Department of Electrical Engineering
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CES 540 Digital Data Transmission
Ch. 5 Link Analysis

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OUTLINE

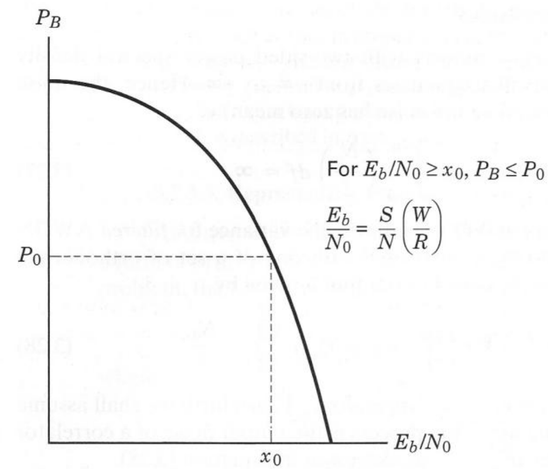
- **Introduction**
- **Channel**
- **Received Signal Power and Noise Power**
- **Link Budget Analysis**
- **Noise Figure**

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 E_b / N_0 and modulation scheme
  - 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

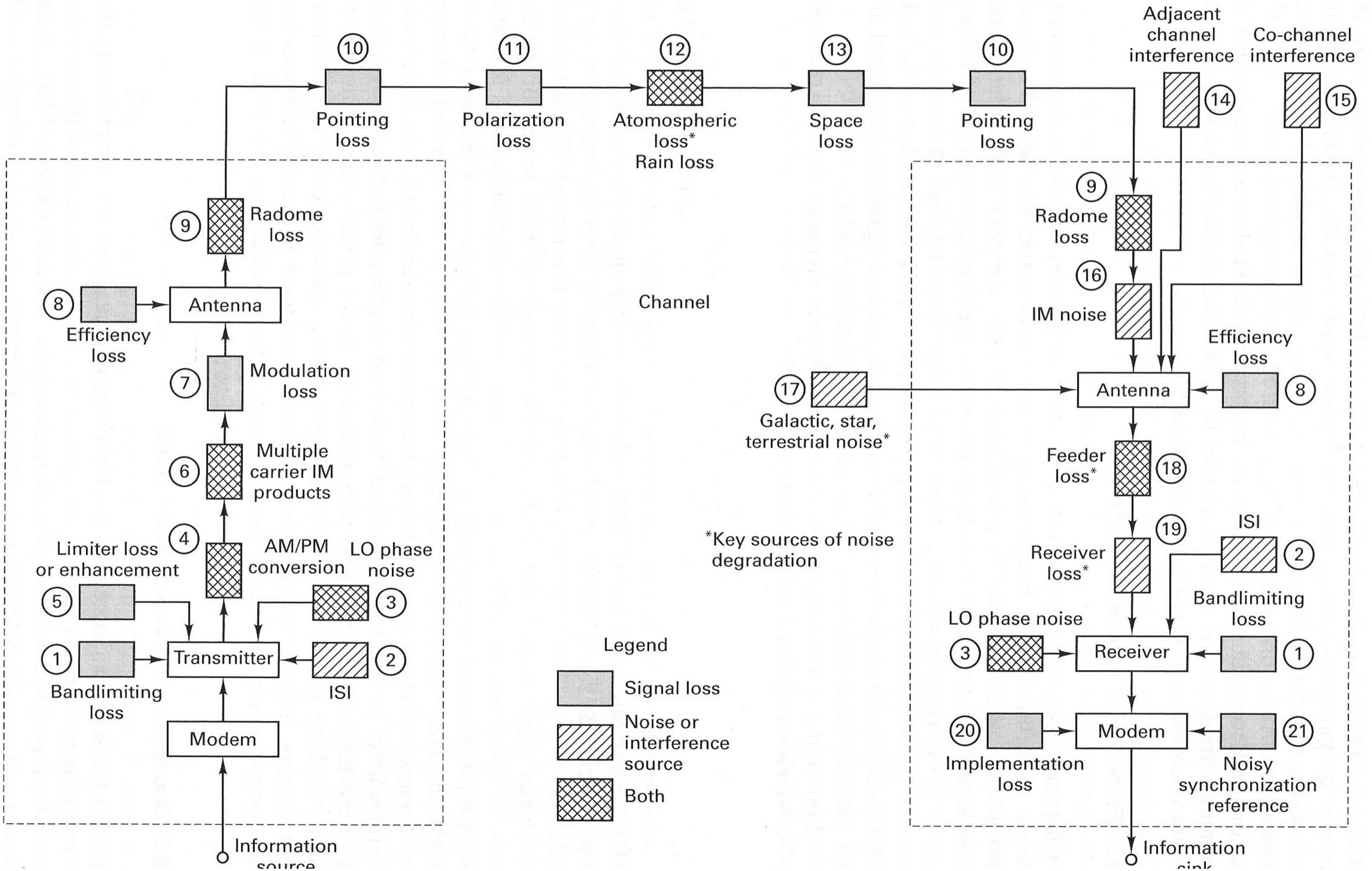
CHANNEL: SNR DEGRADATION

- **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 results in signal loss.
  - 2. ISI (interference source)
    - One symbol might smear into another symbol in time domain and cause ISI.
    - Imperfect filtering, system bandwdith constraints, lost 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



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

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SNR: SIGANL POWER

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

$$EIRP = P_t G_t$$

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

$$L = \frac{P_t}{P_r} \qquad L(dB) = 10\log_{10}\frac{P_t}{P_r}$$

  - 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) = $10\log_{10}\frac{P_t}{1mW}$

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SNR: SIGANL POWER

- **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 ➔ faster electron movement ➔ 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: 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, $N = \kappa T^o W$

$$\frac{C}{N} = \frac{P_r}{N} = \frac{S}{N} = \frac{P_t G_t G_r}{L_o L_s N} = \frac{EIRP G_r}{L_s L_o \kappa T_0 W}$$

  - L_0 : all other losses and degradations not accounted for by other terms.

- **Relationship between C/N and** E_b / N_0

$$\frac{E_b}{N_0} = \frac{P_r}{N}\frac{W}{R}$$

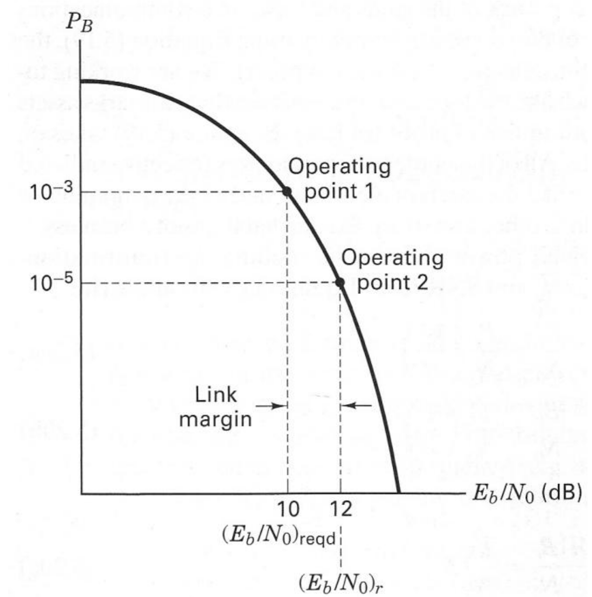
$$\frac{P_r}{N_0} = \frac{E_b}{N_0} R$$

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 $(E_b / N_0)_{reqd}$

$$M(dB) = \left(E_b / N_0\right)_r (dB) - \left(E_b / N_0\right)_{reqd} (dB)$$



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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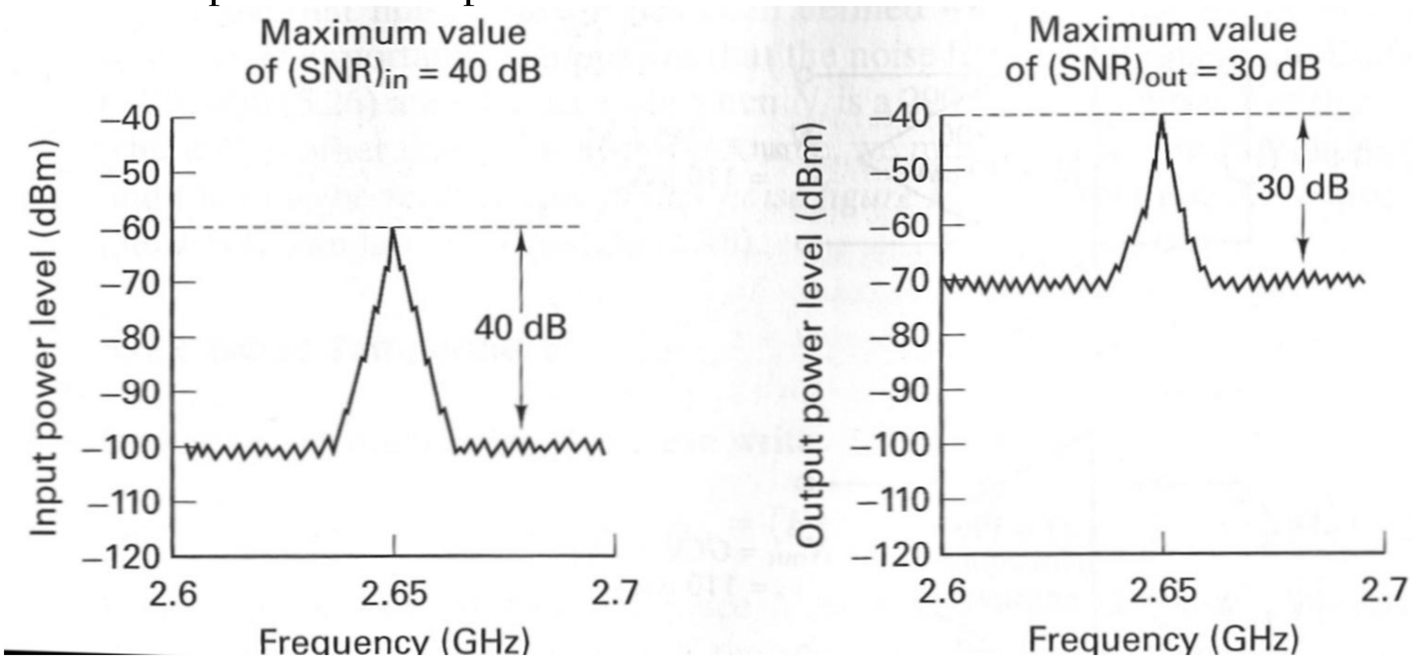
NOISE FIGURE

- **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.



NOISE FIGURE

- **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.

NOISE FIGURE

- **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 ➔ 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.

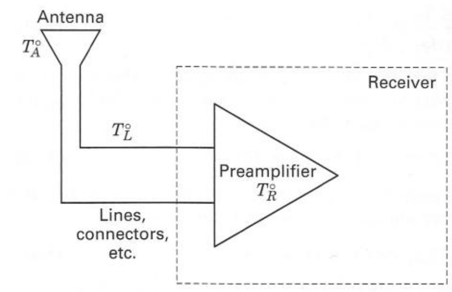
SYSTEM EFFECTIVE TEMPERATURE

- **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)

$$N_{out} = G(N_A + N_R) = Gk(T_A + T_R)W$$



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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

$$N_{out} = GkT_sW = Gk(T_A + T_R)W$$

  - SNR at the input of the amplifier

$$(SNR)_{in} = \frac{S_i}{kT_AW}$$

  - SNR at the output of the amplifier

$$(SNR)_{out} = \frac{GS_i}{GkT_sW} = \frac{S_i}{kT_sW}$$

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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 $10^{-11}W$. The antenna temperature is 150K.
    - Find T_R , T_s , N_{out}, SNR_{in}, SNR_{out}.

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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}

LINK BUDGET ANALYSIS

- **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.