FACTORS IN CHOOSING A FREQUENCY BAND

- Antenna dimensions
  - Gain $\alpha$ (frequency)$^2$

- Propagation factors
  - Rain causes attenuation above 10 GHz
    $\rightarrow$ Submarines use $f < 100$KHz through Earth

- Available orbital slots in Satellites
  - All U.S. Domestic slots for 6/4 GHz are full
    (for Satellite use)

- Equipment availability / cost.
QUALITY CRITERIA IN COMMUNICATIONS

- Performance is specified by:

  Analog Systems –
  
  Signal to Noise ratio, $\frac{S}{N}$

  Digital Systems –
  
  Bit Error Rate, BER

(Strictly, Probability of Bit Error, but “BER” is always used)
PERFORMANCE SPECIFICATION

- $\frac{S}{N}$ or BER is specified at Baseband in the Information Channel.

- E.g. Telephone Channel (one way)
  \[ \frac{S}{N} = 50.0 \text{ dB} \] is objective at receive end.
  - Noise is barely audible.

- E.g. Data link
  \[ \text{BER} = 10^{-7} \]
LINK DESIGN

- Baseband $\frac{S}{N}$ or BER is specified

- $\frac{S}{N}$ and BER are measured at the demodulator output

- $\frac{C}{N}$ at demodulator input will determine output $\frac{S}{N}$ or BER

- We must design for required $\frac{C}{N}$ in IF section of receiver
BASIC TRANSMISSION THEORY
(FRII'S FREE SPACE)

- Start with Isotropic Source radiating $P_t$ watts uniformly into free space

- Flux density at distance $R$ m is given by Eqn. 4.1

$$F = \frac{P_t}{4 \pi R^2} \quad \text{W/m}^2$$
TRANSMISSION THEORY

- We need directive antennas to get power to go in wanted direction

- Define GAIN of antenna as increase in power in a given direction compared to isotropic antenna

\[
G(\theta) = \frac{P(\theta)}{P_0/4\pi} \quad \text{(Eqn 4.2)}
\]

- \( P(\theta) \) is variation of power with angle
ELEVATION

AZIMUTH

Generally $G(\theta)$ given on Polar Plot
EIRP

- We often combine transmitter power and antenna gain into EIRP

[Effective Isotropically Radiated Power]

- EIRP = $P_t \times G_t$ Wats
  (or dBW)
RECEIVED POWER

- Source radiates $P_t G_t$ watts EIRP

- At distance $R$ flux density is

  \[ P_d = \frac{P_t \, G_t}{4 \, \pi \, R^2} \text{ watts/m}^2 \quad (\text{Eqn. 4.3}) \]

- If we collect power with an antenna of area $A_r\text{ (m}^2\text{)}$ we get

  \[ P_r = P_d \times A_r = \frac{P_t \, G_t \, A_r}{4 \, \pi \, r^2} \text{ watts} \quad (\text{Eqn. 4.4}) \]
EFFECTIVE APERTURE

- Real antennas have effective flux collecting areas which are less than the physical aperture area.

- Define Effective Aperture Area

\[ A_e = \eta A_r \]  
(Eqn. 4.5)

where \( A_r \) is actual (Physical) aperture area.

\( \eta = \) aperture efficiency
RECEIVED POWER

- Then

\[ P_r = \frac{P_t G_t A_e}{4 \pi R^2} \text{ watts} \quad \text{(Eqn. 4.6)} \]

\(A_e\) and \(R\) must have same units of length (e.g. meters)

- All antennas have (maximum) gain \(G\) related to effective aperture area \(A_e\) by

\[ G_r = \frac{4 \pi A_e}{\lambda^2} \quad \text{(Eqn. 4.7)} \]

where \(\lambda\) is the wavelength

\[ C = \lambda f \]

\[ \approx 3 \times 10^8 \text{ m/s} \]
LINK BUDGET

- Let's look at Eqn 4.6 for received power, $P_r$

$$\text{Power Received} = \frac{\text{EIRP} \times \text{Antenna Gain}}{\text{Path Loss}}$$

(Eqn 4.9)

- Since $P_r$ will probably be very small, perhaps $10^{-14}$ watts, communications engineers use DECIBELS to handle link calculations.
Note: 20 dBm = -70 dBm

\[
\begin{align*}
\text{Note: DBm} & = \text{DB} \times \frac{10}{\log 10} \\
& = \text{DB} \times \frac{10}{1} = \text{DB} \\
& = \text{DB} \times \frac{10}{\log 10} \\
& \approx 20 \text{ dBm} \\
& 20 \text{ dBm} = 10 \log \frac{10}{\text{mW}}
\end{align*}
\]

Example 1: A variable-throttle provides an output power of 20 dBm.

Explaination of work:

With dB, DBm, and dBW, dBW are industry-wide standards.

dBm, DBW, and dB are important terms you become comfortable with.

Power measurement with respect to 1 watt reference.

When to use dB:

- For milliwatts, dBm is often expressed in dBm.
- In terms of dBm, or “power referenced to 1 milliwatt,” a power signal of dBm can be expressed.
- Express a power level of 1 milliwatt measured across a reference level of 1 milliwatt measured across a reference level of 1 milliwatt.

Power level compared to an accepted level:

\[
\begin{align*}
\text{For voltage: } & H_v = 20 \log \left( \frac{V}{V_0} \right) \\
\text{For power: } & H_p = 10 \log \left( \frac{P}{P_0} \right)
\end{align*}
\]

Note: Decibels are always a ratio, comparing two power levels, or reference voltages.

The above follows, since: \(10 \log \left( \frac{V}{V_0} \right) = 2 \log \left( \frac{V}{V_0} \right) = 20 \log \left( \frac{V}{V_0} \right)\)
Example 2: Express 0.0035 W/m² in dBm.

\[ P_{dBm} = 20 \log \left( \frac{W}{m^2} \right) \]

So

\[ P_{dBm} = 20 \log \left( \frac{0.0035}{m^2} \right) \]

Therefore, \( P_{dBm} = 0 \) dBm.
THE DECIBEL
(The world's most misused unit ?)

- Definition:

\[ X \, \text{dB} = 10 \log_{10} \left( \frac{P_2}{P_1} \right) \]

- Note: the decibel is a logarithmic unit of a ratio.

Although it is defined for a power ratio it is often used for other ratios (Appendix A1).
USING DECIBELS

- Rules

  $- 10 \log_{10} (A \times B)$
  
  $= 10 \log_{10} (A) + 10 \log_{10} (B)$
  
  $= A \text{ dB} + B \text{ dB}$
  
  $= (A + B) \text{ dB}$
  
  $- 10 \log_{10} (A \div B)$
  
  $= 10 \log_{10} A - 10 \log_{10} B$
  
  $= A \text{ dB} - B \text{ dB}$
  
  $= (A - B) \text{ dB}$
dB RULES

- $10 \log_{10} (A)^2 = 2 \times 10 \log_{10} (A)$
  
  $= 20 \log_{10} (A)$
  
  $= 2 \times (A \text{ in dB})$

- $10 \log_{10} (\sqrt{A}) = \frac{10}{2} \log_{10} (A)$
  
  $= \frac{1}{2} \times (A \text{ in dB})$
dB UNITS

- Several units are widely converted to decibel values.
- dBW means “dB greater than 1W”
  e.g. $P$ walts $\quad 10 \log_{10} \left( \frac{P}{1} \right) \quad$ dBW
  $\quad = (P \text{ dB} - 0 \text{ dB}) \text{ in walts}$
  $\quad = P \text{ dBW}$
- dBm means “dB greater than 1 milli walt”
  10 mW $\quad 10 \text{ dBm}$
  1000 mW $\quad 30 \text{ dBm} = 0 \text{ dBW}$
OTHER dB UNITS

- dBK, dB greater than 1 K (noise temperature)
- dBHz, dB greater than 1 Hz (Bandwidth)
- dBm², dB greater than 1 m² (Aperture area)
- dB$, dB greater than $1
LINK BUDGET IN dB

\[ P_r = EIRP + G_r - L_p \quad \text{dBW} \quad \text{(Eqn 4.10)} \]

\[ EIRP = 10 \log_{10} (P_t G_t) \quad \text{dBW} \]

\[ = P_t \text{ dB} + G_t \text{ dB} \]

\[ G_r = 10 \log_{10} (G_r) \quad \text{dB} \]

\[ = 10 \log_{10} \left( \frac{4 \pi A_e}{\lambda^2} \right) \quad \text{dB} \]

\[ L_p = \text{Path Loss} \]

\[ = 20 \log_{10} \left( \frac{4 \pi R}{\lambda} \right) \quad \text{dB} \]
EXAMPLE 4.1.1

- Satellite at 40,000 km
  Transmits 2W
  Antenna gain $G_t = 17$ dB (global beam)

- Calculate
  Flux density on earth’s surface
  Power received by antenna with effective aperture $10m^2$

- Using Eqn 4.3
  \[ F = \frac{P_t G_t}{4 \pi R^2} = \frac{2 \times 50}{4\pi \times (4 \times 10^7)^2} \]
  \[ = 4.97 \times 10^{-14} \text{ W/m}^2 \]
EXAMPLE 4.1.1

In dB:

- \( EIRP = (P_t + G_t) \) dBW
  \[ = 3 + 17 = 20 \text{ dBW} \]

- \( R^2 = 20 \log_{10} (4 \times 10^7) \) dBm\(^2\)
  \[ = 152 \text{ dBm}^2 \]

- \( 4 \pi = 11 \text{ dB} \)

- Hence
  \( F = 20 - 11 - 152 \)
  \[ = -143 \text{ dBW/m}^2 \]
EXAMPLE 4.1.1

Received Power:

\[ P_r = F \times A = F \times 10 \text{m}^2 \]

\[ = 4.97 \times 10^{-15} \times 10 \text{ W} \]

\[ = 4.97 \times 10^{-14} \text{ W} \]

or in dB

\[ P_r = -143 \text{ dBW/m}^2 + 10 \text{ dBm}^2 \]

\[ = -133 \text{ dBW} \]

\[ = (+7 - 140) \text{ dBW} \]

\[ = 5 \times 10^{-14} \text{ W} \]
SYSTEM NOISE

Noise Temperature

- The available power from a source of physical temperature $T_p \, ^\circ K$ delivered to a matched load is $P_n$ where

  $$P_n = k \, T_p \, B$$  \hspace{1cm} \text{(Eqn 4.12)}

- $k = \text{Boltzmann's Constant}$
  $$= 1.38 \times 10^{-23} \, \text{J/K}$$
  $$= -228.6 \, \text{dBW/K/Hz}$$

- $B = \text{bandwidth of power measurement device, in Hz}$
NOISE TEMPERATURE

- Most devices do not deliver all the available power
- Devices can be characterized by their Noise Temperature, $T_n$, then
  \[ P_n = k T_n B \]
- $k T_n$ is the noise power spectral density in watts/Hz
- $k T_n$ is constant up to 300 GHz
- All bodies with $T_p > 0^\circ K$ radiate microwave energy
  "Black Body Radiation"
NOISE

- Performance of system is determined by C/N ratio
- Most systems need $C/N > 10\,\text{dB}$
- Hence $N < C - 10\,\text{dB}$ usually
- We need to know the noise temperature of our receiver so that we can calculate $N$, the noise power ($N = P_n$)
- $T_n$ is in Kelvins (symbol $K$)
Fig. 4.4 Earth station receiver
<table>
<thead>
<tr>
<th>Condition</th>
<th>Percent Time (%)</th>
<th>Carrier Attenuation (dB)</th>
<th>Antenna Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear sky</td>
<td>80</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Moderate rain</td>
<td>0.3</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>Heavy rain</td>
<td>0.01</td>
<td>4</td>
<td>135</td>
</tr>
</tbody>
</table>
SYSTEM NOISE TEMPERATURE

- The noise power we need is at the input to the demodulator.

- For a noiseless receiver with a gain of G (not in dB)

If Bandwidth B, noise temperature $T_S$, the noise power at demodulator is:

$$P_{nd} = kT_SBG \text{ watts} \quad \text{(Eqn 4.13)}$$

- The Carrier power at the demodulator input is:

$$P_{rd} = PrG \text{ watts}$$

- Hence

$$\frac{C}{N} = \frac{P_{rd}}{P_{nd}} = \frac{PrG}{kT_SBG} = \frac{Pr}{kT_SB} \quad \text{(Eqn 4.14)}$$
Fig 4.5A  Equivalent Rcvr Circuit -- replace devices with noiseless components and equivalent noise generators
CALCULATING SYSTEM NOISE TEMPERATURE

- Receiver noise comes from several sources
- We need a method which reduces several sources to a single equivalent noise source at the receiver input.

- Using model in Fig 4.5 a

\[ P_n = G_{IF} kT_{IF} B \]
\[ + G_{IF} G_m k T_m B \]
\[ + G_{IF} G_m G_{RF} K T B (T_{RF} + T_{in}) \]

(Eqn 4.15)
\[
P_n = G_{RF} G_m G_{IF} \left[ kT_s B \right]
\]

where \( T_s = \left[ T_{in} + T_{RF} + \frac{T_m}{G_{RF}} + \frac{T_{IF}}{G_m G_{RF}} \right] \)

\[
T_{in} \rightarrow + \rightarrow G_{RF} G_m G_{IF} \rightarrow P_n
\]

\[
T_s = T_{RF} + \frac{T_m}{G_{RF}} + \frac{T_{IF}}{G_m G_{RF}}
\]
REDUCING NOISE POWER

- Make B as small as possible – just enough bandwidth to accept all of the signal power (C)

- Make $T_S$ as small as possible
  - lowest $T_{RF}$
  - low $T_{in}$ (How?)
  - high $G_{RF}$

- We need a good low noise amplifier (LNA) –
  low $T_{RF}$ / high $G_{RF}$ then rest of receiver does not matter
LOW NOISE AMPLIFIERS

- Ga AS FET
  
  Low noise transistor amplifier
  
  4 GHz : 75 K, 50 dB gain typical
  
  11 GHz : 180 K, 50 dB gain

- Parametric Amplifier (Paramp)
  
  Cooled in liquid nitrogen for lowest noise temperatures (or liquid helium at 4°K)
NOISE TEMPERATURE
Example 4.2.1

- 4 GHz Receiver
  \[ T_{in} = 50 \text{ K} \]
  \[ T_{RF} = 50 \text{ K} \]
  \[ G_{RF} = 23 \text{ dB} \]
  \[ T_{m} = 500 \text{ K} \]
  \[ G_{m} = 0 \text{ dB} \]
  \[ T_{IF} = 1000 \text{ K} \]
  \[ G_{IF} = 30 \text{ dB} \]

- \[ T_S = T_{RF} + T_{in} + \frac{T_{m}}{G_{RF}} + \frac{T_{IF}}{G_{RF} G_{m}} \]
  \[ = 50 + 50 + \frac{500}{200} + \frac{1000}{200} \]
  \[ = 100 + 2.5 + 5 = 107.5 \text{ K} \]
EXAMPLE 4.2.1

- If mixer has 10 dB loss
  
  \[ G_m = -10 \text{ dB} = 0.1 \]

- \[ T_S = 50 + 50 + \frac{500}{200} + \frac{1000}{20} \]
  
  \[ = 152.5 \text{ K} \]

- Comment: \( G_{RF} G_m \) is too small here, so the IF amplifier contribution is large.

  If we made \( G_{RF} = 50 \text{ dB} \)

  \[ T_S = 50 + 50 + \frac{500}{100,000} + \frac{1000}{10,000} \]

  \[ = 100.1 \text{ K} \]
EXAMPLE 4.2.2

- Insert lossy waveguide with 2 dB attenuation between antenna and LNA
- We need a model for a lossy device

\[ P_r \xrightarrow{2 \text{ dB loss}} \alpha P_r \xrightarrow{} P_n \]

- Signal power is attenuated Device generates noise
LOSSY DEVICES

- Model for an ohmic loss

\[ P_r \xrightarrow{\text{Noiseless loss}} G_l \xrightarrow{\text{+}} P_{out} \]

- \( T_i = T_p (1 - G_l) \)
  
  \( T_p = \) physical temperature of lossy device

- \( P_{out} = G_l P_r \)

- \( G_l = \) loss = gain less than unity
EXAMPLE 4.2.2

- Loss of 2 dB, \( G_l = -2 \text{ dB} \)
  
  \[
  G_l = \frac{1}{1.58} = 0.63
  \]

- \( T_l = 290 (1 - 0.63) \)
  
  \[
  = 107.3 \text{ K}
  \]

- Input noise power is attenuated by 2 dB

\[
\therefore \text{New } T_{\text{in}} = T_a G_l + T_l
\]

\[
= 50 \times 0.63 + 107.3
\]

\[
= 138.8 \text{ K}
\]
EXAMPLE 4.2.2

- Comment:
  - Inserting 2 dB loss in the front end of the receiver has reduced carrier power (C) by 2 dB and increased noise temperature by 88.8K, from 107.5 K to 196.3 K
  - N has increased by 2.6 dB
  - C/N has been reduced by 4.6 dB

- Moral:
  - losses before LNA must be kept very small
NOISE FIGURE

- Noise figure is sometimes used instead of noise temperature
- Convert to noise temperature by using:
  \[ T_d = T_o (NF - 1) \]
- \( T_o \) is reference temperature (usually 290°F)
- NF is the noise figure as a ratio (i.e. NOT in dB)
  - for \( F \) dB, \( NF = 10^{F/10} \)

See Fig. 3.1.3.10x1
G / T Ratio

- Link Equation can be rewritten as (Eqn 4.20):

\[
C / N = \frac{P_t G_t G_r}{k T_S B} \left[ \frac{\lambda}{4 \pi R} \right]^2
\]

\[
= \frac{P_t G_t}{K B} \left[ \frac{\lambda}{4 \pi R} \right]^2 \frac{G_r}{T_S}
\]

- \( \frac{C}{N} \propto \frac{G_r}{T_S} \)

so G/T ratio for the earth station determines the C/N in a given system

- G/T is usually quoted in dB/K
EXAMPLE 4.2.4

- Earth Station has \( D = 30 \text{ m} \), \( \eta = 68\% \)
  \( f = 4150 \text{ MHz} \), \( T_S = 79 \text{ K} \)
  - What is \( G/T \) ratio?

- \( G_r = \eta \cdot \frac{4 \pi A}{\lambda^2} = \eta \left( \frac{\pi D}{\lambda} \right)^2 \)

For \( f = 4150 \text{ MHz} \), \( \lambda = 0.0723 \text{ m} \)

\[
G_r = 0.68 \times \left( \frac{\pi \times 30}{0.0723} \right)^2 = 1.16 \times 10^6
= 60.6 \text{ dB}
\]

- \( T_S = 79 \text{ k} = 19.0 \text{ dB k} \)
  \( \therefore G/T = 60.6 - 19.0 = 41.6 \text{ dBK}^{-1} \)

- If \( T_S \) increases to 88 K in rain
  \( G/T = 60.6 - 19.4 = 41.2 \text{ dBK}^{-1} \)