EG2311-Introduction to Space Systems

Satellite Subsystems-Tracking, Telemetry and Command (TT&C)

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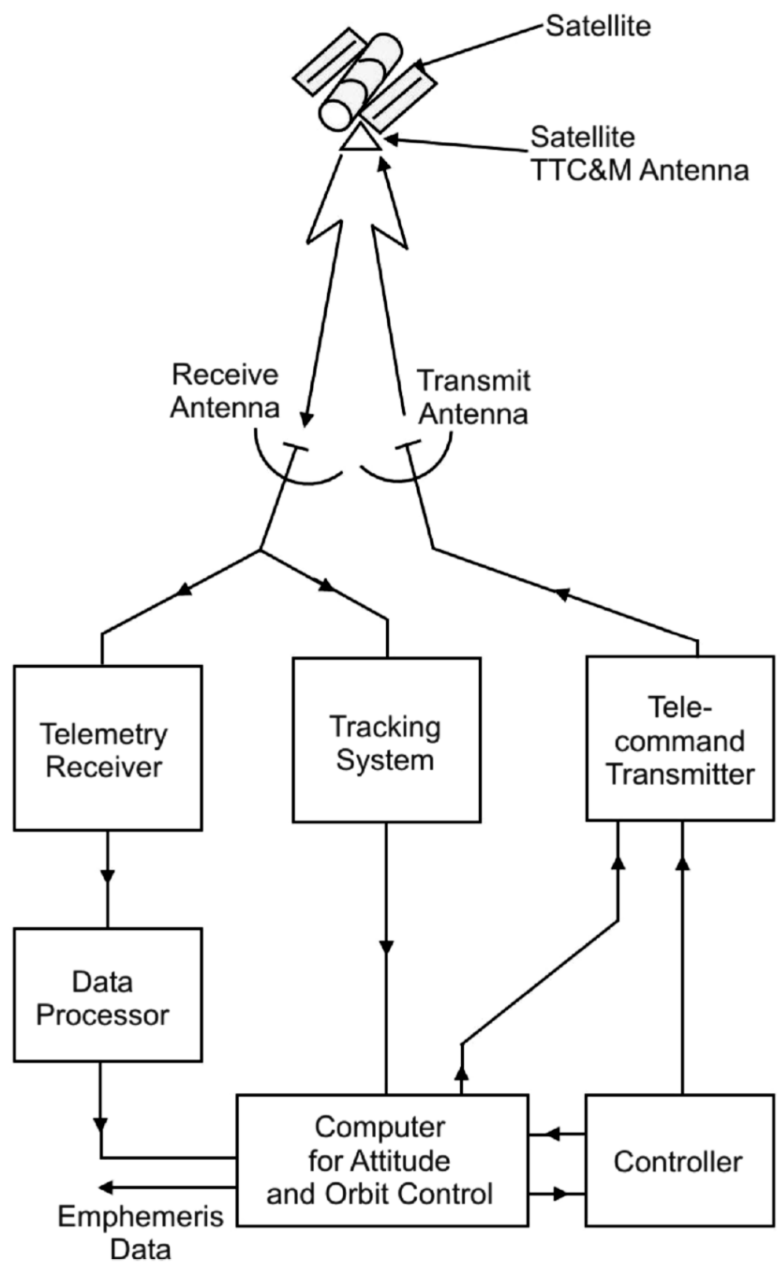
Outlines

- **Objective**
- **Communication system**
- **Electromagnetic (EM) wave**
- **Link budget**
- **Modulation**
- **Coding and encoding**
- **Communication protocol**

Objective

- To monitor and control the satellite right from the lift-off stage to the end of its operation life in space



Tracking

- The **tracking** part determines the position of the spacecraft and follows its using angle, range and velocity information on a regular basis.
  - Angle tracking can be used to determine the azimuth and elevation angles from the Earth station.
  - The time interval measurement technique can be used for the purpose of ranging by sending a signal via the command link and getting a return via the telemetry link.
  - The velocity can be determined by measuring the phase shift of the return signal as compared to that of the transmitted signal.

Telemetry

- The **telemetry** part gathers information on the health of various subsystems of the satellite.
  - During the orbital injection and positioning phase, the telemetry link is primarily used by the tracking system to establish a satellite-to-Earth control center communications channel.
  - After the satellite is put into the desired slot in its intended orbit, its function is to monitor the health of various subsystems on board the satellite. It gathers data from variety of sensors and then transmits that data to the Earth control center.

Command

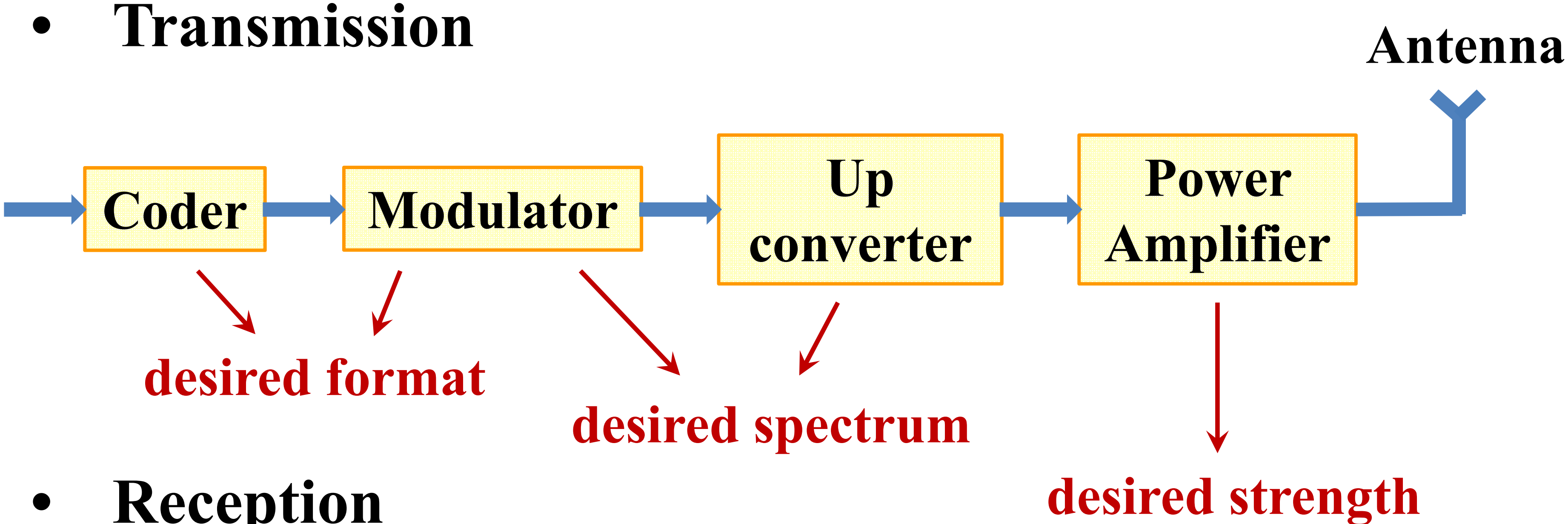
- The **command** element is used to receive, verify and execute remote control commands from the satellite control center to effect changes to the platform function, configuration, position and velocity.
  - The control commands received by the command element on the satellite are first stored on the satellite and then retransmitted back to the Earth control station via a telemetry link for verification.
  - After the commands are verified on the ground, a command execution signal is then sent to the satellite to initiate intended action.

TT&C interfaces

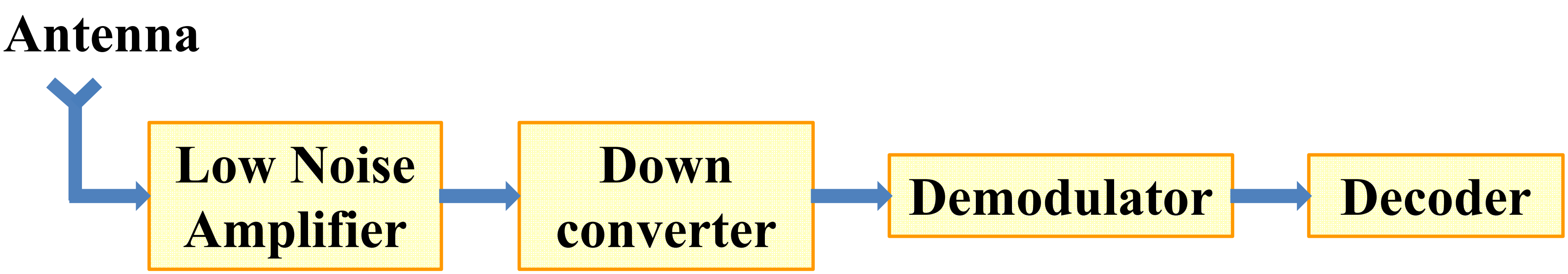
Subsystem	Requirement
Attitude Determination and Control	Antenna pointing
Command and Data Handling	Command and telemetry data rates Clock, bit sync,and timing requirements Two-way comm requirements Autonomous fault detection and recovery Command and telemetry electrical interface
Electrical Power Subsystem	Distribution requirements
Thermal/Structural	Heat sinks for TWTAs Heat dissipation of all active boxes Location of TT&C subsystem electronics Clear field of view and movement for all antennas
Payload	Storing mission data RF and EMC interface requirements Special requirements for modulation and coding

Communication System

- Transmission

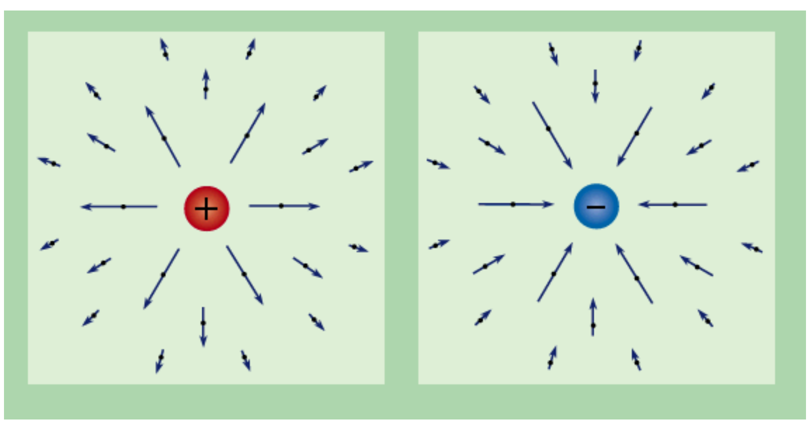


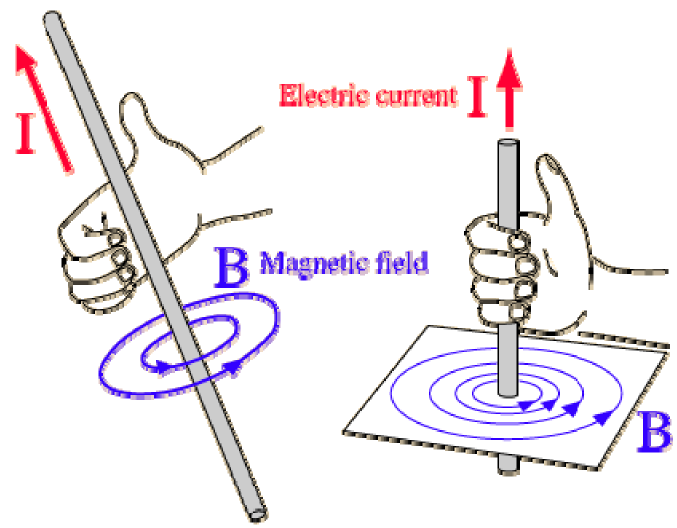
- Reception



Electromagnetic (EM) Wave

- The **electric (E) field** is generated by either a free charge or a time-varying magnetic field. It is measured in volt per meter (V/m).
- The **magnetic (H) field** is generated by either a current or a time-varying electric field. It is measured in ampere per meter (A/m).





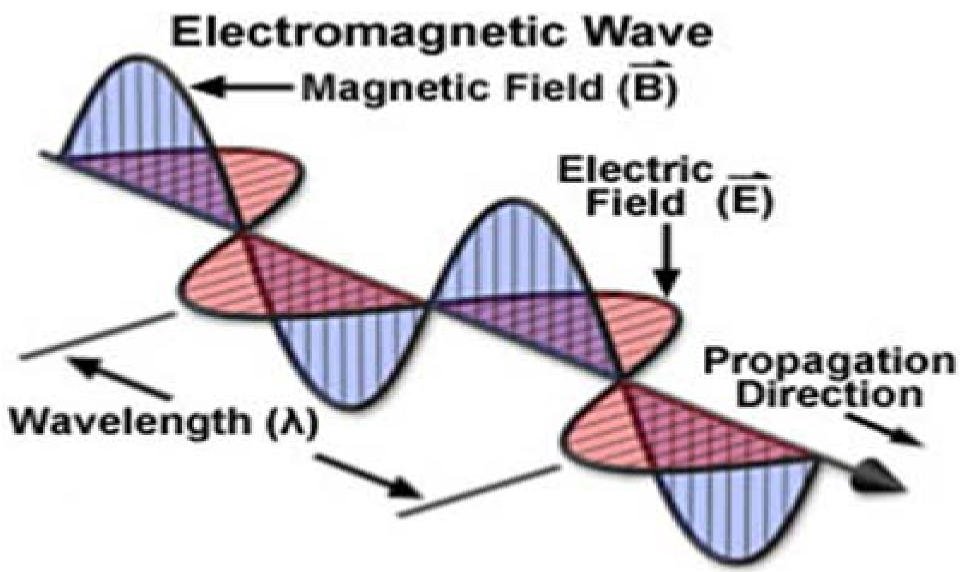
Electromagnetic (EM) Wave

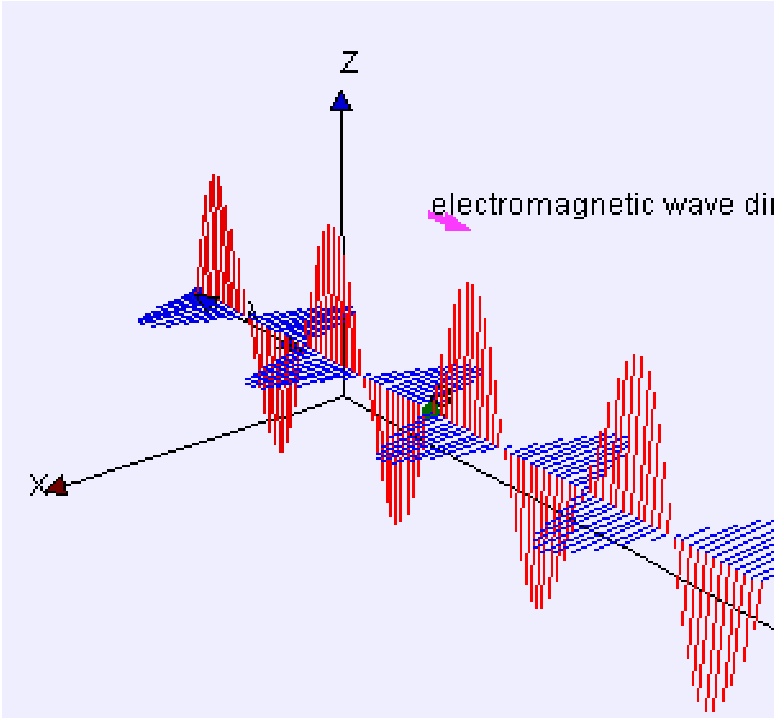
- **Maxwell's equation**: specify the relationship between the variation of the electric field E and the magnetic field H in time and space within a medium.
- A changing magnetic field produces an electric field and a changing electric field produces a magnetic field.

Name	Differential form	Integral form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$	$\oiint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$	$\oiint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	$\oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_{E,S}}{\partial t}$

Electromagnetic (EM) Wave

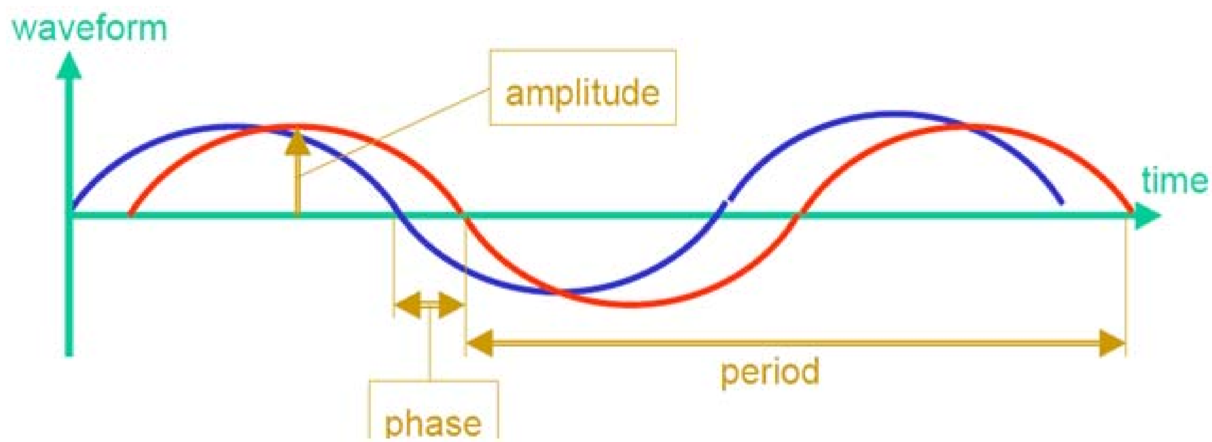
- Radio energy emitted in space exhibits both electric and magnetic fields.
- Direction of wave propagation: $\vec{E} \times \vec{H}$





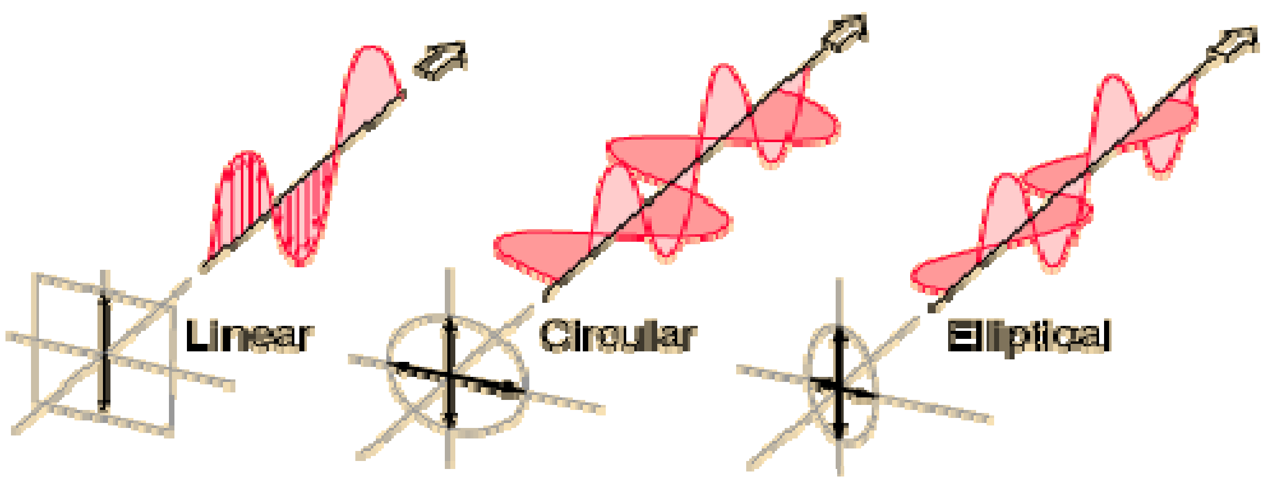
Electromagnetic (EM) Wave

- A electromagnetic (EM) wave is a signal whose characteristics include
  - **Amplitude**: peak value or strength of the signal; measured in volts or watts
  - **Frequency**: rate at which a signal repeats, measured in cycles per second or Hertz (Hz)
  - **Period**: amount of time it takes for one repetition of a signal
  - **Phase**



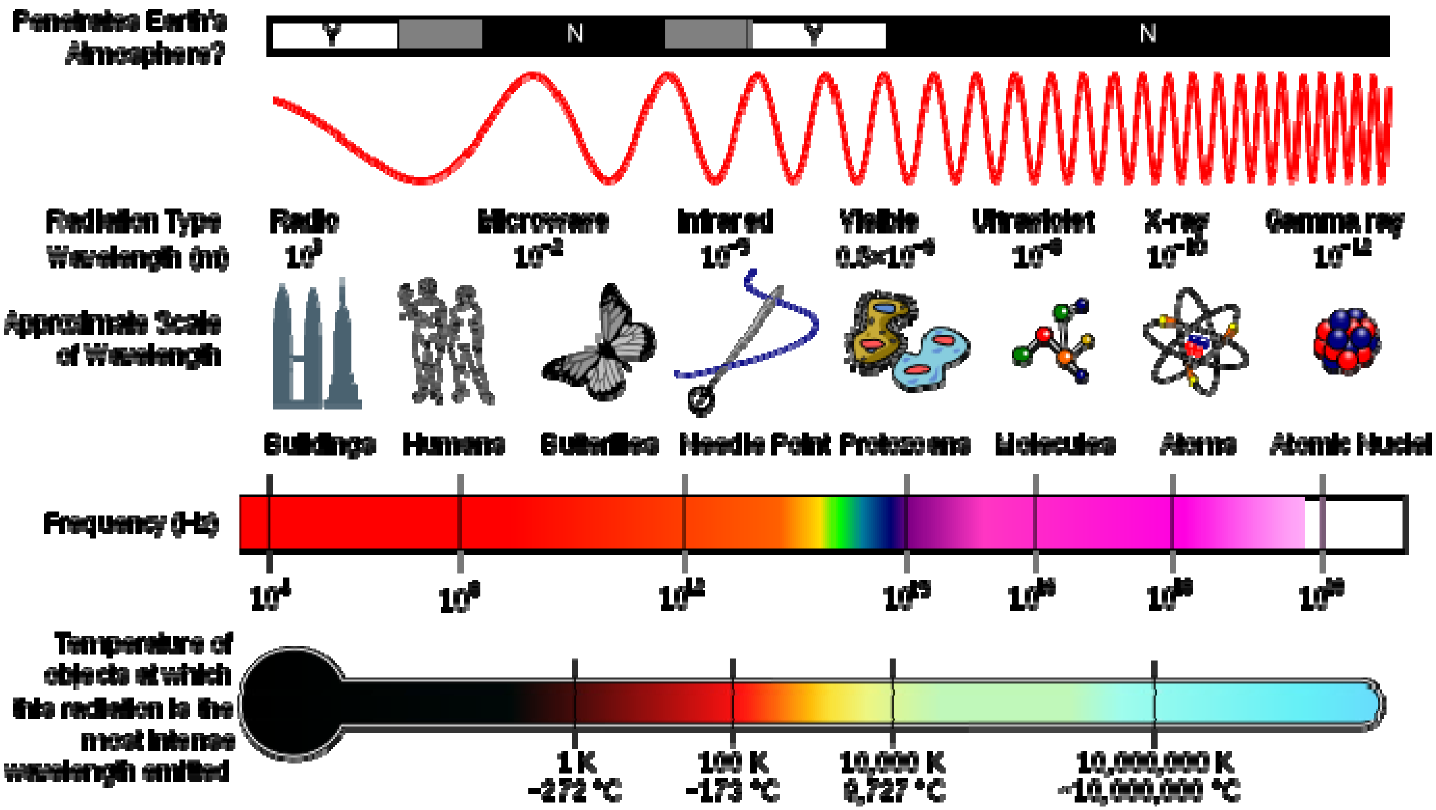
EM Wave - Polarization

- **Polarization** is the alignment of the electric field vector of the plane wave relative to the direction of propagation
  - Linear polarization (vertical, horizontal)
  - Circular polarization (right-hand, left-hand)
  - Elliptical polarization



Frequency consideration

- The **Electromagnetic Spectrum** is the range of all possible frequencies of electromagnetic radiation.



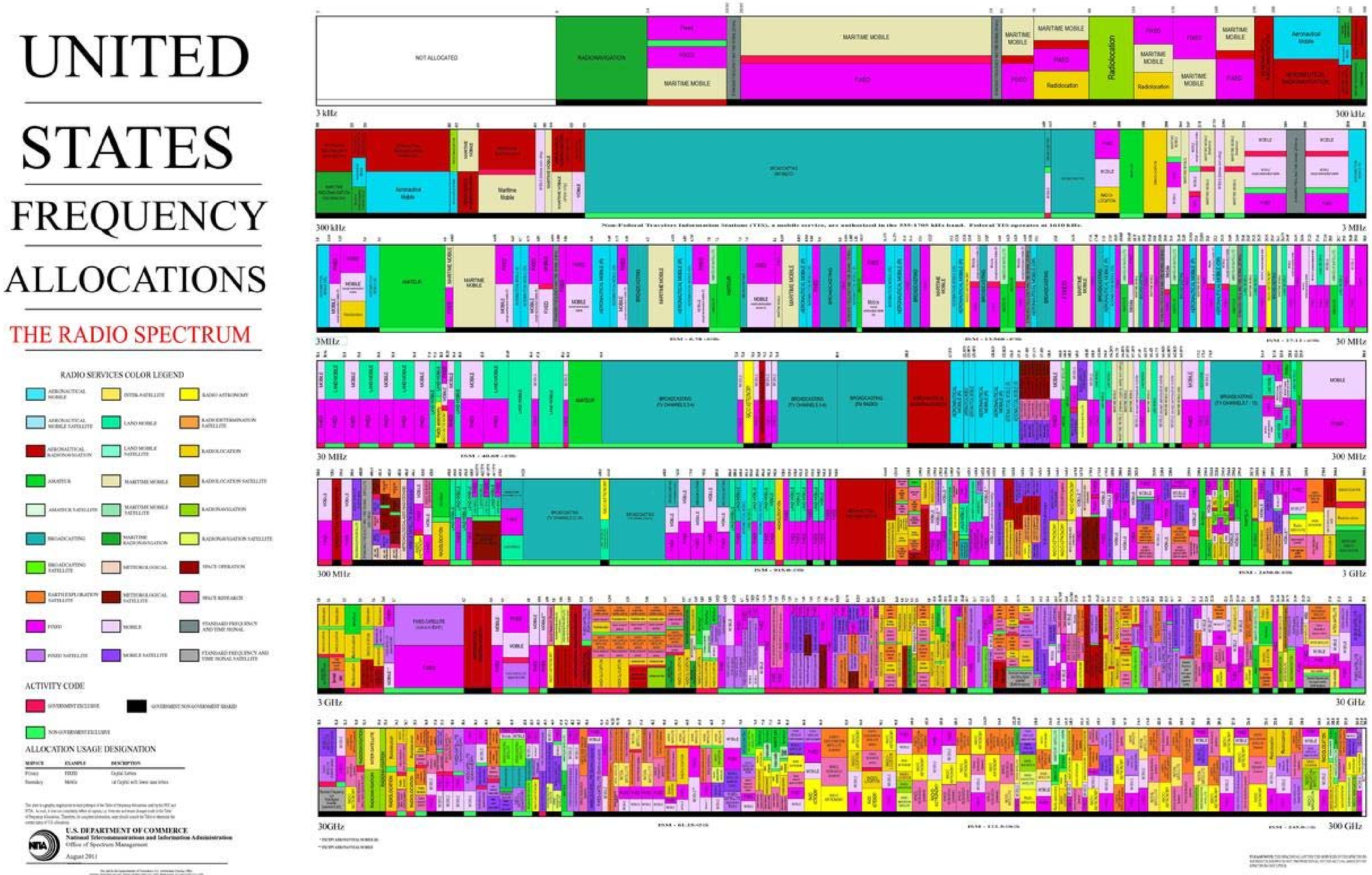
Frequency consideration

- Satellite communication employs EM waves for transmission of information between Earth and space.
- The bands of interest for satellite communication lie above 100 MHz and include VHF, UHF, L, S, C, X, Ku and Ka bands.

Designation	Frequency	Wavelength
VLF (very low frequency)	3KHz ~ 30 KHz	100 Km ~ 10 Km
LF (low frequency)	30 KHz ~ 300 KHz	10 Km ~ 1 Km
MF (medium frequency)	300 KHz ~ 3 MHz	1 Km ~ 100 m
HF (high frequency)	3 MHz ~ 30 MHz	100 m ~ 10 m
VHF (very high frequency)	30 MHz ~ 300 MHz	10 m ~ 1m
UHF (ultra high frequency)	300 MHz ~ 3 GHz	1 m ~ 10 cm
SHF (super high frequency)	3 GHz ~ 30 GHz	10 cm ~ 1cm
EHF (extremely high frequency)	30 GHz ~ 300 GHz	1cm ~ 1mm

Band	Frequency (GHz)
L band	1–2
S band	2–4
C band	4–8
X band	8–12
Ku band	12–18
K band	18–27
Ka band	27–40
V band	40–75
W band	75–110

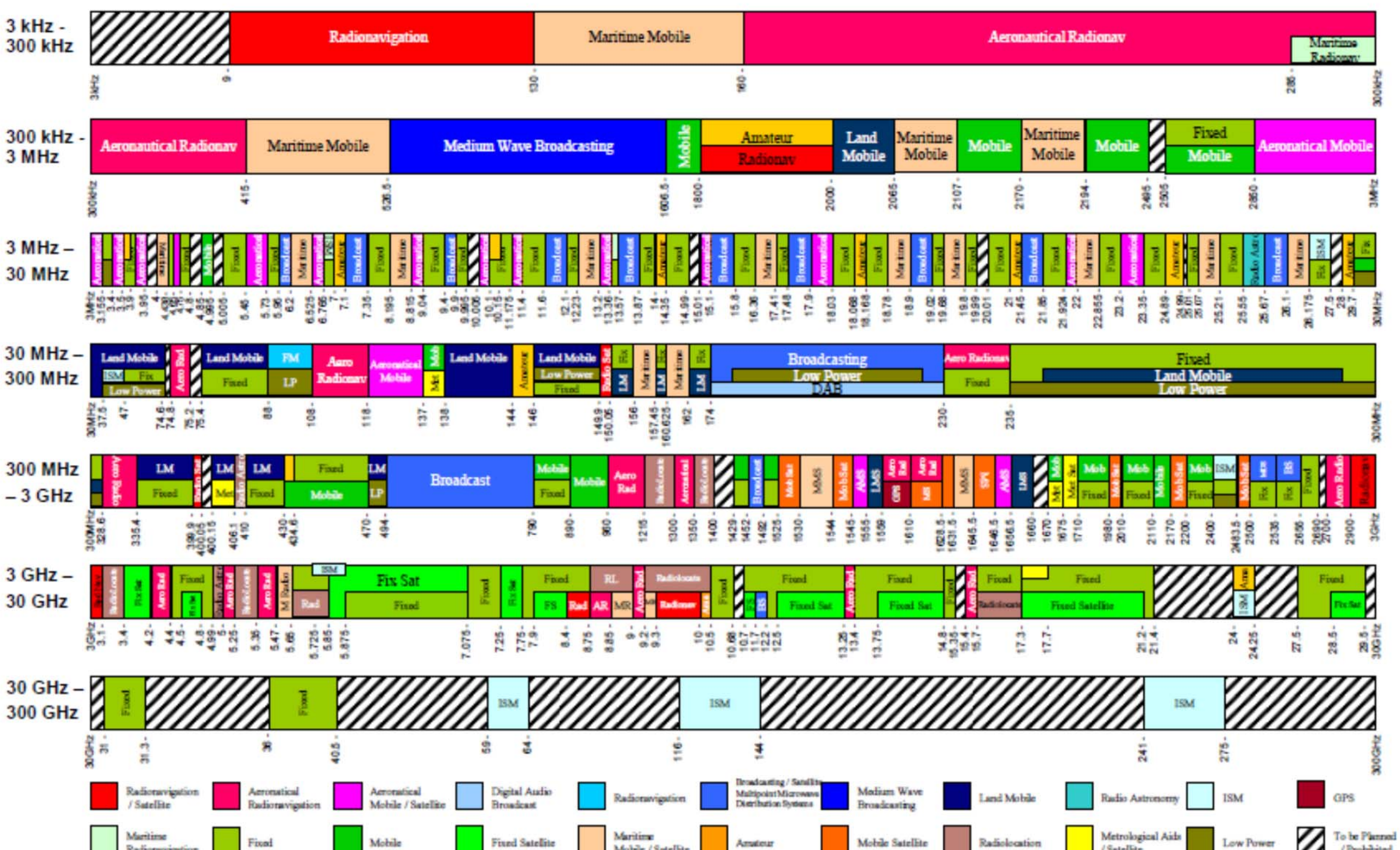
Frequency consideration



Frequency consideration

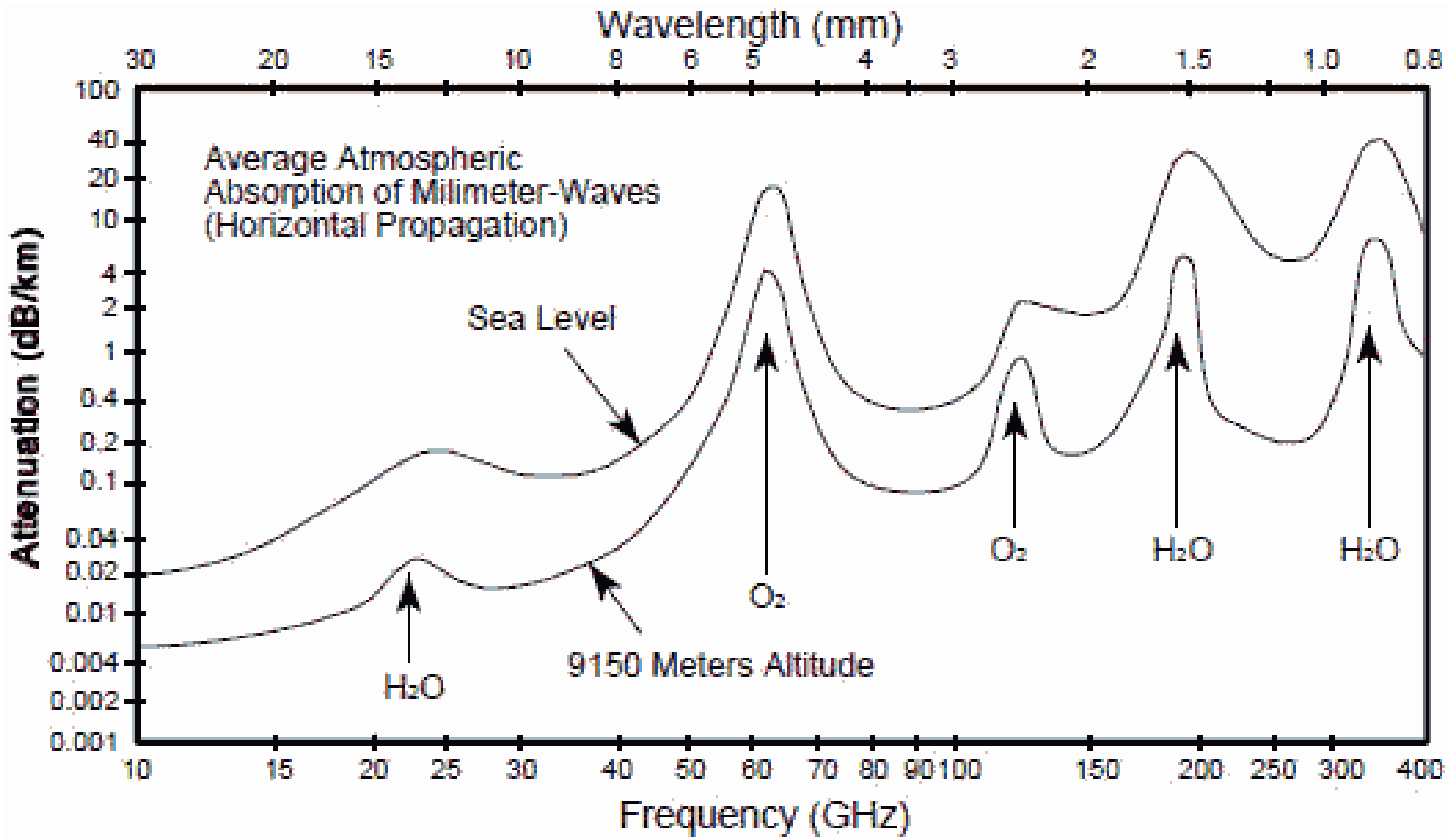
Singapore Spectrum Allocation Chart

*Frequency Spectrum is not drawn to scale.



Frequency consideration

- Atmospheric absorption



Frequency consideration

- Frequency allocation for satellite communication

Frequency band	Satellite service	Examples
VHF (<200 MHz)	Messaging	Starsys constellation of 24 satellites in the LEO orbit, having an uplink frequency of 148–150 MHz and a downlink frequency of 137–138 MHz
UHF (200 MHz–1 GHz)	Messaging and positioning, voice and fax	Gonets is a Russian messaging satellite constellation comprising 18 satellites in the LEO. Uplink frequencies are 312–315 MHz and 1624.5–1643.4 MHz and downlink frequencies are 387–390 MHz and 1523–1541.9 MHz
L band (2/1 GHz)	MSS and positioning	Inmarsat-II satellite having 4 L band transponders supporting mobile-to-mobile services with an uplink frequency of 1.6 GHz and a downlink frequency of 1.5 GHz
S band (4/2.5 GHz)	MSS	NStar-C satellite having 20 S band transponders provides S band mobile communication services to Japan

Frequency consideration

Frequency band	Satellite service	Examples
C band Uplink 5.925–6.425 GHz Downlink 3.7–4.2 GHz	FSS	Palapa-B, Indonesia's domestic satellite comprises 20 C band transponders each capable of carrying 1000 two-way voice circuits or a colour television transmission channel. It has uplink frequencies of 5.925–6.425 GHz and downlink frequencies of 3.7–4.2 GHz
X band Uplink 7.9–8.4 GHz Downlink 7.25–7.75 GHz	Military applications	Hispasat-1B satellite operated by the Spanish government carries four X band transponders for military applications
Ku band Europe FSS Uplink 14–14.8 GHz Downlink 10.7–11.7 GHz	FSS, BSS and Telecom	Hot Bird-6 satellite consists of 28 Ku band transponders, which provide television broadcast and multimedia services over the entire European continent, North Africa and the

http://www.youtube.com/watch?v=YgQQb1BVnu8

Decibel Representation (dB)

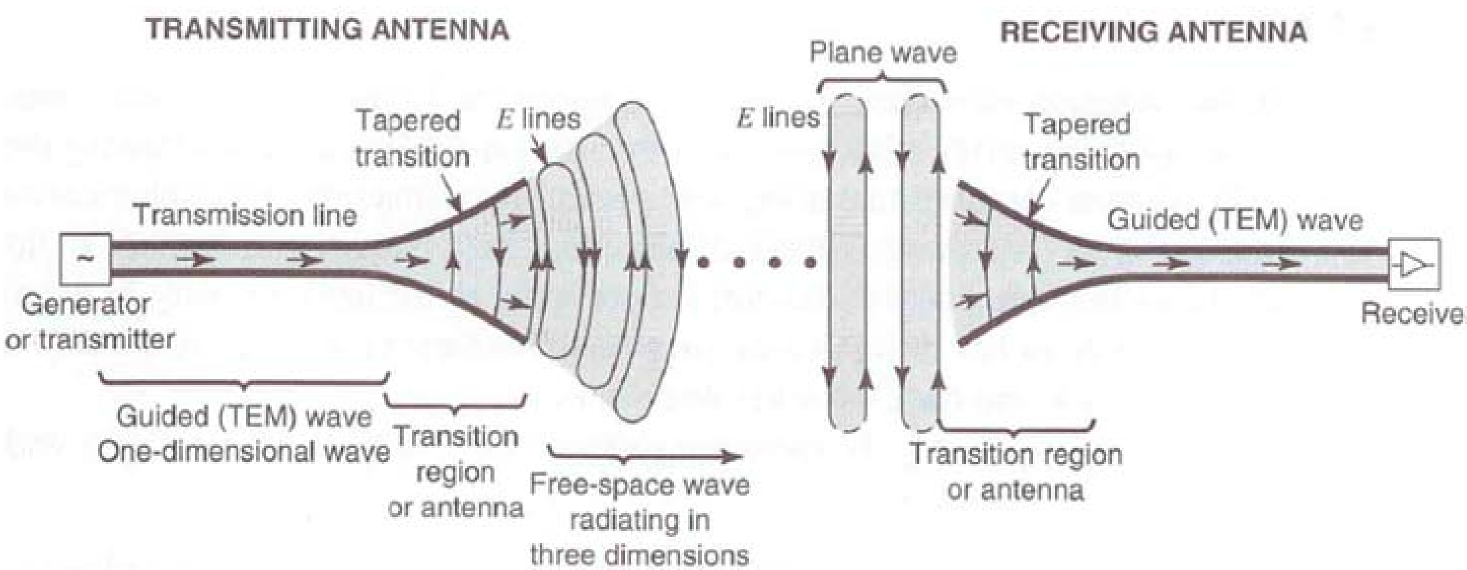
- Decibel representation: a quantity P in decibels (**dB**) is defined as

$$P \text{ in dB} = 10 \log_{10} (P)$$

  - An amplifier of gain 100 is the same as 20 dB
- Power is generally represented in terms of dBW or dBm.
  - Power in dBw = 10 $\log_{10}$ (Power in watts/1 W)
  - Power in dBm = 10 $\log_{10}$ (Power in mW/1 mW)
  - 0.1 watts is equivalent to -10 dBw or 20 dBm

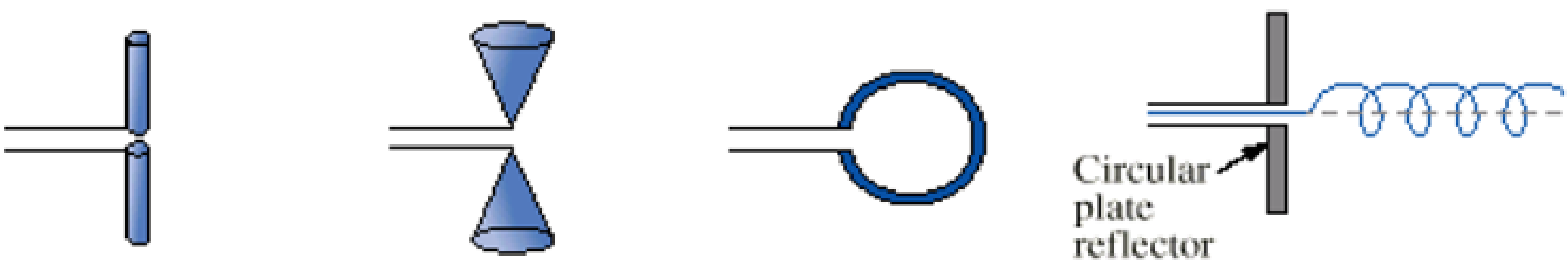
Antenna

- An **antenna** is device that converts a guided electromagnetic(EM) wave on a transmission line into a plane wave propagating in free space.
  - ➢ Antennas are inherently bidirectional, in that they can be used for both transmit and receive functions.
  - ➢ Antennas do not amplify EM waves.



Wire antennas

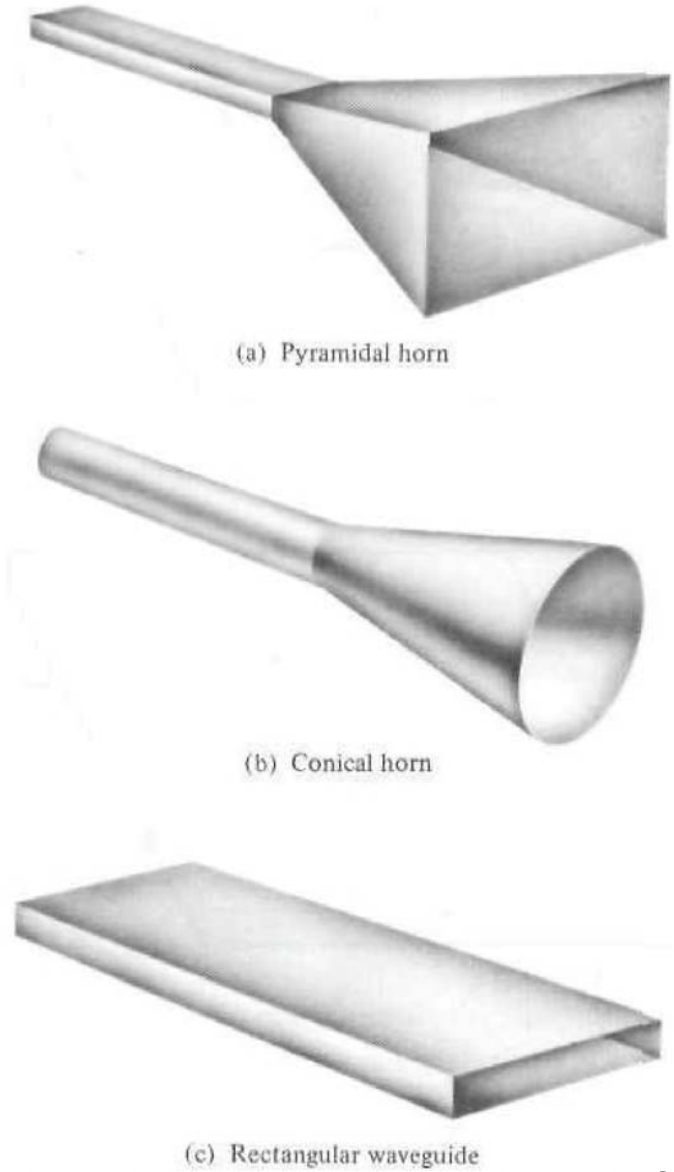
- **Basic structure**: Linear or curved metallic wires carrying current.
- **Examples**: Dipoles, monopoles, loops, sleeve dipoles, Yagi–Uda arrays
- Wire antennas generally have **low gains**, and are most often used at **lower frequencies** (HF to UHF).
- They have the **advantages** of light weight, low cost, and simple design.



(a) Thin dipole (b) Biconical dipole (c) Loop (d) Helix

Aperture antennas

- **Basic structure**: any aperture radiating/receiving electromagnetic waves.
- **Examples**: open-ended waveguides, rectangular or circular horns.
- Aperture antennas are most commonly used at microwave and millimeter wave frequencies.
- They have **moderate to high gains**



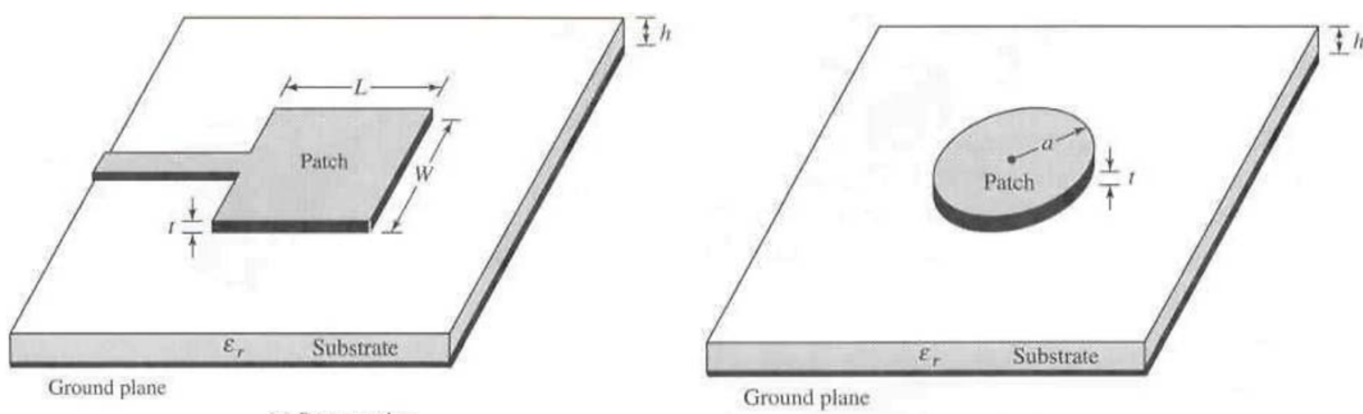
(a) Pyramidal horn

(b) Conical horn

(c) Rectangular waveguide

Microstrip antennas

- **Basic structure**: a metallic patch on a grounded dielectric substrate. The metallic patch can take many different configurations.
- **Examples**: rectangular/circular microstrip (patch) antennas, and microstrip patch array
- Microstrip antennas are conformable to planar/non-planar surfaces, simple and inexpensive to fabricate, and compatible with design of Radio-Frequency, Monolithic Microwave Integrated Circuit (RFIC, MMIC)
- They can be easily arrayed for high gain.

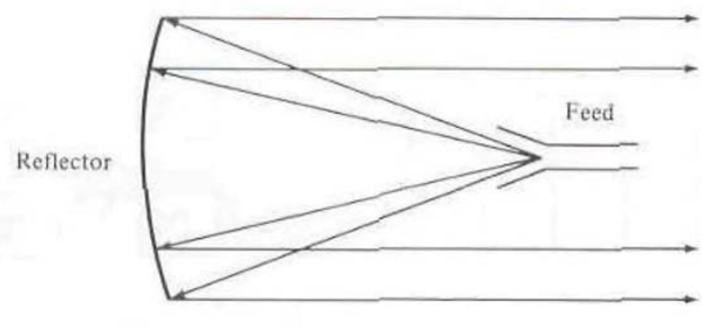


(a) Rectangular

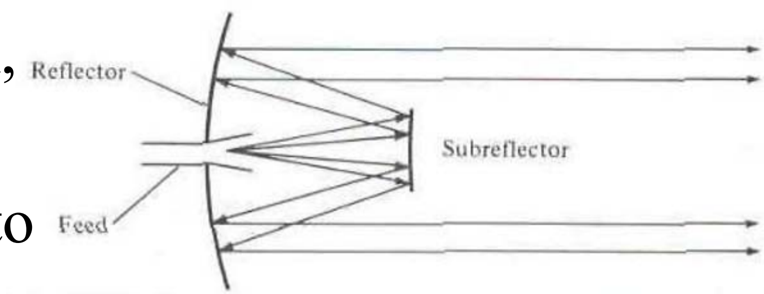
(b) Circular

Reflector antennas

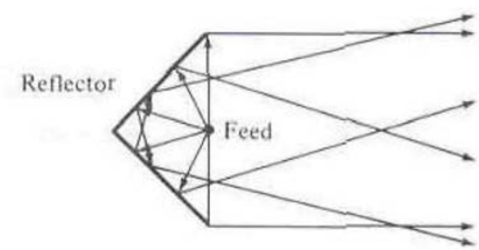
- **Basic structure** has two basic components:
  - ➢ low gain source : primary aperture (feed)
  - ➢ high gain reflector : secondary aperture
- **Examples**: plane reflector, corner reflector, parabolic reflector, Cassegrain, Gregorain
- Reflector antennas are commonly used to transmit or receive signals that had to travel **over long distance**.
- They can achieve **very high gain**, and widely used for long distance communication, satellite tracking, radar and radio astronomy.



(a) Parabolic reflector with front feed



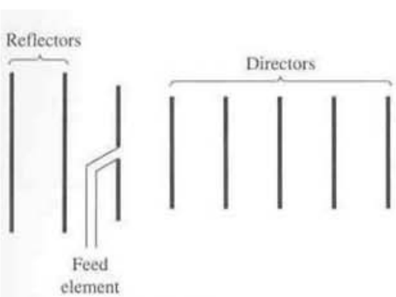
(b) Parabolic reflector with Cassegrain feed



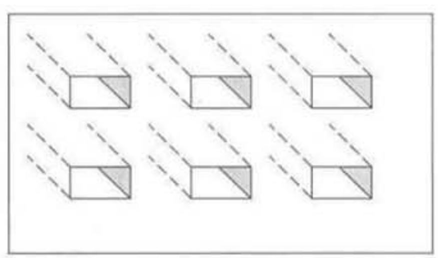
(c) Corner reflector

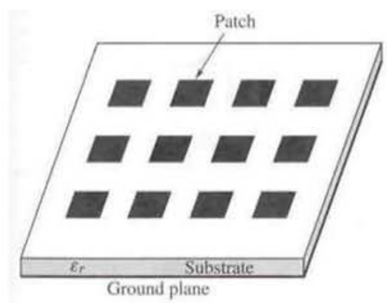
Array antennas

- Many applications require specific radiation characteristics that may not be achieved by a single element
- An assembly of radiating elements in an electrical and geometrical arrangement (*array*) may result in the desired radiation characteristics.
- Radiating elements may be wire antennas, aperture antennas, and microstrip patches
- Used to meet the demands of
  - ➢ very high gain for long distance communication
  - ➢ phased-scanning array and smart antennas
  - ➢ direction finding, null steering, echo cancellation, etc

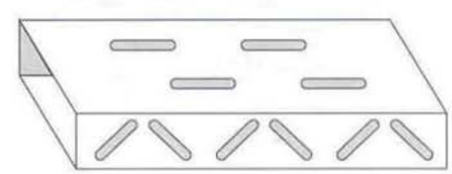


(a) Yagi-Uda array


(b) Aperture array

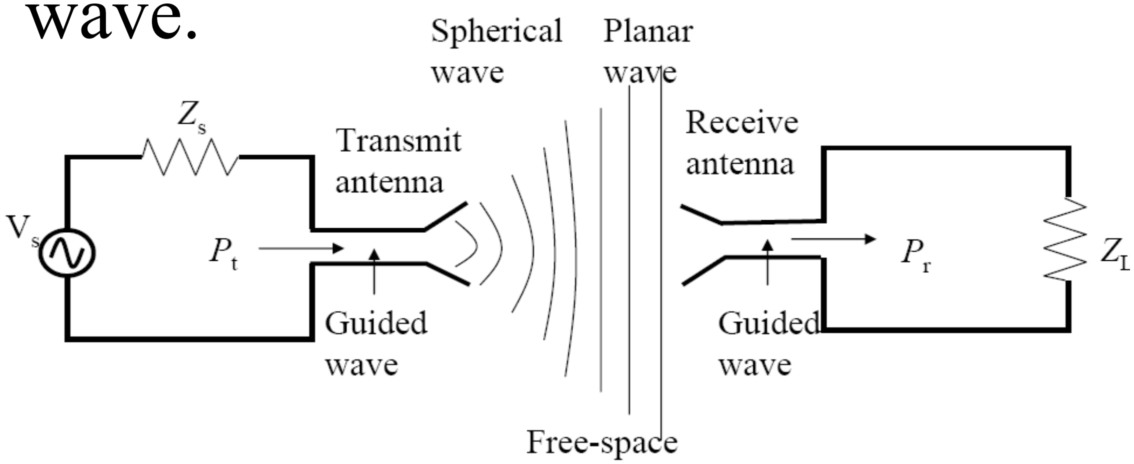


(c) Microstrip patch array

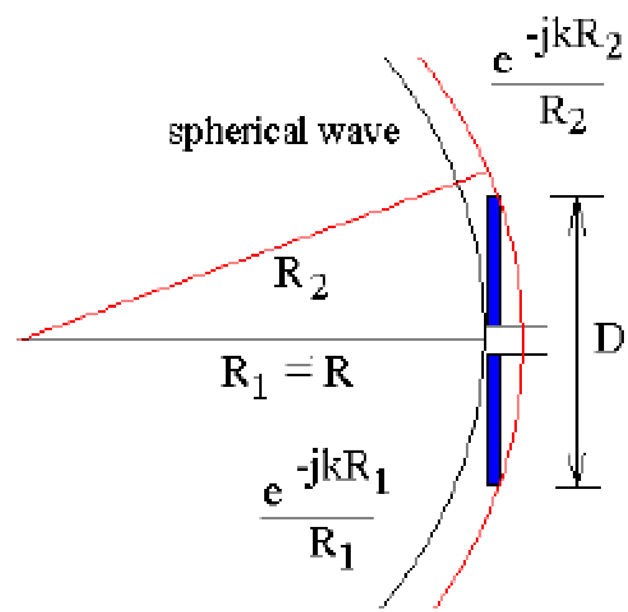

(d) Slotted-waveguide array

Far-Field distance

- The Far-field distance is the distance where the spherical wave front radiated by an antenna becomes a close approximation to the ideal planar phase front of a plane wave.



✓ The actual spherical wave front radiated by the antenna departs less than $\pi/8 = 22.5°$ from a true plane wave front over the maximum extent of the antenna.



Far-Field distance

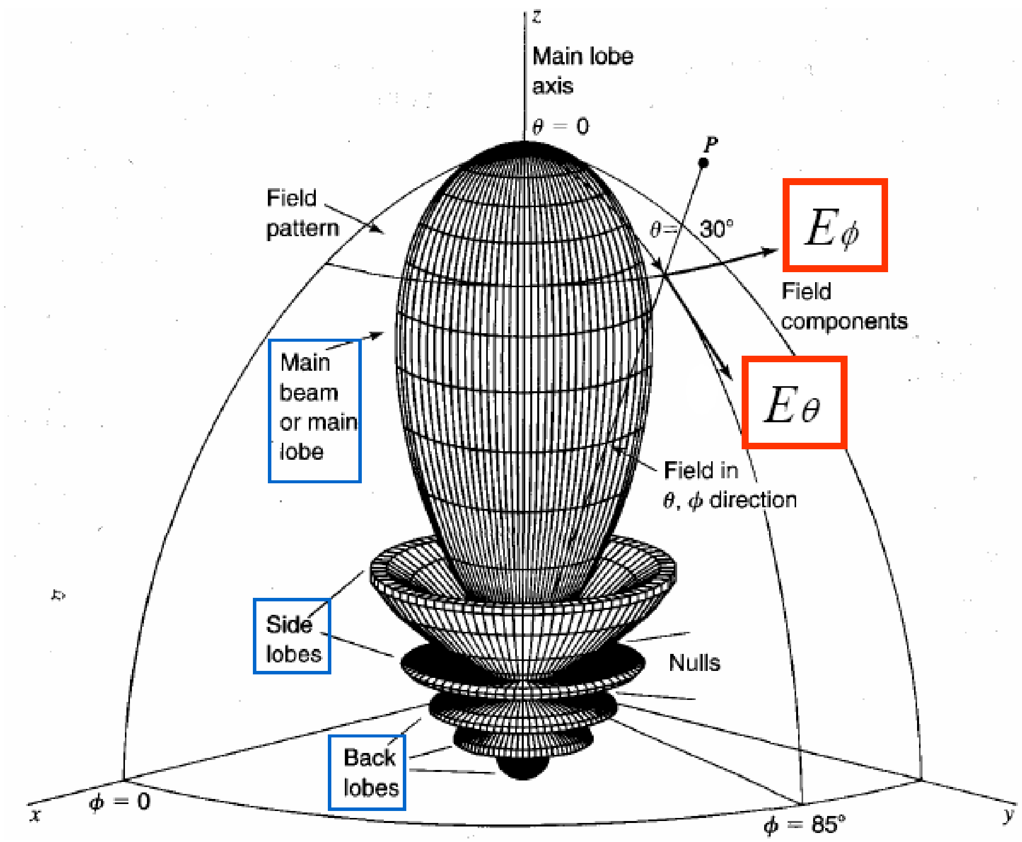
- This approximation applies over the radiating aperture of the antenna, and so it depends on the maximum dimension of the antenna. If we call this maximum dimension *D*, then the far-field distance is defined as,

$$R_{ff} = \frac{2D^2}{\lambda} \text{ m}$$

- For electrically small antennas, such as short dipoles and small loops, this result may give a far-field distance that is too small; in this case, a minimum value of $R_{ff} = 2\lambda$ should be used.

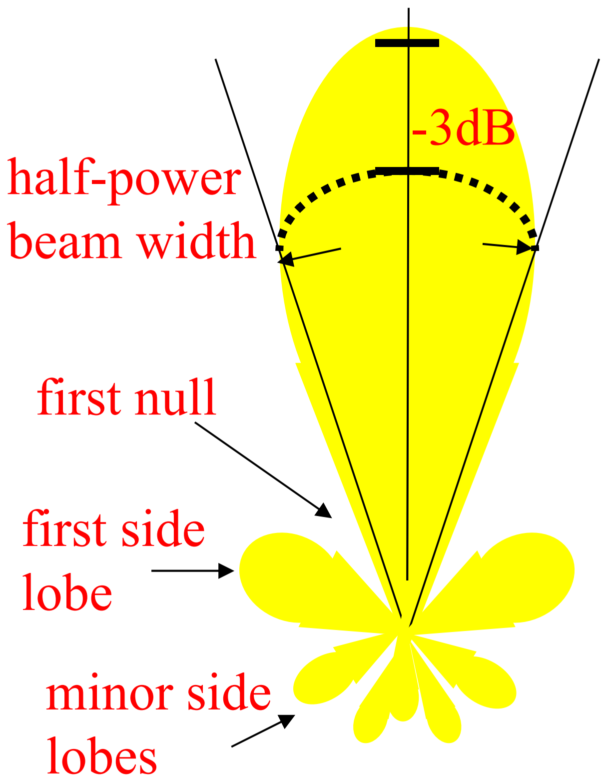
Antenna parameters

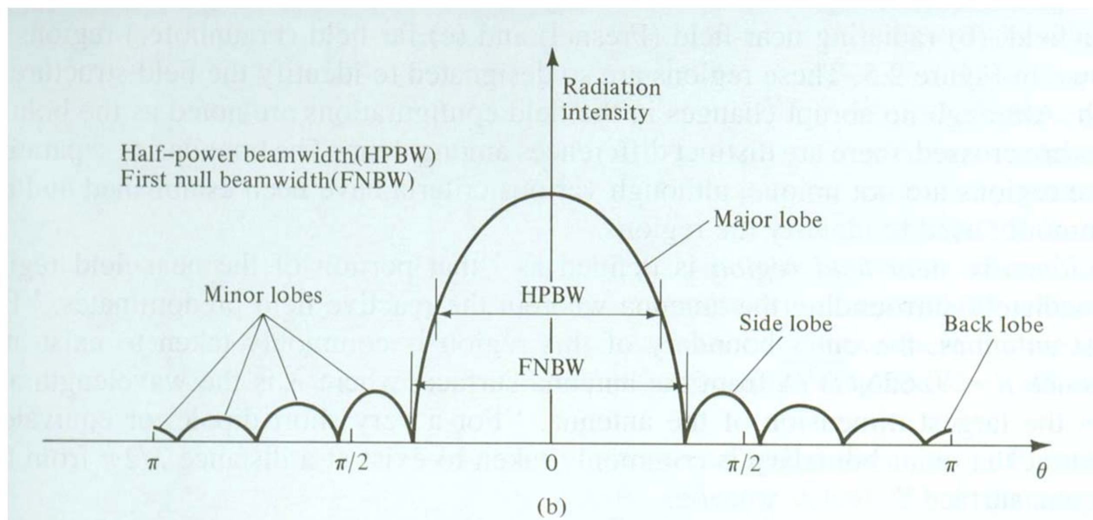
- **Radiation Pattern** refers to the directional dependence of the strength of the EM waves from the antenna.
  - o Amplitude pattern or field pattern (voltage)
  - o Power pattern



Antenna parameters

- The **beam width** is taken as the angular separation either between the half points on its power density radiation pattern or -3dB point on the field intensity radiation pattern.



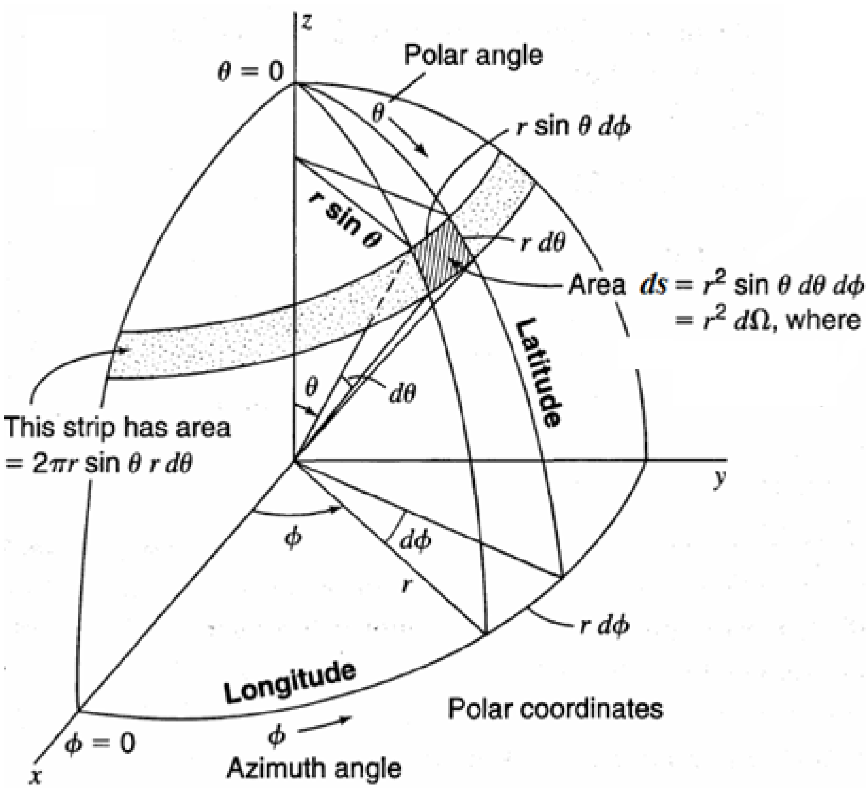


FNBW: Beamwidth between first nulls

Antenna parameters

- **Radiation power**

$$P_{rad} = \oiint_s \overrightarrow{S_{av}} \bullet \overrightarrow{ds} = \frac{1}{2} \oiint_s \mathrm{Re}[\vec{E} \times \vec{H}^*] \bullet \overrightarrow{ds} \;\; (\mathrm{W})$$



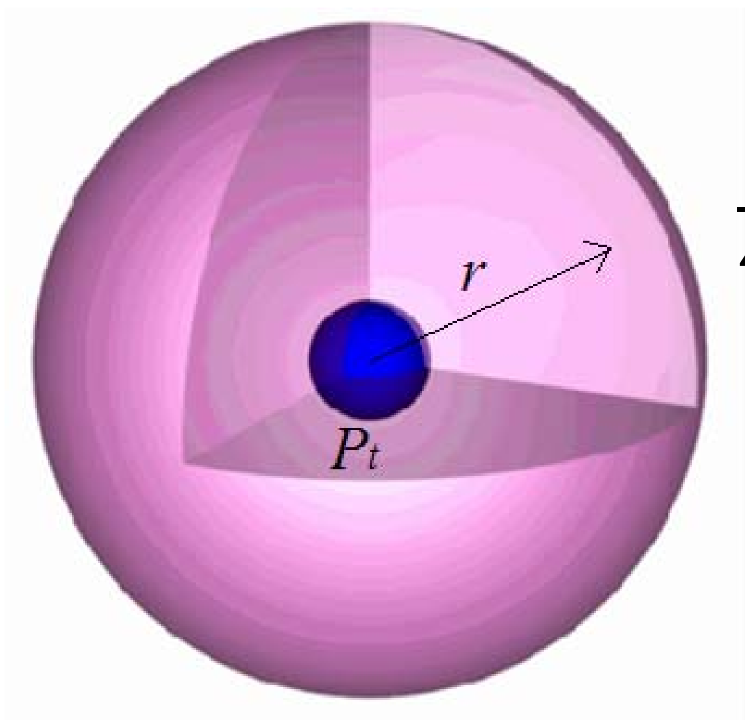
Pointing vector $\quad \vec{S} = \frac{1}{2} \vec{E} \times \vec{H}^*$

Time-average Pointing Vector $\quad \overrightarrow{S_{av}} = \frac{1}{2} \mathrm{Re}[\vec{E} \times \vec{H}^*]$

$$= \frac{1}{2} \hat{r} \frac{E_\theta^2 + E_\phi^2}{Z_0}$$

Antenna parameters

- An **isotropic antenna** radiates the same intensity of EM waves in all directions. It has a directivity of 0 **dBi** (dB relative to isotropic).



$$\frac{P_t}{4\pi r^2}$$

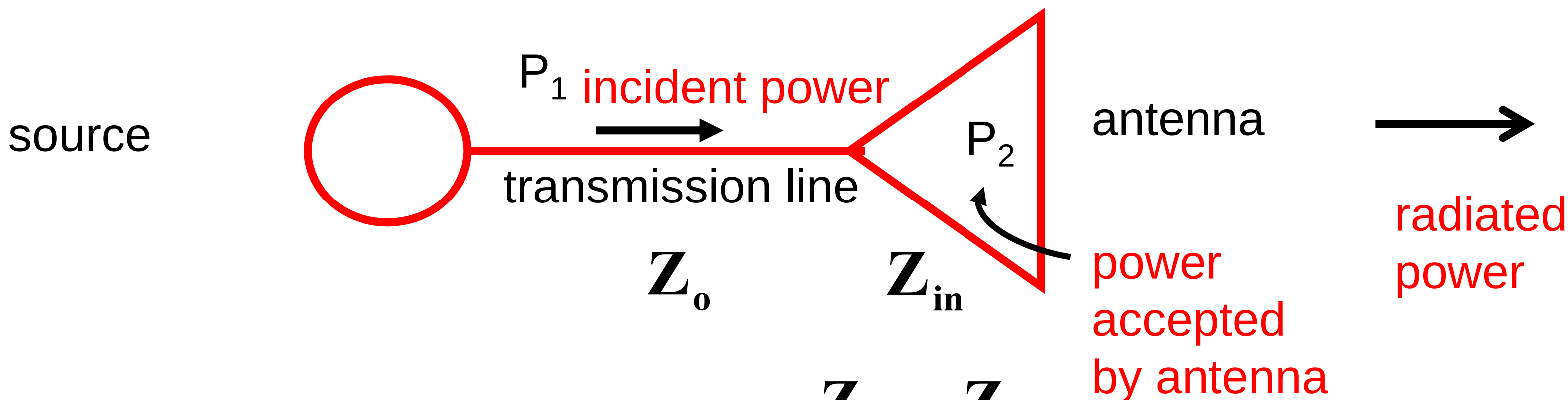
Antenna parameters

- **Antenna impedance**- An antenna can be considered as a one-port device with the impedance of

$$\mathbf{Z_{in} = R + jX}$$ where $$\mathbf{R = R_{rad} + R_{loss}}$$

radiation resistance

account for Ohmic loss

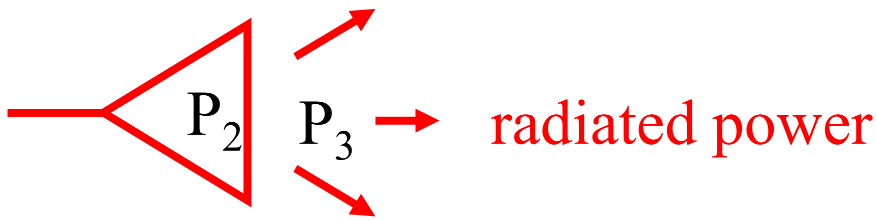


$$\mathbf{P_2 = (1 - |\Gamma|^2) P_1}$$ where $$\mathbf{\Gamma = \frac{Z_{in} - Z_o}{Z_{in} + Z_o}}$$

Antenna parameters

- **Efficiency η**: a function of surface/profile accuracy, physical size, focal length, aperture blockage, mismatch effects, and so on.

$$\eta = \frac{P_3}{P_2}$$



- **Gain G**: the ratio of the power density in the direction of maximum radiation intensity to the power density due to an isotropic radiator for the same input power.
- **Directivity D**

$$G = \frac{S_{av(\max)}}{\dfrac{P_2}{4\pi r^2}} \qquad D = \frac{S_{av(\max)}}{\dfrac{P_3}{4\pi r^2}} \qquad \eta = \frac{G}{D}$$

Antenna parameters

- **Effective isotropic radiated power (EIRP)**: the product of the transmitter power P_t and the antenna gain G_t, i. e., **EIRP = P_t x G_t**.
  - Usually, the EIRP is given in units of dBw: **EIRP(dBW) = P_t(dBW) + G_t(dB)**
  - An antenna with a power gain of 40 dB and a transmitter power of 1000 W would mean an EIRP of 10 x 10^6 W or 70 dBW.

- **Effective Aperture A_e**: the area that captures energy from a passing radio wave

$$A_e = G_r \frac{\lambda^2}{4\pi} \quad (\lambda \text{ is the wavelength} = v/f)$$

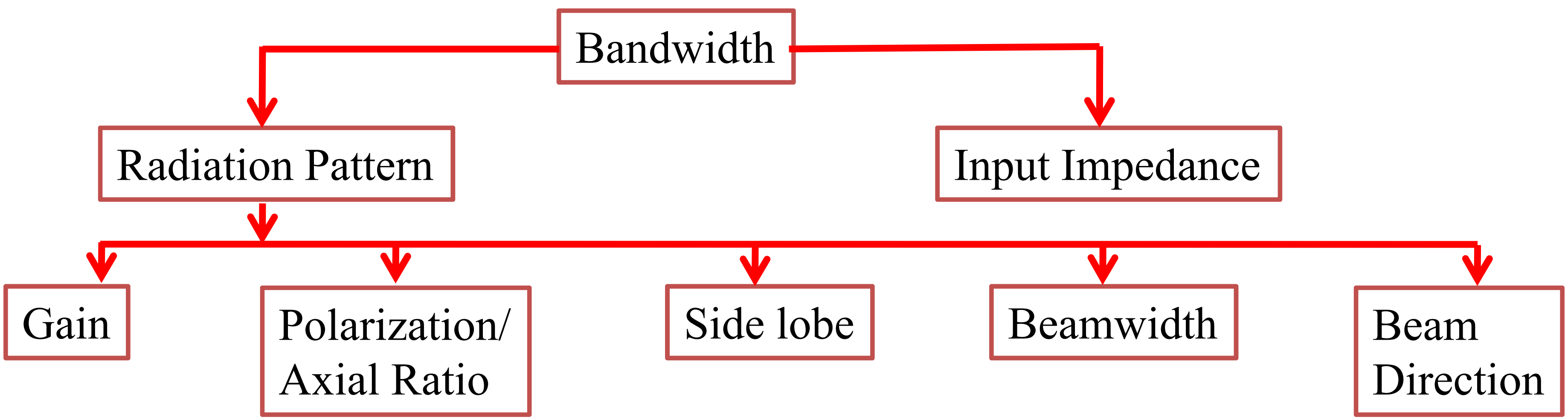
Antenna parameters

- **Polarization loss**: It happens when the received EM wave is of a polarization different from the one the antenna is designed for.
  - In the case of a linearly polarized wave, polarization loss = 20 log ($1/\cos\Phi$), where Φ is angle between the polarization of the received wave and that of the antenna.
- Antenna **bandwidth** is the operating frequency range over which the antenna gives a certain performance.
  - It is usually defined with reference to a certain parameter such as gain, in which case it is taken as the frequency range around the nominal center frequency over which the power gain falls to half of its maximum.

Antenna parameters

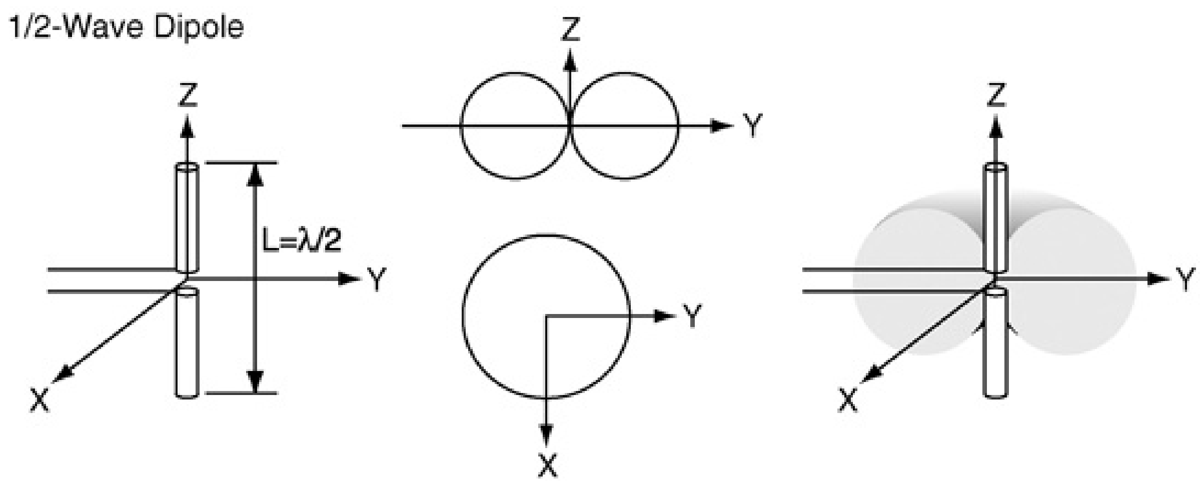
- for broadband antennas: BW = f_{upper}/f_{lower}
- for narrowband antennas such as microstrip patch antennas: Fractional bandwidth

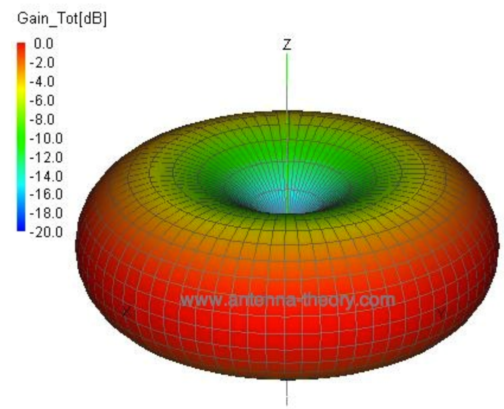
$$BW = \frac{f_{upper} - f_{lower}}{f_{center}} \times 100\,\%$$



Types of antenna - Dipole antenna

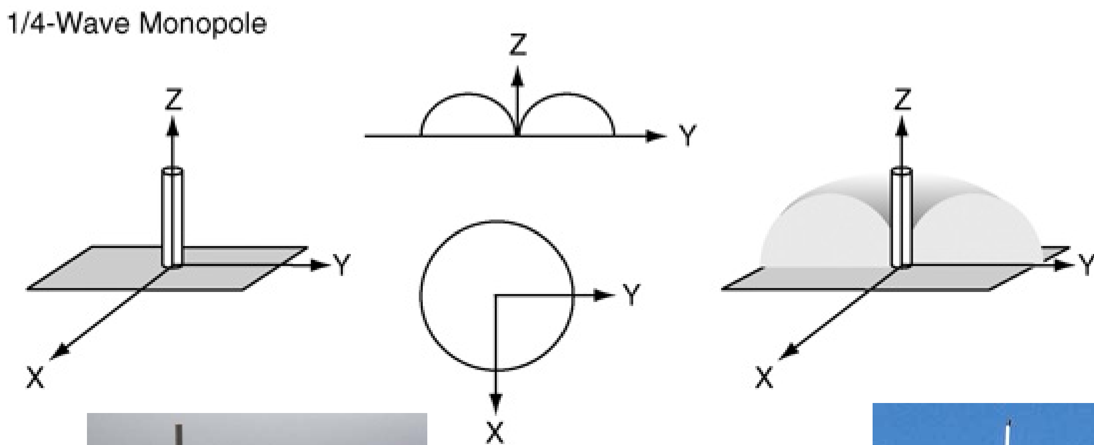
- A **dipole antenna** consists of two metal conductors of rod or wire, in line with each other, with a small space between them. The radio frequency voltage is applied to the antenna at the center, between the two conductors.

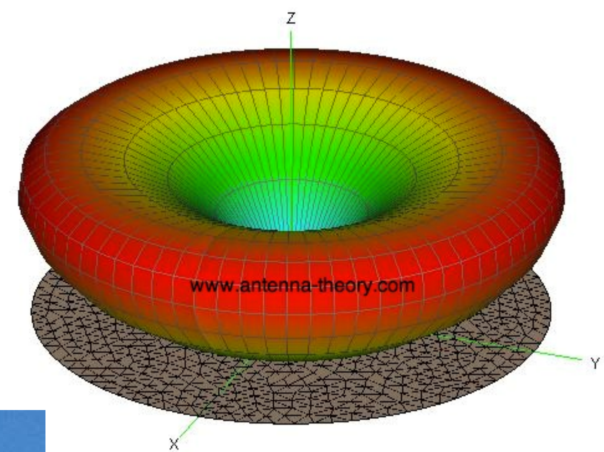




Types of antenna - Monopole antenna

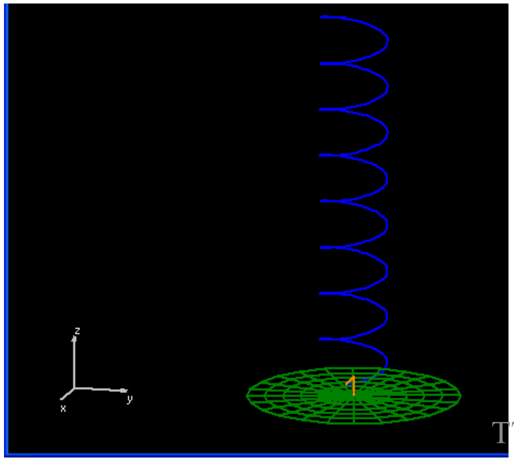
- A **monopole antenna** is one half of a dipole antenna, almost always mounted above some sort of ground plane.

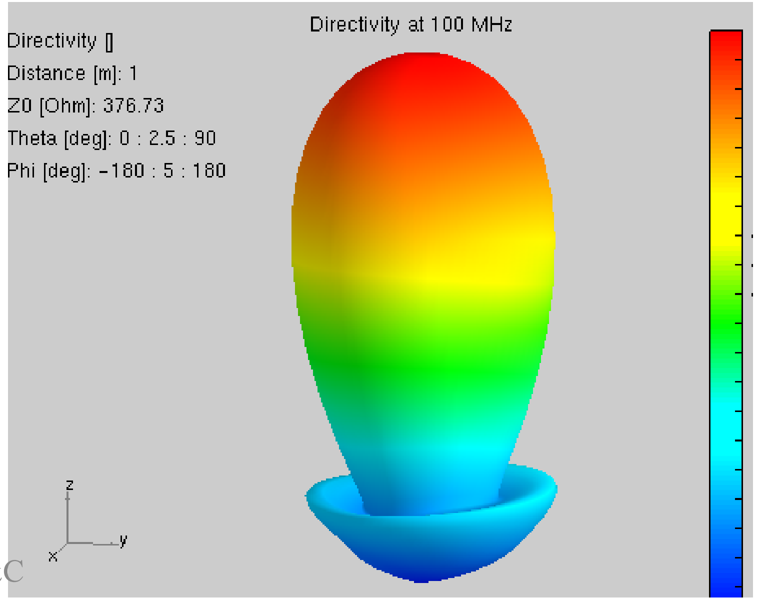




Types of antenna – Helical antenna

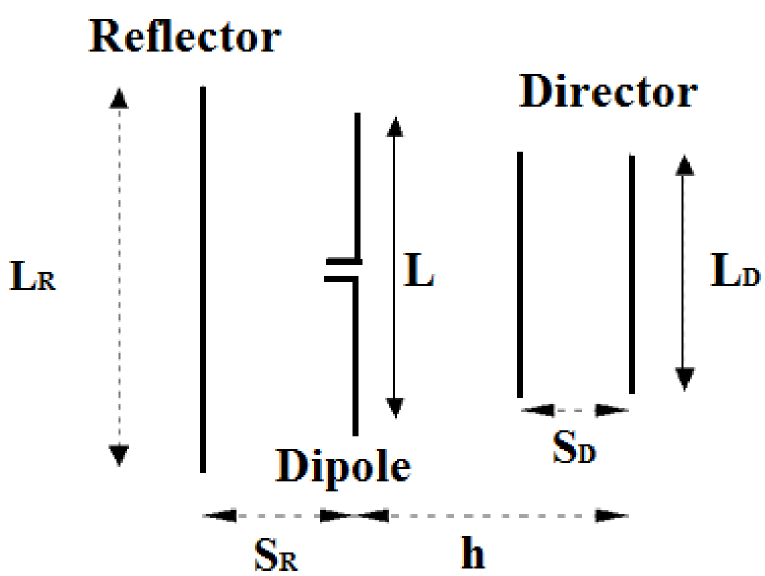
- A **helical antenna** is an antenna consisting of a conducting wire wound in the form of a helix.
  - The feed line is connected between the bottom of the helix and the ground plane.
  - Helical antennas can operate in one of two principal modes: normal mode or axial mode.





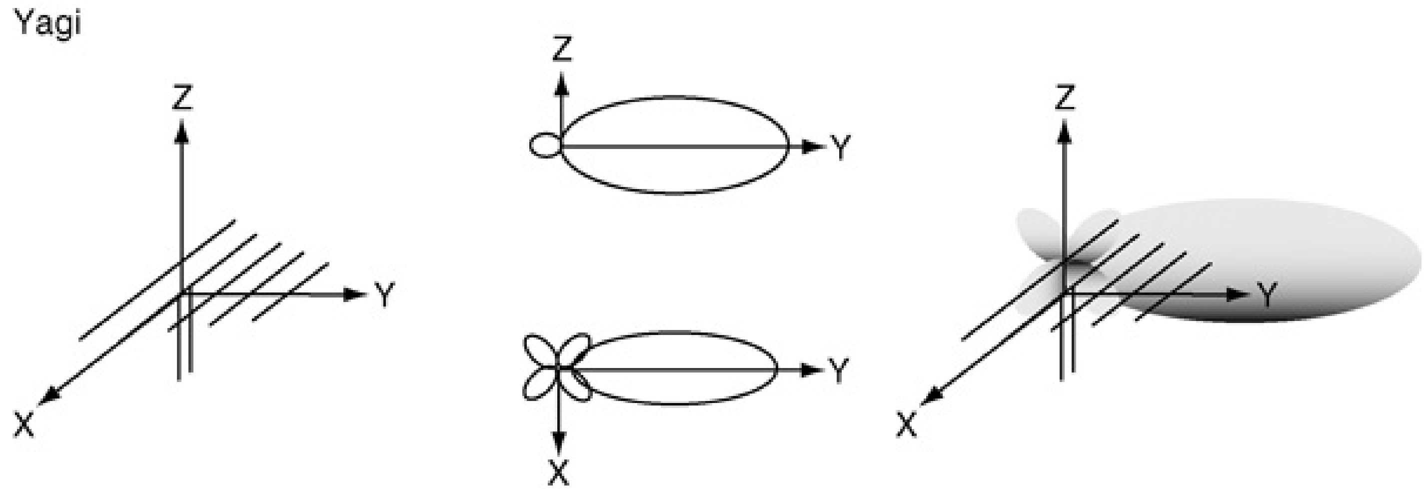
Types of antenna – Yagi-Uda antenna

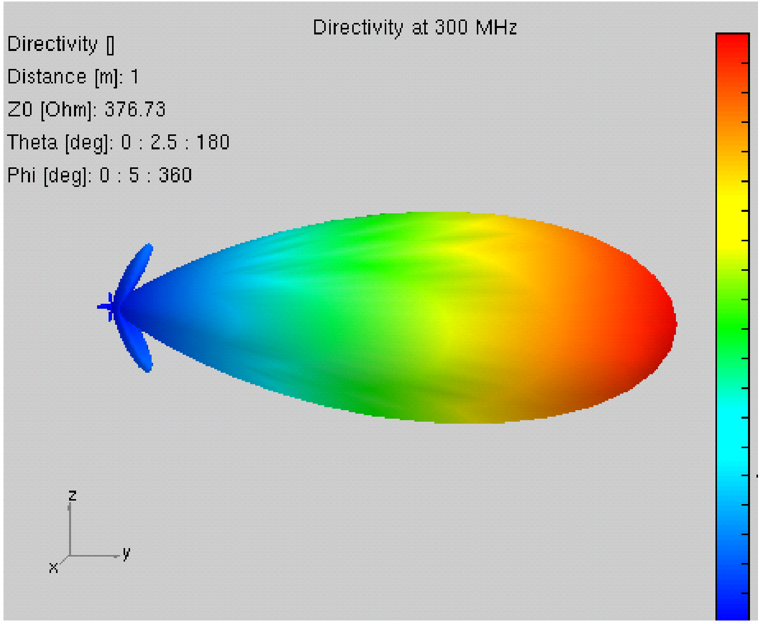
- A **Yagi-Uda array**, commonly known simply as a **Yagi antenna**, is a directional antenna consisting of a driven element (typically a *dipole* or *folded dipole*) and additional parasitic elements (usually a so-called *reflector* and one or more *directors*).



- Reflector: $L_R = 0.47 - 0.52\lambda$
- Driven Element: $L = 0.45\text{-}0.49\lambda$.
- Directors: $L_D = 0.4\text{-}0.45\lambda$.
- Separation between Directors: $S_D = 0.2\text{-}0.35\ \lambda$.
- Radii of directors h: $0.15\text{-}0.25\ \lambda$.
- Separation between driven element and reflector: $S_R = 0.2\text{-}0.35\ \lambda$.

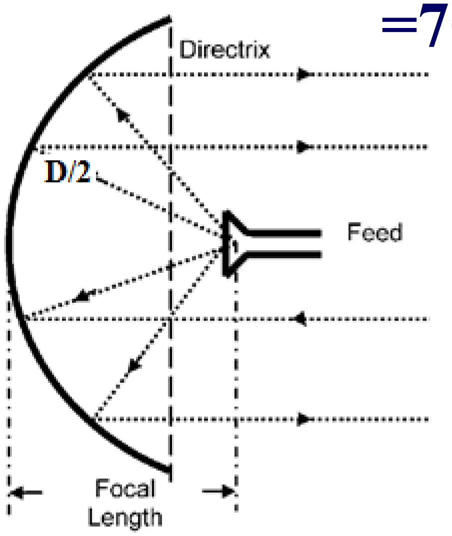
Types of antenna – Yagi-Uda antenna

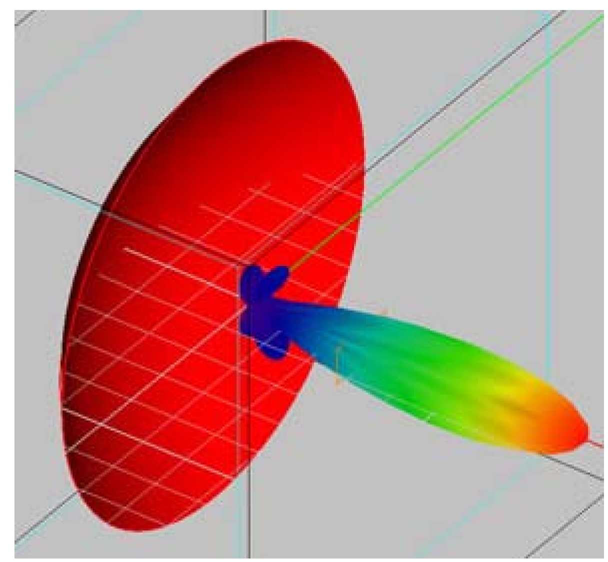




Types of antenna – Parabolic antenna

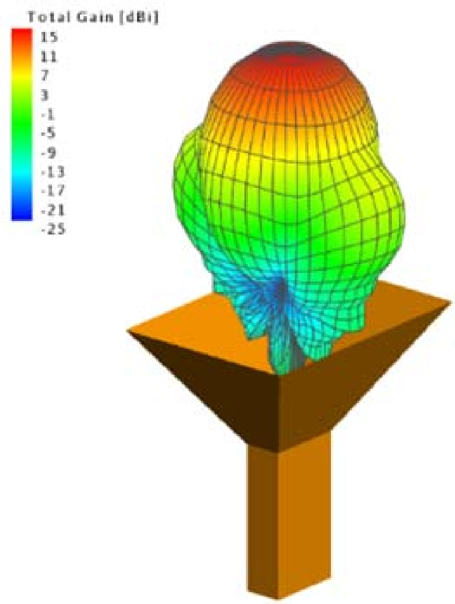
- A **parabolic antenna** is an antenna that uses a parabolic reflector, a curved surface with the cross-sectional shape of a parabola, to direct the radio waves.
  - A parabolic antenna has high directivity and narrow beam width.
  - **$G = \eta\pi^2(D/\lambda)^2$**
  - **The 3dB beam width (degree) $=70(\lambda/D)$**

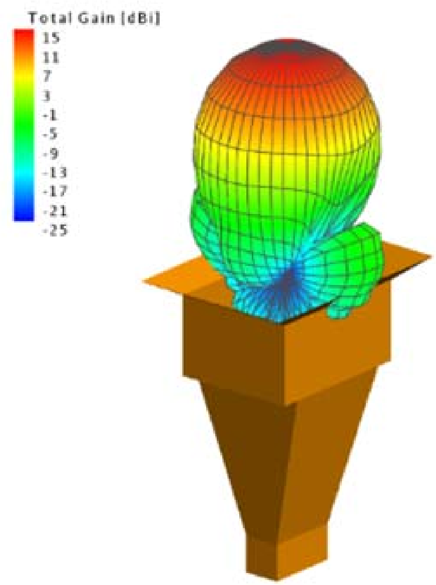




Types of antenna – Horn antenna

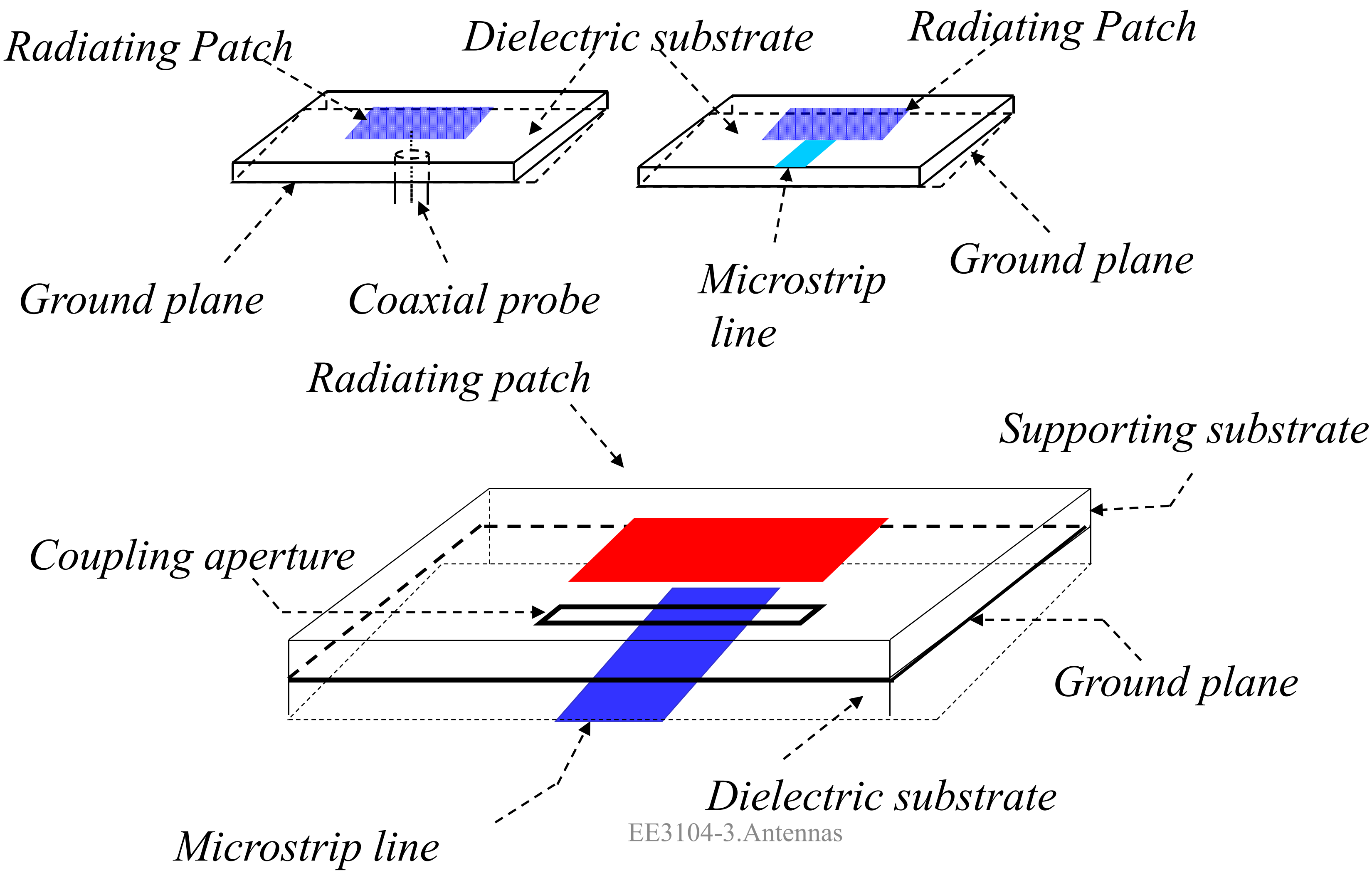
- A **horn antenna** or **microwave horn** is an antenna that consists of a flaring metal waveguide shaped like a horn to direct radio waves in a beam.
  - o Horn antennas often have a directional radiation pattern with a high antenna gain.





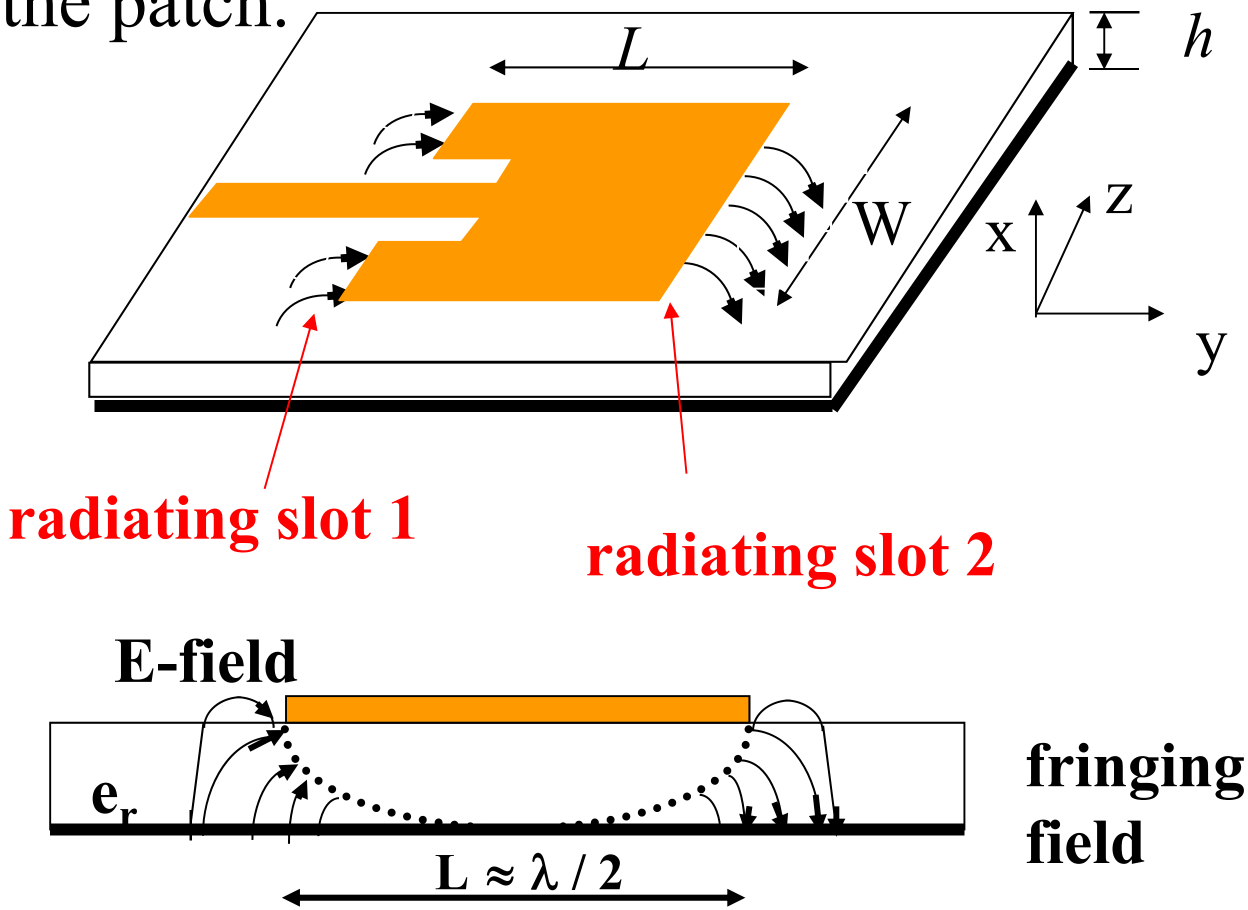
Types of antenna – Microstrip antenna

- It cab be fed by microstrip line or a coaxial feed.



Types of antenna – Microstrip antenna

- The antenna radiates from the two edges as radiating slots.
- It is designed to have maximum radiation in direction normal to the patch.

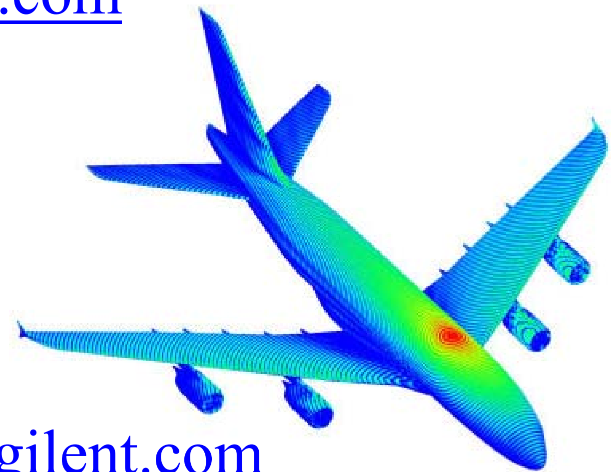


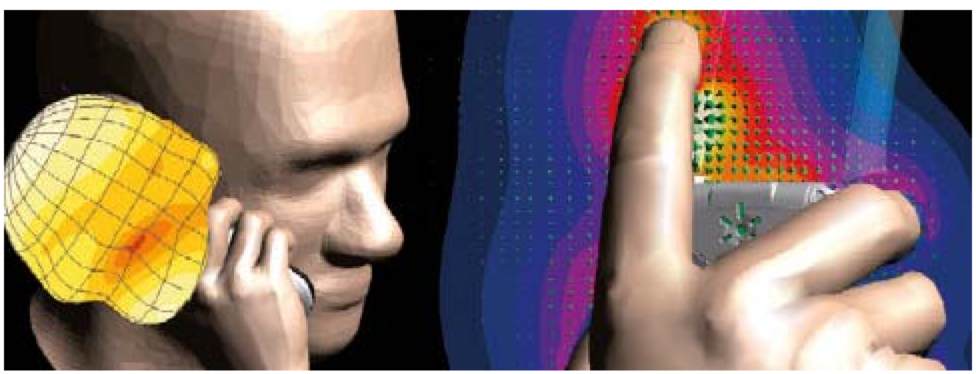
Antenna Summary

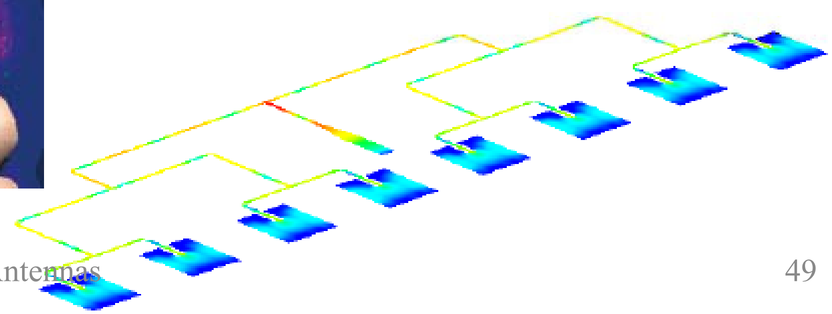
Configuration	Peak gain, dBi	Beam width, deg	Pattern
Half-wave dipole	1.64	—	
Planar array	$10\log\left(\frac{A}{\lambda^2}\right)+8$	—	
Turnstile	0.6	—	—
Horn	$20\log\left(\frac{D}{\lambda}\right)+7$ (Typically 5 to 20 dBi)	$\frac{72\lambda}{D}$	—
Bi-cone	$5\log\left(\frac{D}{\lambda}\right)+3.5$ (Typically 5 dBi)	Typically 45×360	
Helix	$10\log\left(\frac{D^2L}{\lambda^3}\right)+20.2$ (Typically 5 to 20 dBi)	$\frac{16.6}{\sqrt{D^2L/\lambda^3}}$	
Parabola	$20\log(\bar{f})+20\log(D)+17.8$ (Typically 10 to 65 dBi)	$\frac{65.3\lambda}{D}$	
Yagi	$\approx 12dBi$	—	

Analysis methods and CAD tools

- There are various commercial software available for designing antennas
  - Ansoft HFSS/Designer, http://www.ansoft.com
  - Zeland IE3D, http://www.zeland.com
  - CST Studio Suite, http://www.cst.com
  - XFDTD, http://www.remcom.com
  - FEKO, http://www.feko.info
  - SEMCAD, http://www.semcad.com
  - Agilent Momentum/EMDS, http://www.agilent.com
  - Sonnet Suite, http://www.sonnetsoftware.com





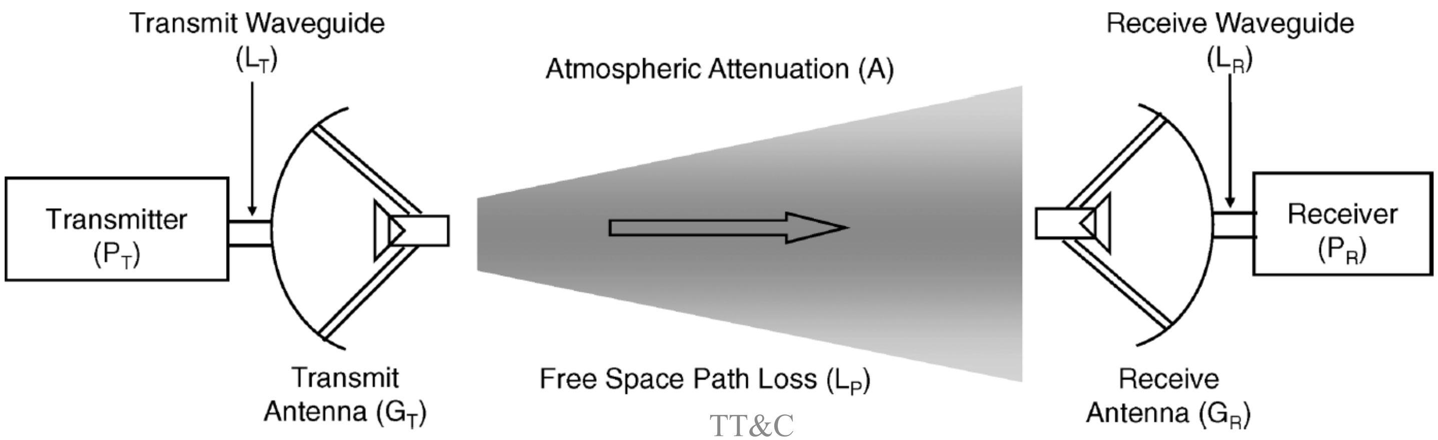


Antenna measurement

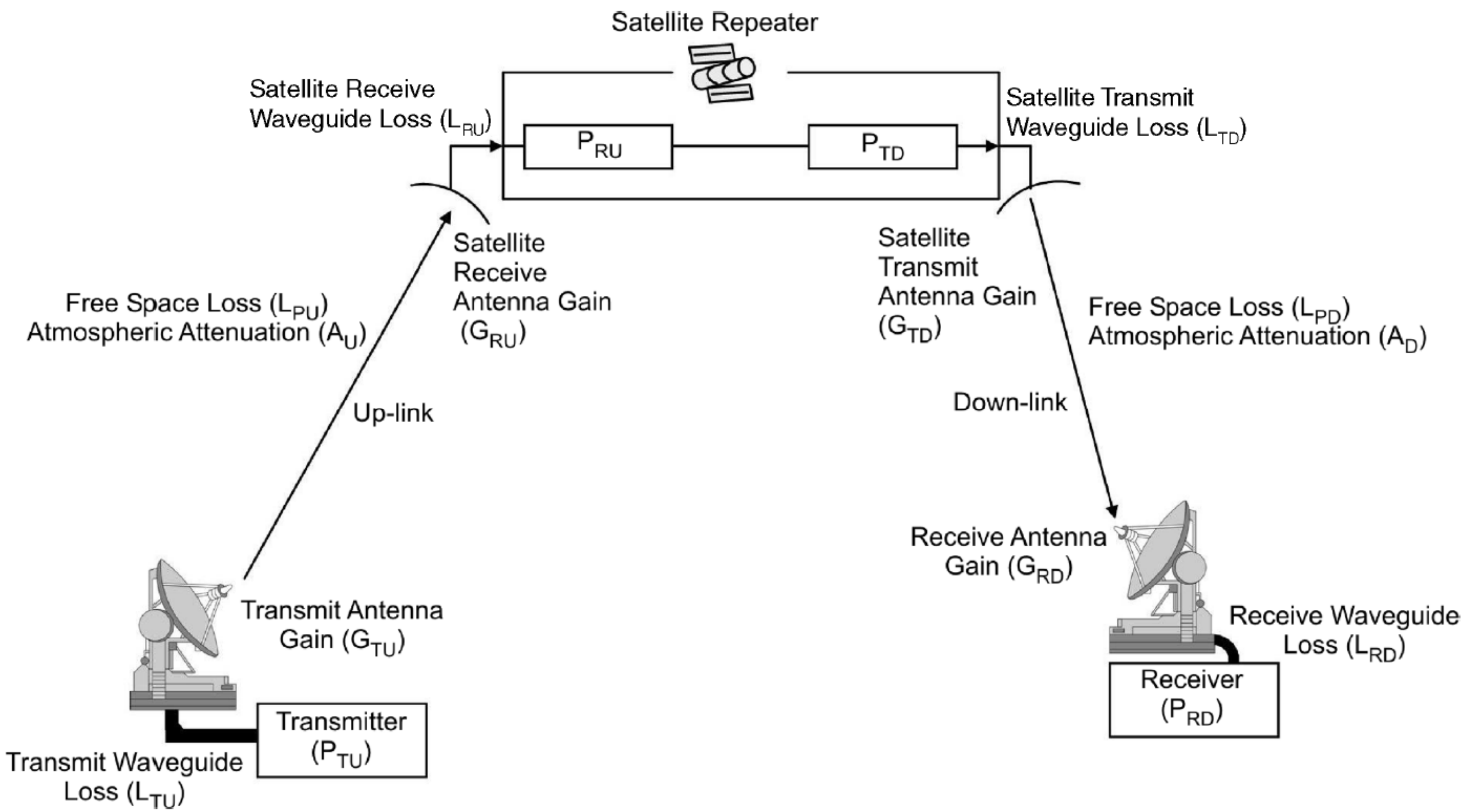
http://www.youtube.com/watch?v=zWO5_DjH-3A

Link Budget

- The **link budget** is the algebraic sum of all gains and losses expressed in decibels(dB) as we move from the transmitter to the receiver.
- The final value obtained provides us the available signal strength at the receiver.
- The difference between the available value and the minimum acceptable level at receiver (threshold level) is known as the link margin.



Link Budget



Satellite Repeater
Satellite Receive Waveguide Loss (L_{RU})
P_{RU}
P_{TD}
Satellite Transmit Waveguide Loss (L_{TD})
Satellite Receive Antenna Gain (G_{RU})
Satellite Transmit Antenna Gain (G_{TD})
Free Space Loss (L_{PU})
Atmospheric Attenuation (A_U)
Free Space Loss (L_{PD})
Atmospheric Attenuation (A_D)
Up-link
Down-link
Receive Antenna Gain (G_{RD})
Transmit Antenna Gain (G_{TU})
Receive Waveguide Loss (L_{RD})
Receiver (P_{RD})
Transmitter (P_{TU})
Transmit Waveguide Loss (L_{TU})

Link Budget

- Various parameters:
  1. Transmitter power P_T
  2. Power loss in the waveguide connecting and the transmitter output to the antenna input L_T
  3. Transmitting antenna gain G_T
  4. Free-space path loss L_P
  5. Attenuation due to rain, clouds, fog, etc., A
  6. Receive antenna gain G_R
  7. Power loss in the waveguide connecting the receive antenna output to the receiver input L_R
  8. Received signal power P_R

Link Budget

- The power balance equation describing the link budget is

$$P_{\mathrm{T}} - L_{\mathrm{T}} + G_{\mathrm{T}} - L_{\mathrm{P}} - A + G_{\mathrm{R}} - L_{\mathrm{R}} = P_{\mathrm{R}}$$

- All the power levels are in dBW or dBm, and gain, attenuation and loss terms are in dB.
- With reference to a satellite link:

$$P_{\mathrm{TU}} - L_{\mathrm{TU}} + G_{\mathrm{TU}} - L_{\mathrm{PU}} - A_{\mathrm{U}} + G_{\mathrm{RU}} - L_{\mathrm{RU}} = P_{\mathrm{RU}} \ldots \qquad \text{Uplink}$$

$$P_{\mathrm{TD}} - L_{\mathrm{TD}} + G_{\mathrm{TD}} - L_{\mathrm{PD}} - A_{\mathrm{D}} + G_{\mathrm{RD}} - L_{\mathrm{RD}} = P_{\mathrm{RD}} \ldots \qquad \text{Downlink}$$

Free space loss

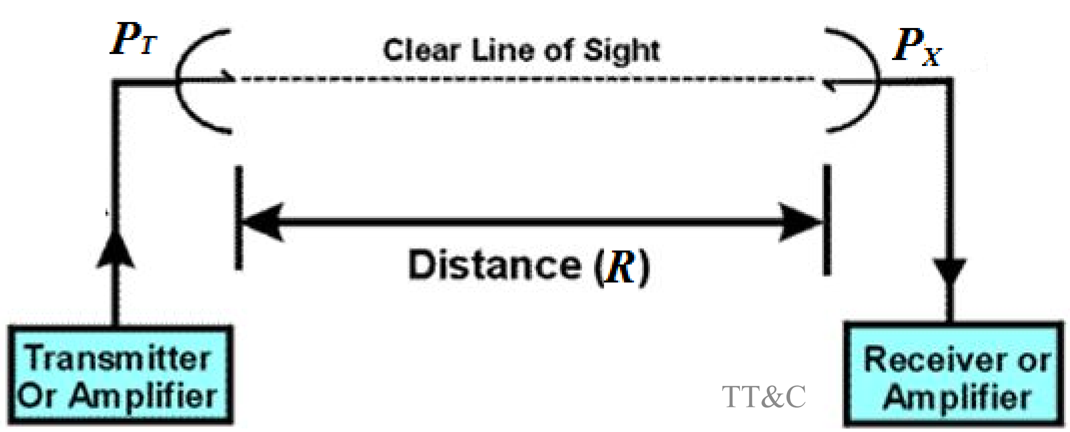
- Free space loss is the loss of signal strength only due to distance from the transmitter.
  - o Firstly, the spreading out of EM energy in free space in determined by the inverse square law.

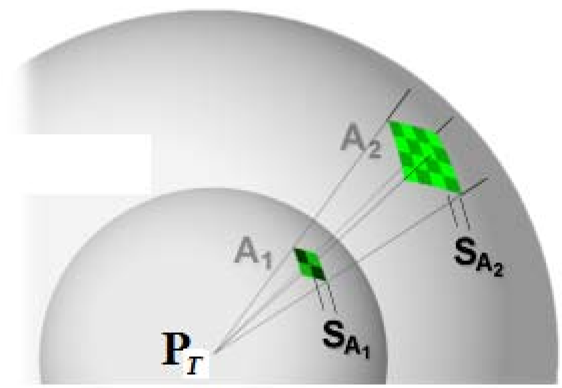
$$S = (P_T / 4\pi R^2)$$

where

S is the power per unit area at distance R (W/m^2)

P_T is the total power transmitted (W)





Free space loss

- The second effect is that of the receiving antenna's aperture, which describes how well an antenna can pick up power from an incoming electromagnetic wave. For an isotropic antenna, this is given by

$$P_R = S\frac{\lambda^2}{4\pi}$$

where PR is the received power and $\lambda = c$ (speed of light)/f is the operating wavelength.

- The free space loss is given by the ratio

$$L_{FS} = \frac{P_T}{P_R} = \left(\frac{4\pi R}{\lambda}\right)^2 = 20log\left(\frac{4\pi R}{\lambda}\right) \text{ dB}$$

Free space loss

$$L_{FS} = \frac{P_T}{P_R} = \left(\frac{4\pi R}{\lambda}\right)^2 = 20log\left(\frac{4\pi R}{\lambda}\right) = 20log\left(\frac{4\pi Rf}{c}\right)$$

$$= 20\log(R) + 20\log(f) + 20\log\left(\frac{4\pi}{c}\right)$$

$$= 20\log(R) + 20\log(f) - 147.55 \text{ (dB)}$$

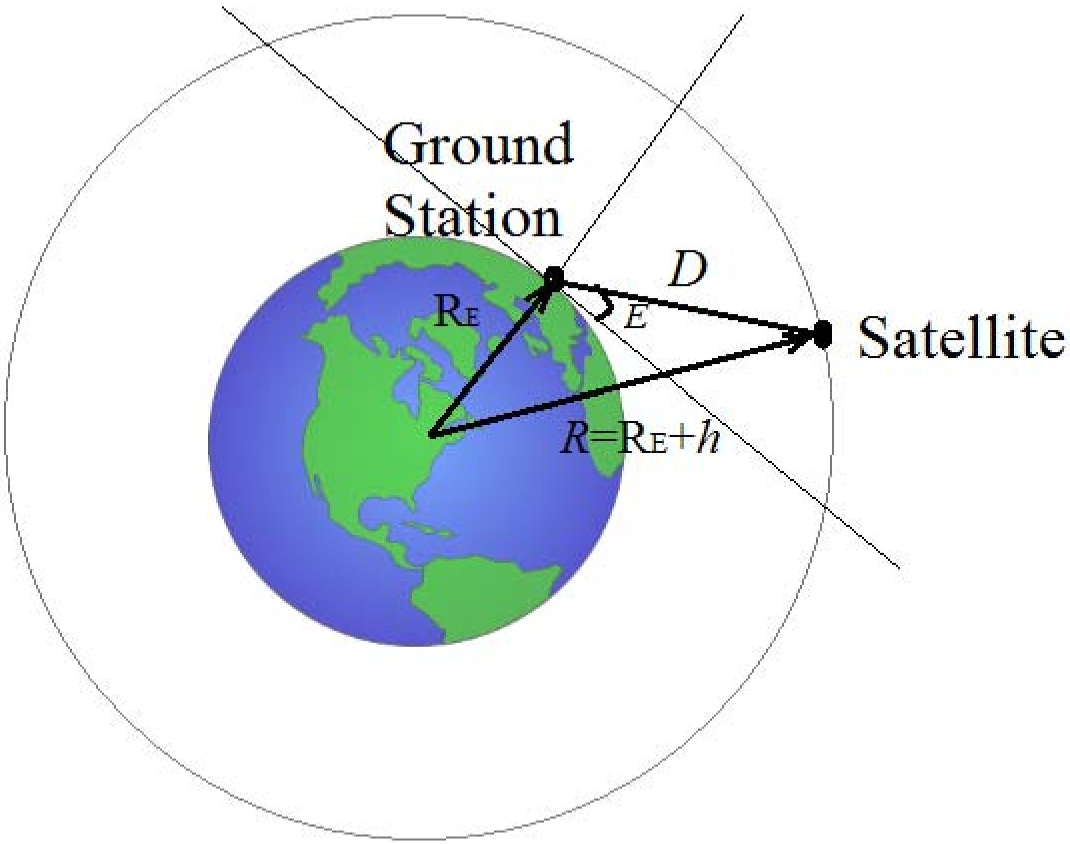
- If f is taken in MHz and R in km,

$$L_{FS}(\text{dB}) = 20\log(R) + 20\log(f) + 32.45$$

- If f is taken in GHz and R in km,

$$L_{FS}(\text{dB}) = 20\log(R) + 20\log(f) + 92.45$$

Slant range



R_E: radius of the Earth
h: satellite altitude
E: elevation angle

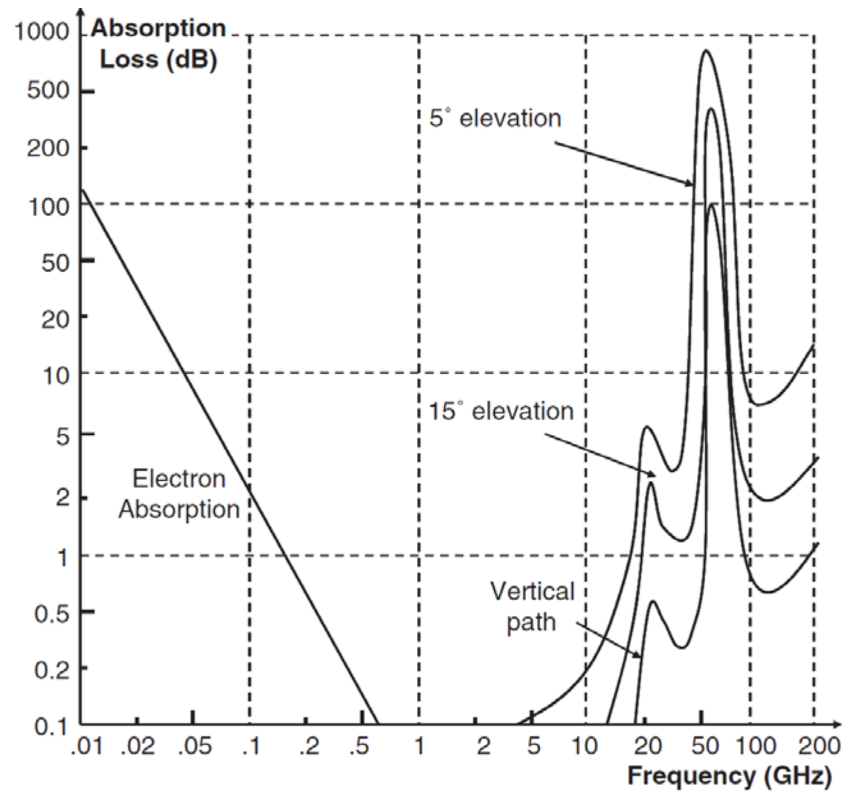
$$D = \sqrt{(R_E sinE)^2 + R^2 - {R_E}^2} - R_E sinE$$

Losses in communication link - A

- **Gaseous absorption** – EM energy gets absorbed and converted into heat due to gaseous absorption as it passes through the troposphere.
  - The absorption is primarily due to the presence of molecular oxygen and uncondensed water vapor. It is not significant in the frequency range of 1 to 15 GHz.
  - The presence of free electrons in the atmosphere causes absorption due to collision of EM waves with these electrons. Electron absorption is significant at frequencies less than 500 MHz.

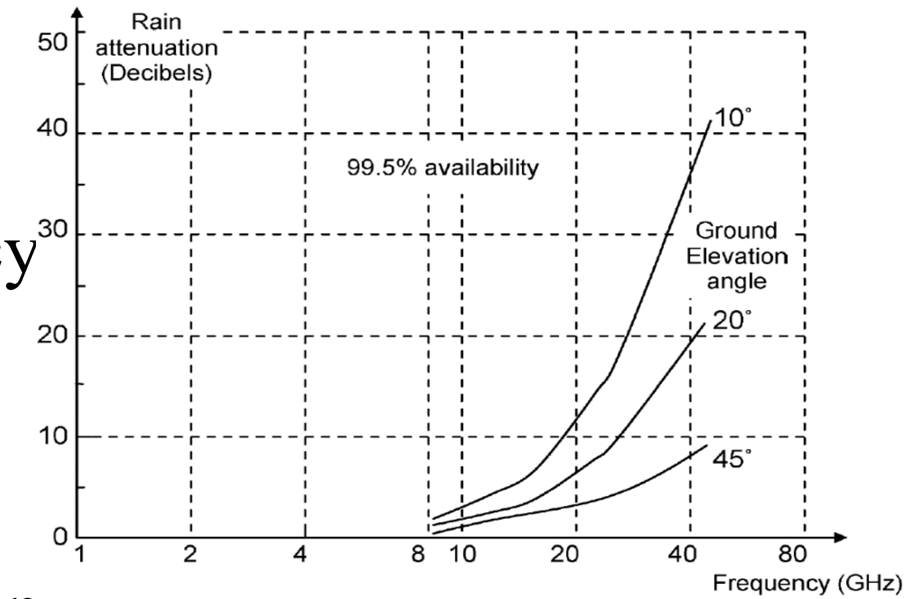
Losses in communication link - A

- The first absorption band is caused due to the resonance phenomenon in water vapour and occurs at 22.2 GHz.
- The second band is caused by a similar phenomenon in oxygen and occurs at 60 GHz.
- Absorption increases with a decrease in elevation angle E due to an increase in transmission path.



Losses in communication link - A

- **Attenuation due to rain.**
  - Losses due to rain increase with an increase in frequency and reduction in elevation angle.
  - An estimate of rain-caused attenuation is made by making extensive measurements at several locations in the coverage area of the satellite system.
  - It reduces the cross-polarization isolation.

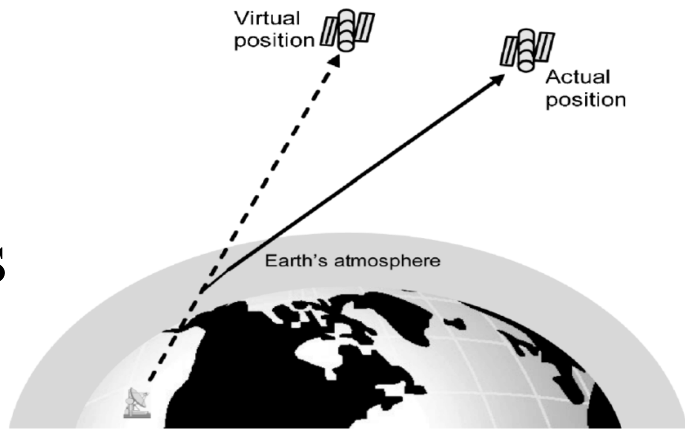


Losses in communication link - A

- **Cloud attenuation**
  - It is more or less irrelevant for lower frequency bands, but is largely relevant for Ka and V band frequencies.
  - Water-filled clouds attenuate EM signals more than ice crystal clouds.
  - Cloud attenuation increases with increase in thickness of the clouds and its probability of occurrence. It also increases for lower elevation angles.

Losses in communication link - A

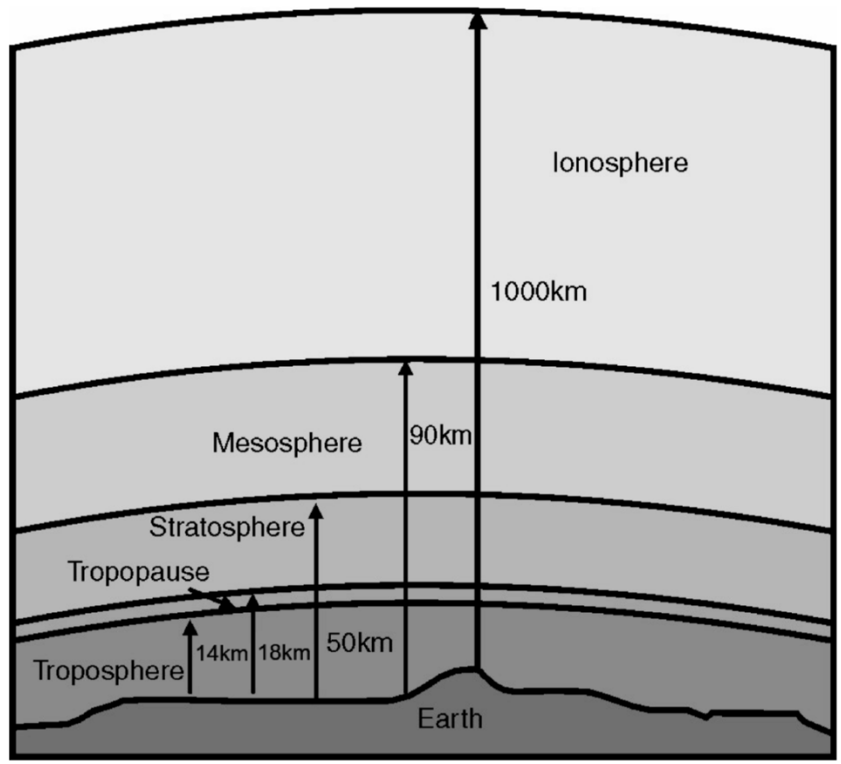
- **Signal fading due to refraction**



  - Refraction is the phenomenon of bending of EM waves as they pass through the different layers of the atmosphere.
  - The result of bending of EM waves leads to a virtual position for the satellite slightly above its true position.
  - Fading is the phenomenon wherein the Earth station receiving antenna receives the signal transmitted by the satellite via different paths with different phase shifts

Losses in communication link - A

- **Ionosphere-related effects**
  - The ionosphere is an ionized region in space, extending from about 80-90 km to 1000km formed by interaction of solar radiation with different constituent gases of the atmosphere.



Losses in communication link - A

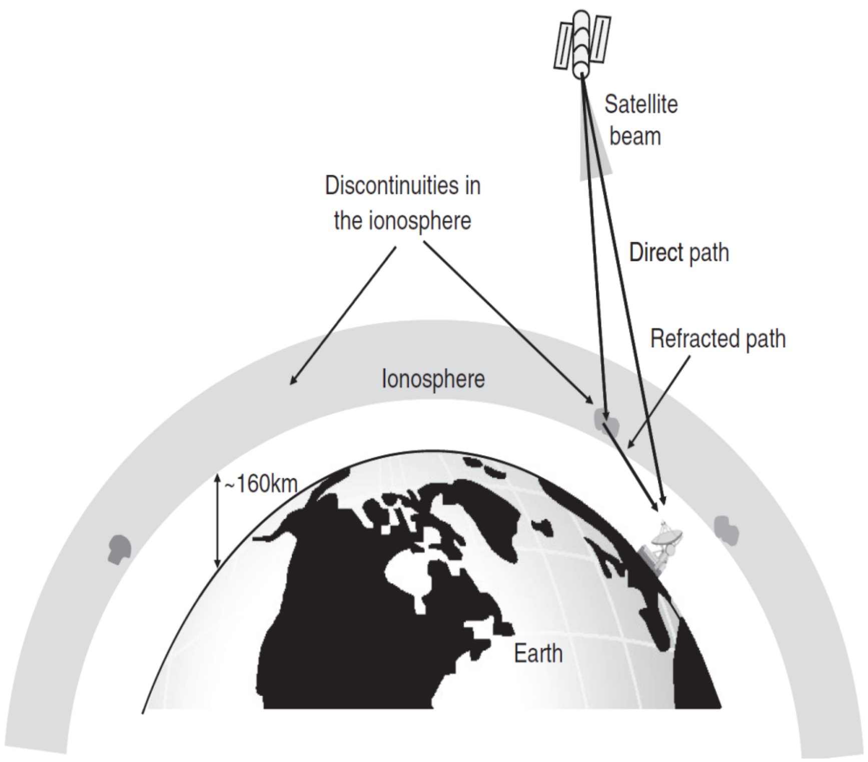
- *Polarization rotation – Faraday effect*
  - When an EM wave passes through the ionosphere, the plane of polarization of the wave gets rotated due to interaction of the EM wave with the Earth's magnetic field.
  - The angle through which the plane of polarization rotates is directly proportional to the total electron content (TEC) of the ionized region and inversely proportional to the square of the operating frequency.
  - The angle also depends upon the state of the ionosphere, time of the day, solar activity, the direction of the incident wave, and so on.

Losses in communication link - A

- *Ionospheric scintillation*
  - Scintillation is the rapid fluctuations of the signal amplitude, phase, polarization or angle-of-arrival.
  - In the ionosphere, scintillation occurs due to small scale refraction index variations caused by local electron concentration fluctuations.
  - The signal reaches the receiving antenna via two paths, the direct path and the refracted path. Multiple signals can lead to both signal enhancement (in-phase) and signal cancellation (out-of-phase).

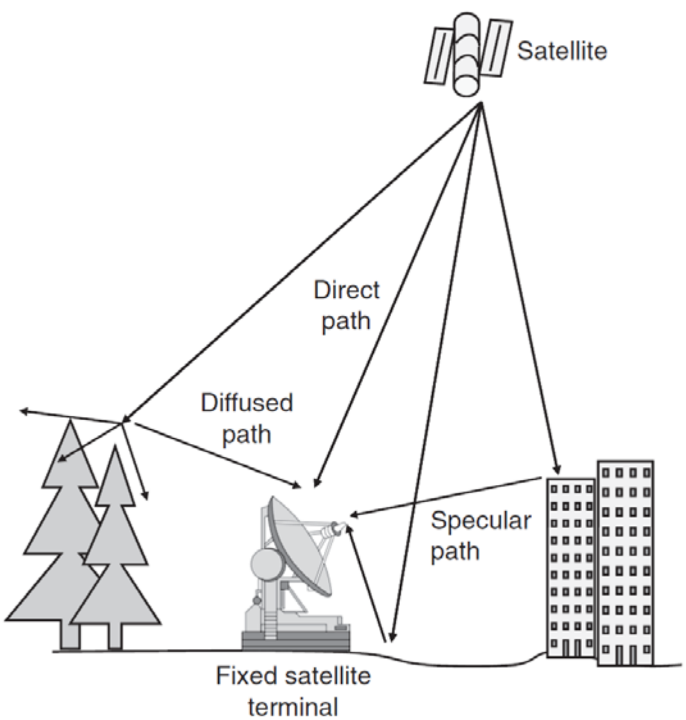
Losses in communication link - A

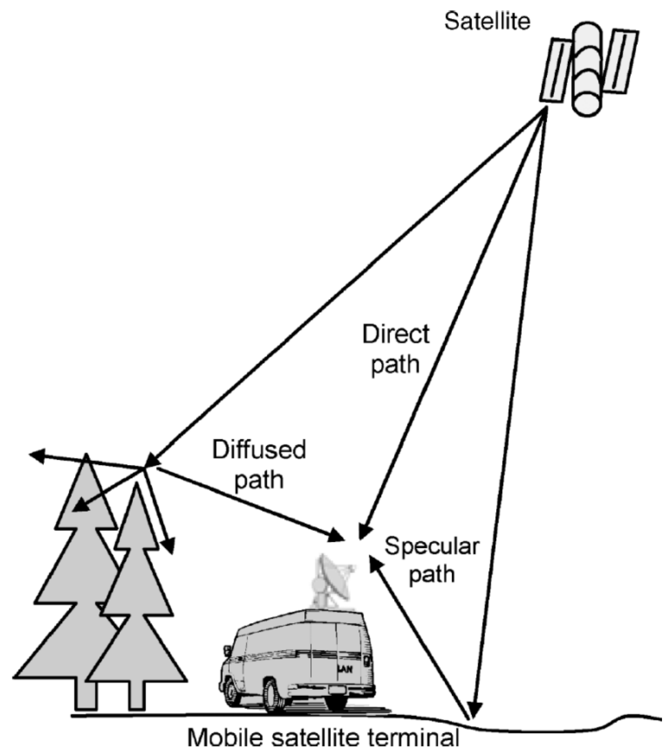
- The scintillation effect is inversely proportional to the square of the operating frequency and is predominant at lower microwave frequencies, typically below 4 GHz.
- Scintillation increases during periods of high solar activity and other extreme conditions such as the occurrence of magnetic storms.



Losses in communication link - A

- **Fading due to multipath signals**
  - o Multiple signals result from reflection and scattering from obstacles such as buildings, trees, hills and other objects.





Problem 1

Compute the free-space path loss in decibels for the following conditions:

1. For a path length of 10 km at 4 GHz operating frequency
2. Earth station transmitting antenna EIRP $= 50\,\text{dBW}$, satellite receiving antenna gain $=$ $20\,\text{dB}$ and received power at satellite $= -120\,\text{dBW}$

Solution:

(a) Path length, $R = 10\,\text{km}$, operating frequency, $f = 4\,\text{GHz}$

$$\text{Operating wavelength, } \lambda = c/f = (3 \times 10^8/4 \times 10^9)\,\text{m} = 0.075\,\text{m}$$

$$\begin{aligned}\text{Path loss (in dB)} &= 20\log(4\pi R/\lambda)\\ &= 20\log(4\pi \times 10\,000/0.075)\\ &= 124.48\,\text{dB}\end{aligned}$$

(b) Path loss can be computed from:

$$\text{Received power} = \text{EIRP} + \text{receiving antenna gain} - \text{path loss}$$

$$\begin{aligned}\text{Therefore, path loss} &= \text{EIRP} + \text{receiving antenna gain} - \text{received power}\\ &= 50 + 20 - (-120) = 50 + 20 + 120 = 190\,\text{dB}\end{aligned}$$

Noise

- **Noise** is defined as the unwanted form of energy that tends to interfere with the reception and accurate reproduction of wanted signals.
- **Thermal noise (white noise)** is generated in any electronic component due to random motion of molecules, atoms and electrons above absolute zero temperature. The thermal noise power P_n,

$$P_n \propto TB = kTB$$

where

$T =$ absolute temperature (in K)
$B =$ bandwidth of interest (in Hz)
$k =$ Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K

Noise Figure

- The **Noise Figure** is of a device can be defined as the ratio of the signal-to-noise power at its input to the signal-to-noise power at its output:

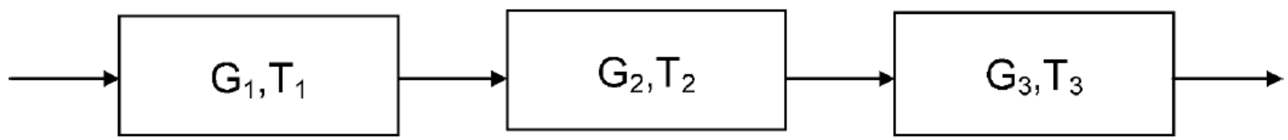
$$F = \frac{S_i/N_i}{S_o/N_o} = \left(\frac{N_o}{N_i}\right)\left(\frac{1}{G}\right)$$

- $N_i = kT_iB$, $N_o = GN_i + \Delta N = GkT_iB + GkT_eB = G\,k(T_i + T_e)B$

$$F = 1 + \frac{T_e}{T_i}$$

where T_e is the equivalent noise temperature. $T_e = T_i(F-1)$

Noise Figure



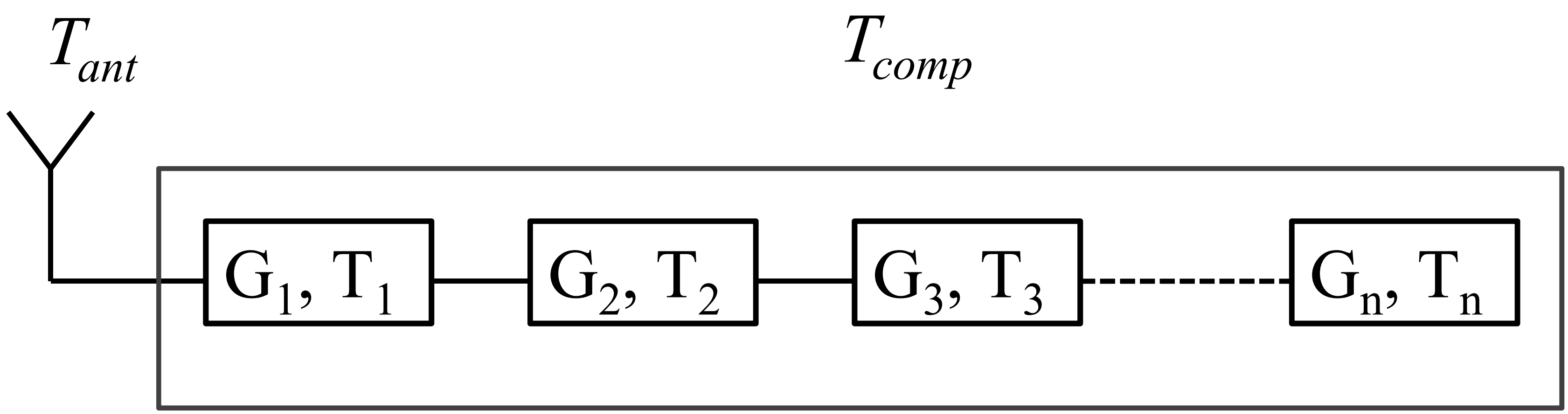
$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3}$$

- In order to keep the overall system noise as low as possible, the first stage should have high power gain and low noise temperature, Low-noise amplifier (LNA)

System Noise Temperature *Ts*

- The **system noise temperature** (*Ts*) is the sum of the antenna noise (T_{ant}) and the composite noise temperature of other components (T_{comp})

$$Ts = T_{ant} + T_{comp}$$

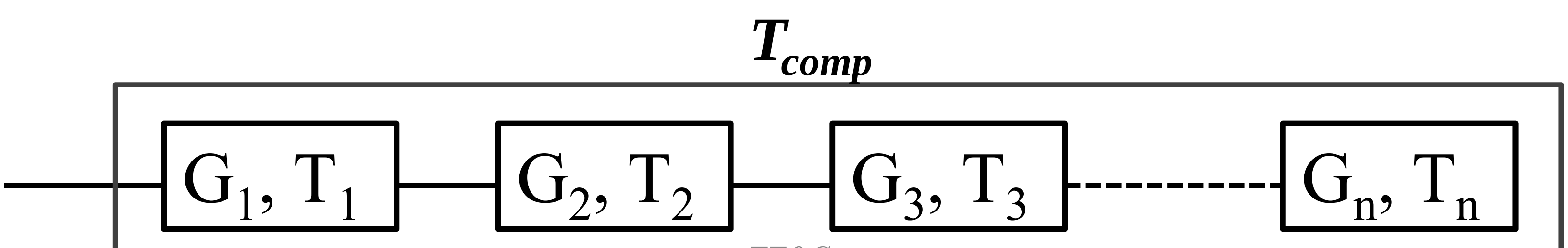


System Noise Temperature *Ts*

- The Antenna noise temperature includes all external source of noise and the thermal internal noise of the antenna
  - Satellite: $T_{ant} \approx 290\ K$
  - Ground Station: $T_{ant} = T_{Sky} + T_{Earth} + T_{Rain}$

- The composite noise temperature

$$T_{comp} = T_1 + \frac{T_2}{G_1} + \frac{T_2}{G_1 G_2} + \cdots + \frac{T_n}{G_1 G_2 \cdots G_{n-1}}$$



Carrier-to-Noise ratio (C/N)

- The carrier-to-noise ratio (CNR or C/N) is defined as the ratio of the received modulated carrier signal power ***C*** to the received noise power ***N*** .
- ***C*/*N***(dB)=10log(***C*/*N***)=***C***(dBW or dBm)-***N***(dBW or dBm)
- **C/N** is used to define the sensitivity of a (analog) system

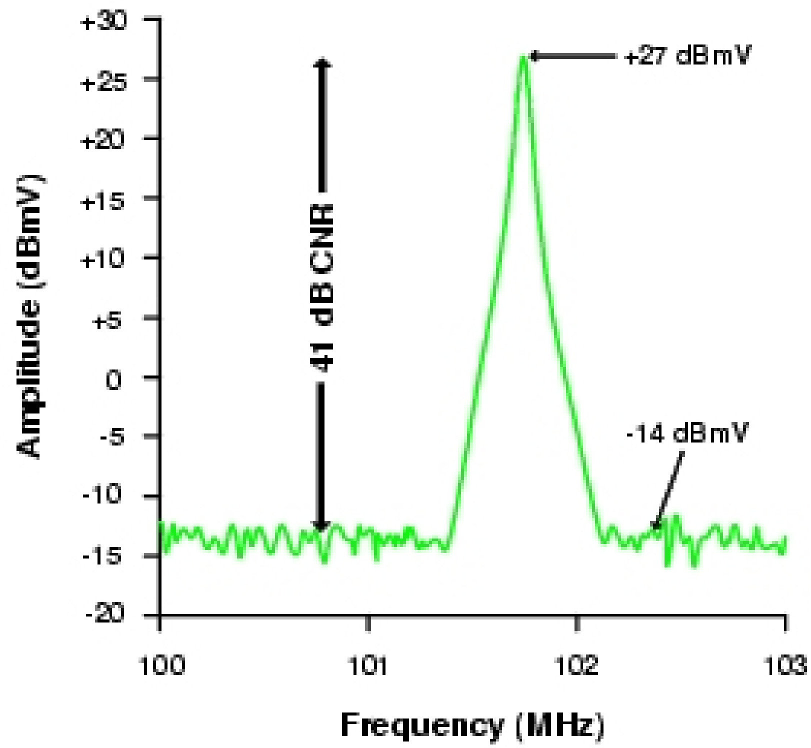


Figure of merit(C/T)

- The ratio C_r/T_s (or simply C/T) is known as the **Figure of Merit**, which indicates the quality of a receiving satellite system and has a unit of dB/K

$$\frac{C}{N} = \frac{P_r}{P_n} = \frac{\frac{P_t G_t G_r}{(4\pi R/\lambda)^2}}{K T_s B} = \frac{G_r}{T_s} \boxed{\frac{P_t G_t}{KB}\left(\frac{\lambda}{4\pi R}\right)^2}$$

$$\frac{C}{N} \propto \frac{G_r}{T_s}$$

Energy-per-bit to Noise dendity (E_b/N_0)

$$E_b = \frac{C}{R} \qquad N_0 = \frac{N}{B} = KT_s$$

$$\frac{E_b}{N_0} = \frac{P_t G_t L_{FS} L_o G_r}{KT_s R}$$

R: data rate
L_o: other loss

$$\frac{\boldsymbol{E_b}}{\boldsymbol{N_0}}(dB) = P_t(dB)+G_t(dB)-L_{FS}(dB)-L_o(dB)+G_r(dB)$$
$$-[10\log(1.38\text{x}10^{-23})+10\log T_s+10\log R]$$

$$\boxed{\textbf{Link Margin} = \left(\frac{E_b}{N_0}\right)_{Received} - \left(\frac{E_b}{N_0}\right)_{Required}}$$

Link Design Procedure

1. Determine the frequency band in which the system will operate.
2. Determine the communication parameters of the satellite.
3. Calculate the signal-to-noise ratio and the bit error rate for the baseband channel.
4. Determine the parameters of the transmitting and receiving Earth station.
5. The design starts with the transmitting Earth station. Determine the carrier-to-noise ratio for the uplink using uplink budget and the transponder noise power budget.
6. Determine the output power of the transponder based on the value of the transponder gain.

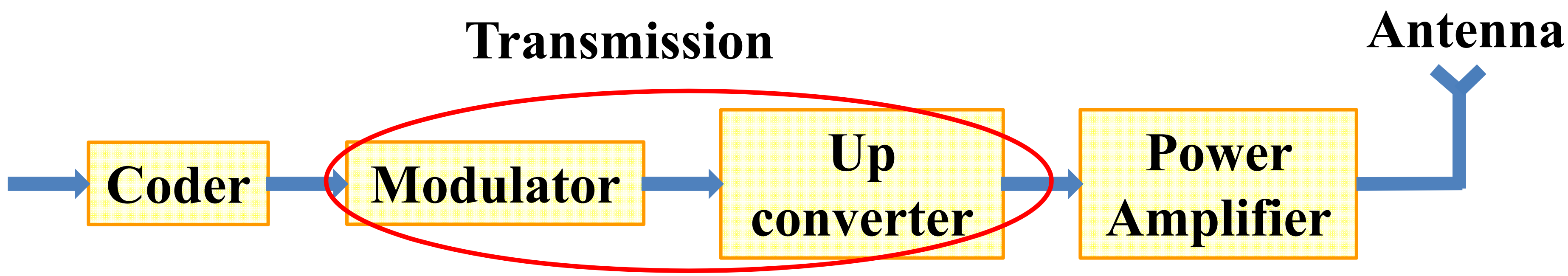
Link Design Procedure

7. Determine the carrier-to-noise ratio for the downlink and establish the noise budget for the receiving Earth station at the edge of the coverage zone.
8. Determine the propagation conditions under which the system operates and calculate the value of atmospheric attenuation and other losses caused due to the atmospheric conditions.
9. Determine the link margin by calculating the link budget. Compare the result with the desired specifications. Change the system parameters to obtain the desired value of the link margin.

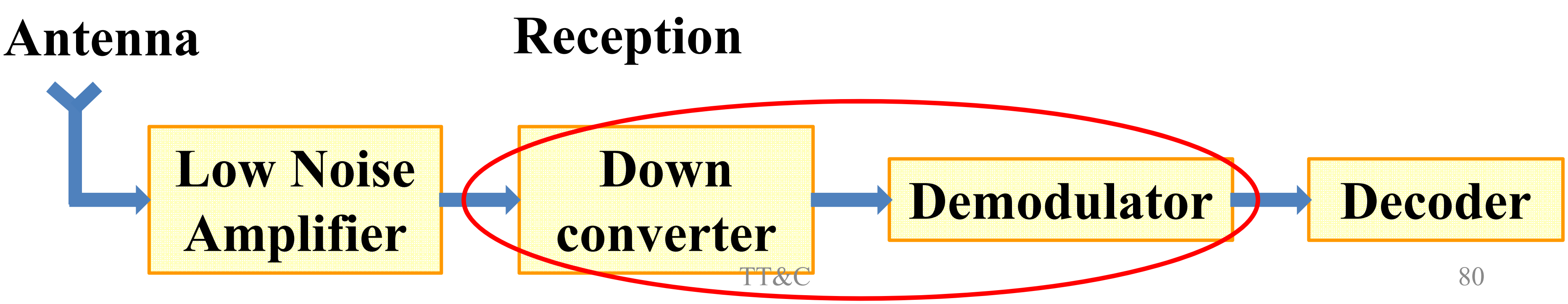
www.amsatuk.me.uk/iaru/AMSAT-IARU_Link_Model_Rev2.5.3.xls

Modulation

- **Modulation** is the process of conveying a message signal inside another signal that can be physically transmitted.

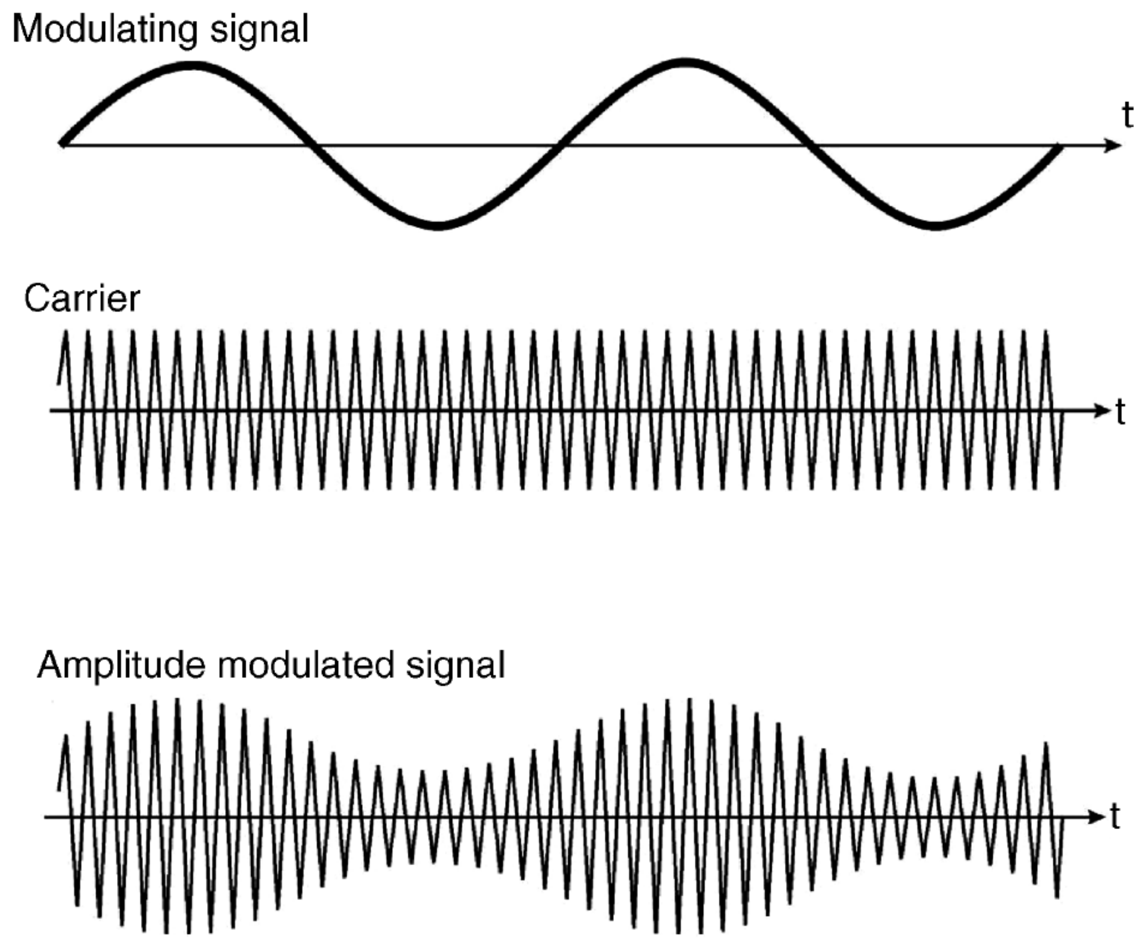


- **Demodulation** is the act of extracting the original information-bearing signal from a modulated carrier wave.



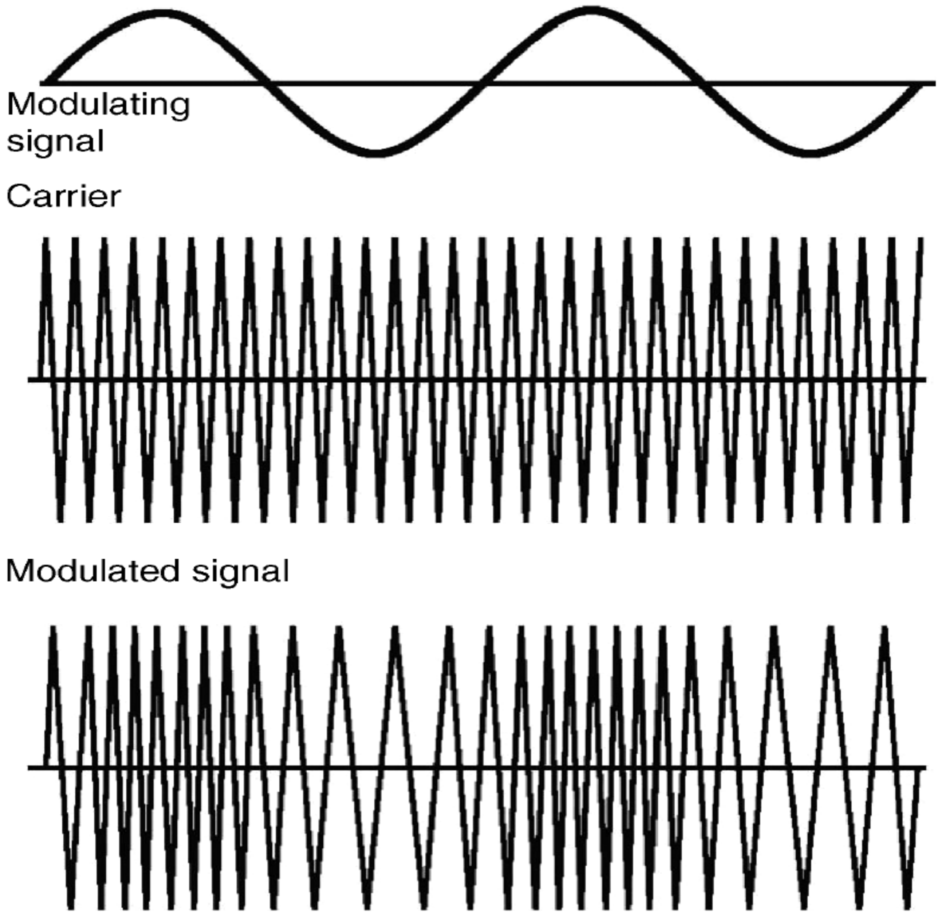
Analog Modulation - AM

- In **amplitude modulation (AM),** the amplitude of the carrier signal is varied in accordance to the instantaneous amplitude of the modulating signal.



Analog Modulation - FM

- In **frequency modulation (FM),** the frequency of the carrier signal is varied in accordance to the instantaneous amplitude of the modulating signal.

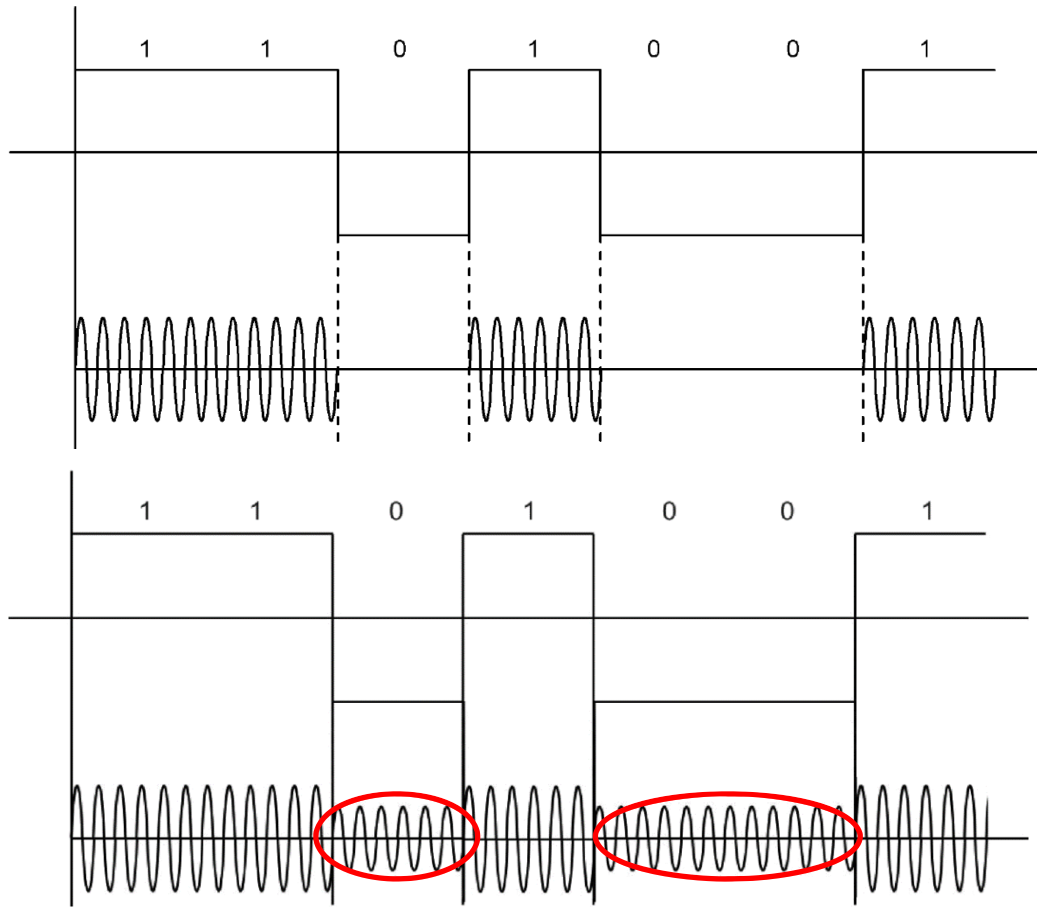


Digital Modulation - ASK

- In the simplest form of **amplitude shift keying (ASK),** the carrier signal is switched ON and OFF depending on whether a '1' or '0' is to be transmitted.

$$x(t) = A \sin \omega_c t \qquad \text{for bit '1'}$$

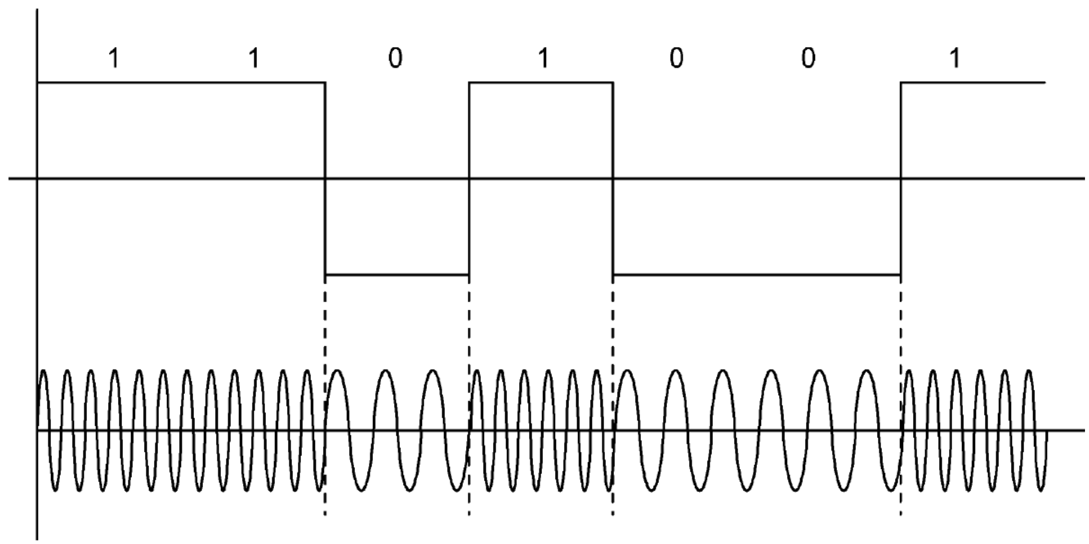
$$= 0 \qquad \text{for bit '0'}$$



Digital Modulation - FSK

- In **frequency shift keying (FSK),** it is the frequency of the carrier signal that is switched between two values, one representing bit '1' and the other representing bit '0'.

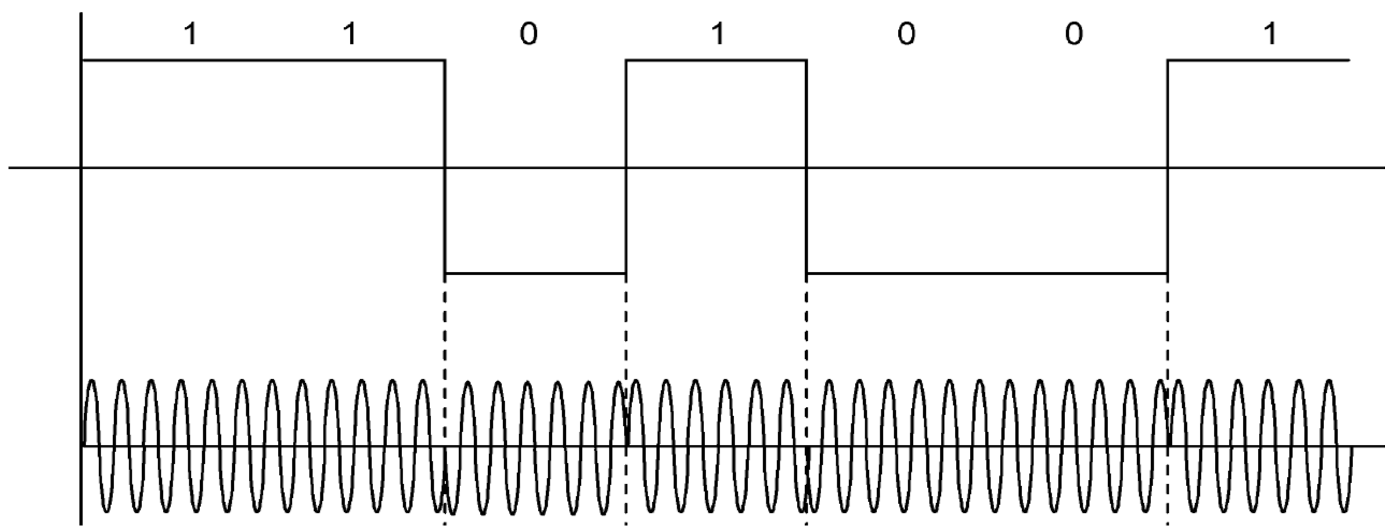
$$x(t) = A \sin \omega_{c1} t \qquad \text{for bit '1'}$$
$$= A \sin \omega_{c2} t \qquad \text{for bit '0'}$$



Digital Modulation - PSK

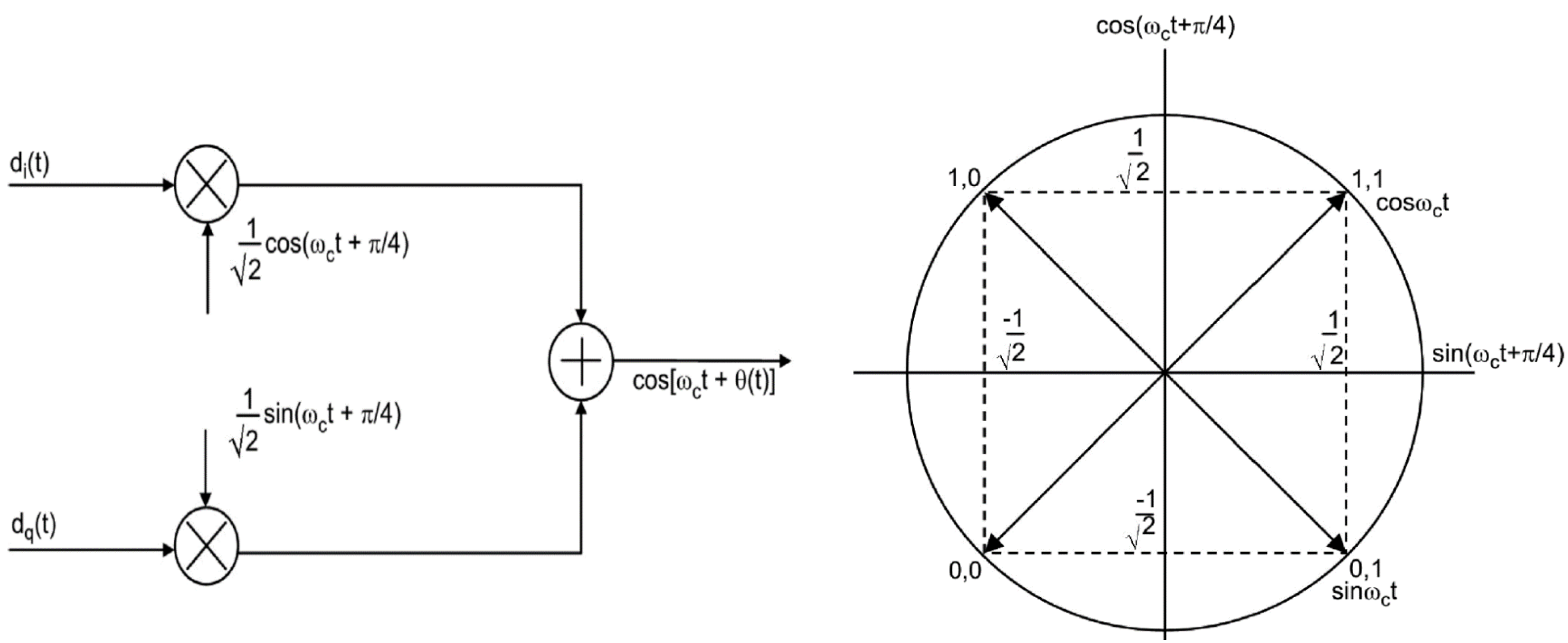
- **Phase shift keying (PSK)** conveys data by changing, or modulating, the phase of the carrier wave.
  - **BPSK** is the simplest form of phase shift keying (PSK). It uses two phases which are separated by 180°.

$$x_{c0}(t) = A\cos(\omega_c t + \theta_0) \quad \text{and} \quad x_{c1}(t) = -A\cos(\omega_c t + \theta_0)$$



Digital Modulation - QPSK

- **Quadrature Phase shift keying (QPSK)** uses four points on the constellation diagram.

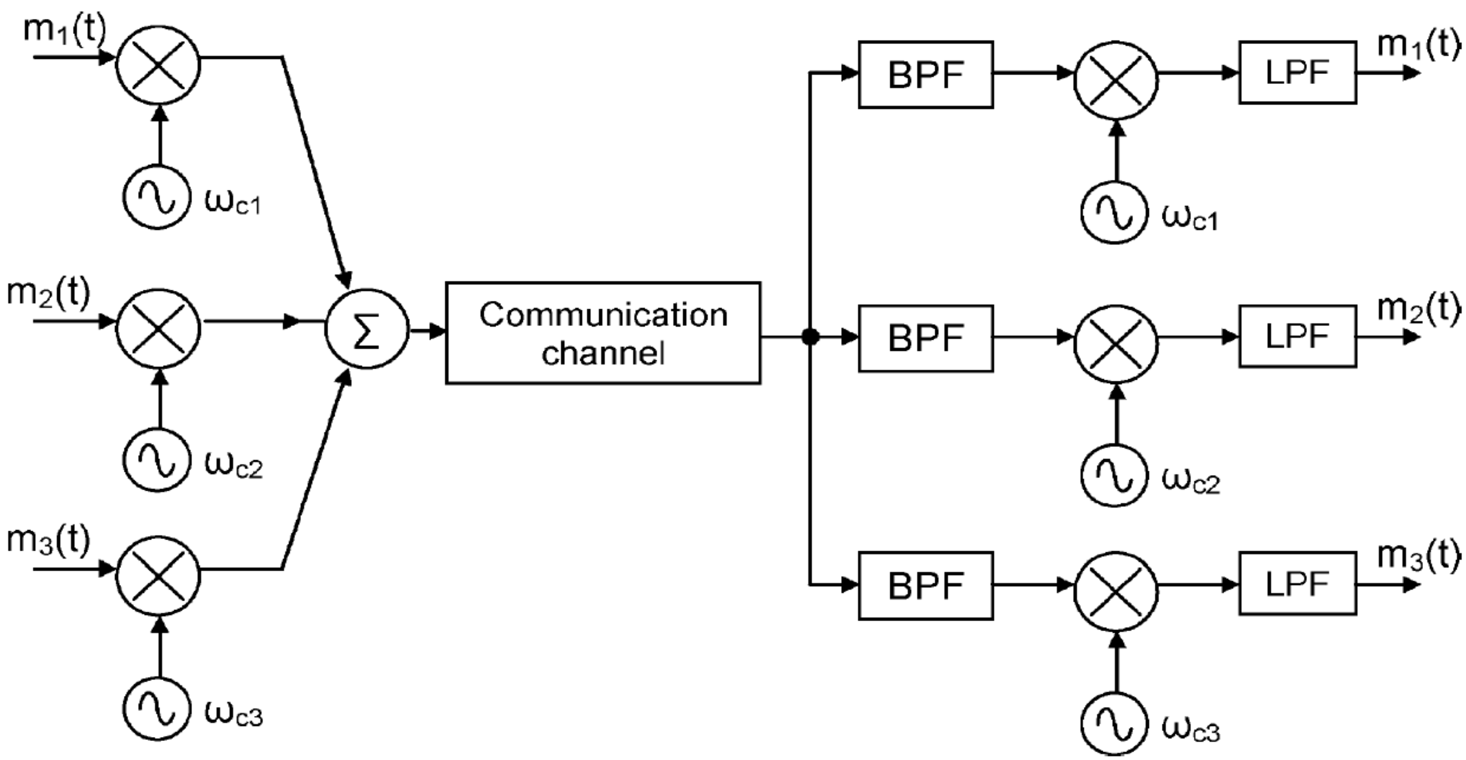


Multiplexing

- **Multiplexing** techniques are used to combine several message signals into a single composite signal so that they can be transmitted over a common channel.
- Multiplexing ensures that the different message signals in the composite signal do not interfere with each other.
- There are two basic multiplexing techniques:
  - Frequency division multiplexing (FDM)
  - Time division multiplexing (TDM)

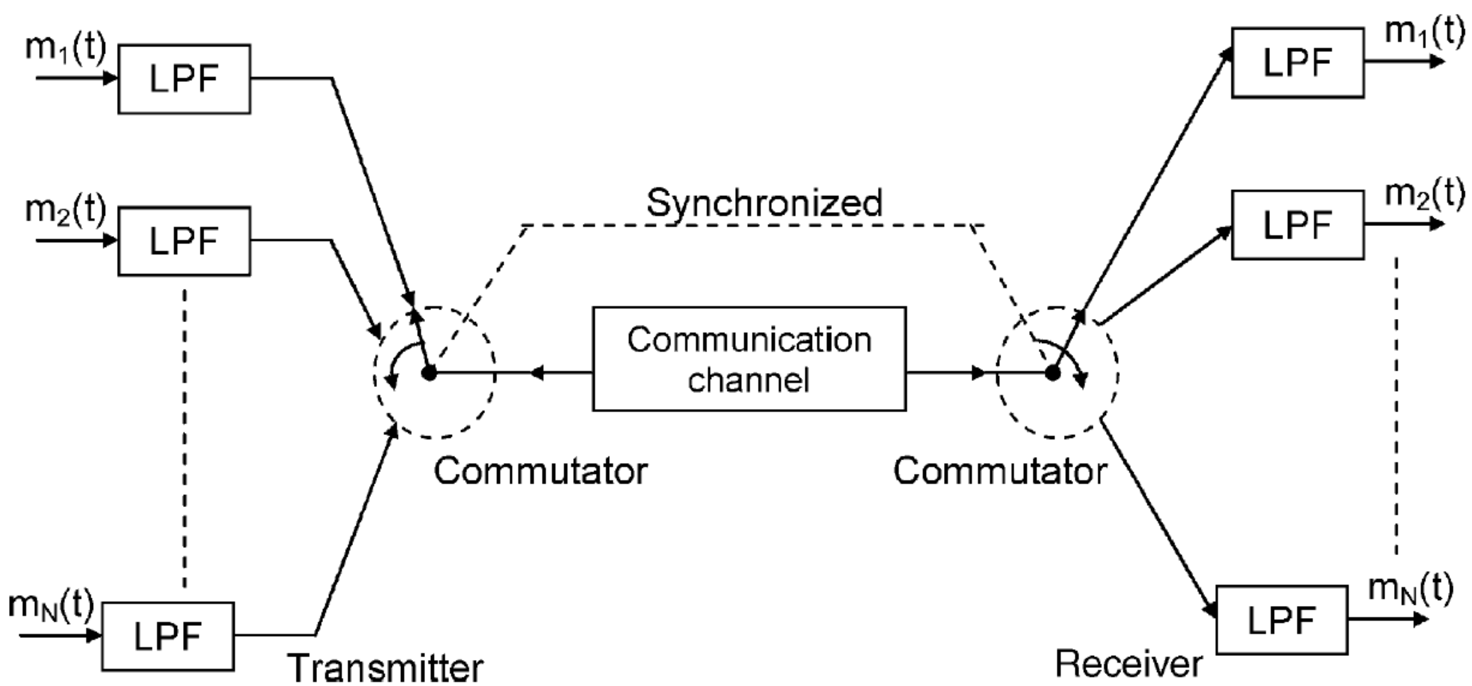
FDM

- In **frequency division multiplexing (FDM)**, different message signals are separated from each other in the frequency domain.



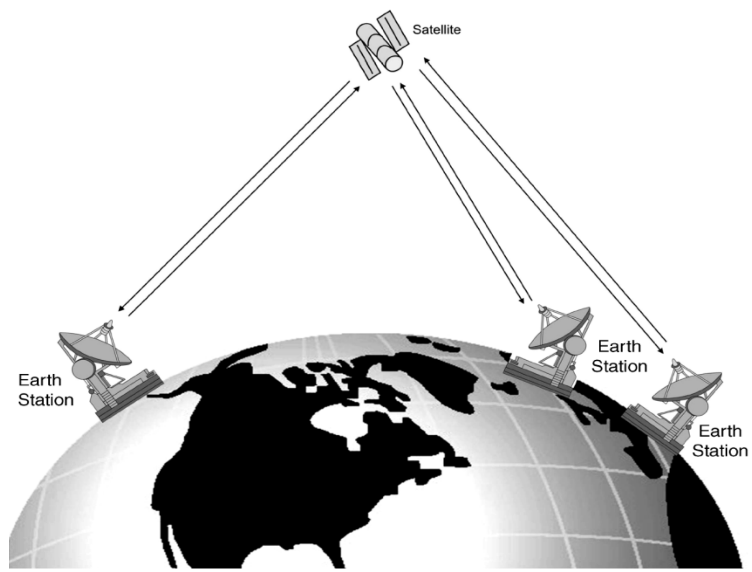
TDM

- **Time division multiplexing (TDM)** is used for simultaneous transmission of more than one pulsed signal over a common communication channel.



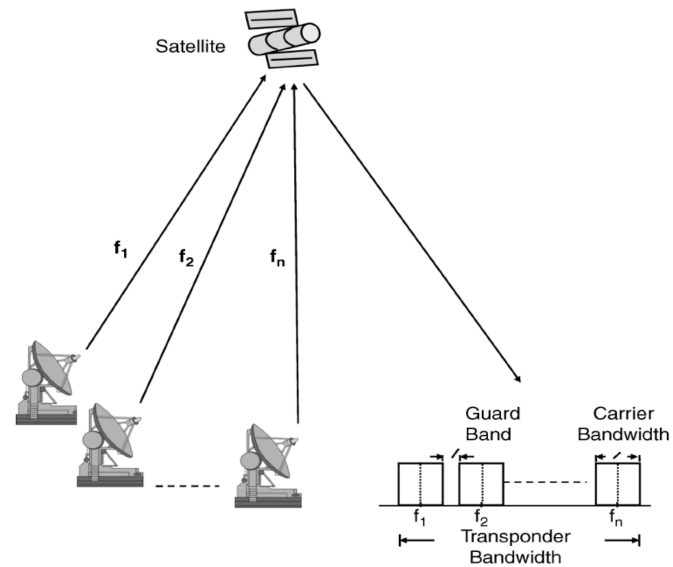
Multiplexing access

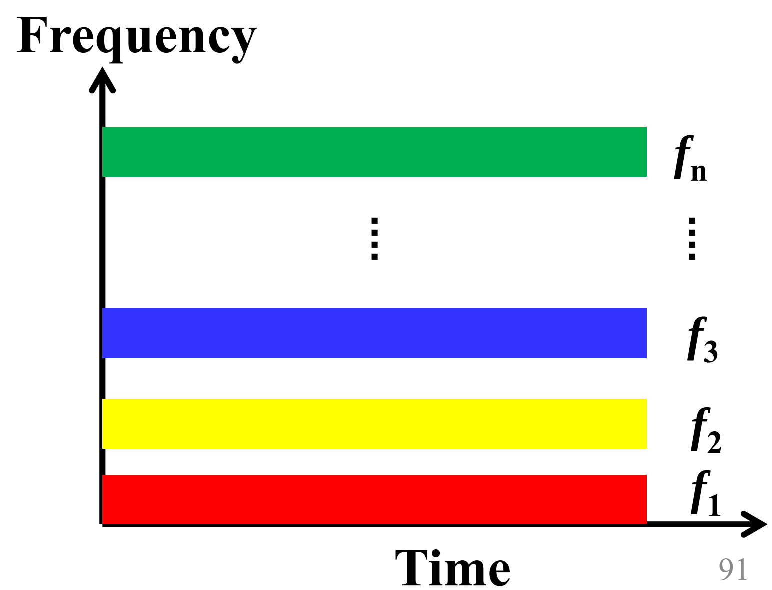
- **Multiplexing access** refers to the fact that many earth stations share the same satellite.
- Uplink multiple access allows many different ground stations to transmit up to the satellite at the same time.
- Downlink multiple access allows a ground station receiver of the satellite to separate any or all the downlink carriers.



Multiplexing access technique- TDMA

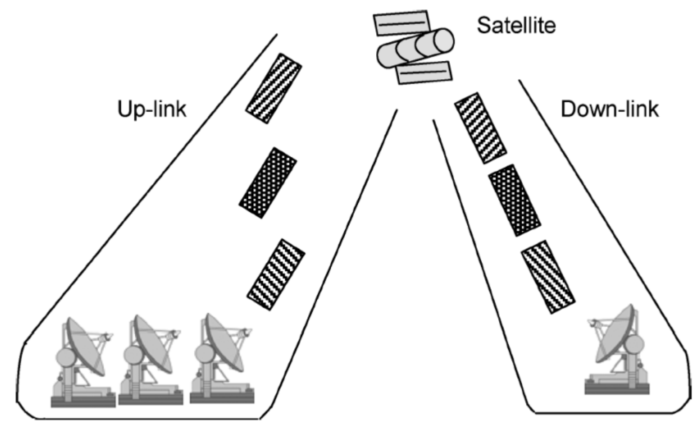
- In **frequency division multiple access (FDMA)**, different Earth stations are able to access the total available bandwidth in the satellite transponder by virtue of their different carrier frequencies.
  - o Simplicity of Earth station equipment
  - o Intermodulation problems

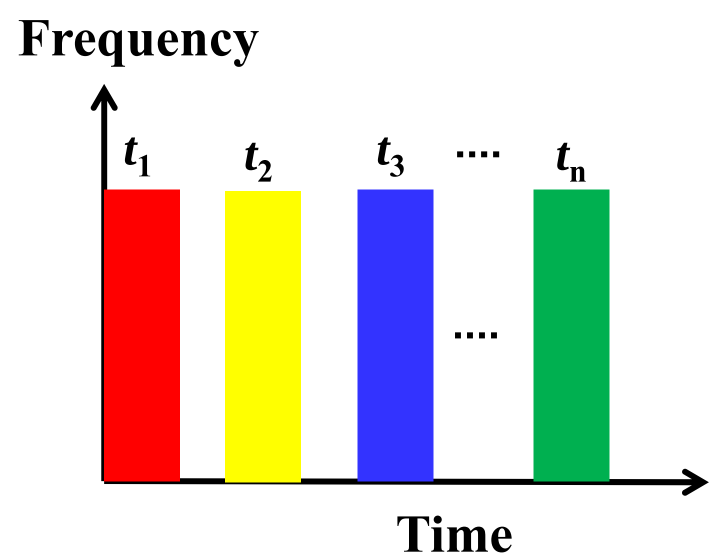




Multiplexing access technique- TDMA

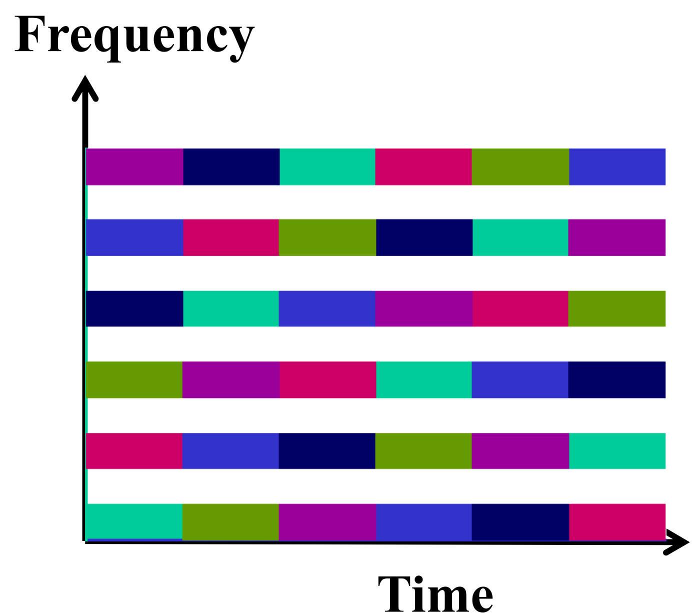
- In **time division multiple access (TDMA)**, different Earth stations make use of the transponder by using a single carrier on a time division basis.
  - o Minimal intermodulation noises
  - o Complex and expensive Earth station equipment
  - o Stringent timing and synchronization requirements
  - o Digital transmission only





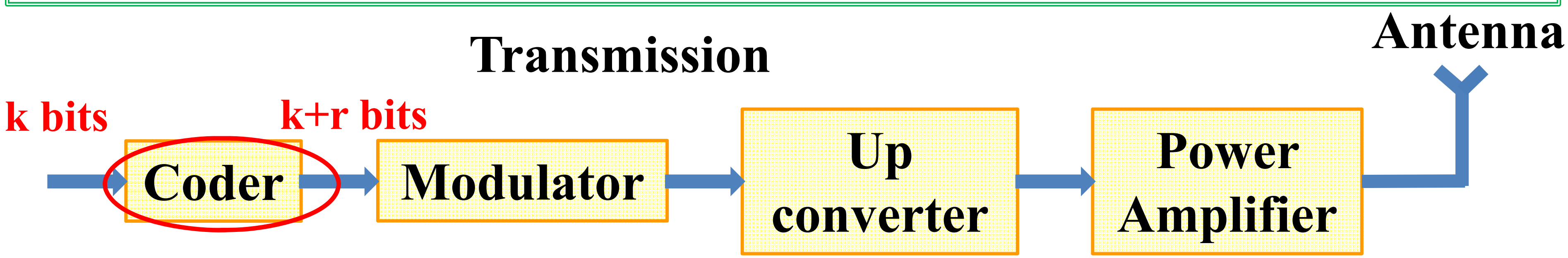
Multiplexing access technique- CDMA

- In **code division multiple access (CDMA)**, all Earth stations transmit simultaneously at all times, so their carrier waveforms overlap on top of each other in time and frequency.
  - The transmitting signals are multiplied by a unique code sequence.
  - Receiving stations recover the desire information by using a matched decoder.

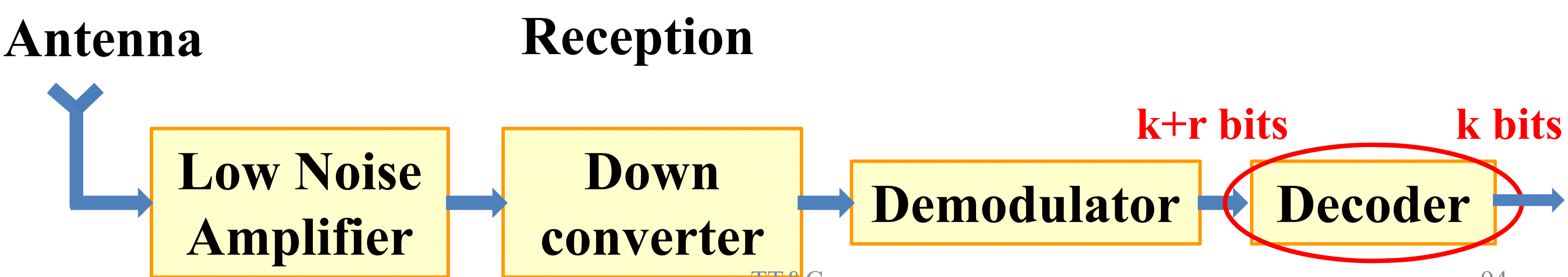


Coding and Decoding

- **Encoding** is the technique of protecting message signals from signal impairment by adding redundancy to the message signal.

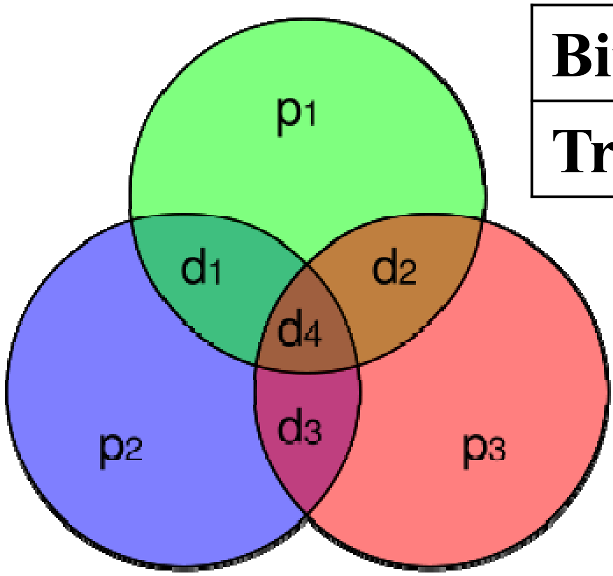


- **Decoding** is the reverse process, converting these codes back into information understandable by a receiver.



Hamming Code (7,4)

- The **Hamming code** adds three additional check bits to every four data bits of the message.
  - o Hamming's (7,4) algorithm can correct any single-bit error



Bit	7	6	5	4	3	2	1
Transmitted bit	d_4	d_3	d_2	p_3	d_1	p_2	p_1

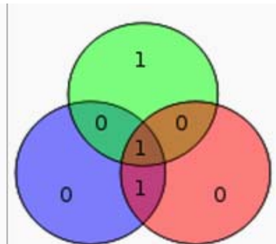
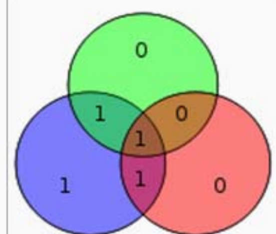
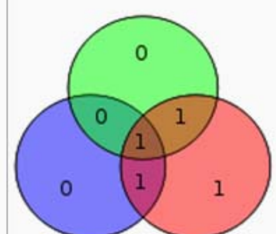
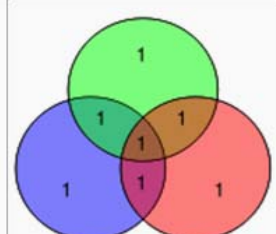
http://www.youtube.com/watch?v=sYO6vm9PTsI

<u>Hamming Code (7,4)</u>

Data (d_1, d_2, d_3, d_4)	Hamming(7,4) Transmitted $(p_1, p_2, d_1, p_3, d_2, d_3, d_4)$	Diagram
0000	0000000	
1000	1110000	
0100	1001100	
1100	0111100	

Data (d_1, d_2, d_3, d_4)	Hamming(7,4) Transmitted $(p_1, p_2, d_1, p_3, d_2, d_3, d_4)$	Diagram
0010	0101010	
1010	1011010	
0110	1100110	
1110	0010110	

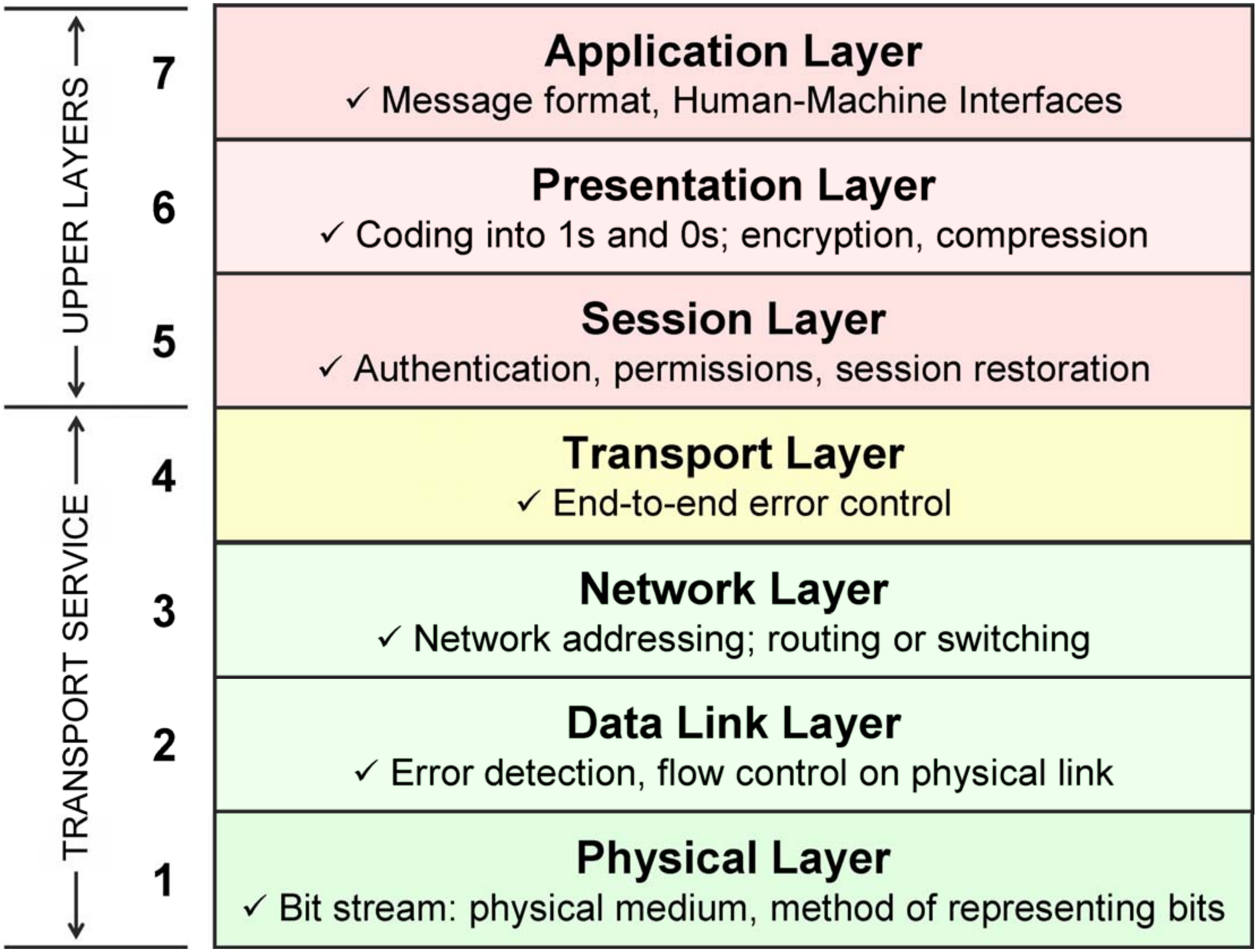
Hamming Code (7,4)

Data	Hamming(7,4)		Data	Hamming(7,4)	
(d_1, d_2, d_3, d_4)	Transmitted $(p_1, p_2, d_1, p_3, d_2, d_3, d_4)$	Diagram	(d_1, d_2, d_3, d_4)	Transmitted $(p_1, p_2, d_1, p_3, d_2, d_3, d_4)$	Diagram
0001	1101001		0011	1000011	
1001	0011001		1011	0110011	
0101	0100101		0111	0001111	
1101	1010101		1111	1111111	

Communication protocol

- A **communications protocol** is a system of digital message formats and rules for exchanging those messages in or between computing systems and in telecommunications.
- Communicating systems use well-defined formats for exchanging messages.
- The **Open System Interconnection (OSI)** model is a prescription of characterizing and standardizing the functions of a communications system in terms of abstraction layers.

Communication protocol



AX.25 protocol

- The **AX.25 protocol** is a common packet radio protocol commonly used for amateur radio bands.
- AX. 25 is a data link layer protocol.
- Frames are small blocks of data to send link layer packet radio transmissions; Each frame is made up of several smaller groups, which are called fields.
- There are three general types of AX. 25 frames:
  - Information frame (I frame)
  - Supervisory frame (S frame)
  - Unnumbered frame (U frame)

http://www.youtube.com/watch?v=c-0bOGek9SY

AX.25 protocol

Type of frame	**Main purpose**
Information frame (I frame)	For the transfer of information within normal flow control
Supervisory frame (S frame)	For supervisory link control such as acknowledging or requesting retransmission of Information frames, as well as link layer window control (i.e. flow control)
Unnumbered frame (U frame)	For maintaining additional control over the link beyond what is accomplished with Supervisory frames, including: • Establishing and terminating link connections • Transmission and reception of information outside of normal flow control

AX.25 protocol

- U and S frame construction

Flag	Address	Control	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	N*8 Bits	16 Bits	01111110

- I frame construction

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	8 Bits	N*8 Bits	16 Bits	01111110

AX.25 protocol

- A **flag field** consists of a zero followed by six ones followed by another zero, 01111110. It occurs at both the beginning and end of each frame. This sequence is not allowed to occur anywhere else inside a complete frame.
- The **address field** identifies both the source of the frame and its destination. In addition, the address field contains the command/response information and facilities for level 2 repeater operation.
- The **control field** is used to identify the type of frame being passed and control several attributes of the level 2 connection.

AX.25 protocol

- The **Protocol Identifier (PID)** field shall appear in information frames (I and UI) only. It identifies what kind of layer 3 protocol, if any, is in use.
- The **information field** is used to convey user data from one end of the link to the other.
- The **frame-check sequence (FCS)** is a sixteen-bit number calculated by both the sender and receiver of a frame. It is used to insure that the frame was not corrupted by the medium used to get the frame from the sender to the receiver. It shall be calculated in accordance with ISO 3309 (HDLC) Recommendations.

Conclusion

- ✓ **Objective**
- ✓ **Communication system**
- ✓ **Electromagnetic (EM) wave**
- ✓ **Link budget**
- ✓ **Modulation**
- ✓ **Coding and encoding**
- ✓ **Communication protocol**

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