

4. \( N_0 \): Noise spectral density is constant up to ~300GHz.

<table>
<thead>
<tr>
<th>Bandwidth: ( B_w )</th>
<th>Thermal Noise Power: ( N ), dBm</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hz</td>
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</tr>
<tr>
<td>10 Hz</td>
<td>-164</td>
<td></td>
</tr>
<tr>
<td>100 Hz</td>
<td>-154</td>
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<tr>
<td>1 kHz</td>
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<tr>
<td>3 kHz</td>
<td>-139</td>
<td>Telephone voice channel</td>
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<tr>
<td>10 kHz</td>
<td>-134</td>
<td>FM channel of 2-way radio</td>
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<tr>
<td>100 kHz</td>
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</tr>
<tr>
<td>180 kHz</td>
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<td>200 kHz</td>
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<td>One GSM channel (ARFCN)</td>
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<tr>
<td>1 MHz</td>
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<tr>
<td>2 MHz</td>
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<tr>
<td>36 MHz</td>
<td>-98</td>
<td>Satellite channel</td>
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<tr>
<td>72 MHz</td>
<td>-95</td>
<td></td>
</tr>
</tbody>
</table>

Thermal Noise Power: \( N \), at \( T_s = 290°K \)
1. System Noise Temperature: $T_s$ is the temperature above $0^\circ$ Kelvin, where there is no random motion of electrons in matter:

$$T_s = T_a + T_e, \ ^\circ\text{Kelvin}$$

where: $T_e$ is the Rx noise temperature.

$$T_a = \text{Sky noise} + \text{Antenna losses}.$$

2. The Receiver’s noise temperature is related to its Noise Figure as:

$$T_e = T_o (F_{\text{sys}} - 1), \text{ where } T_o = 290^\circ \text{K}.$$ 

3. The noise factor: $F_{\text{sys}} = 10^{\text{NF}/10}$, where NF = Noise Figure.

4. Then, the noise factor: $F_{\text{sys}} = 1 + T_e/T_o$. 

<table>
<thead>
<tr>
<th>$T_e$ °Kelvin</th>
<th>Noise Factor: $F_{\text{sys}}$</th>
<th>Noise Figure: $T_e$ °Kelvin</th>
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<td>10</td>
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<tr>
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</tr>
<tr>
<td>500</td>
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<td>4.352</td>
</tr>
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</table>
Antenna Noise
Link Budget Analysis: Getting Started

1. Antenna noise temperature includes noise components **captured** from the environment surrounding the antenna and the noise generated by losses within the antenna, both ohmic loss and reflected mismatch loss.

2. The antenna noise temperature is the result of integrating the antenna’s three-dimensional radiation pattern with the incremental noise temperatures over spherical space. Typically, the environmental noise temperature varies with the antenna’s **elevation angle**: $\phi$
   - The noise temperature below the horizon may be considered as 290 °K.
   - The noise temperature at the local zenith may be less than 5 °K.
   - Low on the horizon, the noise temperature varies from 290 °K at the horizon to 100 °K at very low elevation angles near the horizon to 5 °K near the zenith.

3. For low link margin communications systems, it is generally important to **minimize** the antenna temperature. Therefore, a half-power beam width somewhat less than 180° tends to lower the antenna noise temperature.
Antenna Noise Temperature: $T_a$

Link Budget Analysis: Getting Started

Useful approximation for Earth Station antenna temperature on clear sky:

![Graph showing the relationship between Earth Station Antenna - Noise Temperature and Elevation Angle (degrees).]
Atmospheric & Sky Noise Temperatures

Standard Atmosphere

![Graph showing atmospheric noise temperatures](image-url)
S/N: Signal-to-Noise ratio

Link Budget Analysis: Getting Started

1. External & internal system noise will add to the receive signal/carryer power to produce a Signal-to-Noise ratio: S/N, in **linear form**:

   \[
   \frac{\text{Signal}}{\text{Noise}} = \frac{S}{N} = \frac{P_r}{kT_sB_w} = \frac{P_T G_{Tx} G_{Rx}}{	ext{Losses}} \cdot \frac{1}{kT_sB_w} = \frac{P_T G_{Tx}}{kB_w} \cdot \frac{1}{\text{Losses}} \cdot \left(\frac{G_{Rx}}{T_s}\right)
   \]

   where: \( \text{Signal} = P_r = \frac{P_T G_{Tx} G_{Rx}}{\text{Losses}}, \text{watts} \) and \( \text{Noise} = kT_s B_w, \text{watts} \).

2. The above Signal-to-Noise ratio is expressed in **decibel form** as:

   \[
   \left(\frac{S}{N}\right) = \left(\frac{C}{N}\right) = \text{EIRP} - \text{Losses} + \left(\frac{G_{Rx}}{T_s}\right) - 10\log_{10}(kB_w), \text{dB}
   \]

   where: \( \text{EIRP} = 10\log_{10}(P_T G_{Tx}) \) = Effective Isotropic Radiated Power, dBW.

3. Note that the term: \( G_{Rx}/T_s \) is the **System’s Figure of Merit** and is only related to the receive system.
Closing the Link
Link Budget Analysis: Getting Started

1. Calculate the Link Budget to verify if we are “closing the link”. When the received power is greater than the minimum acceptable carrier power, then the link is ‘closed’:
   \[ P_r \geq C_{\text{min}} \Rightarrow \text{Link closed} \]
   \[ P_r < C_{\text{min}} \Rightarrow \text{Link not closed} \]

2. To ensure acceptable operation in the communication system, assign a “Link Margin” in the Link Budget calculations, which tells how tight we are in closing the link:
   \[ \text{Link Margin} = P_r - C_{\text{min}} \] (usually expressed in dB)

3. Equivalently:
   \[ \text{Link Margin} > 0 \Rightarrow \text{Link closed.} \]
   \[ \text{Link Margin} < 0 \Rightarrow \text{Link not closed.} \]
Link performance and availability

Link Budget Analysis: Getting Started

Two thresholds are defined:

1. **Performance** threshold: Link’s performance above targeted value.
2. **Availability** threshold: Link is not available due to bad performance.

Key link budget equation:

\[ P_r = EIRP + G_{Rx} - FSPL - L_a \text{, dB} \]

where:

- \( P_r \): Received power, dBw.
- \( EIRP \): \( P_t G_{Tx} \), dB.
- \( FSPL \): Free space path loss, dB.
- \( L_a \): Atmospheric losses, dB.

Note: \( L_a \) is a random variable that changes due to condition of the atmosphere between Tx and Rx.
Digital Transmission
Link Budget Analysis: Getting Started

1. Analog communications mostly use mean signal power over mean noise power: $S/N$ as a quality parameter.
2. In analog communications, a waveform can be imagined as a signal with infinitely long duration and not divided in time, therefore with an unlimited amount of energy. It has final mean power and infinitive energy. Therefore, power is a useful parameter for analog communications.
3. With digital communications, symbols are transmitted in a time: $T_s$. If only one symbol is observed, mean power in all the time interval approaches zero. Therefore, power is not a satisfactory parameter for digital systems.
4. In digital communications, more often is used $E_b/N_0$, or normalized version of signal and noise:

$$\frac{S}{N} = \frac{E_b}{N_0} \frac{R_{bit}}{B_w}$$

where: $E_b$ is the energy per bit, watt-second.

$N_0$ is thermal noise in 1 Hz bandwidth, watts/Hz.

$R$ is the data speed in the system, bits per second (bps).

$B_w$ is the frequency bandwidth, Hz.
Link Performance Criteria

Link Budget Analysis: Getting Started

1. For **analog** communication systems, the link performance criteria that determines signal quality is Signal-to-Noise Ratio: $\frac{S}{N}$.
   1. Signal: $S =$ Power level of signal in occupied bandwidth, dBW or dBm.
   2. Noise: $N =$ Noise power in occupied bandwidth, dBW or dBm.

2. For **digital** communication systems, the link performance criteria that determines signal quality is Bit Error Rate (BER)/Probability of Error.
   A. BER is directly related to $\frac{E_b}{N_o}$ and improves as $\frac{E_b}{N_o}$ gets larger.
   B. $E_b = \frac{P_r}{R_{bit}} =$ Received power/Bit rate, Watts/bits/sec. $R_{bit} =$ Bit rate, bps
   C. $N_o =$ Noise power per unit of bandwidth = Noise power density, dBW/Hz.

3. S/N or BER is measured at the demodulator’s output, so they are specified at baseband frequencies:
   A. S/N = 40 dB in television; S/N = 30 dB in analog speech channels.
   B. S/N = 36 to 40dB for FM television $\Rightarrow$ C/N = 8 to 12dB in demodulator’s (modem’s) input.
   C. BER < $10^{-6}$ in data channels $\Rightarrow$ C/N = 12 dB (QPSK) at demod’s input.

4. S/N and BER depend on C/N and on the modulation technique.
**E_b: Energy per bit**

Link Budget Analysis: Getting Started

1. Since **Energy = Power x Time**, the receive signal power: \( S \) (watts) in a digital communication link is related to the energy in the bit interval: \( E_b \) (watt-second,) during the bit time interval: \( T_{bit} \) (sec) as:

\[
E_b = S \times T_{bit} = \frac{S}{R_{bit}}, \text{ watt-sec}
\]

where: \( R_{bit} = 1/T_{bit} \) = User bit rate; number of bits transmitted each second.

2. Expressing the equation in terms of Energy per bit: \( E_b \)

\[
E_b = \frac{S}{R_{bit}} = \frac{P_r}{R_{bit}} = \frac{C}{R_{bit}}, \text{ watt - sec}
\]

3. Where: \( S = P_r = C \) = Received signal/carrier power, watts.
**$E_b/N_0$ : Energy per bit/Noise Spectral Density**

Link Budget Analysis: Getting Started

1. $E_b/N_0$ is the performance criterion for any desired Bit Error Rate.
   A. To represent the minimum carrier performance before link failure.
   B. Is used as the basic measure of how strong the received signal is.
   C. It is the measure at the input to the receiver.
   D. Directly related to the amount of power transmitted from the uplink station.

2. $E_b/N_0$ is equal to the Signal-to-Noise ratio divided by the "gross" link spectral efficiency in (bit/s)/Hz, where the bits in this context are transmitted data bits, inclusive of error correction information and other protocol overhead.

3. $E_b/N_0$ expressed in **linear form**: 

   $$\frac{E_b}{N_0} = \frac{S}{N} \frac{B_w}{R_{bits}}$$

   Expressed in **decibel form**: 

   $$\frac{E_b}{N_0} = \frac{S}{N} + B_w - R_{bits}, dB$$

4. $E_b/N_0 = (S/N) + \text{Noise Bandwidth} - \text{Information Rate}, dB.$
Sources of Link Degradation
Link Budget Analysis: Getting Started

1. Signal **Attenuation/Fading**:
   A. A time-varying response.
   B. Amplitude/envelop/gain/power attenuation.

2. Signal **Distortion**:
   A. Distortion can be introduced within the Transmitter, Receiver or in the channel.
   B. The common types of link distortion are:
      1) Frequency-dependent phase shift.
      2) Gain variation with frequency caused by channel filtering effects.
      3) Gain variation with time as seen in radio/infrared channels.
      4) Frequency offsets between Tx & Rx due to Doppler shift or local oscillator errors.
   C. Distortion can be corrected with equalization or gain/frequency control systems.

3. Signal **Interference**:
   A. Interference arises due to signal contamination in the channel by extraneous signals.
      Most interference signals are impulsive.

4. **Noise**:
   A. Noise is characterized as random, unpredictable electrical signals from natural sources such as: Atmospheric noise, Thermal noise, Shot noise, etc.
   B. Because of the multiplicity of noise sources, it is difficult to define.
   C. It is commonly assumed that noise in communication links fall into the class of Additive White Gaussian Noise (AWGN).
Summary: Link Budget Equations
Link Budget Analysis: Getting Started

1. Effective Isotropic Radiated Power:
   \[ EIRP = 10 \log_{10}(P_t \cdot G_{Tx}) \text{, } dBW \]

2. Receive Signal Power:
   \[ P_r = S = \frac{P_t \cdot G_{Tx} \cdot G_{Rx}}{L_p \cdot L_a \cdot L_{ta} \cdot L_{ra} \cdot L_{pol} \cdot L_{other} \cdot L_r} \text{, watts} \]
   \[ P_r = S = EIRP + G_{Rx} - \text{Losses} \text{, } dBW \]

3. Free Space Path Loss: FSPL
   \[ FSPL = 10 \log_{10}(4\pi R / \lambda)^2 \text{, } dB \]

4. System Noise:
   \[ N = kT_sB_w \text{, watts} \]

5. Signal-to-Noise Ratio:
   \[ \left( \frac{S}{N} \right) = \left( \frac{C}{N} \right) = EIRP - \text{Losses} + \left( \frac{G_{Rx}}{T_s} \right) - 10 \log_{10}(kB_w) \text{, } dB \]

6. Energy per bit:
   \[ E_b = S \cdot T_{bit} = \frac{S}{R_{bit}} \text{, watt-sec} \]

7. Energy/bit per Noise density:
   \[ \frac{E_b}{N_0} = \frac{S}{N} + B_w - R_{bits} \text{, } dB \]

8. Noise spectral density:
   \[ N_0 = \frac{N}{B_w} = \frac{kT_sB_w}{B_w} = kT_s \text{, watts/Hz} \]
Atlanta RF LLC was founded to provide engineering solutions, design software solutions, and product development solutions to the high-frequency RF/microwave industry in the areas of: Telecommunications (ground segment), Satellite (space segment) and military/defense (RF front-ends).

Through teamwork, Atlanta RF applies our diverse technical experience to your project's challenges with creative and innovative solutions while holding ourselves accountable for the results. With professionalism and commitment to our clients, Atlanta RF will be there for you, both today and tomorrow.

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