Communication systems
Dr. Yazid Khattabi
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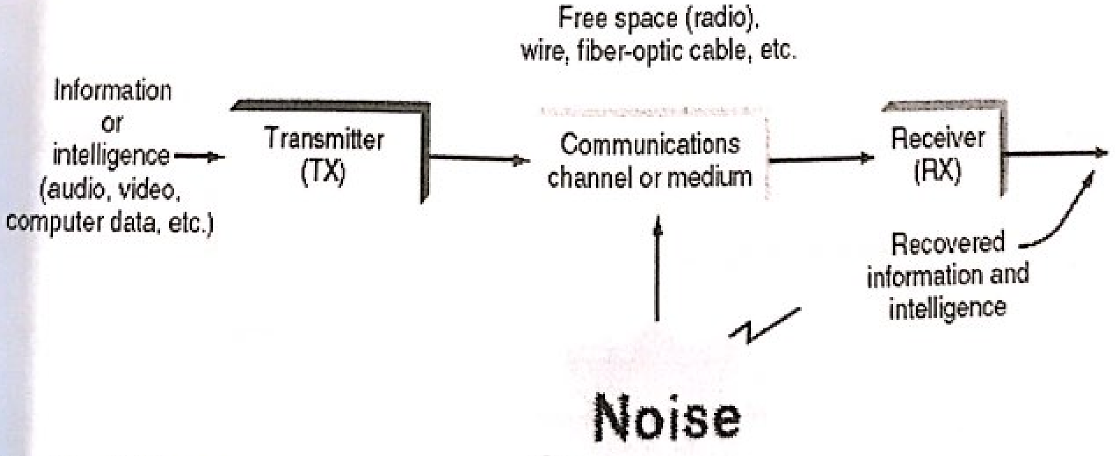
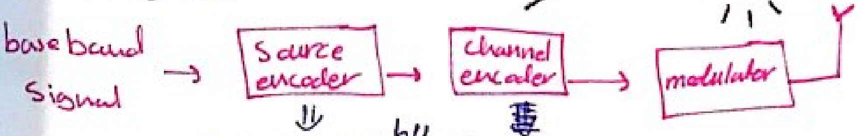
Part 1
Radio Wave Propagation

Instructor: Dr. Yazid Khattabi
Electrical Engineering Department
The University of Jordan
Communication Systems-EE425

General Model of All Communication Systems


Free space (radio), wire, fiber-optic cable, etc.
Information or intelligence (audio, video, computer data, etc.)
Transmitter (TX)
Communications channel or medium
Receiver (RX)
Recovered information and intelligence
Noise

Comm. systems-



Compresses data by eliminating frequent information to make smaller bandwidth

Types of noise :-

$\boxed{1}$ Additive noise

$$\underset{\underline{\underline{Tx}}}{x(t)} \longrightarrow \underset{\underline{\underline{Rx}}}{x(t)+n(t)}$$

$\boxed{2}$ Mutiplicative noise (Fading)

$$y(t) = \underline{\underline{h}}\, x(t) + n(t)$$

$$\underset{\underline{\underline{Tx}}}{10 \text{ watt}} \xrightarrow{*\frac{1}{2}} \underset{\underline{\underline{Rx}}}{5 \text{ watt}}$$

Other Types of Channels

- **Water in Sonar** (**SO**und **N**avigation **A**nd **R**anging) which is a technique that uses sound propagation (usually underwater, as in submarine navigation) to navigate, communicate with or detect objects on or under the surface of the water.
- **The earth** itself can be used as a communication medium, because it conducts electricity and can also carry low-frequency sound waves.
- **Alternating-current (ac) power lines**, the electrical conductors that carry the power to operate virtually all our electrical and electronic devices, can also be used as communication channels.

Types of Communication Systems

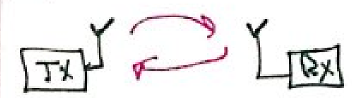
1. Simplex (one way): TV broadcasting.
2. Half duplex (one way at a time): Radio transmission in military, fire, police, aircraft, marine.
3. Full duplex (simultaneous, two-way): Telephone system.

simplex (one direction)

⇒

AM, FM, TV stations

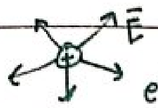
duplex

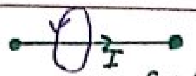


⇒

[1] one way at a time (half duplex)
[e.g] walkie talkie

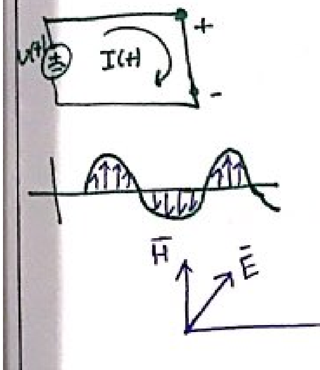
[2] two way (full duplex)
[e.g] telephony systems

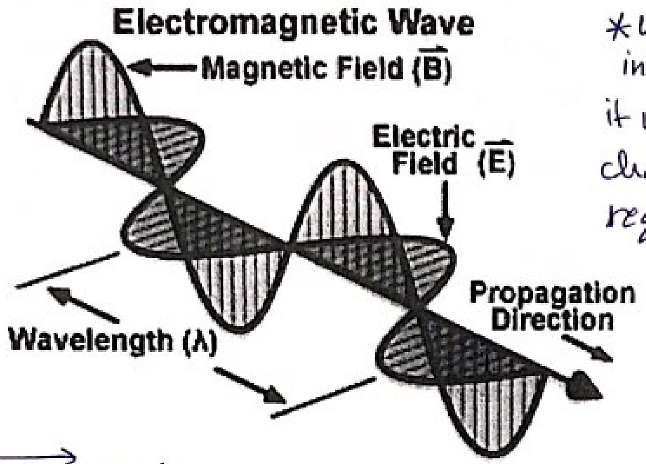




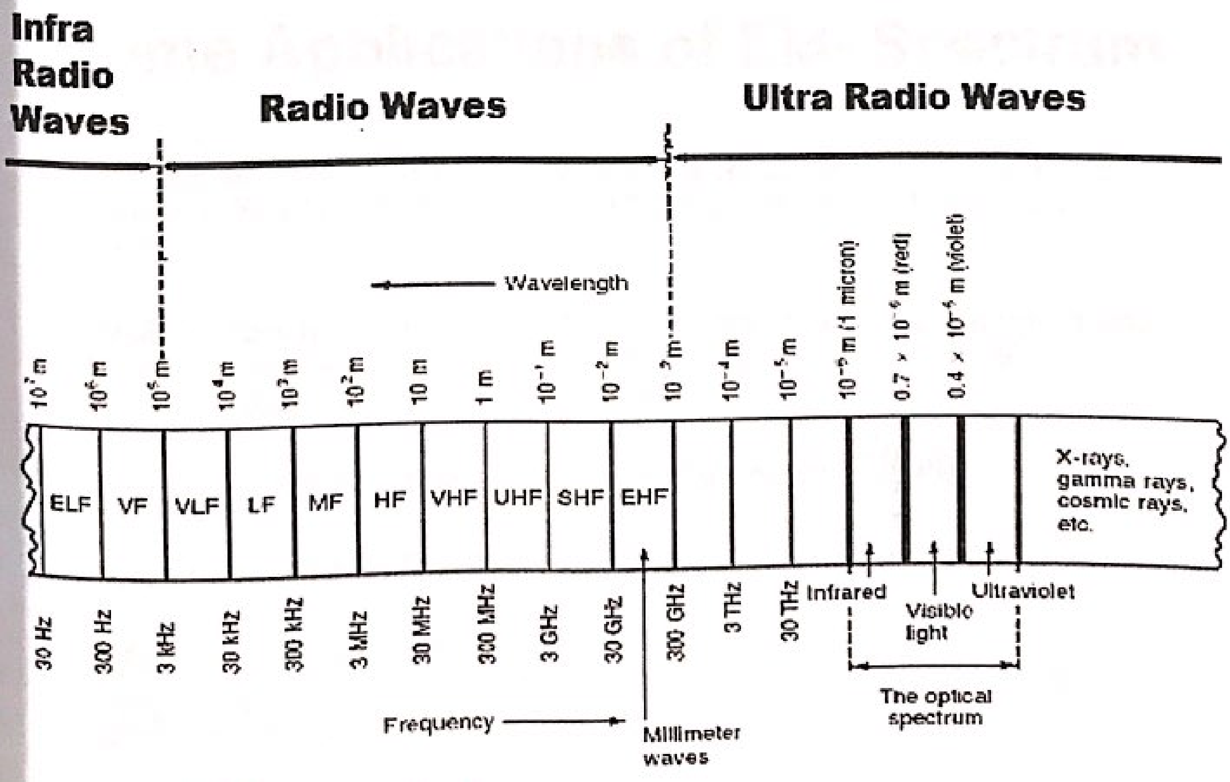
The Electromagnetic Spectrum

- Electromagnetic signals, or radio-frequency (RF) waves, or just radio waves consist of both electric and magnetic fields.
- Signals carried by cable may share the same frequencies of similar signals in the spectrum, but they are not radio signals.





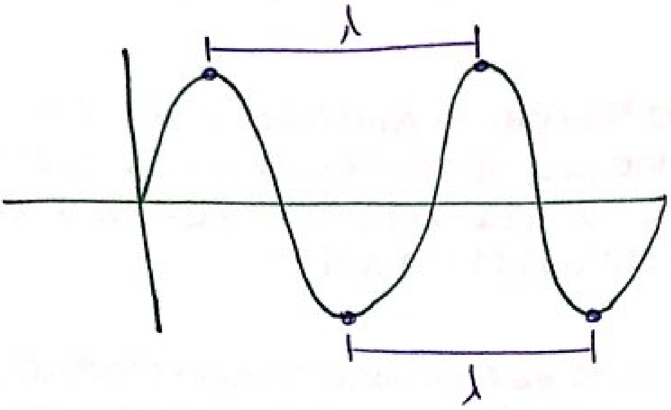
*we can't send information using DC, it must be AC so that change in information requires that change in the electromagnetic wave.



as $f \uparrow \Rightarrow \lambda \downarrow$

Slide 5 :-

$\lambda\ [m] \Rrightarrow$ from peak to peak (min to min OR max to max)



Name	Frequency	Wavelength
Extremely low frequencies (ELFs)	30–300 Hz	10^7–10^6 m
Voice frequencies (VFs)	300–3000 Hz	10^6–10^5 m
Very low frequencies (VLFs)	3–30 kHz	10^5–10^4 m
Low frequencies (LFs)	30–300 kHz	10^4–10^3 m
Medium frequencies (MFs)	300 kHz–3 MHz	10^3–10^2 m
High frequencies (HFs)	3–30 MHz	10^2–10^1 m
Very high frequencies (VHFs)	30–300 MHz	10^1–1 m
Ultra high frequencies (UHFs)	300 MHz–3 GHz	1–10^{-1} m
Super high frequencies (SHFs)	3–30 GHz	10^{-1}–10^{-2} m
Extremely high frequencies (EHFs)	30–300 GHz	10^{-2}–10^{-3} m
Infrared	—	0.7–10 μm
The visible spectrum (light)	—	0.4–0.8 μm

Some Applications of EM- Spectrum

- **Extremely Low Frequencies:** include ac power line frequencies (50 and 60 Hz are common) and the low end of the human audio range.

- **Voice Frequencies(300-3000 Hz):** human speech. Although human hearing extends from approximately 20 to 20,000 Hz, most intelligible sound occurs in the VF range.

- **Very Low Frequencies(3-30K):** military communications.

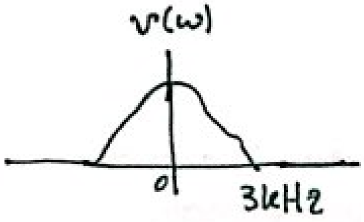
- **Low Frequencies(30-300K):** aeronautical and marine navigation.

- **Medium Frequencies(300K-3M):** AM broadcasting.
- **High Frequencies (3-30M):** Aviation communication, weather stations, public safety (such as police and fire).

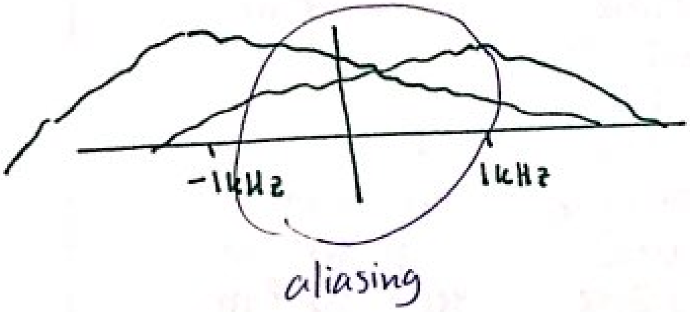
- **Very High Frequencies (30-300M) :** FM radio broadcasting (88 to 108 MHz), and VHF TV.
- **Ultrahigh Frequencies (300M-3G):** UHF TV, cellular telephones, radar.
- **Super High Frequencies(3-30G):** *microwaves, satellite* communication, radar, Wireless local-area networks (WLANs) and many cellular telephone systems.
- **Extremely High Frequencies(30-300G): called** *millimeter waves.* Complex and expensive equipments used for these waves. There is growing use of this range for satellite communication telephony, cellular networks, and some specialized radar.
- **Infrared:** TV remote-control.
- **The Visible Spectrum:** laser communications.
- **Ultraviolet light (UV):** generated by the sun, fluorescent lamps. not used for communication; its primary use is medical.

- Note:

- EM waves with frequencies less than 9KHz are not employed due to the following reasons:
  - ➢ Limited bandwidth resulting in low traffic capacity.
  - ➢ Very large antennas because of long wavelengths.
- Also, frequency bands higher than 100GHz are not usually employed for the time being due to the following reasons:
  - ➢ High free space loss.
  - ➢ High atmospheric attenuation.
  - ➢ Limitations in RF component manufacturing.



$f_c = 1$ kHz (carrier freq)



* To increase B.w we have to increase f_c

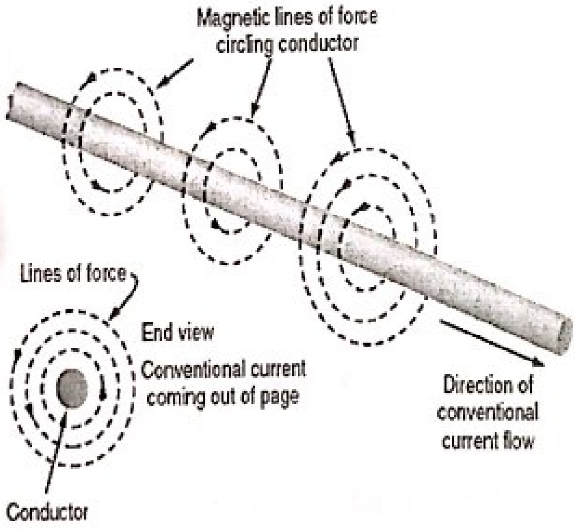
* choosing f_c depends on $\boxed{1}$ B.w   B.w ↑ ⇒ f_c ↑

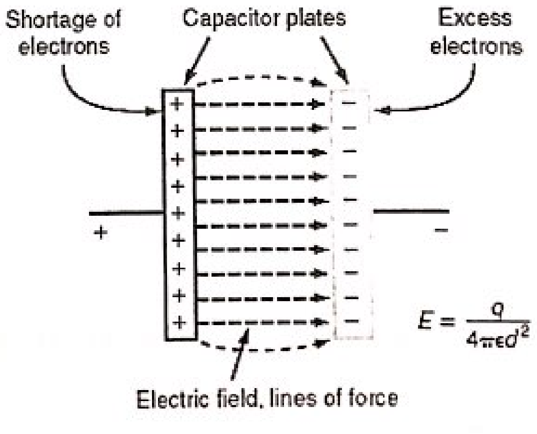
$\boxed{2}$ distance   Distance ↑ ⇒ f_c ↓ (low attenuation
" noise
" power)

f ↑ ⇒ free space loss ↑

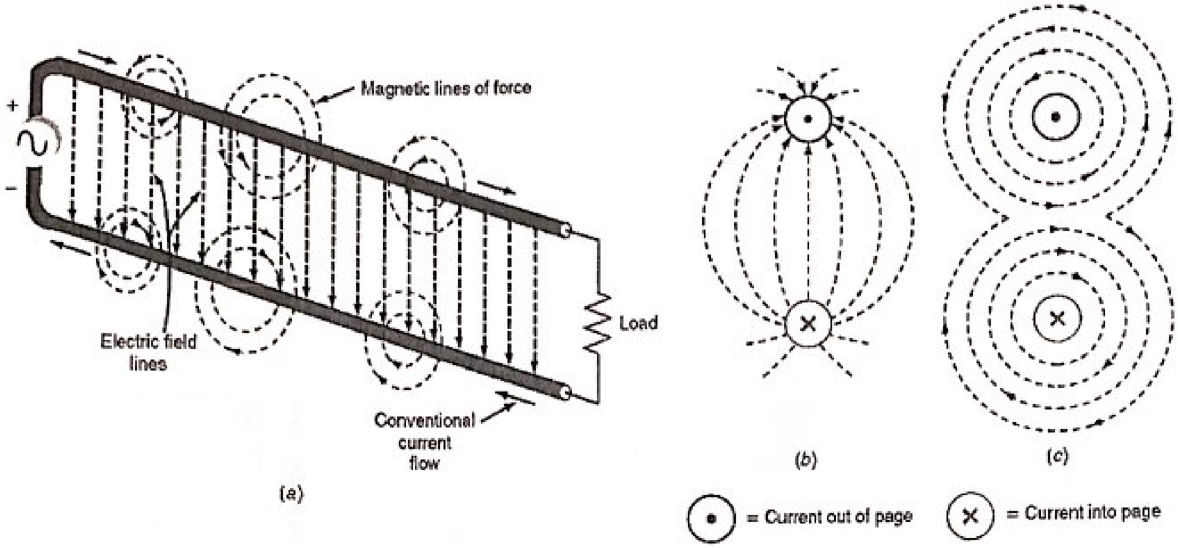
Radio Waves

- A radio signal is called an electromagnetic wave because it is made up of both electric and magnetic fields.
- Whenever voltage is applied to the antenna, an electric field is set up.
- At the same time, this voltage causes current to flow in the antenna, producing a magnetic field.
- The electric and magnetic fields are at right angles to each other.
- These electric and magnetic fields are emitted from the antenna and propagate through space over very long distances at the speed of light.

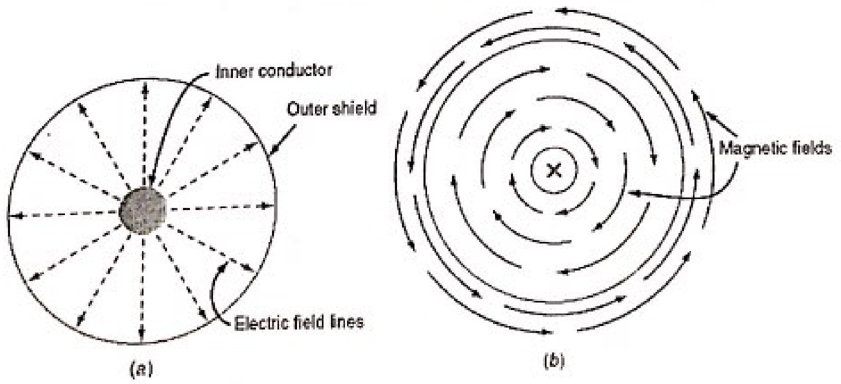




(*a*) Magnetic and electric fields around a transmission line. (*b*) Electric field. (*c*) Magnetic fields.

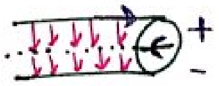


Electric and magnetic fields in a coaxial cable (cross-sectional end view). (*a*) Electric field. (*b*) Magnetic fields.



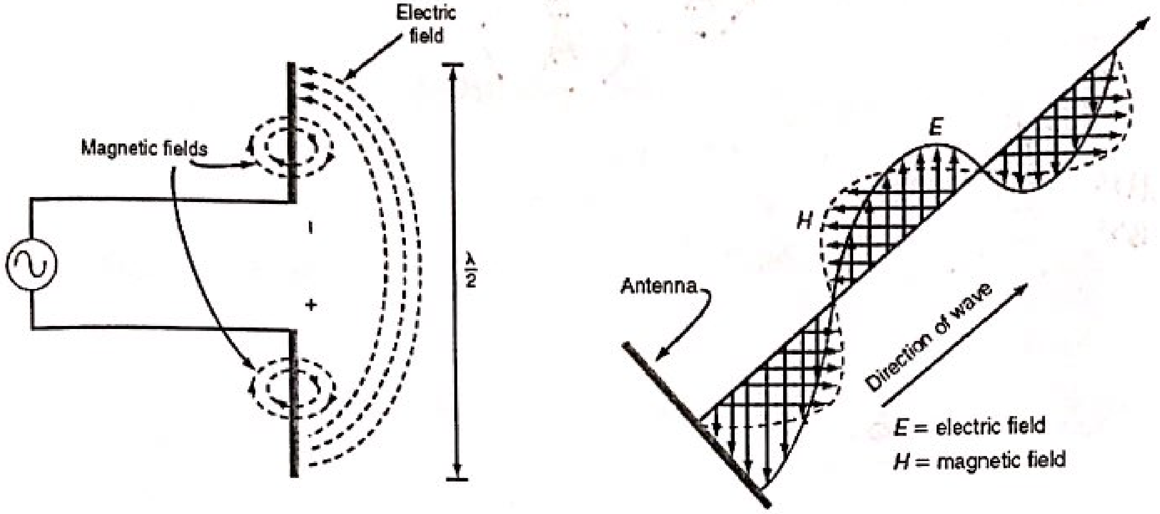
Why coaxial cable is the preferred transmission line for most applications?

- The electric field lines are fully contained by the outer shield of the cable, so none are radiated.
- The inner and outer magnetic fields cancel one another.
- So a coaxial cable does not radiate any electromagnetic energy.



the two currents will cancel each other so information will flow in the coaxial cable.

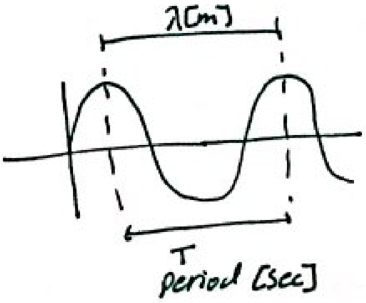
Antenna Operation



Polarization $\Rightarrow$ direction of $\bar{E}$ according to earth surface

1. **Vertical Polarization.**
2. **Horizontal Polarization.**
3. **Circular Polarization.**

$$\lambda = \frac{c}{f}$$



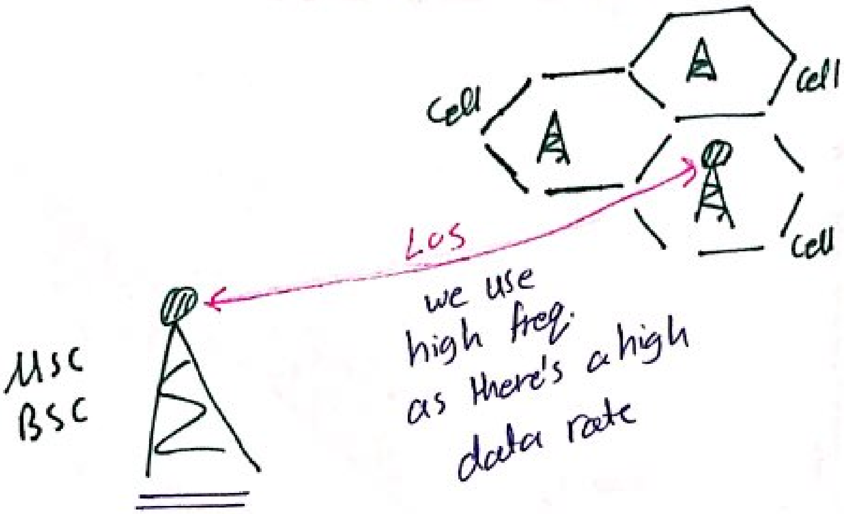
$$f = \frac{1}{T} \; [Hz]$$

$$v = \frac{\lambda}{T} \Rightarrow \boxed{v = \lambda f}$$

$\Longrightarrow$

RF signal : $v = c = 3 \times 10^8$ m/s

$$\underset{\text{free space}}{\lambda} = \frac{v}{f} = \frac{3 \times 10^8}{f}$$

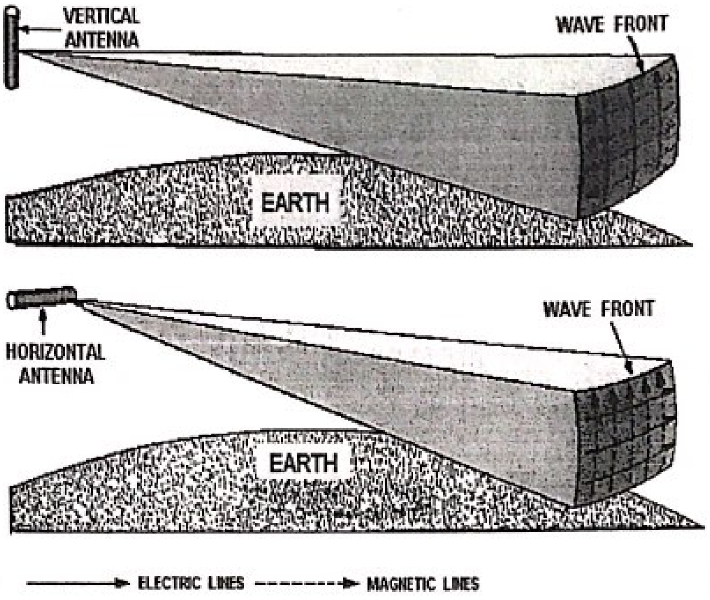


we use high freq. as there's a high data rate

controls Communication between all towers

VERTICAL POLARIZATION

HORIZONTAL POLARIZATION



Media Characteristics

- Permittivity denoted by ϵ in Farad per meter (F/m)
- Permeability denoted by μ in Henry per meter (H/m)
- Conductivity denoted by σ in Siemens per meter (S/m).

In free space, values of the above parameters are:

$$\sigma = 0, \quad \epsilon_0 = 8.85 \times 10^{-12} (\mathrm{F/m}), \mu_0 = 4\pi \times 10^{-7} \ (\mathrm{H/m})$$

عازلة

poor conductivity is equivalent to $\frac{\sigma}{\omega\epsilon} \ll 1$.

$w = 2\pi f$ [rad/s]

$\epsilon = \epsilon_0 \epsilon_r \qquad \mu = \mu_0 \mu_r$

Example. Calculate the conductivity of a piece of land specified by $\sigma = 5\,\text{mS/m}$, $\mu_r = 1$, and $\epsilon_r = 12$ for radiowaves of $f_1 = 10\,\text{KHz}$ and $f_2 = 10\,\text{GHz}$.

Solution: For $f_1 = 10\,\text{KHz}$

$$\frac{\sigma}{\omega \epsilon_r \epsilon_0} = \frac{0.005}{2\pi \times 10^4 \times 8.85 \times 10^{-12} \times 12}$$
$$= 749.3 \gg 1.$$

Thus the land is of good conductivity at f_1, and for $f_2 = 10\,\text{GHz}$. The conductivity index is:

$$\frac{\sigma}{\omega \epsilon_r \epsilon_0} = 7.5 \times 10^{-4} \ll 1.$$

Therefore the land is a good dielectric at f_2. ■

Radio Wave Velocity

$$V = \frac{1}{\sqrt{\epsilon \mu}} = \frac{1}{\sqrt{\epsilon_r \mu_r \times \epsilon_0 \times \mu_0}}. \qquad \lambda = \frac{V}{f}$$

In the above formula each component is defined as follows:

- V is the velocity of radiowave in m/s.
- ϵ and μ are the media permittivity and permeability in F/m and H/m respectively.
- ϵ_0 and μ_0 are the free space permittivity and permeability, respectively.
- ϵ_r and μ_r are the relative permittivity and permeability constants.

In free space, the velocity of radiowave is:

$$V = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 2.9\cancel{98 \times k}\text{m/s} = 2.998 \times 10^8\ \text{m/s}.$$

This value is the same as the light velocity in free space.

Example. Calculate the velocity of a radiowave propagating at 100 MHz in the following media:

1. Sea-water, $\mu_r = 1$ and $\epsilon_r = 81$
2. Air with $\epsilon_r = \mu_r = 1$

Specify λ and V for $f_2 = 1$ GHz

***Solution*:**

1.

$$V_1 = \frac{1}{\sqrt{\mu\epsilon}} = \frac{C}{9} = 3.33 \times 10^7 \text{ m/s}$$

2.

$$V_2 = \frac{1}{\sqrt{\mu_0\epsilon_0}} = C = 3 \times 10^8 \text{ m/s}$$

Example ...

$$f_1 = 100\,\text{MHz} \quad \Rightarrow \quad \lambda_1 = \frac{v_1}{f_1} = 0.333 \text{ m}$$

$$\lambda_2 = \frac{v_2}{f_1} = 3 \text{ m}$$

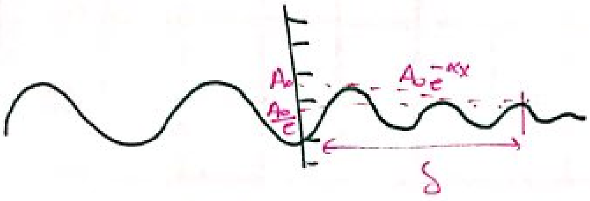
$$f_2 = 1\text{GHz} \quad \Rightarrow \quad \lambda_1' = \frac{v_1}{f_2} = 0.33 \text{ cm}$$

$$\lambda_2' = \frac{v_2}{f_2} = 30 \text{ cm}$$

Depth of Radio Wave Penetration

- The depth of penetration is defined as a distance in the medium (like Earth) at which the wave amplitude of a radio wave incident at surface falls to 1/e (0.368) of its initial value.

$$\delta = 1/\alpha = \frac{1}{\sqrt{\pi f \mu \sigma}} = \sqrt{\frac{2}{\omega \mu \sigma}}$$



$\Rightarrow$

$A_0 e^{-\alpha \delta} = \frac{A_0}{e}$

$e^{-\alpha s} = e^{-1} \Rightarrow \alpha s = 1$

$\delta = \frac{1}{\alpha}$ ~ attinuation factor

$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$

$\boxed{\sigma \uparrow \quad \delta \downarrow}$ (then it's a conductor and the signal won't breakthrough and will be reflected)

$f \uparrow \quad \delta \downarrow$

Media Effects on Radio Waves

- **Radio waves may be affected by the following phenomena:**

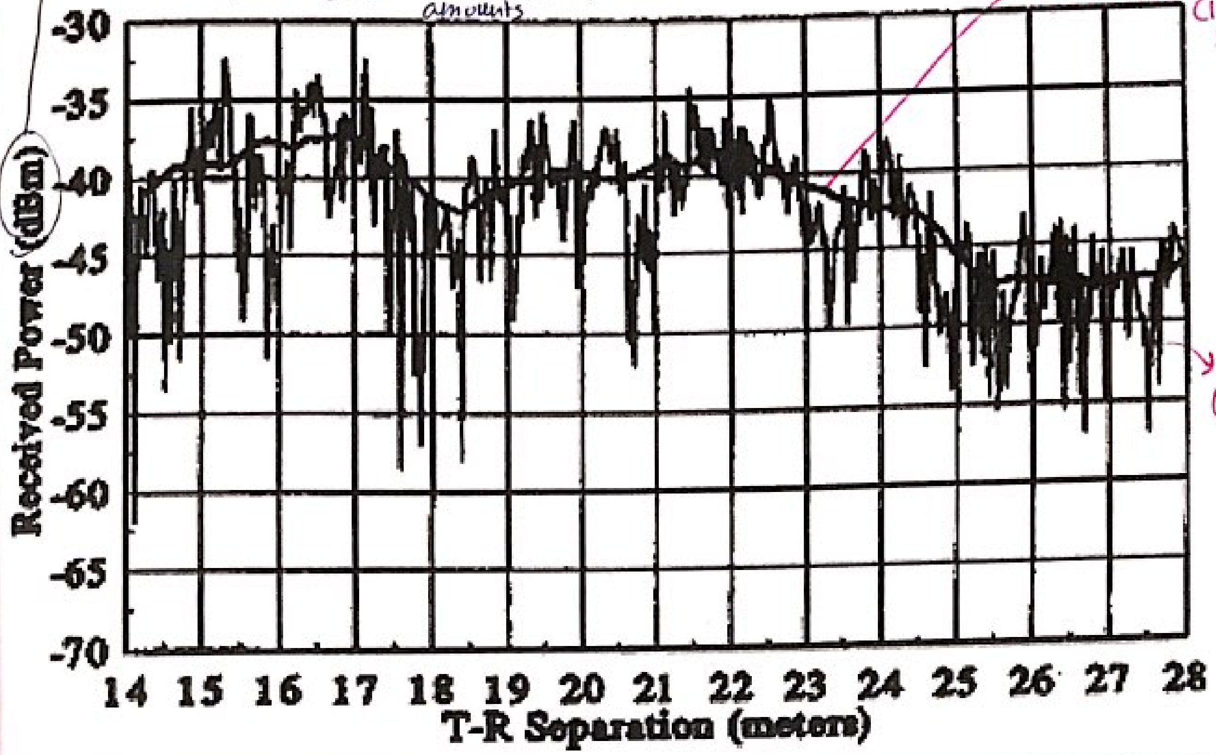
1. Large-scale path loss:

- Attenuation due to distance.
- Reflection.
- Refraction.
- Diffraction.
- Scattering.
- Shadowing due to terrain obstructions (hills, buildings, etc).

2. Small-scale path loss: this is called fading which is rapid fluctuations of the receiver signal strength over very short distances (a few wavelengths) or short time durations (on the order of seconds).

Small-scale and large-scale fading

→ as we have small values of power amounts



→ average signal (large scale)

→ Fading (small scale)

~~Fading~~

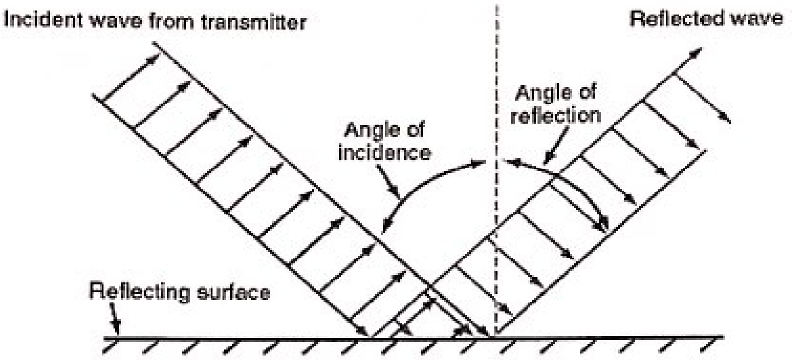
Large-Scale Path Loss

* they cause large and small scale path loss.

Reflection
Refraction

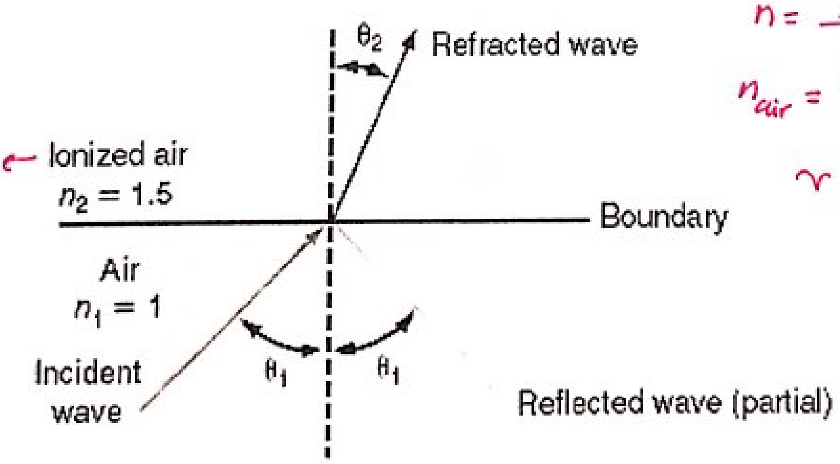
Reflection

- Radio waves are reflected by any conducting surface.
- Reflection is also produced by other partially conductive surfaces, such as the earth and water.
- Reflection follows the principles of light wave reflection. That is, the angle of reflection is equal to the angle of incidence.
- The reflection process reverses the polarity of a wave. This is equivalent to a 180° phase shift.



Refraction

- When light in air passes through another medium, such as water or glass, it slows down. This causes the light waves to bend.



ـــ الطبقات العليا من الجو

$n = \frac{3\times10^8}{v}$

$n_{air} = \frac{3\times10^8}{c} = 1$

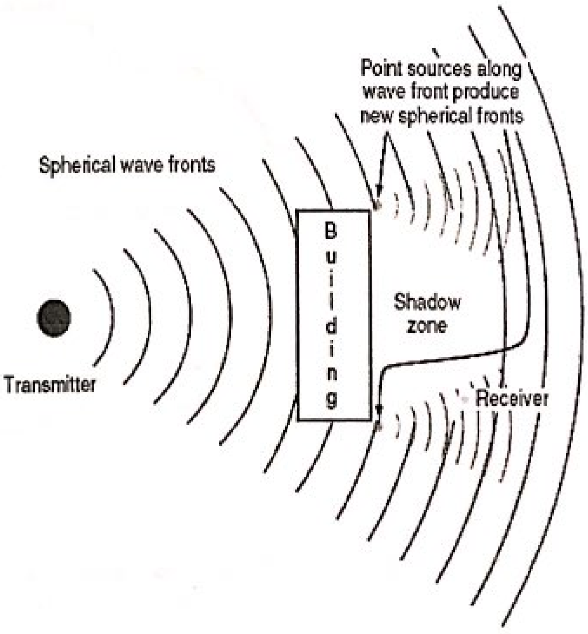
$v = \frac{1}{\sqrt{\mu\epsilon}}$

- The relationship between the angles and the indices of refraction is given by a formula known as *Snell's law:*

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where n_1 = index of refraction of initial medium
n_2 = index of refraction of medium into which wave passes
θ_1 = angle of incidence
θ_2 = angle of refraction

Diffraction



Huygens' principle is based on the assumption that all electromagnetic waves, light as well as radio waves, radiate as spherical wave fronts from a source. Each point on a wave front at any given time can be considered as a point source for additional spherical waves. When the waves encounter an obstacle, they pass around it, above it, and on either side.

Scattering

UHF and higher
usually high freq. signals are affected by scattering

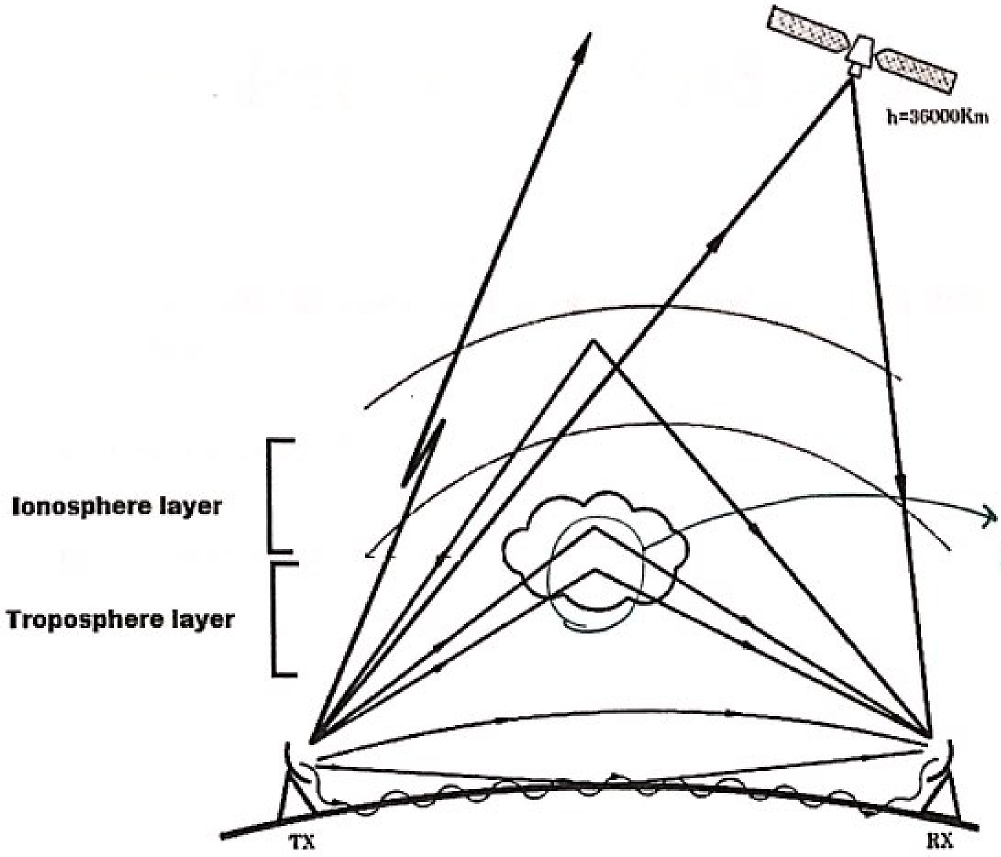
- **Due to objects in the medium that are small** compared to wavelength and the number of objects is many (e.g., foliage (tree leaves), street signs, lamp posts, rain, shower).

scattering

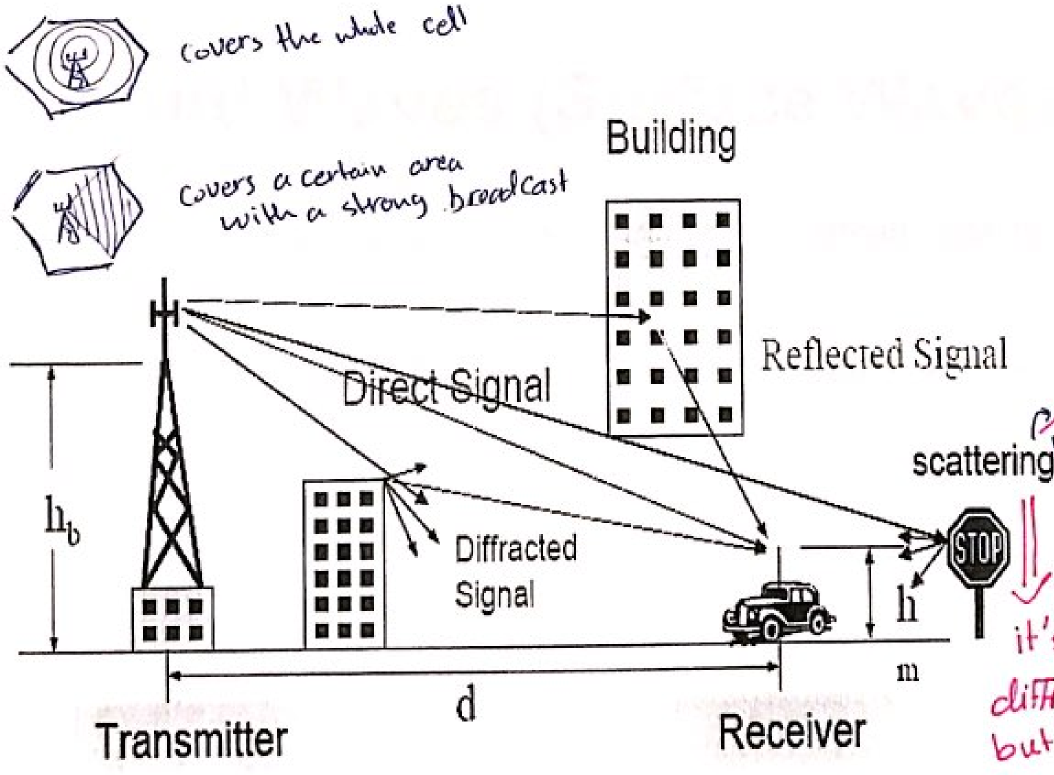
Radio Waves Transmission Media

FREE SPACE
EARTH ATMOSPHERE
GROUND SURFACE & SURROUNDING MEDIUM
OCEAN & SEA-WATER
INSIDE EARTH

Among the above stated media, the first three are more important on which a lot of efforts have been spent during recent decades at national and international levels.



→ Refraction & diffraction



covers the whole cell

covers a certain area with a strong broadcast

~~(i) it's like Diffract but for small objects~~

it's like diffraction but for small objects

Basic Paths For Propagation

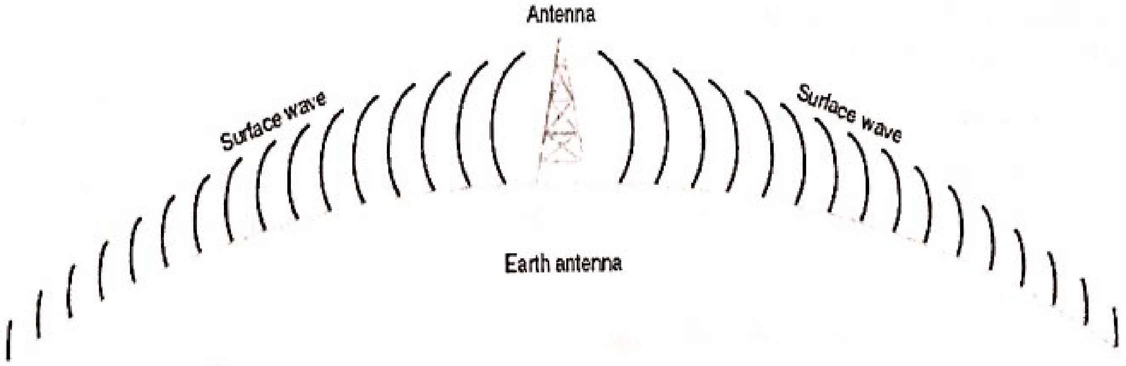
- **The three BASIC paths that a radio signal can take through space are:**

1. Ground Wave (Surface Wave).
2. Sky Wave.
3. Space Wave (Direct Wave).

Ground Waves (Surface Waves)

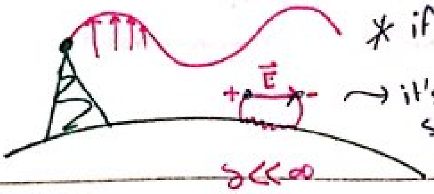
low and medium freq.

- Ground or surface waves leave an antenna and remain close to the earth.
- Ground waves actually follow the curvature of the earth and can, therefore, travel at distances beyond the horizon.



- Ground waves must have vertical polarization to be propagated from an antenna. Horizontally polarized waves are absorbed or shorted by the earth.
- Ground wave propagation is strongest at the low- and medium-frequency ranges. That is, ground waves are the main signal path for radio signals in the 30-kHz to 3-MHz range.
- The signals can propagate for hundreds and sometimes thousands of miles at these low frequencies.
- AM broadcast signals are propagated primarily by ground waves during the day and by sky waves at night.

- The conductivity of the earth determines how well ground waves are propagated. The better the conductivity, the less the attenuation and the greater the distance the waves can travel.
- The best propagation of ground waves occurs over salt water because the water is an excellent conductor. Conductivity is usually lowest in low- moisture areas such as deserts.
- At frequencies beyond 3 MHz, the earth begins to attenuate radio signals. Objects on the earth and features of the terrain become the same order of magnitude in size as the wavelength of the signal and thus absorb or adversely affect the signal.
- For this reason, the ground wave propagation of signals above 3 MHz is insignificant except within several miles of the transmitting antenna.



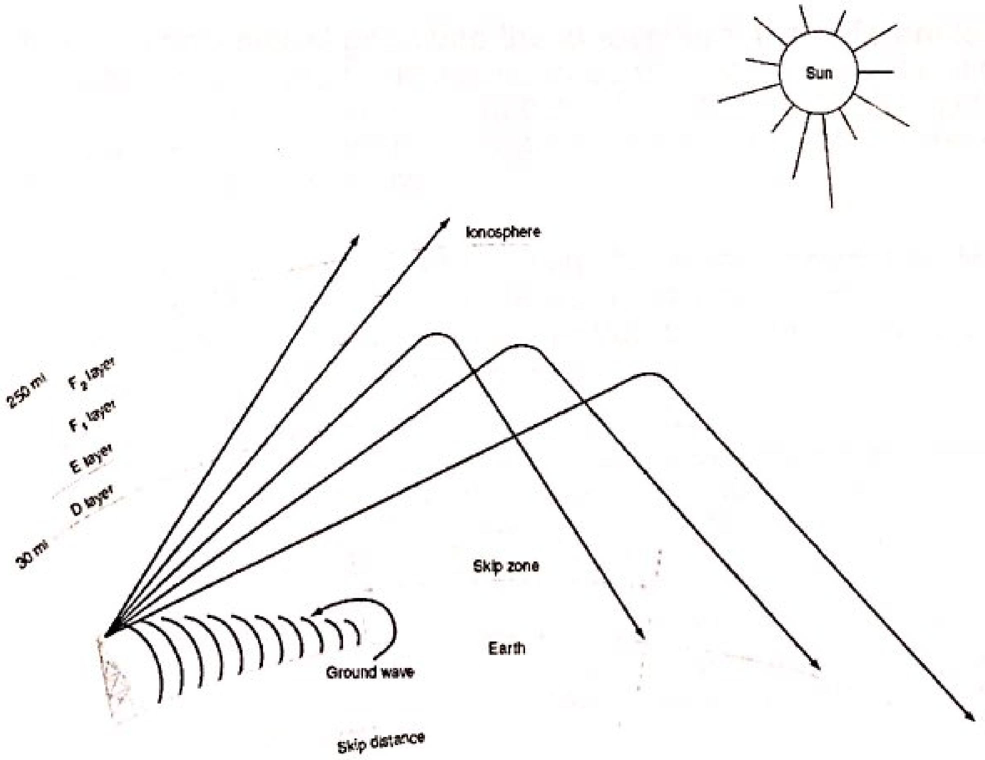
* if the polarization was horizontal!

→ it's like a short circuit since there's no voltage diffrence, so there will be absorbtion to power and the signal will be attenuated.

Sky Waves

- Sky wave signals are radiated by the antenna into the upper atmosphere, where they are bent back to earth.

- This bending of the signal is caused by reflection or refraction in a region of the upper atmosphere known as the ionosphere.



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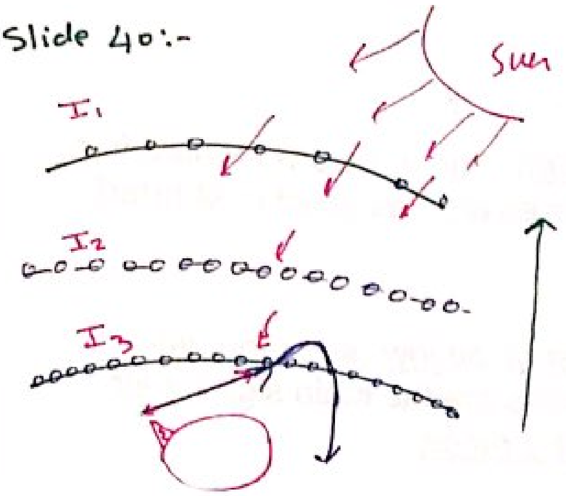
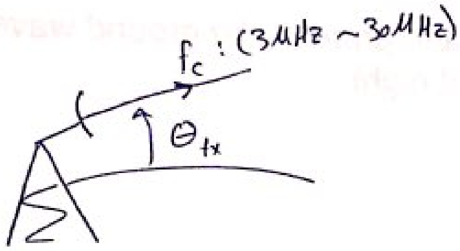
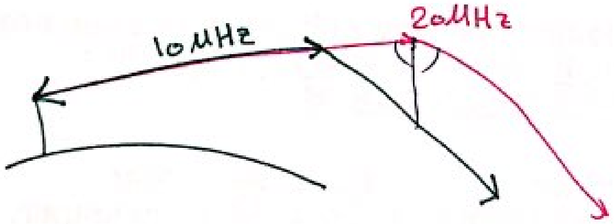


$I_1 < I_2$

$I_3 < I_2$

* biggest ionization happens at I_2





$$\overset{\text{energy}}{E} = \overset{\text{Blank}}{h}\,\overset{\text{frequency}}{f}$$

$f\uparrow$ $E\uparrow$

* VHF
UHF
Microwaves

are not affected by the Ionosphere, so we Use them in satalite Communcations.

- Ultraviolet radiation from the sun causes the upper atmosphere to ionize, i.e., to become electrically charged.
- The atoms take on or lose electrons, becoming positive or negative ions. Free electrons are also present.
- At its lowest point, the ionosphere is approximately 30 mi (50 km) above the earth and extends as far as 250 mi (400 km) from the earth.
- The ionosphere is generally considered to be divided into three layers, the D layer, the E layer, and the F layer; the F layer is subdivided into the F1 and F2 layers.
- The D and E layers, the farthest from the sun, are weakly ionized. They exist only during daylight hours, during which they tend to absorb radio signals in the medium-frequency range from 300 kHz to 3 MHz (so sky-wave is not possible at day time).

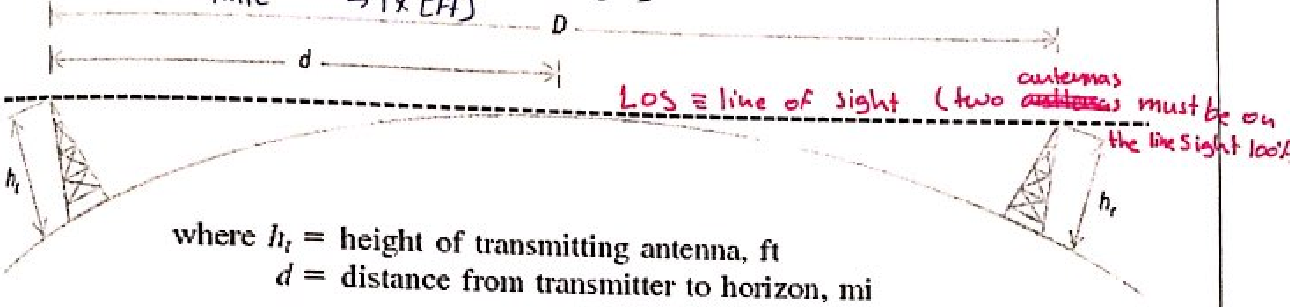
- When a radio signal goes into the ionosphere, the different levels of ionization cause the radio waves to be gradually bent. The direction of bending depends on the angle at which the radio wave enters the ionosphere and the different degrees of ionization of the layers, as determined by Snell's law.
- At very high frequencies, essentially those above about 50 MHz, refraction seldom occurs regardless of the angle. VHF, UHF, and microwave signals usually pass through the ionosphere without bending.
- In some cases, the signal reflected back from the ionosphere strikes the earth, is reflected back up to the ionosphere, and is re-reflected back to earth. This phenomenon is known as multiple-skip or multiple-hop transmission. For strong signals and ideal iono-spheric conditions, as many as 20 hops are possible. Multiple-hop transmission can extend the communication range by many thousands of miles. The maximum distance of a single hop is about 2000 mi, but with multiple hops, transmissions all the way around the world are possible.

Space Waves (Direct Waves)

- A direct wave travels in a straight line directly from the transmitting antenna to the receiving antenna. Direct wave radio signaling is often referred to as line-of-sight communication. Direct or space waves are not refracted, nor do they follow the curvature of the earth.

$d = \sqrt{2h_t}$
$D = \sqrt{2h_t} + \sqrt{2h_r}$

$$\Rightarrow \boxed{\underset{\text{mile}}{D} = \underset{\text{Tx [ft]}}{\sqrt{2h_t}} + \underset{\text{[ft]} \to \text{feet}}{\sqrt{2h_r}}}$$



where h_t = height of transmitting antenna, ft
d = distance from transmitter to horizon, mi

d is called the radio horizon.

- For example, if a transmitting antenna is 350 ft high and the receiving antenna is 25 ft high, the longest practical transmission distance is?

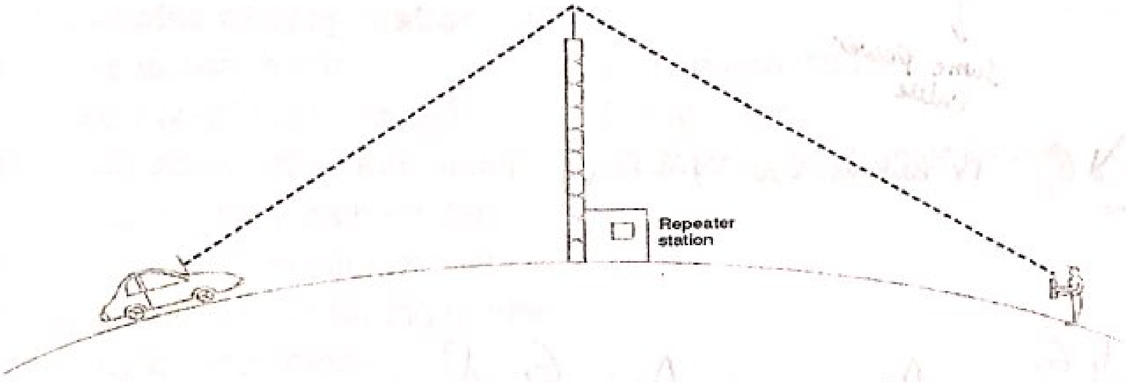
$$D = \sqrt{2(350)} + \sqrt{2(25)} = \sqrt{700} + \sqrt{50} = 26.46 + 7.07 = 33.53 \text{ mi}$$

- Line-of-sight communication is characteristic of most radio signals with a frequency above approximately 30 MHz, particularly VHF, UHF, and microwave signals. Such signals pass through the ionosphere and are not bent. Transmission distances at those frequencies are extremely limited, and it is obvious why very high transmitting antennas must be used for FM and TV broadcasts.

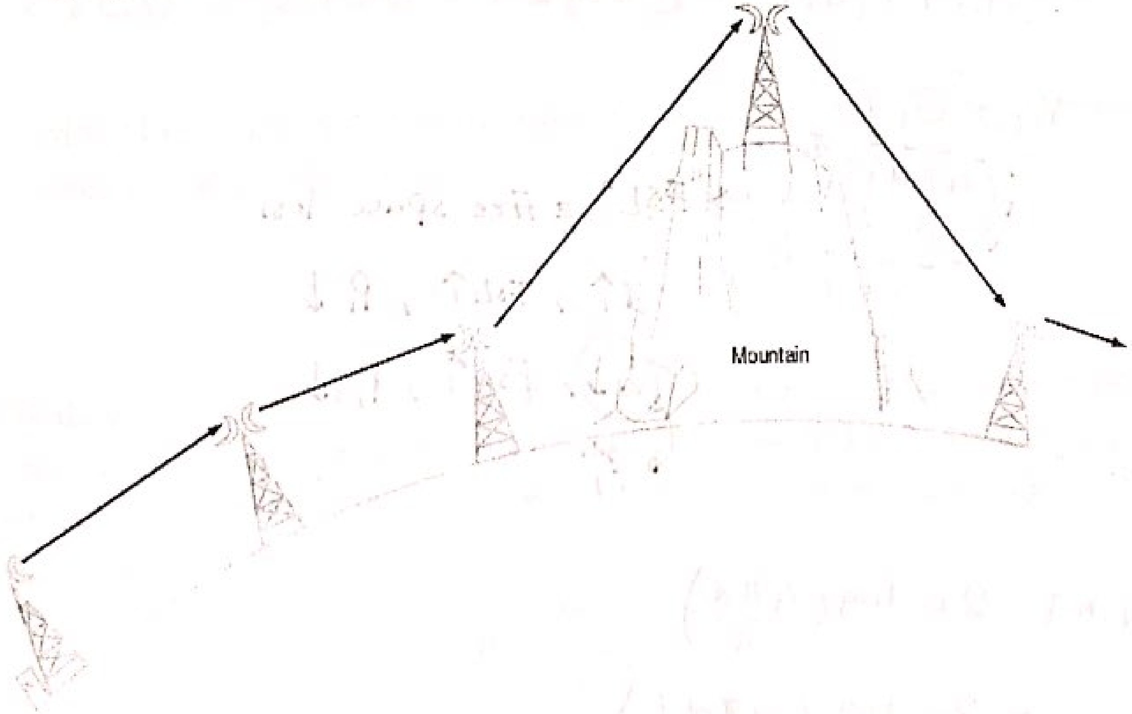
- The antennas for transmitters and receivers operating at the very high frequencies are typically located on top of tall buildings or on mountains, which greatly increases the range of transmission and reception.

- To extend the communication distance at VHF, UHF, and microwave frequencies, special techniques have been adopted. The most important of these is the use of repeater stations. The repeater picks up a signal from a remote transmitter, amplifies it, and retransmits it (on another frequency) to a remote receiver.

- Communication satellite is an example of a repeater.



Using repeater stations to increase communication distances at microwave frequencies.



Propagation Models

- Wired channels are stationary and predictable, whereas radio channels are extremely random and have complex models.
- Modeling of radio channels is done in statistical fashion based on measurements for each individual communication system or frequency spectrum.

- **Examples of propagation models:**

1. Free space model.
2. Two ray reflection model.
3. Knife-edge diffraction model.
4. Long-distance path model.
5. Radar cross section model.
6. Log-normal shadowing model.
7. Longley Rice model.
8. Okumara model.
9. Hata model.
10. Attenuation Factor Model.

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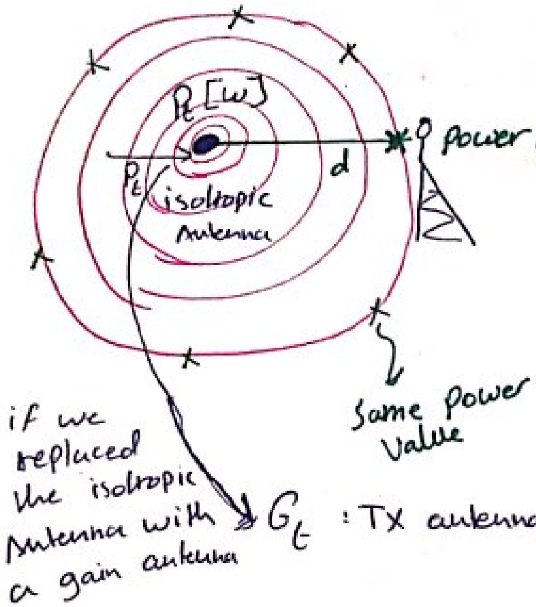

power density = $\frac{P_t G_t}{4\pi d^2}$ [w/m²]

G_t : TX antenna gain [unitless]

$$P_{r[w]} = \frac{P_t G_t}{4\pi d^2} \cdot A_e \quad , \quad A_e = \frac{G_r \lambda^2}{4\pi}$$

$$P_{r[w]} = \frac{P_t G_t G_r \lambda^2}{(4\pi d^2)(4\pi)}$$

$$\boxed{P_{r[w]} = \frac{P_{t[w]} G_t G_r}{\left(\frac{4\pi d}{\lambda}\right)^2}}$$

$\longrightarrow$ "FSL" ≡ free space loss

d↑ , FSL↑ , P_r↓

λ↓ , FSL↑ , P_r↓

f↑

$$FSL_{[dB]} = 20 \log\left(\frac{4\pi d}{\lambda}\right)$$
$$= 20 \log\left(\frac{4\pi d f}{c}\right)$$

$$\boxed{P_{r[dBw]} = P_{t[dBw]} + G_{t[dB]} + G_{r[dB]} - FSL_{[dB]}}$$

$$FSL = \left(\frac{4\pi d}{\lambda}\right)^2 , \quad \lambda = \frac{c}{f}$$

$$\boxed{FSL_{[dB]} = 20 \log\left(\frac{4\pi f d}{c}\right)}$$

$$FSL_{[dB]} = 20 \log\left(\frac{4\pi}{c}\right) + 20 \log(f) + 20 \log(d)$$

Free Space Propagation Model

Radiation of radio power P_t by an isotropic antenna in free-space results in power flux density P_0 at a distance d:

$$P_0 = \frac{P_t}{4\pi d^2} = \frac{E_0^2}{2\eta_0}.$$

In the above formula P_t is the transmitter power in Watts, d is the distance from antenna in m, E_0 is the electric field magnitude in V/m and η_0 is the free space intrinsic impedance equal to $120\pi\,\Omega$. Applying G_t as TX antenna gain , the power flux density P will be:

$$P = \frac{P_t \times G_t}{4\pi d^2}$$

Using a receiving antenna with an effective aperture area A_e, the received signal power would be:

$$P_r = P \times A_e.$$

A_e according to the EM waves theory is:

$$A_e = \frac{G_r \times \lambda^2}{4\pi}.$$

By manipulating the last three relations, the following formula is derived:

$$P_r = \frac{P_t \times G_t}{4\pi d^2} \times \frac{G_r \times \lambda^2}{4\pi} = \frac{P_t \times G_t \times G_r \times \lambda^2}{(4\pi d)^2}.$$

To calculate free-space loss by using the above relation and assuming $G_t = G_r = 1$:

$$L_{fb} = FSL = 10 \log \frac{P_t}{P_r} = -10 \log \frac{\lambda^2}{(4\pi d)^2}$$

$$\Rightarrow FSL = 20 \log \frac{4\pi d}{\lambda}$$

Considering $\lambda = c/f$ we have:

$$FSL = 20 \log \frac{4\pi f.d}{c}.$$

The above formula is a generic form of FSL in metric system of units. Since in actual links the frequency is in MHz or GHz and distance in km, by putting $c = 3 \times 10^8$ m/s, then FSL is specified by one of the following formulas:

$$FSL(\text{dB}) = 32.4 + 20 \log f(\text{MHz}) + 20 \log d(\text{km})$$

$$FSL(\text{dB}) = 92.4 + 20 \log f(\text{GHz}) + 20 \log d(\text{km})$$

Example . In a radio link of 40 km length and working at 7.5 GHz, 60% of free-space loss is compensated by using high-gain TX and RX antennas.

1. How much is the received signal level (RSL) at the output of RX antenna with one watt TX output power and considering 15 dB additional losses.
2. Find fade margin of the link if RX threshold is to be $P_{\text{th}} = -78\ \text{dB}_m$

***Solution*:**

1.

$$FSL = 92.4 + 20\ \log f.d = 141\ \text{dB}$$

$$P_t = 1\ \text{W} \quad \Rightarrow \quad P_t(\text{dB}_m) = 30\ \text{dB}_m$$

$$P_r = RSL = P_t(\text{dB}_m) - 0.4\,FSL - L_a$$

$$= 30 - 56.8 - 15 = -41.4\ \text{dB}_m$$

2.

$$FM = P_r(\text{dB}_m) - P_{\text{th}}(\text{db}_m) = -41.4 + 78 = 36.6\ \text{dB}$$

■

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$P_t = 1\,W$

$d = 40\,km$

$f = 7.5\,GHz$

$L_a = 15\,dB$

$$P_{t\,[dBW]} = 0\,dBW \Rightarrow P_{t\,[dBm]} = 30\,dBm$$

$$P_{r\,[dBm]} = P_{t\,[dBm]} + G_{t_{dB}} + G_{r_{dB}} - FSL_{dB} - 15_{dB}$$

$$FSL_{dB} = 141\,dB$$

$$G_{t_{dB}} + G_{r_{dB}} = (0.6)(141)_{dB}$$

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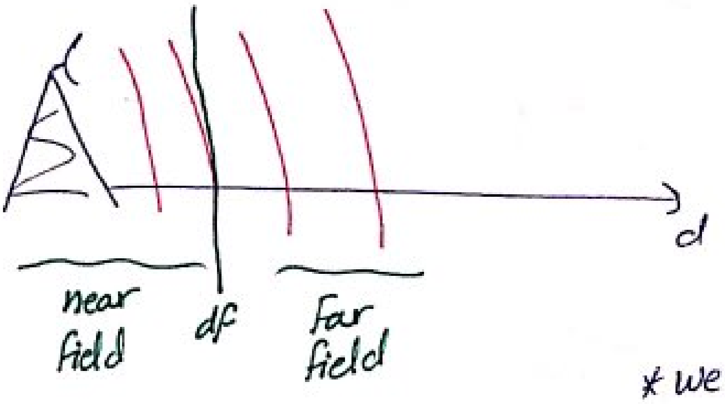
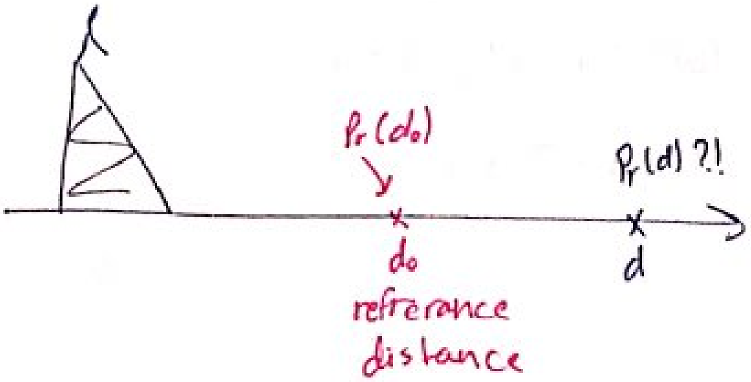


* we can apply the polarized formula only when $d > d_f$



$$\frac{P_r(d)}{P_r(d_o)} = \frac{\frac{\cancel{P_t G_t G_r \lambda^2}}{(4\pi d)^2}}{\frac{\cancel{P_t G_t G_r \lambda^2}}{(4\pi d_o)^2}} = \left(\frac{d_o}{d}\right)^2$$

$$\boxed{P_r(d) = P_r(d_o)\left(\frac{d_o}{d}\right)^{\textcircled{2}}} \rightarrow \text{Free space path loss exponent}$$

- The fields of an antenna can broadly be classified in two regions, the far field and the near field.
- *The Friis equation is used only beyond the far field distance, df , which is dependent upon the largest dimension of the antenna as*

$$d_f = 2D^2/\lambda.$$

- Also we can see that the Friis equation is not defined for d=0. For this reason, we use a close in distance, *do*, as a reference point. The power received, *Pr*(*d*), is then given by:

$$P_r(d) = P_r(d_o)(d_o/d)^2$$

$$P_r(d)_{[dBw]} = P_r(d_o)_{[dBw]} + \underset{\underset{\uparrow}{(2)(10)}}{\boxed{20}} \log\left(\frac{d_o}{d}\right)$$

Ex. 1: Find the far field distance for a circular antenna with maximum dimension of 1 m and operating frequency of 900 MHz.

Solution: Since the operating frequency f = 900 Mhz, the wavelength

$$\lambda = \frac{3 \times 10^8 m/s}{900 \times 10^6 Hz} m$$

. Thus, with the largest dimension of the antenna, D=1m, the far field distance is

$$d_f = \frac{2D^2}{\lambda} = \frac{2(1)^2}{0.33} = 6m$$

Ex. 2: A unit gain antenna with a maximum dimension of 1 m produces 50 W power at 900 MHz. Find (i) the transmit power in ~~dBm~~ and ~~dB~~ dBw (ii) the received power at a free space distance of 5 m and 100 m.

Solution:

(i) Tx power = 10log(50) = 17 ~~dB~~ dBw = (17+30) dBm = 47 dBm

(ii) $d_f = \frac{2 \times D^2}{\lambda} = \frac{2 \times 1^2}{1/3} = 6m$

Thus the received power at 5 m can not be calculated using free space distance formula.

At 100 m .

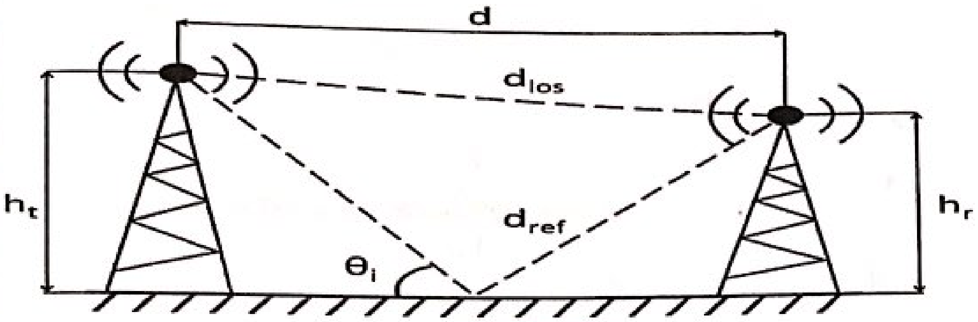
$$P_R = \frac{P_T G_T G_R \lambda^2}{4\pi d^2}$$

$$= \frac{50 \times 1 \times (1/3)^2}{4\pi 100^2}$$

$$= 3.5 \times 10^{-3} mW$$

$$P_R(dBm) = 10 log P_r(mW) = -24.5 dBm$$

Two Ray Reflection Model

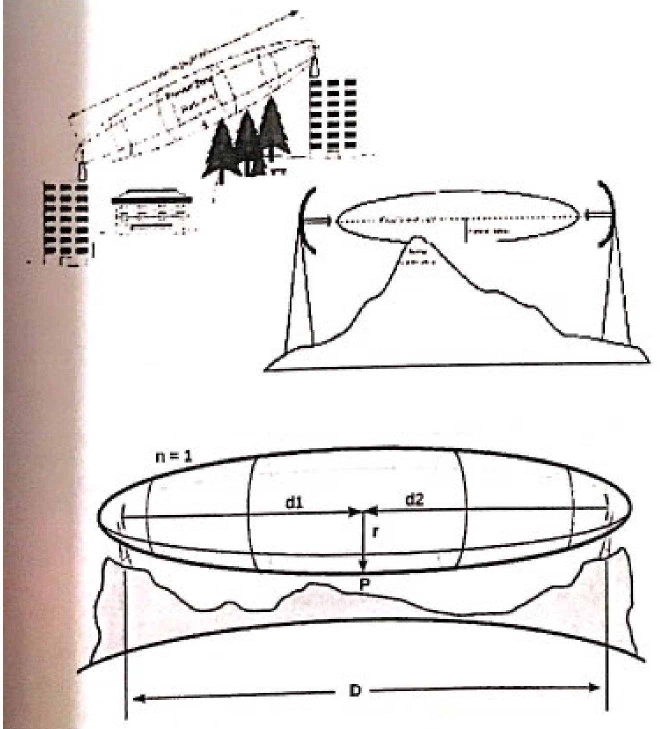


$$\boxed{P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{L d^4}.}$$

$PL(\text{dB}) = 40\log d$ [redacted]

L: is the system hardware losses (L ≥ 1) are usually due to: transmission line attenuation, filter losses, and antenna losses in the communication system. A value of L = 1 indicates no loss in the system hardware.

Diffraction



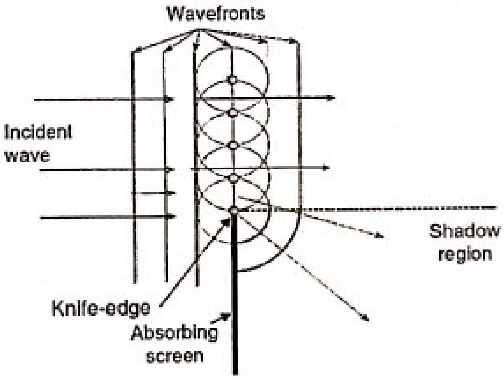


Figure 3.13: Huygen's principle for knife-edge diffraction

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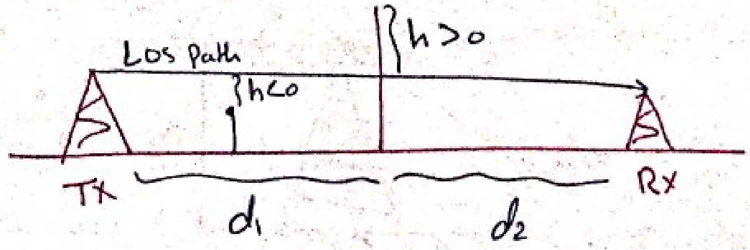

$$d_1+d_2=d$$

$$P_{r_{[dBW]}} = P_{t_{[dBW]}} + G_t + G_r - FSL_{dB} - L_a - |G_{dB}(d)|$$

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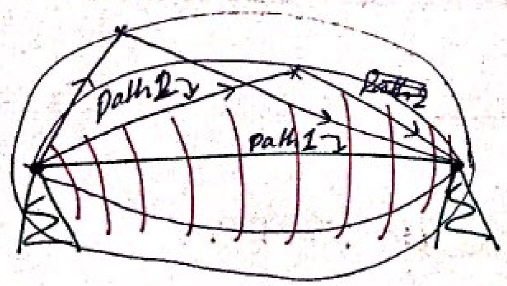


$$path2 - path1 = \frac{\lambda}{2}$$

$$\boxed{\Delta n = n\,\frac{\lambda}{2}}$$

$n = 1, 2, \ldots$

Direct : $\cos(\omega t)$

Indirect : $\cos(\omega t + \phi_w)$

$$\phi_n = 2\pi\,\frac{\Delta n}{\lambda}$$

$$= 2\pi\,\frac{n\,\cancel{\lambda}}{\cancel{\lambda}\,2}$$

$$\boxed{= n\pi}$$

Knife-edge Diffraction Model

- This is the simplest of diffraction models.
- The attenuation (propagation loss) caused by diffraction can be estimated by treating the obstruction as a diffracting (absorbing) knife-edge

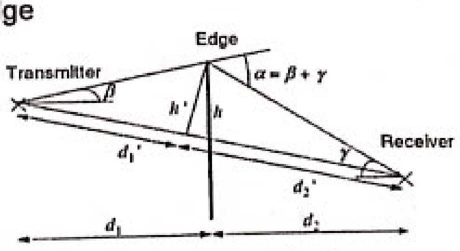


Figure 3.16: Knife-edge diffraction parameters

- Approximate diffraction gain (loss) expressions:

$$G_d(dB) = 0 \qquad \nu \le -1$$
$$G_d(\mathrm{dB}) = 20\log(0.5 - 0.62\nu) \qquad -1 \le \nu \le 0$$
$$G_d(\mathrm{dB}) = 20\log(0.5\exp(-0.95\nu)) \qquad 0 \le \nu \le 1$$
$$G_d(\mathrm{dB}) = 20\log\left(0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2}\right) \qquad 1 \le \nu \le 2.4$$
$$G_d(\mathrm{dB}) = 20\log\left(\frac{0.225}{\nu}\right) \qquad \nu > 2.4$$

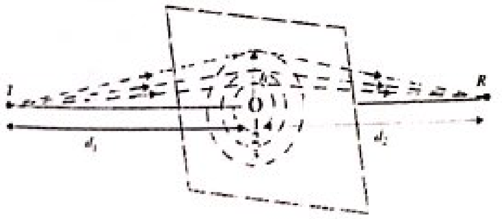
will be given in the exam

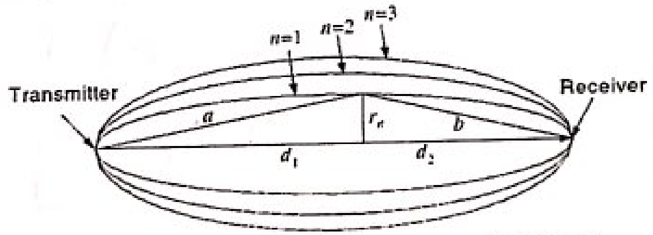
must be in meter

Where $\nu = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}$ is the Fresnel diffraction parameter. $\phi = \frac{\pi}{2}\nu^2$

Note: v is –ve when h is –ve
Note: this diffraction loss is finally added to the FSL (in dB)

Diffraction: Fresnel zones





$$a + b = d_1 + d_2 + \frac{n\lambda}{2} \qquad r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

- Concentric circles which define the boundaries of successive Fresnel zones

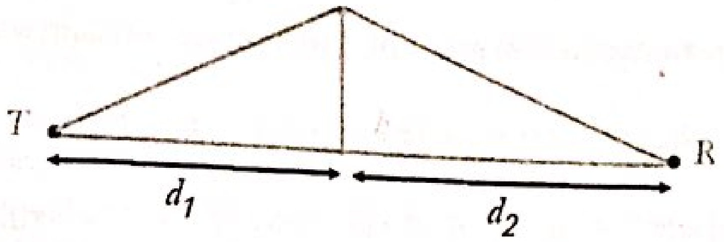
- Fresnel zones have the effect of alternately providing constructive and destructive interference to the total received signal.

- The radius of the nth Fresnel zone circle is denoted by r_n, and has delta_n=nλ/2 path difference, or 2*pi*delta_n/Lamda = nπ phase difference to the LOS (derive?).

- A rule of thumb is that as long as 55% (many materials say 60%) of the first Fresnel zone is kept clear, the diffraction loss will be minimal.

Knife-edge diffraction geometry:

How to determine the number of the Fresnel zones *n*?



When d_1 , $d_2 >> h$, $h >> \lambda$, the excess path length (difference between the direct path and the diffracted path) is

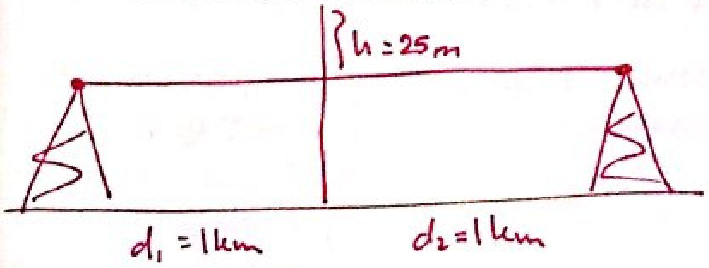
$$\Delta \approx \frac{h^2}{2}\frac{d_1+d_2}{d_1 d_2}$$

The corresponding phase difference is

$$\phi = \frac{2\pi\Delta}{\lambda} \approx \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{d_1+d_2}{d_1 d_2}$$

Then let delta=delta_n and then find n

- Example on kife-edage diffraction loss:
- wave length = 1/3
- Tx power = 1 watta
- d_1=d_2= 1km
- h= 25 m
- G_t=G_r=1
- Find: number of Fresnel zones, diffraction loss, received power.



f_c = 900MHz

$\lambda = \frac{1}{3}$ m

P_c = 1W $\hat{=}$ 0dB

$G_t = G_r = 1$

Solution :-

diffraction loss :-

$$\Rightarrow v = 25\sqrt{\frac{6(2000)}{10^8}} = 25\sqrt{\frac{12}{1000}} = 2.73.$$

$$\Rightarrow G_d\,(dB) = 20\log\left(\frac{0.225}{2.73}\right) = -21.67\ dB$$

$$\Rightarrow P_{r_{[dBw]}} = P_{t_{[dBw]}} + G_{t_{dB}} + G_{r_{dB}} - FSL - 21.67$$

$$= -FSL - 21.67$$

$$FSL = 20\log\left(\frac{4\pi d}{\lambda}\right) = ----$$

phase shift $\Rightarrow \cos(w(t+\Delta t))$

$$, \cos(wt + \underbrace{w\Delta t}_{\text{This is the phase shift}})$$

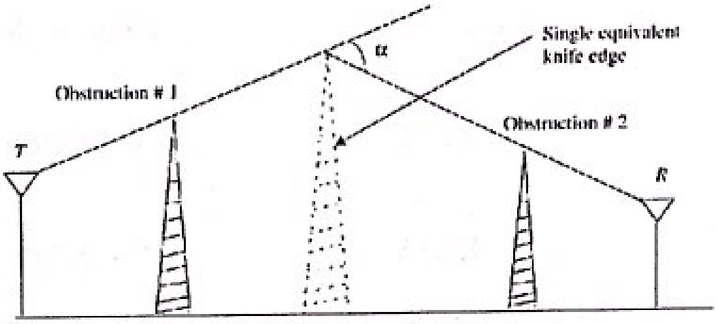
$$\Delta = \Delta n$$

$$\frac{h^2}{2}\,\frac{d_1+d_2}{d_1 d_2} = n\,\frac{\lambda}{2}$$

Find $n = 3.6$

Multiple Knife-edge Diffraction

- When there are multiple obstructions, the problem becomes much more complicated.
- Many models have been developed to estimate the diffraction losses due to multiple obstructions
- Bullington suggested that the series of obstacles be replaced by a single equivalent obstacle so that the path loss can be obtained using single knife-edge diffraction models. This method oversimplifies the calculations and often provides very optimistic estimates of the received signal strength



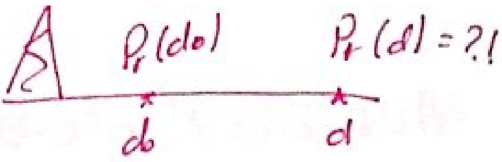
Long-distance Path Model

- Most radio propagation models are derived using a combination of analytical and empirical models
- Over many years, some classical propagation models have been developed, which are used to predict large-scale coverage for mobile communication system design

$$\overline{PL}(\text{dB}) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

is the RSL at distance d. increasing n decreases RSL.

- ❖ n is the path loss exponent: *indicates the rate at which the path loss increases with distance,*
- ❖ d0 is the close-in reference distance: *is determined from measurements close to the transmitter.*
- In large coverage cellular systems, 1 km reference distances are commonly used, whereas in microcellular systems, much smaller distances (such as 100 m or 1 m) are used.



$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)$$

n: path loss exponent

$$\underbrace{P_r(d)}_{\text{dBw}} = \underbrace{P_r(d_0)}_{\text{dBw}} + 10\,n\,\log\left(\frac{d_0}{d}\right)$$

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Small-scale path loss: Fading

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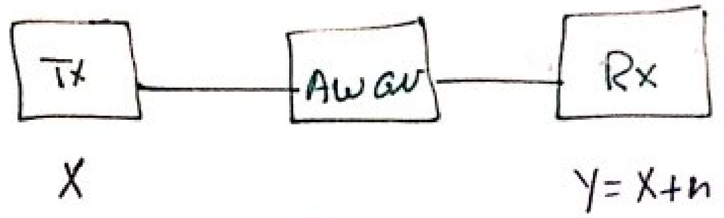
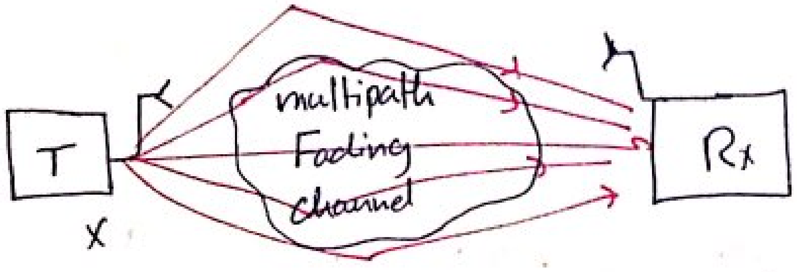


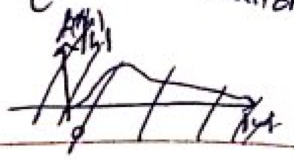


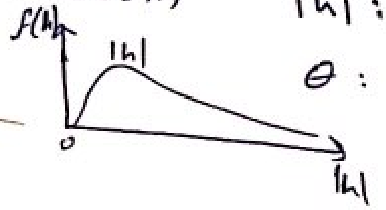
fading Coefficient $Y = hx + n$

h = complex R.V

$= |h| e^{j\theta} \leftarrow$ uniform $\sim U(0, 2\pi)$

Rayleigh ↗





h: Fading coeff.

|h| : envelope

θ : phase

wireless communication

Fading

- Fading: causes the received signal to vary in amplitude, typically making it smaller.

- **Fading is caused by different factors:**

1. Variation in distance between transmitter and receiver: This type of fading is generally gradual and does not result in severe or rapid swings in signal amplitude.

2. Objects (large buildings, mountains, a car enters a tunnel, rainstorm, snowstorm) coming between the transmitter and receiver. Known as shadow fading.
   - Weather related effects are especially pronounced at the higher microwave frequencies, where the signal wavelengths are in the same size range as the raindrops or snow flakes that produce massive signal scattering by reflection.

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3. **Multipath.** One of the worst sources of fading is multipath interference. Sometimes called Rayleigh fading, this type of fading occurs when a transmitted signal takes multiple paths to the receiver because of reflections. The result is that multiple signals reach the receiver antenna at different times (so different phase-shift).

4. Relative motion between the transmitter and receiver. This introduces a signal frequency change called a Doppler shift. Movement that causes the transmitter and receiver to get closer to each other causes the signal frequency to increase. Movement that increases the distance causes a frequency decrease. Large signal-frequency changes produce lower-level signals because the signals are partially out of the pass-band of the receiver's selective filters. In digital systems that predominantly use some form of phase-shift modulation, the Doppler shift confuses the demodulator and produces bit errors.

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x_1	x_2	x_3	......	x_n

$y_1 = h_1 x_1 + n$

$y_2 = h_2 x_2 + n$

$\vdots$

$y_n = h_n x_n + n$

same noise
diffrent h

mobility ↑ ⇒ $\uparrow \Delta h$ ⇒ doppler shift will increase

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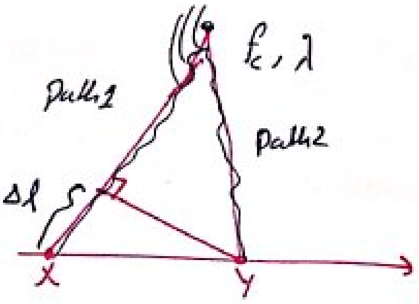
v [m/sec]

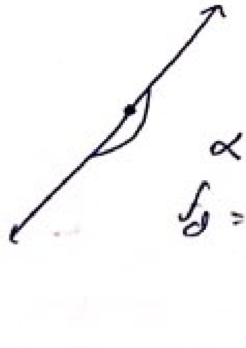
path1 − path 2 $\approx \Delta l$



$\omega_d = 2\pi f_d$
↗
Doppler shift

$\cos(\omega_c t) \rightsquigarrow \cos(\omega_c t + \Delta\theta)$, $\Delta\theta = \omega_d \Delta t$

$$\boxed{f_d = \frac{v}{\lambda} \cos \alpha}$$



$\alpha = 180°$

$f_d = \frac{-v}{\lambda}$

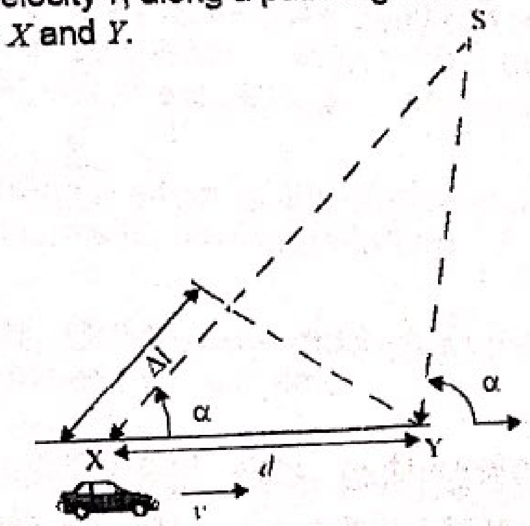
Doppler Shift

- Doppler Shift
  - A mobile moves at a constant velocity v, along a path segment having length d between points X and Y.
  - Path length difference

    $\Delta l = d\cos\alpha = v\Delta t\cos\alpha$
  - Phase change

    $$\Delta\phi = \frac{2\pi\Delta l}{\lambda} = \frac{2\pi v\Delta t}{\lambda}\cos\alpha$$
  - Doppler shift

    $$f_d = \frac{1}{2\pi}\cdot\frac{\Delta\phi}{\Delta t} = \frac{v}{\lambda}\cos\alpha$$



Doppler frequency depends on the velocity, carrier frequency and the aspect angle.

Doppler frequency is positive when the mobile is moving towards the source S and it is negative if the mobile is moving away from the source

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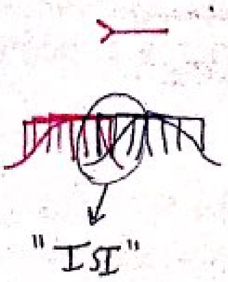
- If you have ever used a cell phone from a moving car in a changing environment, you know that fading can cause significant signal variations, including no service at all.
- When digital communication is involved, multipath fading can cause inter-symbol interference.



- equilzer
- RAKE Rx
- OFDM

Solutions of Fading

1. Built-in fading margin. That is, they have a high enough transmitter power and sufficient receiver sensitivity to ensure that the weaker reflective signals do not degrade the direct signal as much.

2. Using highly directive antennas, either at the transmitter or at the receiver or at both. This reduces the multipath fading.

3. Broadband signals (OFDM, CDMA) are much less sensitive to multipath fading than narrowband signals are.

4. Diversity Systems: A diversity system uses multiple transmitters, receivers, or antennas to mitigate the problems caused by multipath signals.

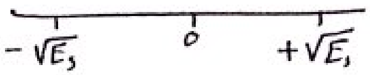
- **Two common types of diversity:**

1. Frequency diversity, two separate sets of transmitters and receivers operating on different frequencies are used to transmit the same information simultaneously. This system is expensive and there is a scarcity of frequency spectrum. Therefore, this system is impractical. It is rarely used except in cases where extreme reliability is a must.

2. Space or Spatial diversity. It uses two receiver antennas spaced as far apart as possible to receive the signals. Diversity systems are used mainly at base stations rather than in portable or handheld units.

- Many systems use the relationship $h/d = 11$ to determine a minimum spacing for antennas. In this relationship, h is the height of the antenna and d is the spacing distance.

Bpsk :

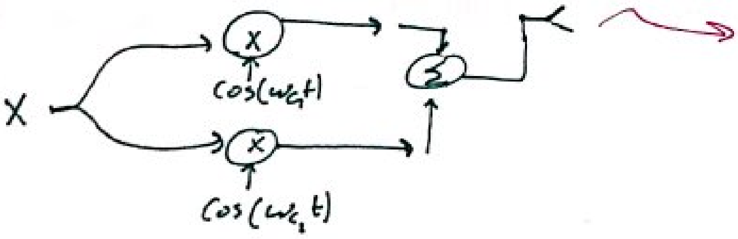


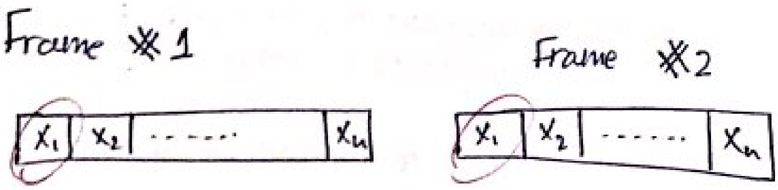
$$"1" \longrightarrow x(t) = \cos(\omega_c t + \theta_1) \longrightarrow y(t) = \cos(\omega_c t + \underbrace{(\theta_1 + \overset{\text{doppler}}{\Delta\theta})}_{\Downarrow\ \phi})$$

$$"0" \longrightarrow x(t) = \cos(\omega_c t + \theta_2)$$

Slide 70:-

Diversity : Transmitting same information signal (symbol) over multiple independent fading channels



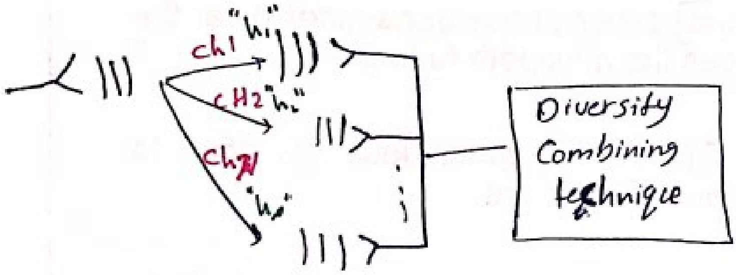


has been sent two times but the spectral effeciency will be decreased.

Slide 71:-

Space Diversity →
- SIMO
- MISO
- MIMO

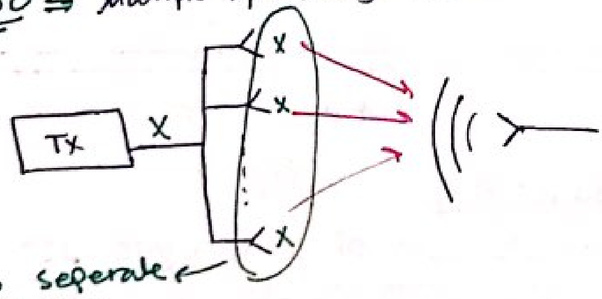
SIMO => single input, multiple output



ⓐ MRC: Maximum ratio Combining

ⓑ selection Combining

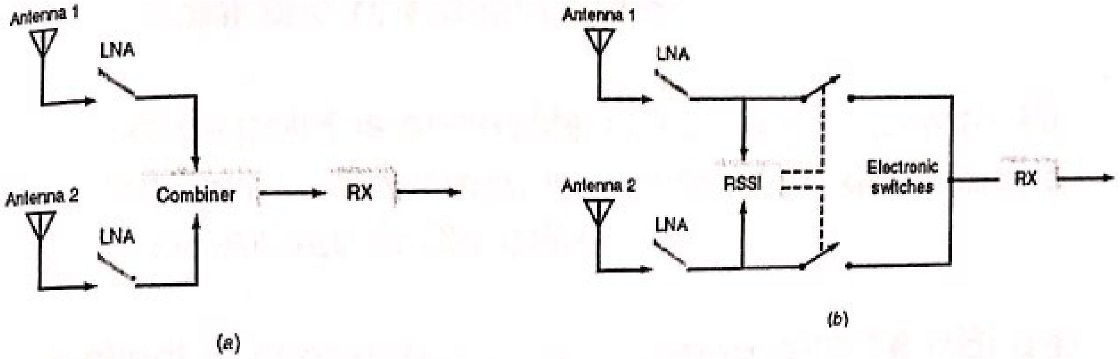
MISO => Multiple input, single output



to seperate them ←

use space time - Coding: "Alamonti"

- Spatial diversity



RSSI: received signal strength indicators .

- Diversity systems are widely used in the newer cell phone systems and in wireless LANs that work indoors and, in some cases, with mobile wireless units (laptop computers, PDAs (personal-digital-assistants), etc.) that are frequently in motion.

- New techniques such as multiple-input, multiple-output (MIMO), and smart (adaptive) antennas are now being used to further improve transmission in multipath environments.

Example: Link Budget Calculations

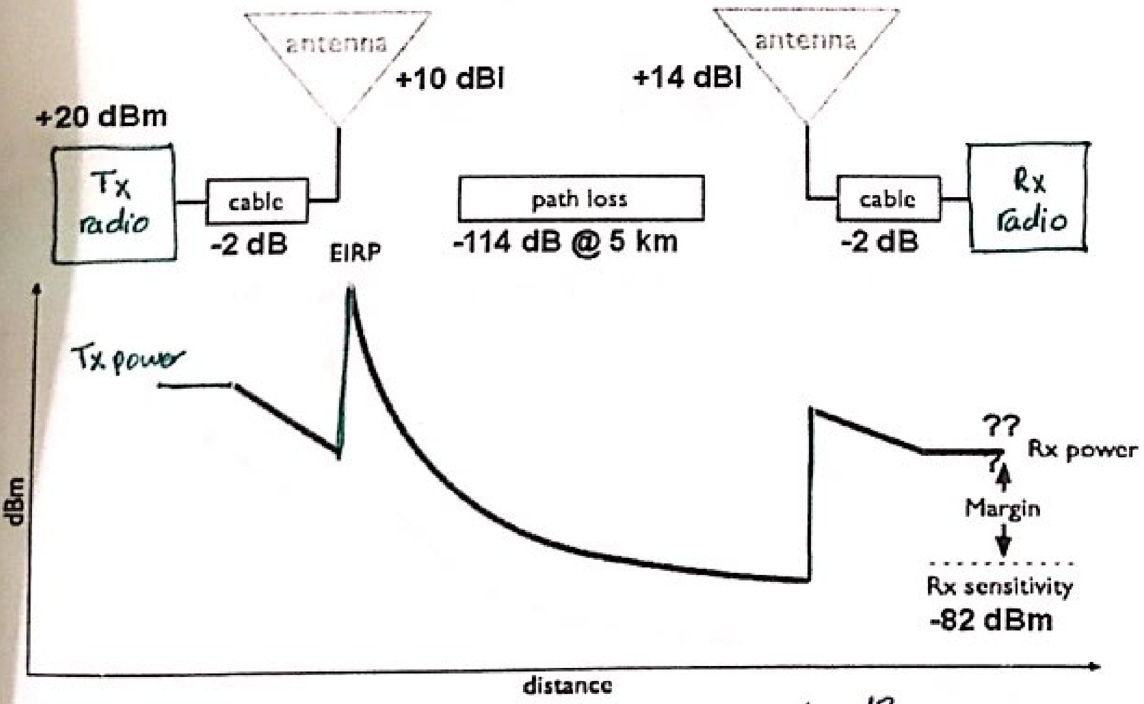
Let's estimate the feasibility of a **5 km** link, with one access point and one client radio.

The access point is connected to an antenna with **10 dBi** gain, with a transmitting power of **20 dBm** and a receive sensitivity of **-89 dBm**.

The client is connected to an antenna with **14 dBi** gain, with a transmitting power of **15 dBm** and a receive sensitivity of **-82 dBm**.

The cables in both systems are short, with a loss of **2dB** at each side at the 2.4 GHz frequency of operation.

AP to Client link



$20\,dBm_{} - 2_{dB} + 10_{dB} - 114_{dB} + 14 - 2 = -74\ \underline{\underline{dBm}}$ same as the transmitting power

$FSL = 20\log\left(\frac{4\pi\lambda}{d}\right) = -114\ dB$

Link budget: AP to Client link

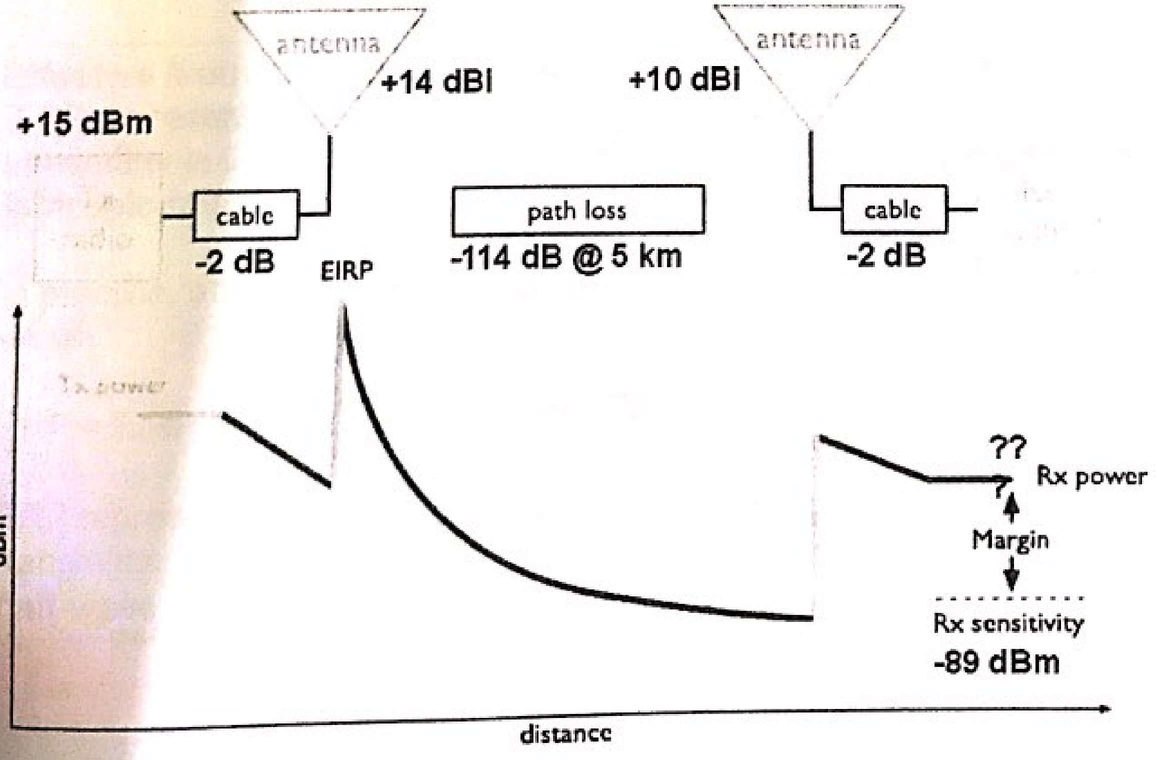
20 dBm (TX Power AP)
+ 10 dBi (Antenna Gain AP)
- 2 dB (Cable Losses AP)
+ 14 dBi (Antenna Gain Client)
- 2 dB (Cable Losses Client)

40 dB Total Gain
-114 dB (free space loss @5 km)

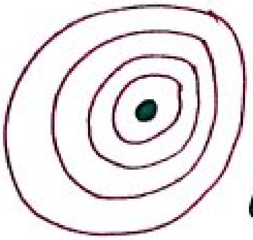
~~-73~~ -74 dBm (expected received signal level)
--82 dBm (sensitivity of Client)

8 dB (link margin)

Opposite direction: Client to AP



"Isotropic Antenna"



$G_i = 1$

$G_i = 0dB$

half wave dipole

$G = 2.15dB$

$1dB_d = 2.15\,dB_i$

$14\,dB_i = 11.85\,dB_d$

$$\boxed{dB_i = dB_d + 2.15}$$

Link budget: Client to AP link

15 dBm (TX Power Client)
+ 14 dBi (Antenna Gain Client)
- 2 dB (Cable Losses Client)
+ 10 dBi (Antenna Gain AP)
- 2 dB (Cable Losses AP)

35 dB Total Gain
-114 dB (free space loss @5 km)

-78 dBm (expected received signal level)
--89 dBm (sensitivity of AP)

10 dB (link margin)

EIRP and ERP

Effective isotropic radiated power (EIRP): EIRP = Pt Gt
EIRP represents the maximum radiated power available from a transmitter in the direction of maximum antenna gain, **compared to an isotropic radiator.**

In practice, **effective radiated power (ERP) is more commonly used:**

ERP = EIRP /1.64 or ERP (dB) = EIRP (dB) – 2.15

ERP represents the maximum radiated power available from a transmitter in the direction of maximum antenna gain, **compared to a half-wave dipole antenna.**

Link Margin

- In a wireless communication system, the **link margin**, measured in dB, is the difference between the receiver's sensitivity (i.e., the received power at which the receiver will stop working) and the actual received power.

- A 15 dB link margin means that the system could tolerate an additional 15 dB of attenuation between the transmitter and the receiver, and it would still just barely work.

Link Margin ...

- It is typical to design a system with at least a few dB of link margin, to allow for attenuation that is not modeled elsewhere.

- For example, a satellite communications system operating in the tens of gigahertz might require additional link margin in order to ensure that it still works with the extra losses due to rain fade or other external factors.

- A system with a negative link margin would mean the system is insufficient to transfer data, usually this means a better receiver is needed, with improved sensitivity.