OUTLINE

• Introduction

• Channel

• Received Signal Power and Noise Power

• Link Budget Analysis

• Noise Figure
INTRODUCTION

• **Communication Link**
  – The entire communication path
    • Starting from information source
    • Ending at information sink.
    • Includes all the encoding, modulation, channel, demodulation, decoding steps involved during the transmission of the information.

• **Link analysis**
  – The calculations and tabulation of useful signal power and interfering noise power at the receiver.
    • Calculate the SNR at receiver by consider all the effects through the communication link:
      – Distance
      – Frequency
      – Temperature
      – Bandwidth
      – Interference
      – ……
INTRODUCTION

• **Link budget**
  – The results of link analysis
  – An estimation of the error performance of communication system.
  – Example: find out the value of $E_b/N_0$ at receiver through link analysis, then find out the error probability through the BER v.s. $E_b/N_0$ curve.

• **Why link analysis?**
  – Find out the necessary parameters to meet certain system requirement.
  – Find out whether the designed system will meet the requirements
    • E.g. whether the error probability is below a certain value.
  – Find out the performance constraining factors in the system
  – Find out the trade-off that can be made in the system
    • Adjust certain parameters to meet requirements.
  – Estimate the power, cost for implementing a system.
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CHANNEL

• Channel
  – The propagation medium of the electromagnetic signals that bear the information.
    • Wired channel
      – Twisted pair
      – Coaxial cable
      – Fiber optic cable
    • Wireless channel
      – Vacuum
      – Air
      – Water
  – Different channels have different impacts on the transmitted signals.
CHANNEL: FREE SPACE

• **Free space**
  – An ideal RF propagation path
  – The RF energy arriving at the receiver is assumed to be a function only of distance between Tx and Rx.
  – Free of all hindrances to RF propagation, such as
    • Absorption,
    • Reflection
    • Refraction
    • Diffraction
    • These factors will be discussed in the Wireless Communications course
  – Only free space propagation will be considered in this chapter.
CHANNEL

• **Error performance degradation**

\[
\frac{E_b}{N_0} = \frac{S}{N} \frac{W}{R}
\]

– Error probability depends on \( \frac{E_b}{N_0} \) and modulation scheme
– \( \frac{E_b}{N_0} \) depends on
  • S: average signal power
  • N: average noise power
  • W: bandwidth
  • R: bit rate
– Signal power and noise power are affected by the channel.
– SNR degradation can be contributed by two factors
  • Signal loss (the power of the signal becomes weaker)
  • Noise
• **Sources of SNR degradation**
  - 1. Bandlimiting loss (signal loss)
    - All communication systems use filters to constrain the bandwidth of the signal to avoid interference to other users.
    - This will result in signal loss.
  - 2. ISI (interference source)
    - One symbol might smear into another symbol in time domain and cause ISI.
    - Imperfect filtering, system bandwidth constraints, loss of synchronization will cause ISI.
  - 3. Local oscillator (LO) phase noise (signal loss and noise source)
    - In coherent detection, if the phase of the reference signal is different from the phase of the received signal, it will result in signal energy loss.
    - Phase fluctuations or jitter will also add noise to the signal.
CHANNEL: SNR DEGRADATION

• **Sources of SNR degradation**
  – 4. Antenna efficiency (signal loss)
    • The receiver antenna can only capture partial of the signal power.
  – 5. Space loss (signal loss)
    • The longer the transmission distance, the weaker the received signal.
  – 6. Co-channel interference (noise source)
    • Caused by other users/communication systems that are using the same channel
  – 7. Adjacent channel interference (noise source)
    • Unwanted signals spilled over from neighboring channels.
  – 8. Thermal noise (noise source)
    • Always present in communication system
  – .....
CHANNEL: SNR DEGRADATION

Diagram showing various loss mechanisms in a communication channel, including:

- Pointing loss
- Polarization loss
- Atmospheric loss
- Space loss
- Pointing loss
- Radome loss
- Antenna
- Modulation loss
- Multiple carrier IM products
- Limiter loss or enhancement
- AM/PM conversion
- LO phase noise
- Transmitter
- Modem
- Information source

Key sources of noise degradation:
- Galactic, star, terrestrial noise
- Feeder loss
- Receiver loss
- LO phase noise
- Implementation loss
- Bandlimiting loss
- ISI
- Adjacent channel interference
- Co-channel interference

Legend:
- Signal loss
- Noise or interference source
- Both

Diagram arrows indicate the flow of information or signal through these processes.
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SNR: SIGNAL POWER

- **Free space propagation equation**

\[ P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2} \]

- \( P_t \): power at transmitter
- \( G_t \): transmitter antenna gain
- \( G_r \): receiver antenna gain
- \( \lambda = c / f \): wavelength. (the distance of propagation within one period).
- \( d \): distance between Tx and Rx.

- **Antenna gains**

\[ G = \frac{4\pi A_e}{\lambda^2} \]

- \( A_e \): antenna effective area \( A_e = \eta A_p \)
  - \( \eta \): antenna efficiency. \( A_p \): actual antenna area.
- \( \lambda = c / f \): wavelength. (the distance of propagation within one period)
SNR: SIGNAL POWER

• **EIRP (effective isotropic radiated power)**

\[
EIRP = P_t G_t
\]

• **Pathloss**
  - The ratio between transmit power and receiver power

\[
L = \frac{P_t}{P_r}
\]

\[
L(dB) = 10 \log_{10} \frac{P_t}{P_r}
\]

  - L is always bigger than 1.
  - L(dB) is always bigger than 0.

\[
L(dB) = 10 \log_{10} P_t - 10 \log_{10} P_r
\]

  - 1 (dBW) = \(10 \log_{10} \frac{P_t}{1W}\)
  - 1 (dBm) = \(10 \log_{10} \frac{P_t}{1mW}\)
• Free space loss
  – The pathloss due to free space propagation only
    • DO NOT consider the effects of antenna gain

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

– With free space loss, the received signal power can be expressed as

\[ P_r = \frac{P_t G_t G_r}{L_s} \]
SNR: SIGNAL POWER

• **Example**
  – A transmitter has an output of 2 W at a carrier frequency of 2 GHz. Assume that the transmitting and receiving antennas are parabolic dishes each 1 meter in diameter. Assume the efficiency of the Tx antenna is 0.6, and the efficiency of the Rx antenna is 0.4.
  
  • 1. Evaluate the gains of the two antennas.
  • 2. Calculate the EIRP of the transmitted signal in unit of dBW.
  • 3. If the Rx antenna is 30 km from the Tx antenna over a free-space path, find the free space loss
  • 4. Find the received signal power in unit of dBW.
**SNR: THERMAL NOISE POWER**

- **Thermal noise**
  - Caused by the thermal motion of electrons in all conductors
    - Higher temperature $\Rightarrow$ faster electron movement $\Rightarrow$ larger noise power
  - Modeled as: AWGN
    - The PSD is flat up to $10^{12}$ Hz.
  - The single sided PSD is
    \[
    N_0 = \kappa T^o
    \]
    - $\kappa = 1.38 \times 10^{-23} \, J / K$ : Boltzmann’s constant
    - $T^o$ : absolute temperature in the unit of Kelvin. (0 K = -273.15 centigrade).
  - Power of thermal noise for a communication system with bandwidth $W$
    \[
    P = N_0 W = \kappa T^o W
    \]
LINK BUDGET ANALYSIS

• Example:
  – A satellite system with EIRP 40 dBW, frequency of 10GHz, and data rate 10 Mbps. The distance between Tx and Rx is 38,000km. Assume the required $E_b / N_0$ is 10 dB, the temperature is 600 K, and the rooftop dish has an efficiency of 0.55. What is the minimum diameter of the dish?
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• **Link Budget Analysis**

• Noise Figure
LINK BUDGET ANALYSIS: C/N

• **Link budget analysis**
  – The main quantity of interest in link budget analysis is the SNR or $E_b / N_0$ at receiver.
  – In communication link, the receiver SNR is often called **carrier-to-noise ratio (C/N)**.

• **Carrier-to-noise ratio**
  – If all the carrier energy is devoted to signal, then the C/N is defined as the ratio between received signal power, $P_r$, and noise power, $N = kT_0 W$

  \[
  C = \frac{P_r}{N} = \frac{S}{N} = \frac{P_t G_t G_r}{L_o L_s N} = \frac{EIRP G_r}{L_s L_o k T_0 W}
  \]

  – $L_o$: all other losses and degradations not accounted for by other terms.

• **Relationship between C/N and** $E_b / N_0$

  \[
  \frac{E_b}{N_0} = \frac{P_r W}{N R} \quad \frac{P_r}{N_0} = \frac{E_b}{N_0} R
  \]
LINK BUDGET ANALYSIS: LINK MARGIN

- **Two \( E_b / N_0 \) values of interest**
  - 1. Received \( E_b / N_0 \): the actual \( E_b / N_0 \) at receiver. Denoted as \( (E_b / N_0)_r \)
  - 2. Required \( E_b / N_0 \): the required \( E_b / N_0 \) to achieve a certain error probability. Denoted as \( (E_b / N_0)_{reqd} \)

- **Link margin**
  - To ensure the proper operation of the system, design a system with \( (E_b / N_0)_r > (E_b / N_0)_{reqd} \), thus have a safety margin.
  - Link margin is defined as the difference between \( (E_b / N_0)_r \) and \( (E_b / N_0)_{reqd} \)

\[
M (dB) = (E_b / N_0)_r (dB) - (E_b / N_0)_{reqd} (dB)
\]
LINK BUDGET ANALYSIS

- Link budget are typically in Decibles

\[
\left( \frac{E_b}{N_0} \right)_r (dB) = M (dB)
\]

- Self-study: Section 5.4.3 and 5.4.4
LINK BUDGET ANALYSIS

• Example
  – A communication system with the following parameters: frequency is 3GHz, BPSK, BER is $10^{-3}$, data rate= 1kbps, link margin = 3dB, EIRP = 10 W, receiver antenna gain = 10 dB, distance between Tx and Rx is 4,000 km. Find the maximum allowed noise power spectral density.
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**NOISE FIGURE**

- **Operation noise figure**
  - At the communication receiver, the received signal needs to be amplified.
  - The amplifier will
    - 1. Amplify the signal component and noise component.
    - 2. Add its own noise.
  - Therefore, the SNR at the output of the amplifier is lower than the SNR at the input of the amplifier.

![Graph showing input and output power levels with frequency range from 2.6 to 2.7 GHz, maximum input SNR of 40 dB at 2.65 GHz, and maximum output SNR of 30 dB at 2.65 GHz.](image-url)
• **Operation noise figure: definition**
  - the SNR degradation caused by an amplifier.

\[
F_{op} = \frac{(SNR)_{in}}{(SNR)_{out}} = \frac{S_i / N_i}{GS_i / [G(N_i + N_{ai})]}
\]

- \(S_i\): signal power at input of amplifier
- \(N_i\): noise power at input of amplifier
- \(N_{ai}\): noise power added by amplifier
- \(G\): amplifier gain

  - Simplify the operation noise figure equation

\[
F_{op} = \frac{N_i + N_{ai}}{N_i} = 1 + \frac{N_{ai}}{N_i}
\]

- Operation noise figure depends on the input noise power.
- The input noise power depends on temperature.
- **Operation noise figure depends on temperature!**

• **Noise figure:**
  - The value of \(F_{op}\) when the input noise has the temperature of 290 K.
Example

An amplifier has a noise figure of 4 dB, a bandwidth of 500 kHz, and an input resistance of 50 Ohm. If the input SNR = 1, find the output SNR when the amplifier is connected to a signal source of 50 Ohm at 200 K.
EFFECTIVE NOISE TEMPERATURE

- **Effective noise temperature** \( T_R \)
  - The temperature that corresponds to the additional noise power, \( N_{ai} \), introduced by the receiver
    \[
    F = 1 + \frac{N_{ai}}{N_i} \Rightarrow N_{ai} =
    \]
    \[
    T_R = (F - 1)290K
    \]
  - Characterizes the noisiness of an amplifier
  - It has a one-to-one relationship with noise figure \( \Rightarrow \) equivalent to noise figure
  - an amplifier can be either characterized by noise figure, \( F \), or effective noise temperature,

- **The total noise power at the output of an amplifier**

  \[
  N_{out} = G\kappa T_g W + G\kappa(F - 1)290W
  \]

  \( T_g \): temperature of the source
EFFECTIVE NOISE TEMPERATURE

• Example
  – If an amplifier has a noise figure of 4dB, find the effective noise temperature of the amplifier.
SYSTEM EFFECTIVE TEMPERATURE

• Noise Power in a Communication System
  – 1. Antenna will insert noise to the received signal
    • Antenna noise temperature: \( T_A \)
    • Noise power inserted by antenna: \( N_A = kT_A W \)
  – 2. Amplifier will insert noise to the received signal
    • Amplifier noise temperature: \( T_R = (F - 1)290K \)
    • Noise power inserted by amplifier at the input: \( N_R = kT_R W \)
  – Total noise power before the amplifier: (from antenna alone)
    \[ N_{in} = N_A = kT_A W \]
  – Total noise power after the amplifier: (from both antenna and amplifier)
    \[ N_{out} = G(N_A + N_R) = Gk(T_A + T_R)W \]
SYSTEM EFFECTIVE TEMPERATURE

• **System Effective Temperature**
  
  – The system effective temperature is the combination of the antenna noise temperature and the amplifier noise temperature

  \[
  T_s = T_A + T_R
  \]

  – Total noise power at the output of the amplifier

  \[
  N_{out} = GkT_s W = Gk(T_A + T_R) W
  \]

  – SNR at the input of the amplifier

  \[
  (SNR)_{in} = \frac{S_i}{kT_A W}
  \]

  – SNR at the output of the amplifier

  \[
  (SNR)_{out} = \frac{GS_i}{GkT_s W} = \frac{S_i}{kT_s W}
  \]
SYSTEM EFFECTIVE TEMPERATURE

- **Example**
  - A receiver front end (amplifier) has a noise figure of 10dB, a gain of 80 dB, and a bandwidth of 6MHz. The input signal power is $10^{-11} \text{W}$. The antenna temperature is 150K.
  - Find $T_R$, $T_s$, $N_{out}$, $\text{SNR}_{in}$, $\text{SNR}_{out}$.
**LINK BUDGET ANALYSIS**

**Example**

- A satellite communication system uses a Tx that produces 20W of RF power at a carrier frequency of 10GHz that is fed into a 1-meter parabolic antenna. The distance to the receiving earth station is 20,000 nautical miles. The receiving system uses a 2-meter parabolic antenna and has a 100-K system noise temperature. Each antenna has an efficiency of 0.6. Also assume that the incidental losses amount to 2 dB.

  - Calculate the maximum data rate that can be used if the modulation is non-coherent DPSK and the bit error probability is not to exceed $10^{-4}$. 
• **Example**

  – Given the following link parameters, find the maximum allowable receiver (amplifier) noise figure. The modulation is coherent BPSK with BER of $10^{-3}$ for a data rate of 10Mbps. The carrier frequency is 12GHz. The EIRP is 0 dBW. The receiving antenna diameter is 0.2 m with efficiency 0.55. The antenna temperature is 750K. The distance between Tx and Rx is 10km. The margin is 3dB and the incidental losses are assumed to be 0dB.