Link Budget

Communication Systems
Lecture 4
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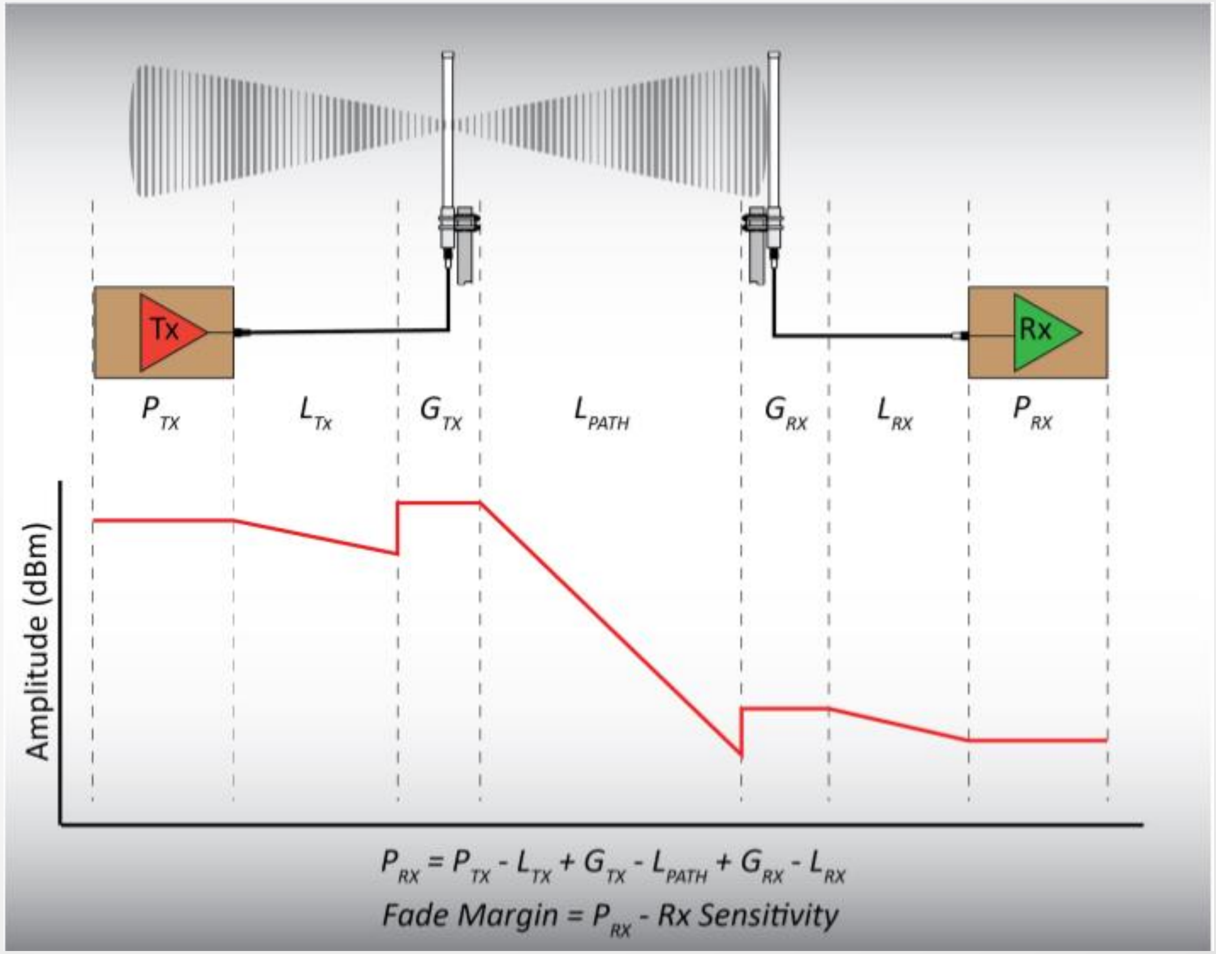
How Would You Plan A Road Trip To A Remote Location?

- Fuel requirement
  - \- Considers the storage capacity
  - \- Rate of consumption
  - \- Calculate the fuel required to reach the destination, also arrive
  - \- **With some level of reserve or margin of safety; accounting for the unforeseeable.**

What is Link Budget?

An account of all the various gains and losses between the transmitter and the receiver is referred to as the link budget.



P_{TX} = the transmit power in dBm.
L_{TX} = the total system loss in dB at the transmitter.
G_{TX} = the antenna gain in dBi at the transmitter.
L_{PATH} = the total propagation losses in dB between the transmit and receive antennas.
G_{RX} = the antenna gain in dBi at the receiver.
L_{RX} = the total system loss in dB at the receiver.
P_{RX} = the receive power in dBm.

Fade Margin

- The level of received power in excess of that required for a specified minimum level of system performance is referred to as the **fade margin.**
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- Provides a margin of safety in the event of a temporary attenuation or fading of the received signal power.
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- The minimum required received power level used for the link budget is decided by designer's knowledge and experience with receiver's sensitivity.
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- Receiver's sensitivity specifies the minimum RF input power required to produce a useable output signal.
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- Typical values for receiver sensitivity fall within the range of –90 to –120 dBm.

Transmit Power

Converting power Watt to dB & dBm

System Loss

- System loss is the sum of the total **insertion loss** in the transmission line plus **any loss due to an impedance mismatch with the antenna.**
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- **Insertion Loss**

Each device in the transmission line that does not produce a signal gain (amplifier) will exhibit some degree of signal loss. A decrease in the signal level at its output relative to its input is known as **insertion loss**. Ex: Cables, connectors, bandpass filters, etc.

Example for Cable Loss - Attenuation Specification for Belden 9914

Nom. Attenuation:	
Freq. (MHz)	**Attenuation (dB/100 ft)**
5	0.4
10	0.5
50	1.0
100	1.4
200	1.8
400	2.6
700	3.6
900	4.1
1000	4.4
1500	5.5
1800	6.1
2000	6.5
2500	7.5
3000	8.3
4000	9.9

Impedance Mismatch Loss

$$ML = -10\log\left\{1 - \left[\frac{VSWR - 1}{VSWR + 1}\right]^2\right\}$$

Antenna Gain

Relative to an isotropic radiator, a standard half wave vertical dipole antenna will exhibit an intrinsic gain of 2.15 dB in the horizontal.

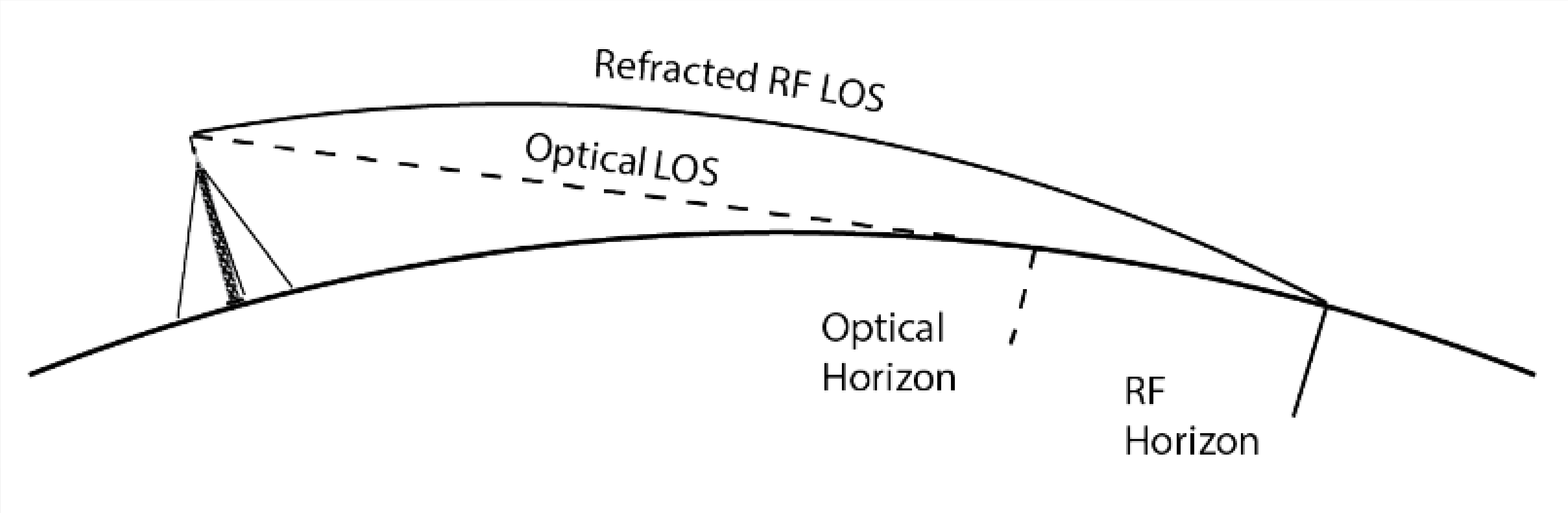
$$dBi = dBd + 2.15$$

Path Loss

The sum of free space loss plus additional losses induced by the interaction of the EM (electromagnetic) wavefront with the terrain and/or obstructions along the path of propagation.

Line of Sight Propagation

Therefore, for a single antenna, the maximum path of propagation is limited by the distance to the RF horizon.



Optical Horizon vs. RF Horizon

An RF LOS follows a curved path that is initially parallel to the earth’s surface but is progressively bent toward the surface due to the refractive properties of the atmosphere. Therefore, the distanced to the RF horizon will be somewhat (≈7%) greater than the distance to the optical horizon.

For a standard atmosphere (standard refraction = k = 1.33) over a smooth earth, the distance to the RF horizon is related to the height of the antenna as follows:

$$d_{HOR} = 4.124\sqrt{h}$$

Where:

d_{HOR} = distance in kilometers to the RF horizon

h = the antenna height in meters above a smooth earth

For a link to be considered as having a line-of-sight path of propagation, the distance between the transmitting and receiving antennas must be equal to or less than the maximum line-of-sight path distance:

$$d_{PATH} \leq LOS_{MAX}$$

Free Space Propagation Model

Free space loss equation

$$FSL_{dB} = 32.45 + 20\log(d) + 20\log(f)$$

FSL $_{dB}$ = free space loss in dB
d = distance in kilometers
f = frequency in Megahertz

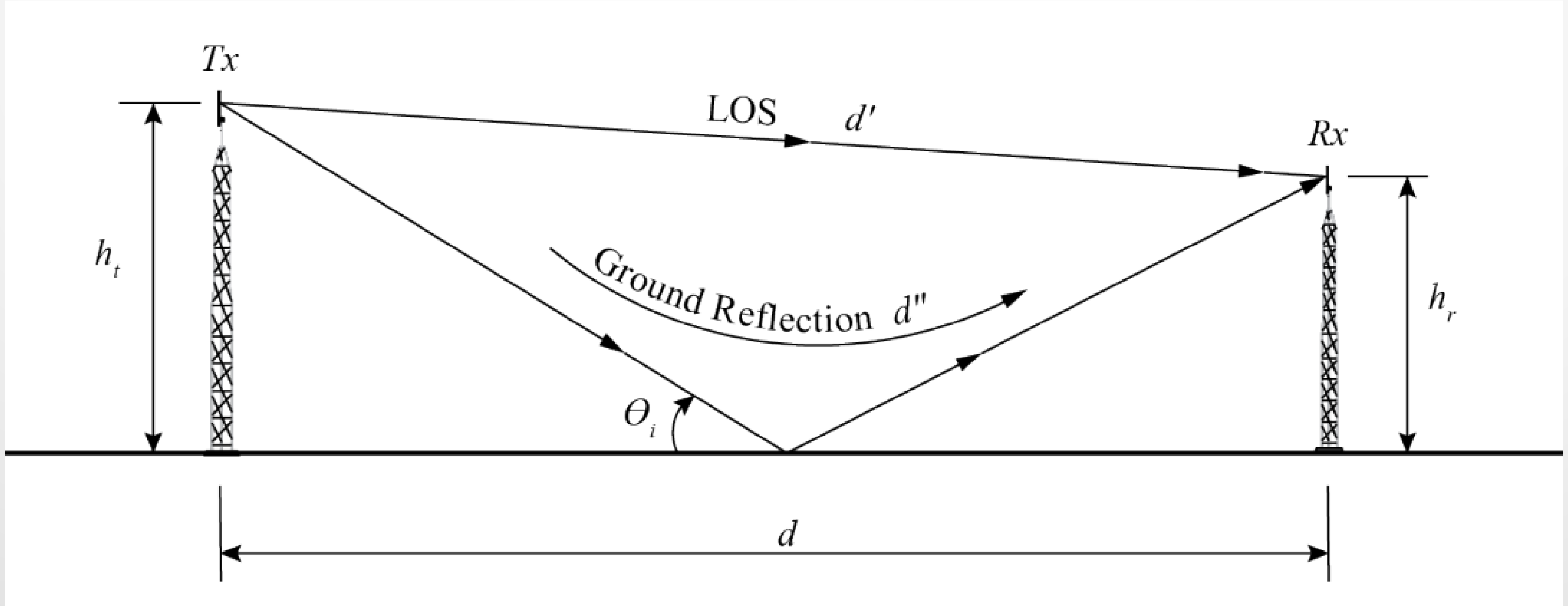
Atmosphere, reflective surfaces or obstructions are not considered!

2-Ray Multipath Propagation Model

- In the more typical terrestrial setting, the EM wave must propagate through nonhomogeneous atmosphere over a path of often mixed terrain and uneven topography.
- Additionally, system design constraints may require that a link be established over a path containing unavoidable manmade or natural obstructions.
- Many of these non-free-space elements in the physical environment can cause the **propagating wavefront to be absorbed, scattered, refracted, reflected, or diffracted**.

2-Ray Multipath Propagation Model

The effect of the ground reflected wavefront on the received signal is largely dependent on the **distance between the transmitting and receiving antennas, the relative height of the antennas, and the reflective properties** of the earth's surface.



2-Ray Multipath Propagation Model

- Factors affecting path loss are **greatly dependent on the relative heights of the antennas** and the **path distance**.
- When the difference in **antenna heights is large** and **the path distance is less than a critical distance (d_c)**, the direct and reflected wavefronts will alternate between constructive and destructive interference for successive values of d.

2-Ray Multipath Propagation Model

When the **path distance is equal to or greater than the critical distance**, **the relative antenna heights become very small compared to the path distance**, and the angle of incidence will approach 0°. For this path geometry, the phase shift contributable to a difference in path lengths becomes very small, and the phase shift induced in the reflected wave approaches 180° for both vertical and horizontal polarization.

Under above conditions, the path loss can be calculated using the following equation:

$$PL_{2Ray} = 120 - 20\log(h_{TX} h_{RX}) + 40\log(d)$$

PL_{2Ray} = 2-ray path loss in dB
h_{TX} = height of the transmitting antenna in meters
h_{RX} = height of the receiving antenna in meters
d = distance between antennas in kilometers

The critical distance is calculated as follows:

$$d_c = \frac{4\pi h_{TX} h_{RX}}{\lambda}$$

Where:

d_c	= critical distance in meters
h_{TX}	= height of the transmitting antenna in meters
h_{RX}	= height of the receiving antenna in meters
λ	= wavelength of the propagating EM wave

Received Signal Level

$$P_{RX} = P_{TX} - L_{TX} + G_{TX} - L_{PATH} + G_{RX} - L_{RX}$$

Fade Margin

By subtracting the receiver's specified sensitivity from the calculated received signal level, we can determine the extent to which transient path losses or signal fading can be tolerated before system performance is impacted.

$$\boxed{\textit{Fade Margin} = P_{RX} - \textit{Rx Sensitivity}}$$

Example

- RF320 radio (both ends): RF output power = 5 watts (37 dBm); sensitivity = 0.25 μV (–119 dBm) for 12 dB SINAD (signal-to-noise-and-distortion ratio); operating frequency = 170 MHz.

• Omnidirectional antenna (both ends) is an FG1683: gain = 3 dBd (5.15 dBi); VSWR (voltage standing wave ratio) < 2:1.

• The elevation of the transmitting antenna is 30 meters.

• Transmission line at transmitter: pn 31332 Surge Suppression Kit (loss ≈ 0.5 dB); 100 ft. of Belden® 9914 coaxial cable (loss ≈ 1.7 dB @ 170 MHz); miscellaneous connector loss ≈ 0.5 dB.

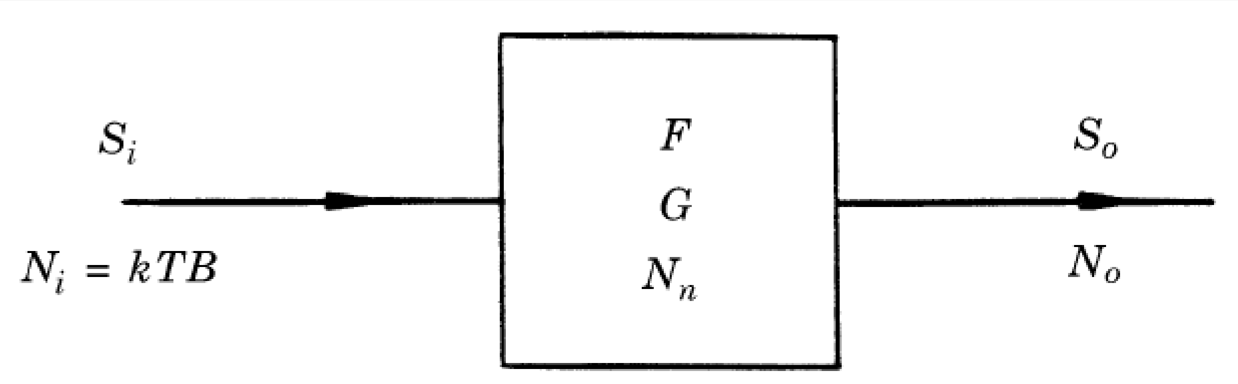
• The elevation of the receiving antenna is 10 meters.

• Transmission line at receiver: pn 31332 Surge Suppression Kit (loss ≈ 0.5 dB); 50 ft. of Belden 9914 coaxial cable (loss ≈ 0.85 dB @ 170 MHz); miscellaneous connector loss ≈ 0.5 dB.

• The path of propagation is an unobstructed line of sight (LOS) over a smooth earth.

• The distance between the transmitting and receiving antennas is 20 miles (32.2 km).

Receiver Noise Figure



For a cascade system

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}}$$

$$N_i = kT_0 B \quad \text{(W)}$$

$$F = \frac{N_o}{G k T_0 B}$$

The gain and noise figure in the first stage are critical in achieving a low overall noise figure.

It is very desirable to have a low noise figure and high gain in the first stage.

For a passive component with loss L in ratio, we will have G = 1/L and F = L

Receiver Noise Figure and Maximum Distance

$$F = \frac{S_i/N_i}{S_o/N_o}$$

$$\begin{aligned} S_i = S_{i,\min} &= N_i F \left(\frac{S_o}{N_o}\right)_{\min} \\ &= kTBF \left(\frac{S_o}{N_o}\right)_{\min} \end{aligned}$$

$$R_{\max} = \left[\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 kTBF (S_o/N_o)_{\min} L_{\text{sys}}}\right]^{1/2}$$

The Output S/N at a Distance R

$$\frac{S_o}{N_o} = \frac{P_t G_t G_r}{kTBFL_{\text{sys}}} \left(\frac{\lambda_0}{4\pi R} \right)^2$$

The Output S/N at a Distance R

$$\frac{S_o}{N_o} = \frac{P_t G_t G_r}{kTBFL_{\text{sys}}} \left(\frac{\lambda_0}{4\pi R} \right)^2$$

Example 1

In a two-way communication, the transmitter transmits an output power of 100 W at 10 GHz. The transmitting antenna has a gain of 36 dB, and the receiving antenna has a gain of 30 dB.

Calculate the received power level at a distance of 40 km

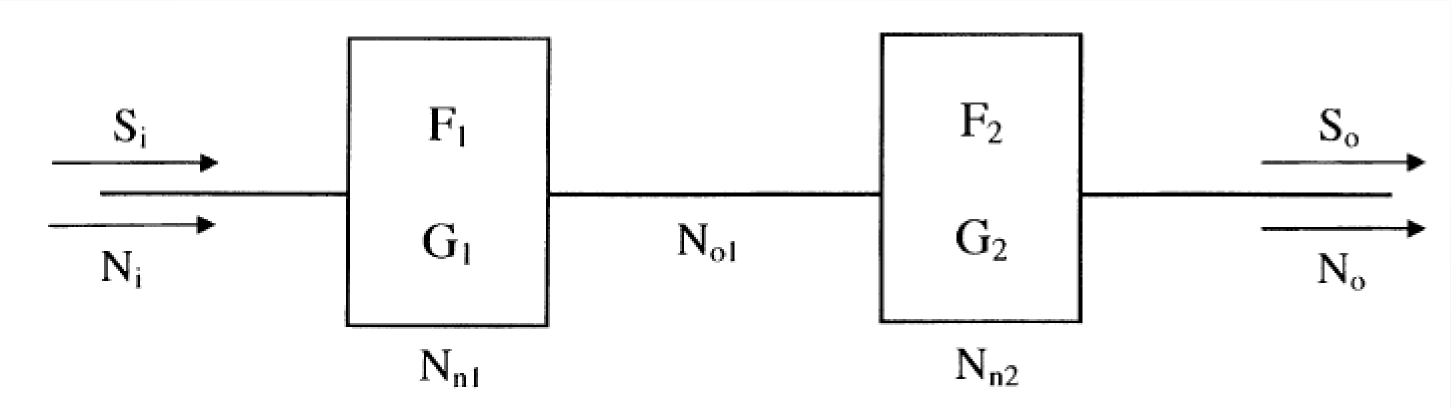
(a) if there is no system loss and

(b) if the system loss is 10 dB

Example 2

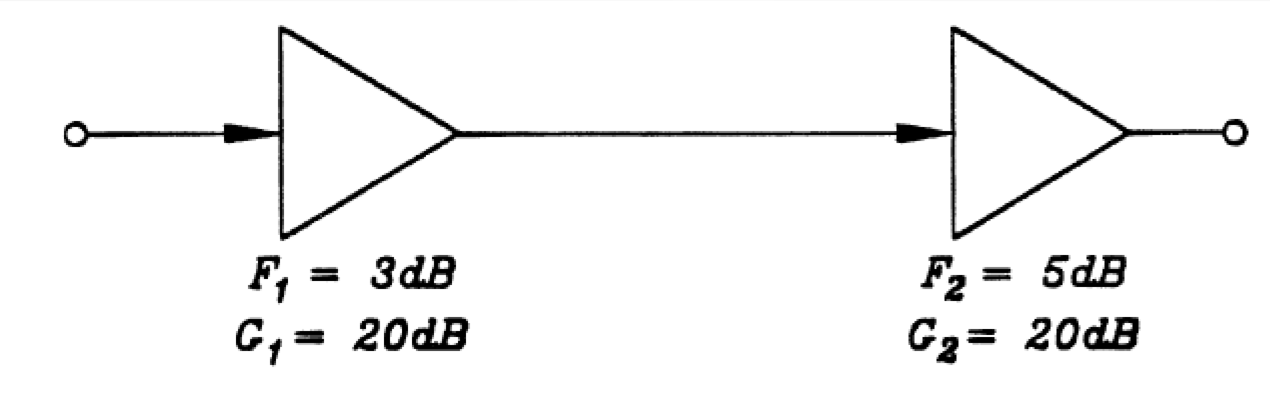
For the two-element cascaded circuit , prove that the overall noise factor is

$$F = F_1 + \frac{F_2 - 1}{G_1}$$

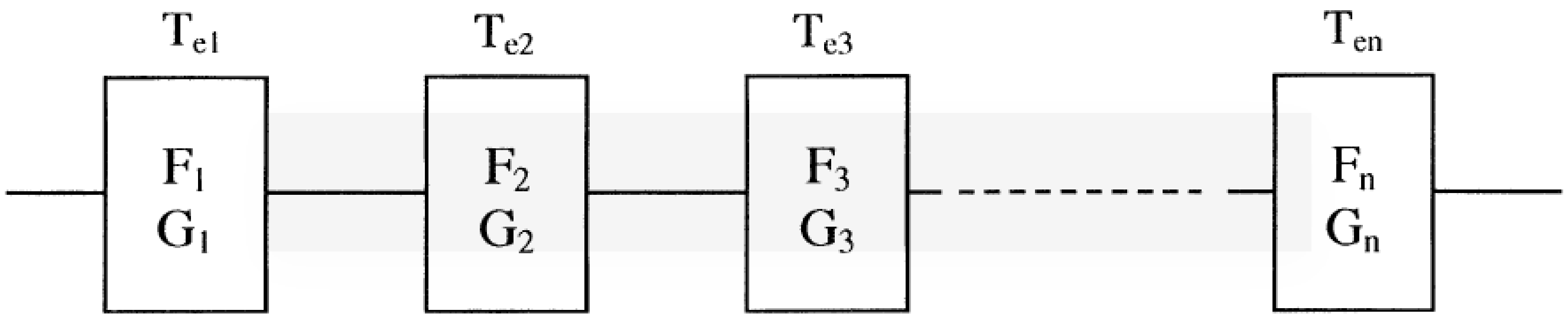


Example 3

Calculate the overall gain and noise figure for the system.



Overall Equivalent Noise Temperature



$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots + \frac{T_{en}}{G_1 G_2 \cdots G_{n-1}}$$

In Kelvin

System Noise Temperature Involving Antenna

If an antenna noise temperature is T_A , the overall system noise temperature including the antenna is

$$T_S = T_A + T_e$$

where T_e is the overall cascaded circuit noise temperature.
The antenna noise temperature is approximately equal to 290 K for an antenna pointing to earth.
The antenna noise temperature could be very low (a few kelvin) for an antenna pointing to the sky.

Compression Points, Minimum Detectable Signal & Dynamic Range

- In a mixer, an amplifier, or a receiver, operation is normally in a region where the output power is linearly proportional to the input power.

- The proportionality constant is the conversion loss or gain.

- This region is called the dynamic range.

- If the input power is above this range, the output starts to saturate.

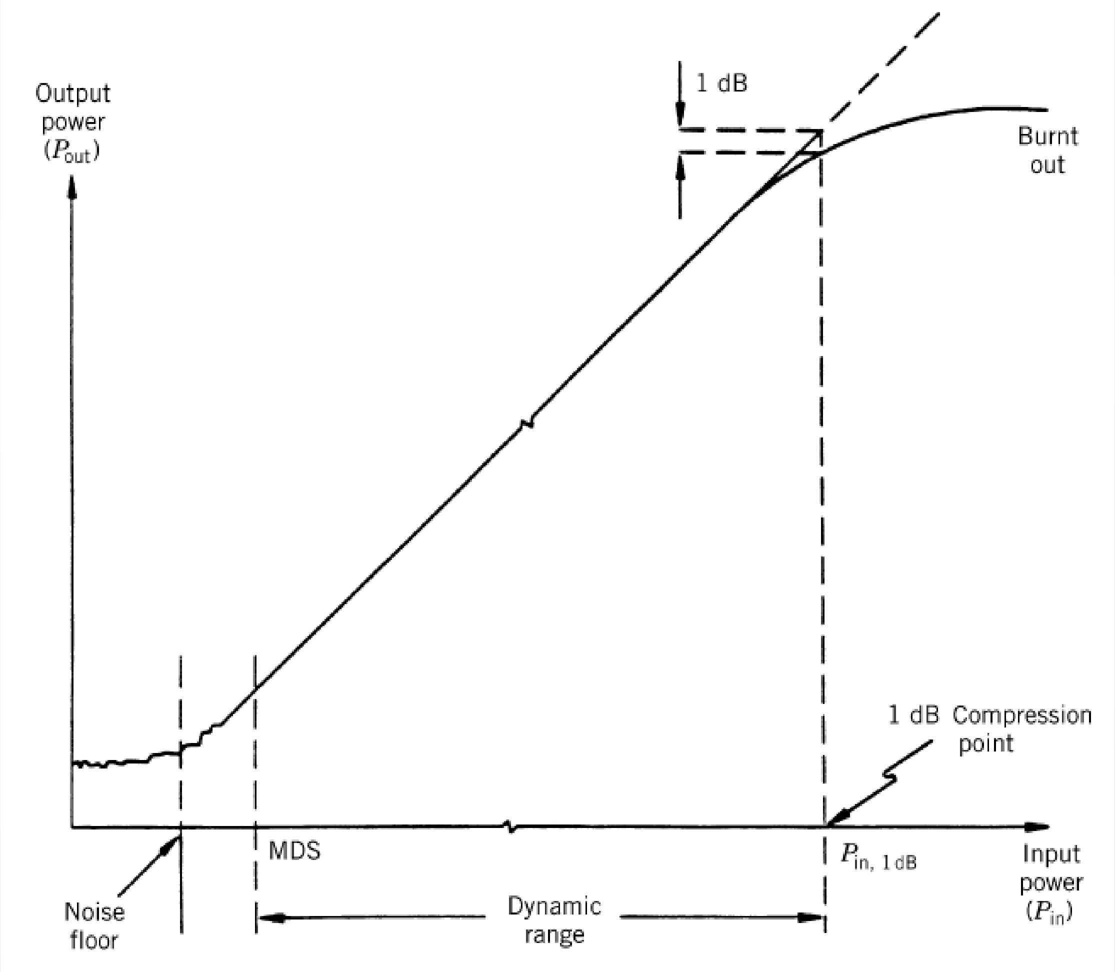
- If the input power is below this range, the noise dominates.

Compression Points, Minimum Detectable Signal & Dynamic Range

- The **Dynamic Range** is defined as the range between the 1-dB compression point and the minimum detectable signal (MDS).

- The input power level at which the conversion loss increases by 1 dB, called the **1-dB compression point,** is generally taken to be the top limit of the dynamic range.

- The Dynamic Range can be defined as the difference between the input signal level that causes a **1-dB compression gain** and the **minimum input signal level that can be detected above the noise level**.



Compression Points, Minimum Detectable Signal & Dynamic Range

-The noise floor due to a matched resistor load is

$$N_i = kTB$$

Assume room temperature (290 K) and 1 MHz bandwidth for a mixer

$$N_i = 10 \log kTB = 10 \log(4 \times 10^{-12} \text{ mW}) = -114 \text{ dBm}$$

The MDS is defined as 3 dB above the noise floor and is given by

$$\text{MDS} = -114 \text{ dBm} + 3 \text{ dB} = -111 \text{ dBm}$$

Example 4

A receiver operating at room temperature has a noise figure of 5.5 dB and a bandwidth of 2 GHz. The input 1-dB compression point is 110 dBm. Calculate the minimum detectable signal and dynamic range.

Reference

- KAI CHANG, “RF and Microwave Wireless Systems”