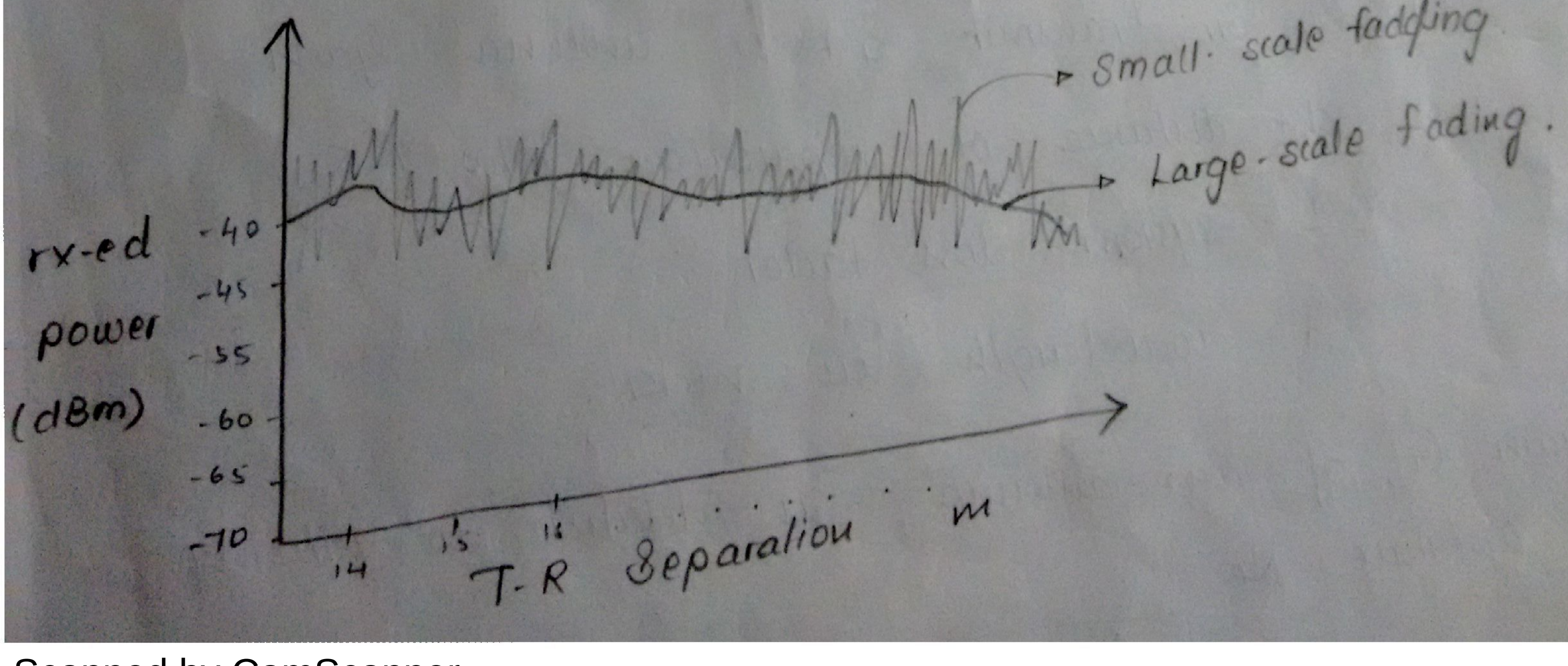
Radio Wave Propogation:

- radio channels are extremely random and cannot be easily analysed.
- ⇒ ∴ Modeling a radio channel is difficult compared to wired channel.

Propogation models that predict the mean signal strength for an arbitrary transmitter - receiver separated by a large distance (ie) several hundreds & thousands of meters are called <u>large SCALE PROPOGATION MODEL</u>

- Propogation models that characterize the rapid fluctuations of a received signal strength over a short distance (ie) a few wavelength (or) short duration are called <u>small scale PROPOGATION MODEL</u>.



FREE SPACE PROPOGATION MODEL :

- Satellite communication systems & microwave line of sight radio undergo free space propogation.
- free space propogation model is used to predict the received power signal strength when transmitter & rx-er has clear line of sight.

In large scale radio wave propogation model received power delays as a fn of T-R separation distance raised to power 2.

$$P_r \propto \frac{1}{d^2}$$

According to FRIIS SPACE EQUATION

$$\boxed{P_r(d) = \frac{P_t . G_t . G_r . \lambda^2}{(4\pi)^2 d^2 L}} \quad \text{——— (1)}$$

Where P_t - transmitted power

$P_r(d)$ - rx-ed power as a fn of T-R separation

G_t, G_r, transmit & rx-er antenna gain

d - distance of separation b/w T-R

L - system loss factor

λ - wavelength in meters.

Gain G, of an antenna is related to effective aperture A_e.

$$\boxed{G = \frac{4\pi A_e}{\lambda^2}}$$

where A_e is related to antenna size &

$$\boxed{\lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c}}$$

where f - carrier freq (Hz)

ω - carrier freq (radians/second)

Here P_t & P_r must be expressed in same units &

G_t & G_r - dimensionless quantities.

$L = 1$ indicates no loss in system hardware.

from eq ① - rxed power decays with distance at a rate of 20 dB/decade.

An isotropic antenna radiates power with unit gain uniformly in all directions.

Effective isotropic radiated power.

$$\boxed{EIRP = P_t G_t}$$

Generally ERP is used instead of EIRP.

where ERP will be 2.15 dB smaller than EIRP.

<u>Path loss</u>: represents the signal attenuation and is defined as the difference b/w effective transmit power and received power.

$$PL\,(dB) = 10 \log \frac{P_t}{P_r} = -10 \log \left[\frac{G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 d^2} \right]$$

when unity gain is assumed.

$$PL(dB) = 10 \log \frac{P_t}{P_r} = -10 \log \left[\frac{\lambda^2}{(4\pi)^2 d^2}\right]$$

friis free space model is valid only for value of d which are in far-field region.

far field, fraunhofer region is defined as region beyond df.

$$\boxed{d_f = \frac{2D^2}{\lambda}}$$

D - largest physical dimension of antenna

$$d_f >> D$$

$$d_f >> \lambda$$

large scale propogation at a distance d_0 ; $d > d_0$

also $d_0 \geq d_f$

$$\boxed{P_r(d) = P_r(d_0) \cdot \left[\frac{d_0}{d}\right]^2} \quad d \geq d_0 \geq d_f$$

P) find the far-field distance for an antenna with maximum dimension of 1m and operating freq of 900 MHz.

Largest dimension of antenna, D = 1m

$$f = 900\,MHz, \quad \lambda = c/f = \frac{3 \times 10^8\ m/s}{900 \times 10^6\ Hz} = 0.33\,m$$

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

1) If a transmitter produces 50W of power, express the transmit power in units of a) dBm and b) dBW. If 50W is applied to a unity gain antenna with 900 MHz carrier frequency, find the received power in dBm at a free space distance of 100m from the antenna. What is $P_r(10km)$? Assume unity gain for receiver antenna.

Transmit power, $P_t = 50 W$

Carrier frequency, $f_c = 900 MHz$

a) Transmitter power

$$P_t(dBm) = 10 \log [P_t(mW)/(1mW)]$$

$$= 10 \log [50/1\times10^{-3}]$$

$$= 10 \log [50 \times 10^3] = 47 dBm$$

b) Transmit power.

$$P_t(dBW) = 10 \log [P_t(W)/(1W)]$$

$$= 10 \log 50 = 17 dBW$$

c) Received power

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{900\times10^6} = 1/3$$

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

$$= \frac{50 . (1) . (1) . [1/3]^2}{(4\pi)^2 \times 100^2 \times (1)} = (3.5 \times 10^{-6}) W$$

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

$$P_r(dBm) = 10\log[P_r(mW)/1mW]$$

$$= 10\log\left[\frac{3.5\times10^{-3}\times(1\cancel{mW})}{1\cancel{mW}}\right]$$

$$= 10\log[3.5\times10^{-3}]$$

$$= -24.5\ dBm$$

d) rx-ed power at 10km can be expressed in ~~the~~ in terms of dBm.

where $d_o = 100m$

$d = 10\ km$

$$P_r(d) = P_r(d_o)\left[\frac{d_o}{d}\right]^2$$

taking log.

$$P_r(\overset{10}{\cancel{d}})\ dBm = P_r(100) + 20\log\left[\frac{d_o}{d}\right]$$

$$= -24.5\ dBm + 20\log\left[\frac{100}{10000}\right]$$

$$= -24.5\ dBm - 40\ dB$$

$$= -64.5\ dBm$$

Three Basic Propogation mechanisms:

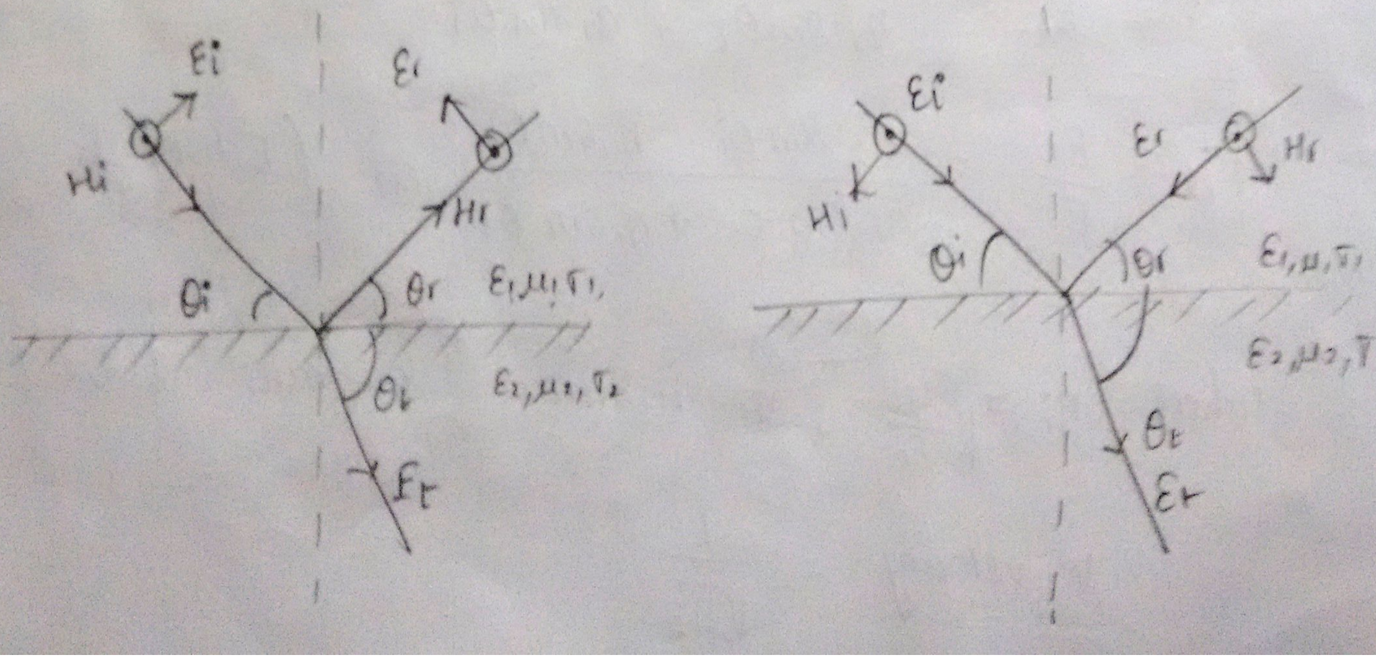
- Reflection
- Diffraction
- Scattering

Reflection:

- Reflection occurs when an electromagnetic wave impinges on an object having very large dimensions compared to the wavelength of propogating wave.
- When a radio wave impinges on a medium with different electrical properties, the wave is partially reflected & partially transmitted.
- Fresnel reflection co-efficient:

The electric field intensity of the reflected & transmitted wave are related to the incident wave in the medium of origin by fresnel reflection co-eff.

(a) E field - r to POI



- Fig shows an EM wave with an incident angle θ_i, reflected angle θ_r & part of energy transmitted in second medium θ_t.
- Plane of incidence: is the plane containing the incident, reflected & transmitted rays.
- In the figure,
  - → i, r, t refers to incident, reflected and transmitted fields
  - → $\varepsilon_1, \mu_1, \sigma_1$ & $\varepsilon_2, \mu_2, \sigma_2$ represents the permittivity permeability & conductance of the 2 media.
- In fig (a), the E field polarization is ||le with plane of incidence & H field is ⊥r to plane of incidence.
- In fig (b), the E-field polarization is ⊥r to the plane of incidence & H field is ||le to plane of incidence.
- The reflection coeff's for 2 cases of ||le & ⊥r E-field polarization is given as

$$\Gamma_{11} = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_t - \eta_1 \sin\theta_i}{\eta_2 \sin\theta_t + \eta_1 \sin\theta_i} \quad \text{—①} \quad (\text{E field ||le to POI})$$

$$\Gamma_{12} = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_i - \eta_1 \sin\theta_t}{\eta_1 \sin\theta_i + \eta_1 \sin\theta_t} \quad \text{—②} \quad (\text{E field ⊥r POI})$$

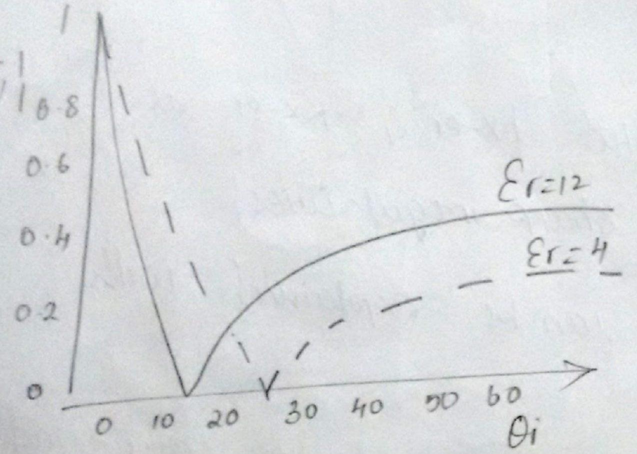
where $\eta_i = \sqrt{\frac{\mu_i}{\varepsilon_i}}$ —③, η_i - intrinsic Impedance. $i=1,2$

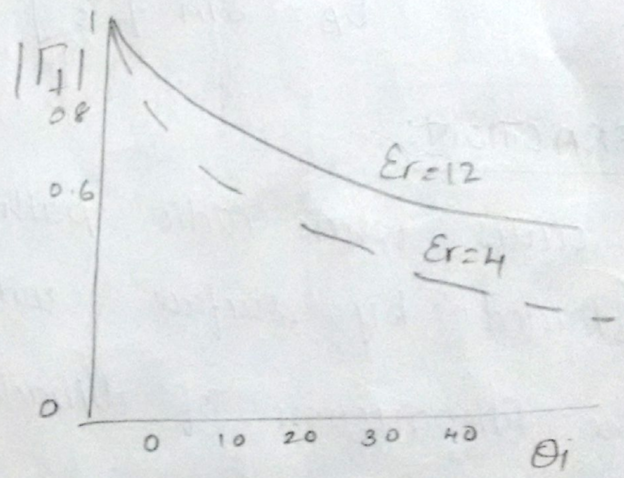
$$v, \text{velocity} = \frac{1}{\sqrt{\mu\varepsilon}}$$

Substituting ① ② ③ in ① & ② & after simplification vertical & horizontal polarization becomes.

$$\Gamma_{\parallel} = \frac{-\varepsilon_r \sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}{\varepsilon_r \sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}$$

$$\Gamma_{\perp} = \frac{\sin\theta_i - \sqrt{\varepsilon_r - \cos^2\theta_i}}{\sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}$$





magnitude of reflection co-eff's as a fn of angle of incidence, when it propogates in free space.

Brewster Angle:

- It is the angle at which no reflection occurs in the medium of origin.
- It occurs when the incident angle θ_B is such that the reflection co-eff $\Gamma_{\parallel} = 0$

$$\therefore \sin\theta_B = \sqrt{\frac{\varepsilon_1}{\varepsilon_1 + \varepsilon_2}}$$

Brewster Generalized expression

$$\sin \theta_B = \frac{\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r^2 - 1}}$$

P) Calculate the Brewster angle for a wave impinging on ground having a permittivity of $\varepsilon_r = 4$

$$\sin \theta_B = \frac{\sqrt{4-1}}{\sqrt{4^2-1}} = \sqrt{\frac{1}{5}}$$

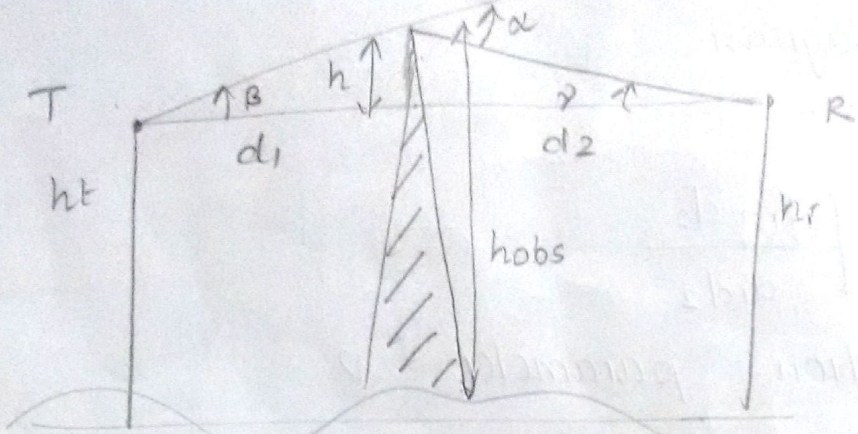
$$\theta_B = \sin^{-1}\left[\frac{1}{5}\right] = 26.56^\circ$$

DIFFRACTION:

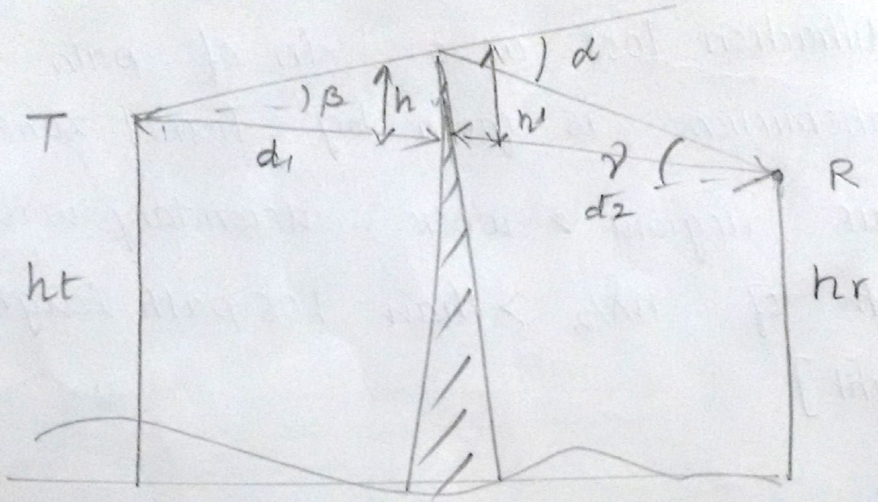
- It occurs when radio path b/w Tx-er & Rx-er is obstructed by surface with sharp irregularities.
- The Phenomenon of diffraction can be explained with huygen's principle.
  "all pts. on a wavefront is considered as point source for production of secondary wavelets & these wavelets combine to produce new wavefronts in the propogating direction"
- Diffraction is caused by propogation of secondary wavelet into a shadowed region.

Fresnel Zone Geometry

- Consider a Tx-er & Rx-er separated in free space.
- An obstruction screen is placed between them with height h & width infinity & at a distance of d_1 from Tx & d_2 from Rx.



It is clear that wave propogating from Tx to RX via top of screen travels longer than direct line of sight.



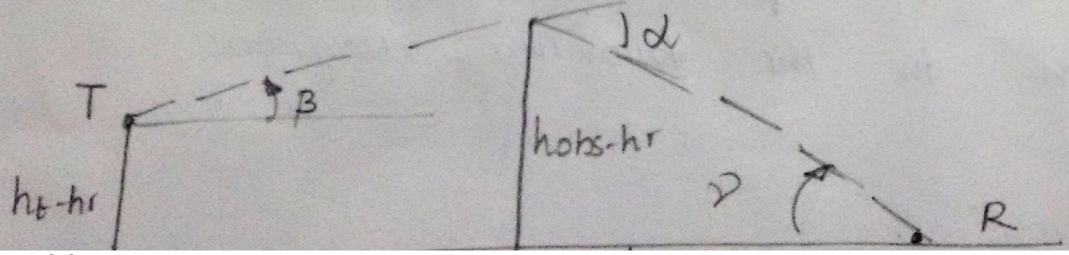
Assuming $h \ll d_1, d_2$ & $h \gg \lambda$, the diff b/w direct path & diffracted path called excess path length (Δ)

$$\boxed{\Delta = \frac{h^2}{2}\frac{(d_1+d_2)}{d_1 d_2}}$$

corresponding phase diff.

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

In practical case, it is better to reduce all heights to constant so that the geometry is simplified.



from the diagram

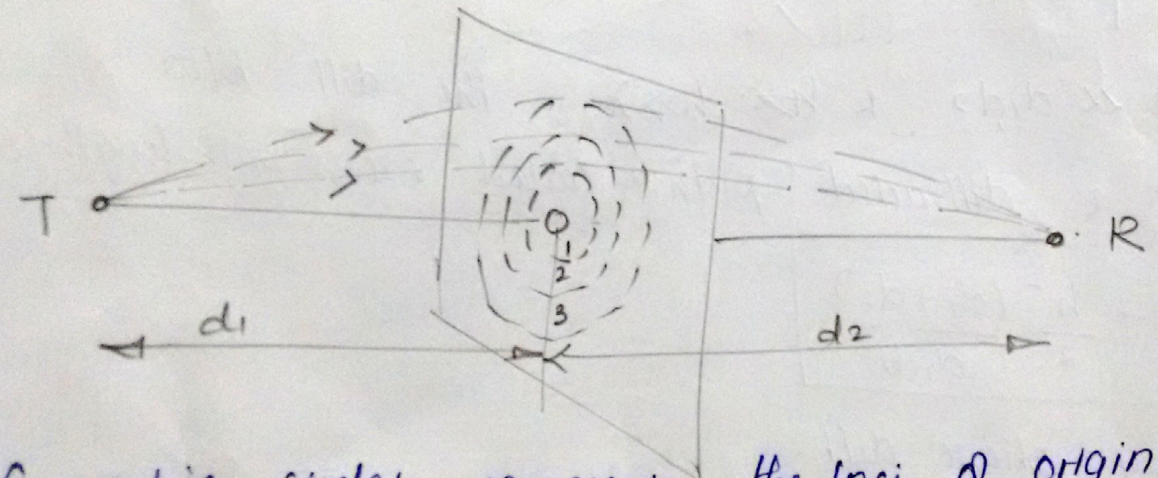
$$\alpha = \beta + \gamma$$

$$\alpha = h \left[\frac{d_1 + d_2}{d_1 d_2} \right.$$

fresnel diffraction parameter v

$$v = h \sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = \alpha \sqrt{\frac{2 d_1 d_2}{\lambda (d_1+d_2)}}$$

- Concept of diffraction loss as a fn of path difference around an obstruction is given by fresnel zones.
- Fresnel zones are regions where secondary waves have a path length of $n\lambda/2$ > than LOS path length [Line of Sight]



- Concentric circles represents the loci of origin of sec. waves.
- These circles are fresnel zones.
- The successive fresnel zone alter b/w constructive & destructive interference.

Diffrent ~~kf~~ knife edge diffraction scenarios are shown in the following diagrams.

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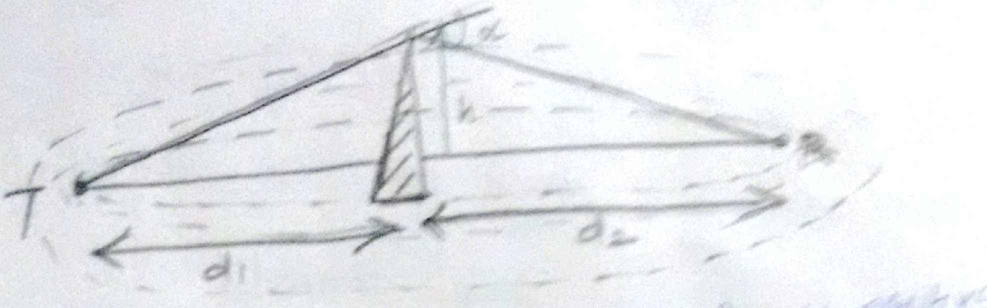
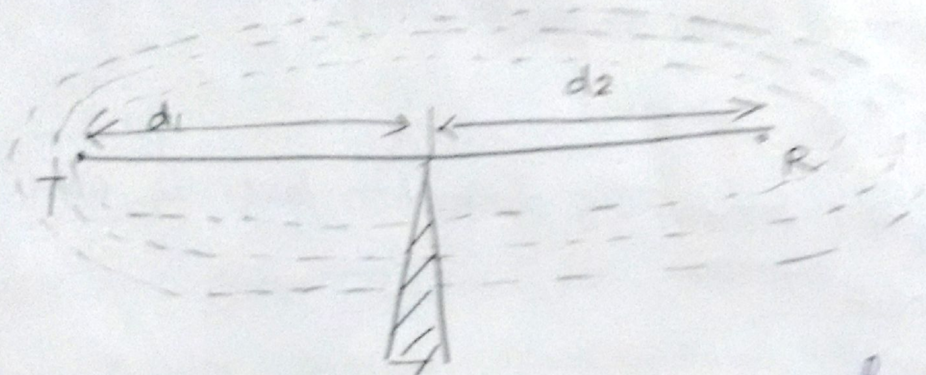
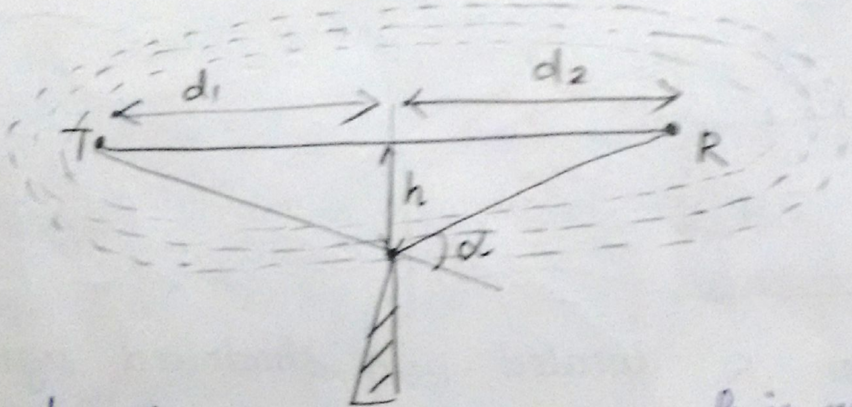


α and v are positive since h is positive



α and v are equal to zero since $h=0$

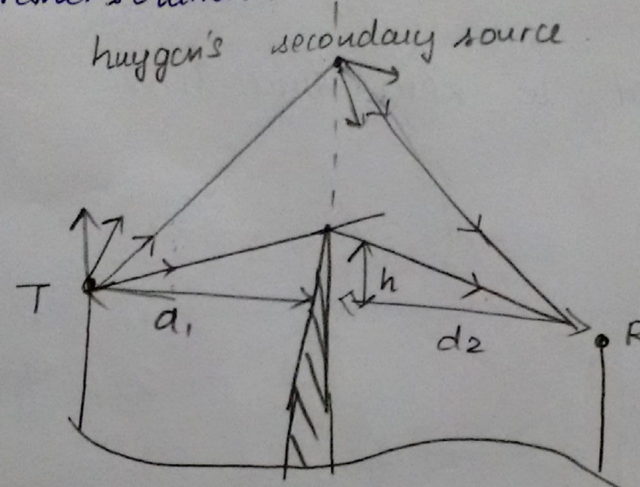


α and v are negative, since h is negative.

- We conclude that if the obstruction does not block the volume contained in the first fresnel zone. the diffraction loss will be minimum
- Generally Line of sight microwave link is designed in such a way that 55% of Fresnel zone is clear (i.e) without obstruction.

- **Knife Edge Diffraction model:**

- Estimating the signal attenuation caused by diffraction of radio waves over hills & buildings is difficult.
- When Shadowing is caused by single object (hill), it can be considered as a diffracting knife edge & attenuation can be estimated.
- It is the simplest model & diffraction loss is estimated using fresnel solution.



- Consider a receiver R located in a shadowed region
- field Strength at Pt. R is vector sum of fields due to secondary Huygen's source in the plane above knife edge

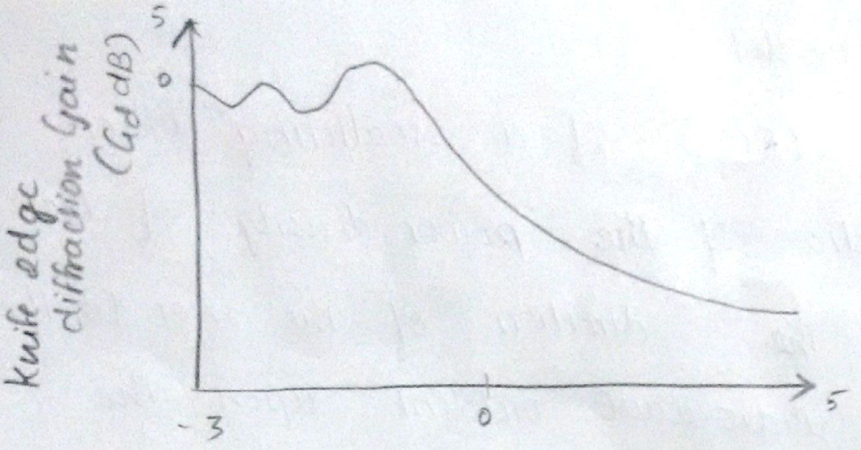
$$\frac{E_d}{E_o} = F(v) = \frac{1+j}{2} \int_{v}^{\infty} \exp\left(-j\pi t^2\right)/2 \, dt$$

E_o is the free space field Strength

$F(v)$ is the complex fresnel integral

$\therefore$ Diffraction gain

$$\boxed{G_d(dB) = 20 \log |F(v)|}$$



SCATTERING

- Scattering occurs when the medium through which the wave travels consists of object with dimensions smaller than the wavelength & the no. of obstacles per unit volume is large.
- When a radio wave impinges on a rough surface the reflected wave is spread in all directions due to scattering thereby providing additional radio energy at the rxer.
- Surface roughness is tested using Rayleigh criteria which defines critical heigh h_c of surface protuberances for an angle of incidence θ_i.

$$\boxed{h_c = \frac{\lambda}{8\sin\theta_i}}$$

- A surface is smooth, if its min to max protuberance h is less than h_c.
- It is considered rough, if its min to max protuberance is greater than h_c.

Radar Cross Section model

- The radar cross section (RCS) of a scattering object is defined as the ratio of the power density of the signal ~~scattering~~ed in the direction of the rx-er to the power density of the radio wave incident upon the scattering object.

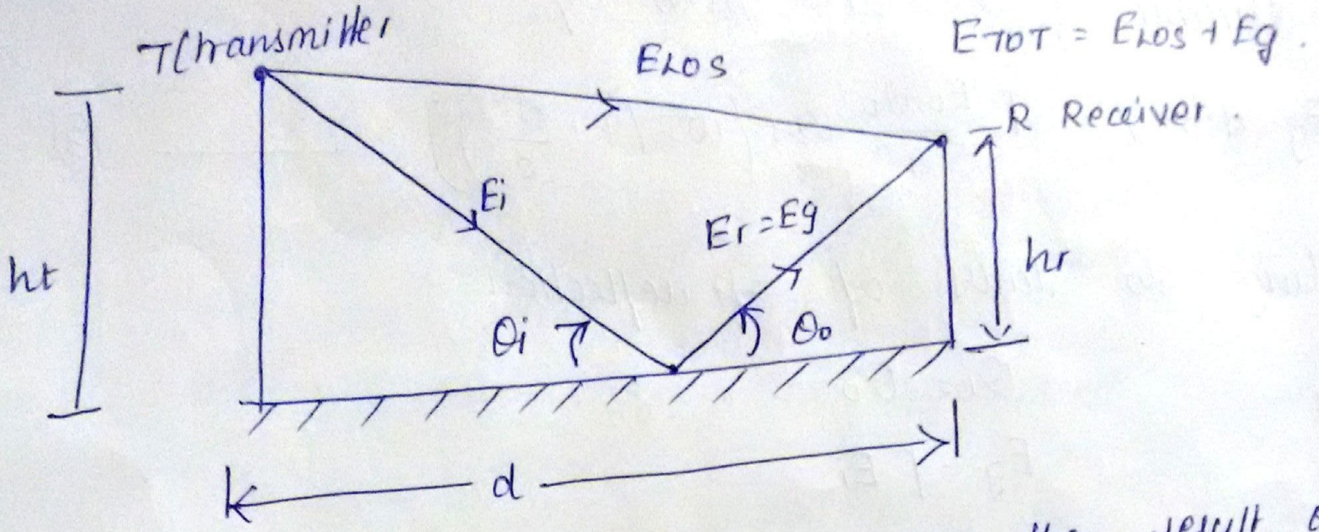
- for urban mobile radio systems, received power is given by.

$$P_R\,(dBm) = P_T\,(dBm) + G_T\,(dBi) + 20\log(\lambda) + RCS\,[dBm^2] - 30\log(4\pi) - 20\log d_T - 20\log d_R$$

- Where d_T & d_R - distance from the scattering object to the tx-er and rx-er.
- The variable RCS is given in units of $dB.m^2$

GROUND REFLECTION MODEL: [TWO-RAY MODEL]

- Two ray ground reflection model considers both direct path & ground reflectioned propogation path between tx-er & rx-er.



- The total rx-ed E-field E_{TOT} is the result of direct line-of-sight component (~~Et~~ E_{LOS}) and ground reflected component E_g.
- In the above figure, h_t is the height of tx-er.

h_r - height of the receiver.

E_0 is the free space E-field at a distance d_0, $(d > d_0)$

E-field is given by,

$$E(d,t) = \frac{E_0 d_0}{d} \cos\left[\omega_c\left(t - \frac{d}{c}\right)\right] \quad (d > d_0) \quad \text{①}$$

where $\boxed{|E(d,t)| = \frac{E_0 d_0}{d}}$, is the envelop of E-field.

E field due to LOS component which travels a distance d' is given by.

$$E_{LOS}(d',t) = \frac{E_0 d_0}{d'} \cos\left[\omega_c\left(t - \frac{d'}{c}\right)\right] \quad \text{②}$$

E-field due to ground reflected wave which travels a distance of d'' is given by.

$$E_g(d'',t) = \Gamma \frac{E_0 d_0}{d''} \cos\left[\omega_c\left(t - \frac{d''}{c}\right)\right] \quad \text{③}$$

According to laws of reflection

$$\theta_i = \theta_0$$

$$E_g = \Gamma E_i$$

$$E_t = (1+\Gamma) E_i$$

Γ - reflection co-eff.

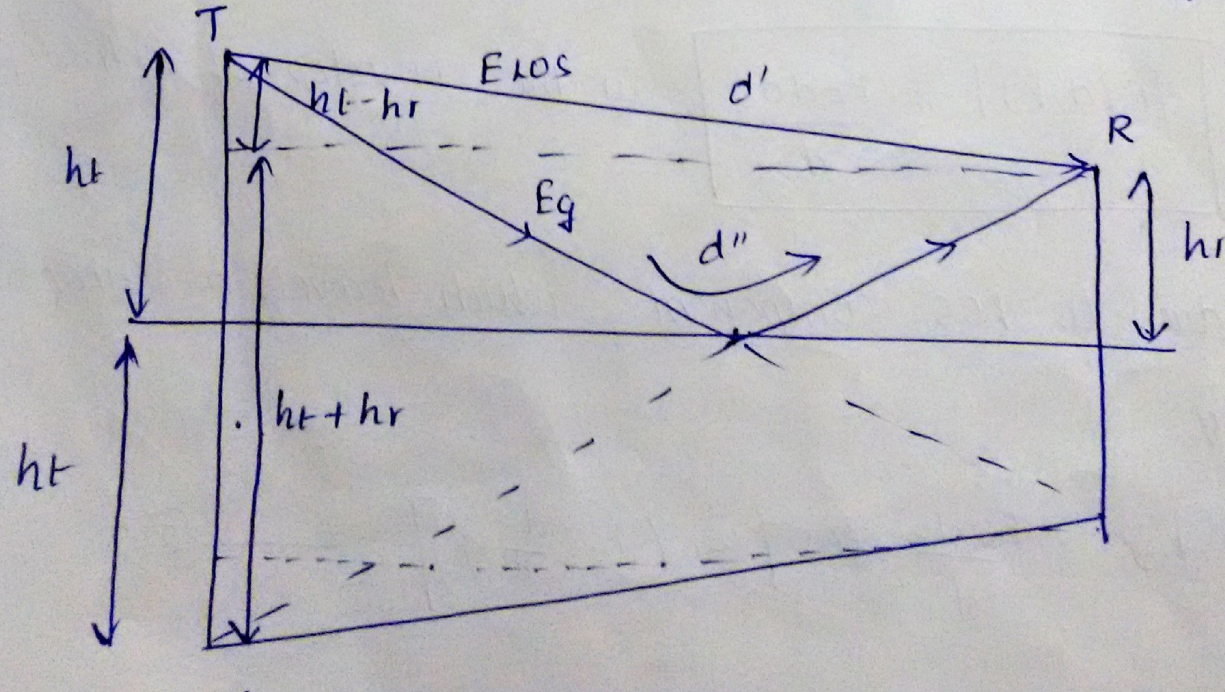
Assuming E-field to be horizontally polarized.

$$\Gamma_{\perp} = -1 \quad , \quad E_t = 0$$

$$|E_{TOT}| = |E_{LOS} + E_g| \quad \text{④}$$

(i.e) E_{TOT} is sum of ② & ③

$$E_{TOT}(d,t) = \frac{E_0 d_0}{d'} \cos\left[\omega_c\left(t - \frac{d'}{c}\right)\right] + (-1)\frac{E_0 d_0}{d''} \cos\left[\omega_c\left(t - \frac{d''}{c}\right)\right] \quad \text{⑤}$$



Method of Images.

using method of images, path difference Δ, between LOS & ground reflected path.

$$\Delta = d'' - d'$$

$$= \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \quad \text{—— (6)}$$

when d is very large compared to $(h_t + h_r)$

$$\Delta = d'' - d' \simeq \frac{2 h_t h_r}{d} \quad \text{—— (7)}$$

Phase difference θ_Δ & time delay is given by

$$\theta_\Delta = \frac{2\pi\Delta}{\lambda} = \frac{\Delta\, \omega_c}{c} \quad \text{—— (8)}$$

$$\tau_d = \frac{\Delta}{c} = \frac{\theta_\Delta}{2\pi f_c} \quad \text{—— (9)}$$

When d is large d' & d'' are almost equal.

i.e.

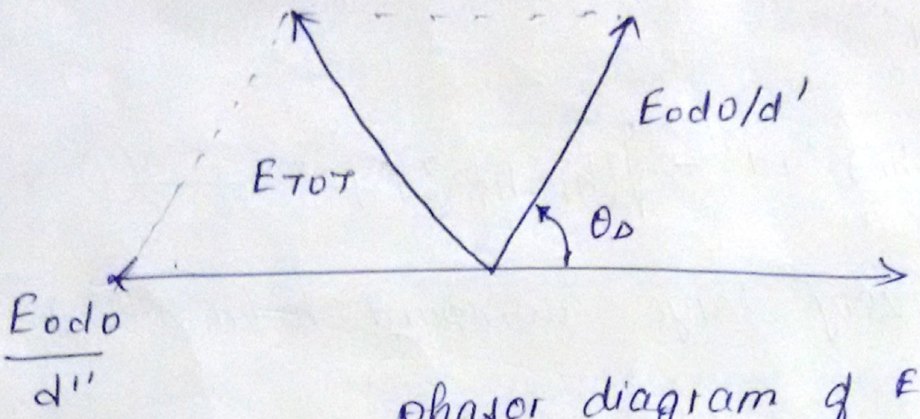
$$\left|\frac{E_0 d_0}{d}\right| \approx \left|\frac{E_0 d_0}{d'}\right| \approx \left|\frac{E_0 d_0}{d''}\right| \quad \text{—— (10)}$$

Received E-field at time $t = d''/c$ can be written from eq. (5). as

$$E_{TOT}\left(d, t = \frac{d''}{c}\right) = \frac{E_0 d_0}{d'} \cos\left(\omega_c \left[\frac{d'' - d'}{c}\right]\right) - \frac{E_0 d_0 \cos 0}{d''} \quad \text{—— (11)}$$

$$= \frac{E_0 d_0}{d'} \angle \theta_\Delta - \frac{E_0 d_0}{d''}$$

$$= \frac{E_0 d_0}{d} [\angle \theta_\Delta - 1]$$



phasor diagram of E field component.

from the phasor diagram E field at distance d is given by.

$$|E_{TOT}(d)| = \sqrt{\left(\frac{E_0 d_0}{d}\right)^2 (\cos\theta_\Delta - 1)^2 + \left(\frac{E_0 d_0}{d}\right)^2 \sin^2\theta_\Delta} \quad \text{--- (12)}$$

Using trignometric identities it is simplified as

$$|E_{TOT}(d)| = 2\frac{E_0 d_0}{d} \sin\left[\frac{\theta_\Delta}{2}\right] \quad \text{--- (13)}$$

where $\boxed{\sin\left(\frac{\theta_\Delta}{2}\right) \simeq \frac{\theta_\Delta}{2}}$

using (7) & (8).

$$\therefore \frac{\theta_\Delta}{2} \approx \frac{2\pi h_t h_r}{\lambda d}.$$

$\therefore$ Eq. (13) becomes.

$$E_{TOT}(d) = \frac{2 E_0 d_0}{d} \cdot \frac{2\pi h_t h_r}{\lambda d} \quad \text{--- (14)}$$

∴ Received power at a distance d is given by

$$\boxed{P_r = P_t \cdot G_t \cdot G_r \frac{h_t^2 h_r^2}{d^4}} \quad \text{——— (15)}$$

(i.e) received power falls at a rate of 40dB/decade.

$$P_L(dB) = 40 \log d - [10 \log G_t + 10 \log G_r + 20 \log h_t + 20 \log h_r] \quad \text{(16)}$$

* **Practical Link Budget Design using Path Loss Models.**

- radio propogation models can be derived using analytical & emprical methods.
- Emprical methods are based on curve fitting.
- It takes into account all propogation factors.
- Disadv: it is not valid when environment changes.
- Path Loss model can be used to estimate the rxed power as a function of distance.

Log-distance path Loss model:

- Avg rx-ed signal power decreases Logarithmically with distance
- Avg large scale path loss for a TR seperation is expressed as a fn of distance using path Loss exponent, n.

$$\overline{PL}(d) \propto \left[\frac{d}{d_0}\right]^n$$

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

n is the path loss exponent

d_0 - reference distance

d - TR separation distance.

Log-normal Shadowing:

disadv in log-distance path loss model:

- It does not consider the fact the environment is different for two diff locations having same T-R separation.

∴ many times measure signal is different from the average value.

so we go for log-normal shadowing; which considers the fact that path loss at a particular location is random & log-normally distributed. (i.e)

$$\boxed{PL(d)\,[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10\log\frac{d}{d_0} + X_\sigma}$$

$$P_r(d)\,[dBm] = P_t\,[dBm] - PL(d)\,[dB]$$

- Where X_σ is a zero-mean Gaussian distributed random variable.
- Log normal distribution describes the random shadowing effect which occurs over a large no. of measurement locations for the same TR separation distance but ~~at~~ in diff environment. This is called Log normal shadowing.

Outdoor Propogation model:

- Radio wave transmission takes place over a irregular terrain.
- ∴ Terrain profile has to be considered inorder to estimate the path loss.
- A no. of models are available to predict path loss over irregular terrain.

(i) OKUMURA MODEL:

- This model is widely used for signal prediction in urban areas.
- It is used for Base Station antenna height of 30m - 1000m.
- Okumura developed a set of curves which gives median attenuation A_{mu} relative to free space in urban area over quasi smooth terrain with antenna height of 200m (h_{te}) and 3m (h_{re})

h_{te} - transmitter (BS) antenna height.

h_{re} - receiver (MS) antenna height.

- curves are plotted as a fn of frequency range ~~from~~ 100 MHz to 1920 MHz also as a fn of distance from BS in the range 1Km to 100 km.

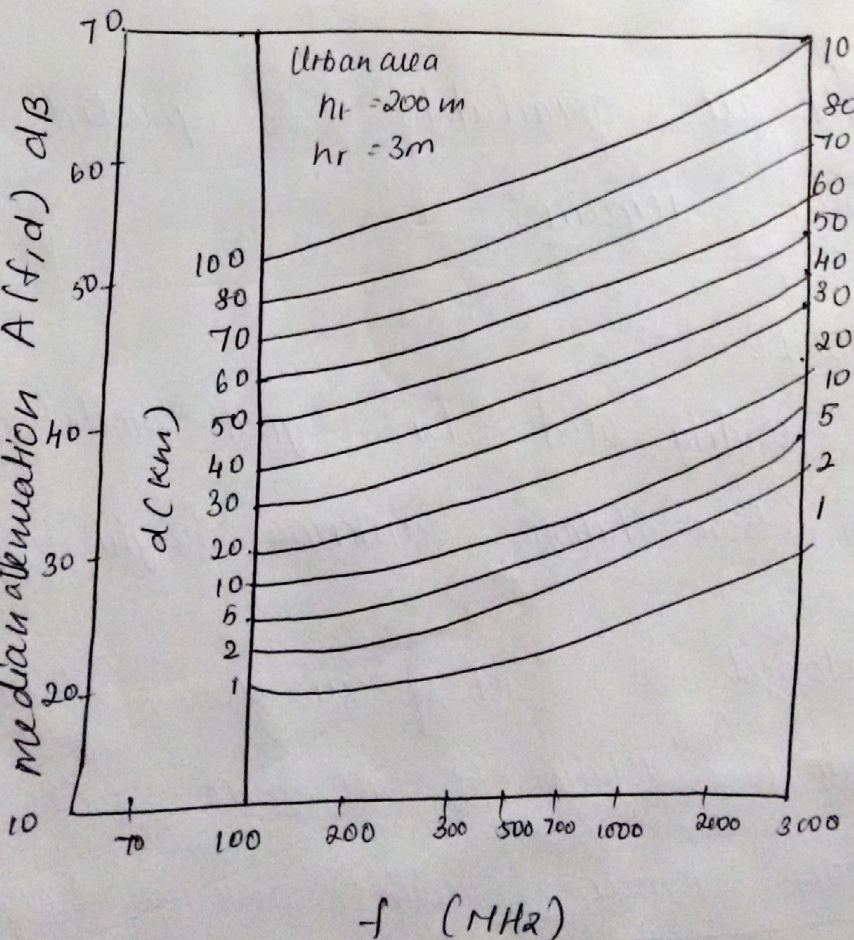
- Path loss (50^{th} percentile) L_{50} (dB)

$$\boxed{L_{50}(dB) = L_F + A_{mu}(f, d) - G(h_{te}) - G(h_{re}) - G_{AREA}}$$

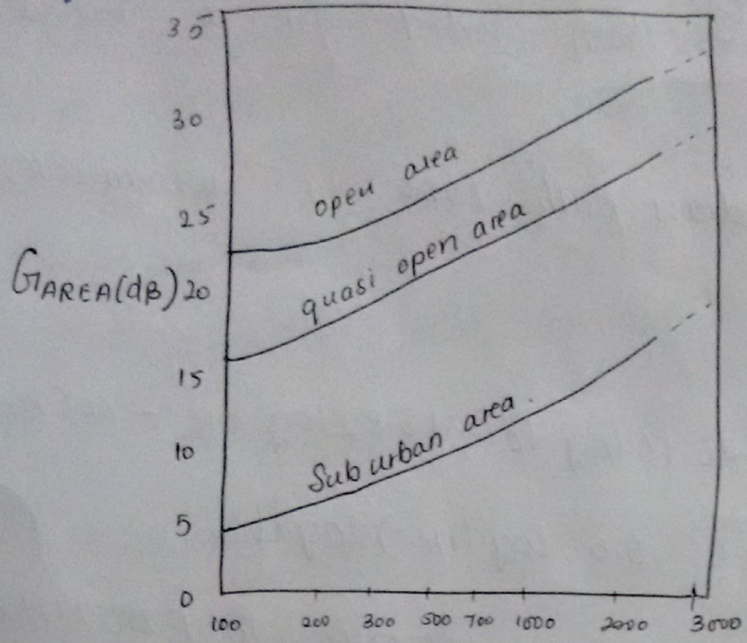
G_{area} - gain due to environment.

$G(h_{te})$ - BS antenna height gain factor

$G(h_{re})$ - MS antenna height gain factor.



- Plot of Amu (f,d) and G_{AREA} for diff freq



$$G(h_{te}) = 20 \log \left[\frac{h_{te}}{200}\right] \quad 1000m > h_{te} > 30m$$

$$G(h_{re}) = 10 \log \left[\frac{h_{re}}{3}\right] \quad h_{re} \leq 3m$$

$$G(h_{re}) = 20 \log \left[\frac{h_{re}}{3}\right] \quad 10m > h_{re} > 3m$$

Okumura found that,

- $G(h_{te})$ varies at a rate of 20dB/decade &
- $G(h_{re})$ varies at a rate of 10dB/decade less than 3m.

adv:

- It is simplest & accurate method.

disadv:

- Slow response to rapid changes in terrain
- It is good in urban & suburban areas but not good in ~~rapi~~ rural areas.

• HATA MODEL

• HATA model is empirical method valid for a range from 150 MHz to 1500 MHz.

• Standard formula for median path loss in urban area is given by.

$$L_{50}(\text{urban})(dB) = 69.55 + 26.16 \log f_c - 13.82 \log h_{te} - a(h_{re}) + (44.9 - 6.55 \log h_{te}) \log d$$

f_c is the frequency from 150 MHz to 1500 MHz.

h_{te} - effective transmitter antenna height. (30m - 200m)

h_{re} - effective receiver antenna height (1m to 10m)

d - T-R separation distance

$a(h_{re})$ - correction factor as a fn. of antenna height.

where the correction factor for small to medium city.

$$\boxed{a(h_{re}) = (1.1 \log f_c - 0.7) h_{re} - (1.56 \log f_c - 0.8)\ dB}$$

for large city it is given by.

$$a(h_{re}) = 8.29 (\log 1.54 h_{re})^2 - 1.1\ dB \quad \text{for } f_c \leq 300\ MHz$$

$$a(h_{re}) = 3.2 (\log 11.75 h_{re})^2 - 4.97\ dB \quad \text{for } f_c \geq 300\ MHz$$

Prediction of Hata model compare very closly with original Okumura model as long as d exceeds 1km.

- Indoor Propogation model varies from outdoor propogation model in 2 aspects.
  - distance covered are much smaller
  - variability of environment is much greater for a much smaller range of TR separation distance.
- Propogation within buildings is influenced by layout of the building, construction materials, building type.

Partition losses : (same floor)

- partitions that are formed as part of building structure - hard partition.
- partitions that can be moved and that do not span to the ceiling are called soft partitions.
- partitions vary widely in physical & electrical char.
- In indoor propogation models, each material have different loss at diff frequencies.

Partition losses between floors :

- Losses b/w floors is determined by external dimensions, materials of the building etc.
- Floor Attenuation factor increases with increase in no. of floors.

- Log-distance Path loss model:

distance power law is given by

$$PL(dB) = PL(d_0) + 10n \log\left[\frac{d}{d_0}\right] + X_r$$

where n depends on surrounding building.

X_r - normal random variable.

SMALL SCALE FADDING

Small scale fading describes rapid fluctuations of amp, phases & multipath delay of radio signal over a short period of time.

fadding: It is caused by interference between two or more versions of tx-ed signal that arrive a rx-er with slightly diff time.

multipath signals in radio channel creates small-scale fadding effects.

FACTORS INFLUENCING SMALL SCALE FADING:

- Multipath Propogation:

→ The reflecting objects & the scatterers in the environment causes signal energy in amplitude, phase & time to vary.

- This effects causes multiple versions of tx-ed signal to arrive at the rx-er.
- where these multiple version signals vary in time & space (with respect) w.r.to one another.
- This random phase & amplitude causes fluctuations in signal strength, inducing small-scale fading.

Speed of the mobile:

- relative motion between the B.S and the mobile results in different Doppler shift on ~~the~~ each multipath component.
- Doppler shift is positive or negative depending ~~on~~ on whether mobile is moving towards or away from B.S.

Speed of surrounding objects:

- when objects in a radio channel are in motion, ~~by~~ they induce time ~~varing~~ varying doppler shift.
- If objects move at a greater rate than the mobile then this effects dominates small scale fadding else it can be neglected.
- 'Coherence time' defines the 'staticness of the channel'

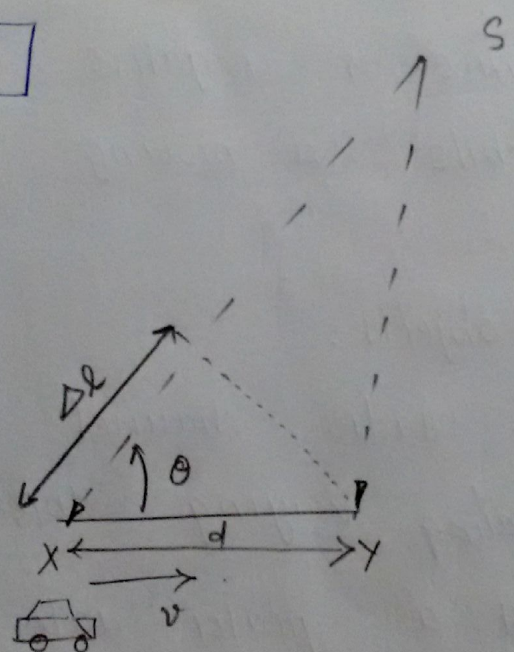
- Transmission bandwidth of the signal :-

- When transmitted radio signal B.W is greater than B.W of multipath channel, the received signal is distorted.

- B.W of the channel is quantified by coherence bandwidth.

- Coherence bandwidth is a measure of maximum frequency difference for which signals are still strongly correlated in amplitude.

DOPPLER SHIFT



- Consider a mobile moving at a constant velocity v, along a path segment of length d between pts X & Y.

- Source S.

- Difference in path length (Δl) travelled by the wave from Sourse S to mobile at pt X & Y is given by

$$\Delta l = d\cos\theta = v\,\Delta t\cos\theta$$

Δt time required for MS to travel from X to Y.

- Phase change in received signal,

$$\boxed{\Delta\phi = \frac{2\pi\,\Delta l}{\lambda} = \frac{2\pi\,v\,\Delta t}{\lambda}\cos\theta}$$

- apparent change in freq, Doppler Shift.

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

① SMALL - SCALE FADING

(Based on multipath time delay spread)

FLAT FADING

1. B.W of Signal < B.W of channel
2. Delay Spread < Symbol Period

FREQUENCY SELECTIVE FADING

1. B.W of Signal > B.W of channel
2. Delay Spread > Symbol period

② SMALL - SCALE FADING

(Based on Doppler Spread)

FAST FADING

1. High Doppler Spread
2. Coherence time < Symbol period
3. Channel variations faster than baseband signal variation.

SLOW FADING

1. Low Doppler Spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations.

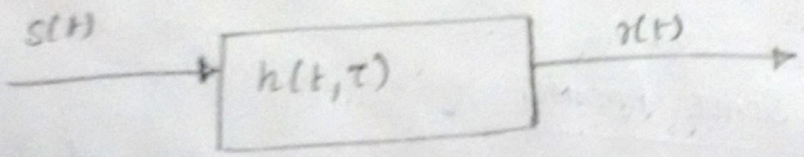
Types of Small Scale fading

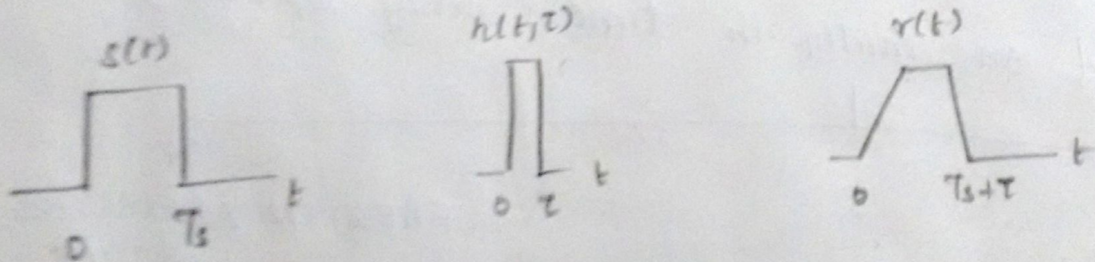
- fading effects due to multipath Time delay Spread

Time dispersion due to multipath causes the transmitted signal to undergo either flat or frequency selective fading.

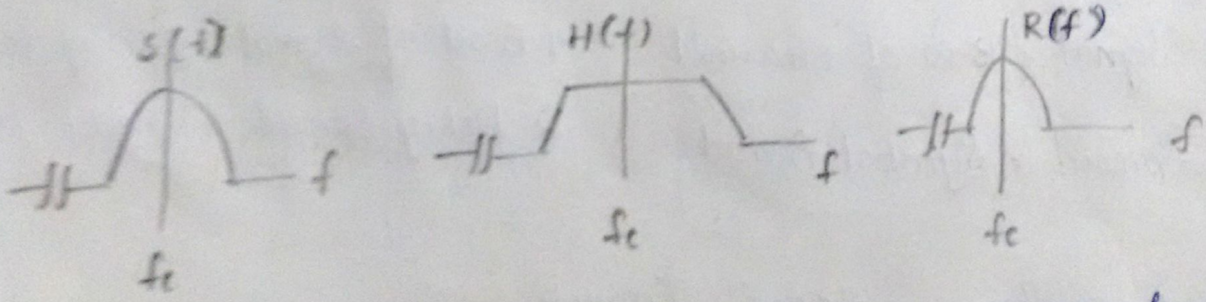
1) flat fading:

When a mobile radio channel has constant gain and linear phase response over a B.W greater than B.W of the transmitted signal, then the rx-ed signal undergoes flat fading.





$\tau << T_s$



- flat fading is also refered as narrowband channels since B.W of applied signal is narrow compared to channel B.W.

- Signal undergoes flat fading if

$$B_s << B_c$$

$$T_s >> \sigma_\tau$$

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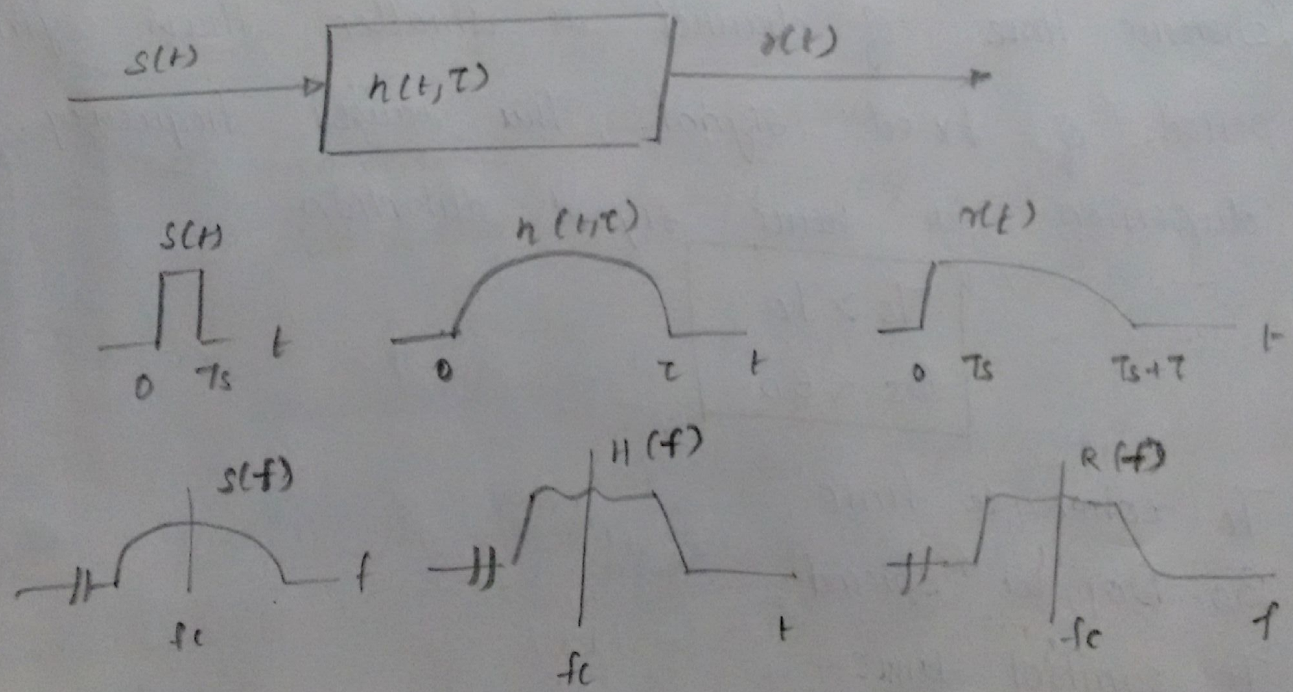
where T_s is the reciprocal of bandwidth B_s.

σ_τ is the rms delay spread

B_c is the coherence bandwidth.

(ii) Frequency Selective fading:

- When a mobile radio channel has constant gain and linear phase response over a B.W that is smaller than B.W of the transmitted signal, then the rx-ed signal undergoes frequency selective fading.
- frequency selective fading is due to time dispersion of the transmitted symbols within the channel.
- Thus channel induces ISI



- Frequency selective fading is caused by multipath delay ~~with~~ which exceed the symbol period of the transmitted symbol.
- It is also known as wideband ~~st~~ channels since bandwidth of the signal s(t) is wider than the bandwidth of the channel.

signal undergoes frequency selective fading

$$\boxed{\begin{matrix} B_s > B_c \\ T_s < \sigma_\tau \end{matrix}}$$

• Fading Effects due to Doppler Spread :

i) fast fading :

Based on how rapidly the transmitted signal changes compared to the rate of change of channel channel is classified into fast & slow fading channel.

• fast fading : channel impulse response changes rapidly within the symbol duration.

• Coherence time of channel is smaller than symbol period of tx-ed signal, This causes frequency

• dispersion & hence signal distortion

$$\boxed{\begin{matrix} T_s > T_c \\ B_s < B_D \end{matrix}}$$

T_c - coherence time

B_D - Doppler Spread

T_s - symbol time

B_s - Bandwidth of the tx-ed signal

(ii) Slow fading :

• Channel impulse response changes at a rate much slower than the transmitted baseband signal s(t)

- In frequency domain, Doppler spread of the channel is much smaller than bandwidth of the baseband signal.

∴ Signal undergoes slow fading if

$$T_s << T_c$$

$$B_s >> B_D$$

- MATRIX illustrating type of fading experienced by a signal as a fn of symbol period

Symbol Period of Transmitting symbol

	$< T_c$	$> T_c$
T_s	flat slow fading	flat fast fading
σ_τ	freq selective slow fading	freq selective fast fading

$\rightarrow T_s$

Transmitted Symbol Period

- matrix illustrating type of fading experienced by signal as a fn of baseband signal B.W

Transmitted Baseband Signal B.W

$\uparrow B_S$	freq Selective fast fading	freq selective slow fading
B_C	flat fast fading	flat slow fading

$\rightarrow B_s$

Transmitted Baseband Signal B.W

Rayleigh fading Distribution:

Rayleigh distribution has a probability fn given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left[-\frac{r^2}{2\sigma^2}\right] & (0 \le r \le \infty) \\ 0 & (r < 0) \end{cases}$$

σ is the rms value of the received voltage

σ^2 is the time-average power of the rx-ed signal

- Cumulative distribution fn.

$$\boxed{P(R) = 1 - \exp\left[\frac{-R^2}{2\sigma^2}\right]}$$

- mean value r_{mean} of Rayleigh distribution

$$\boxed{r_{mean} = E[r] = \int_0^\infty r p(r)\, dr = 1.2533\,\sigma}$$

- Variance of rayleigh distribution.

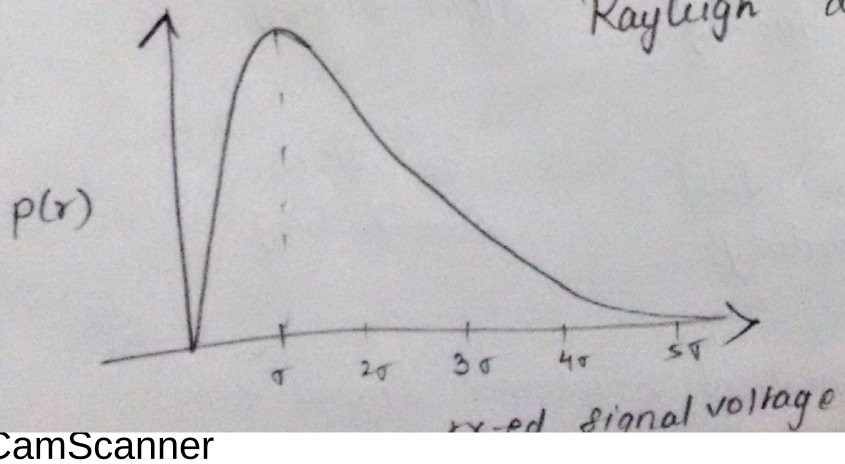
$$\boxed{\sigma_r^2 = 0.42\,\sigma^2}$$

σ is the standard deviation of original signal

- median value of r, r_{median}

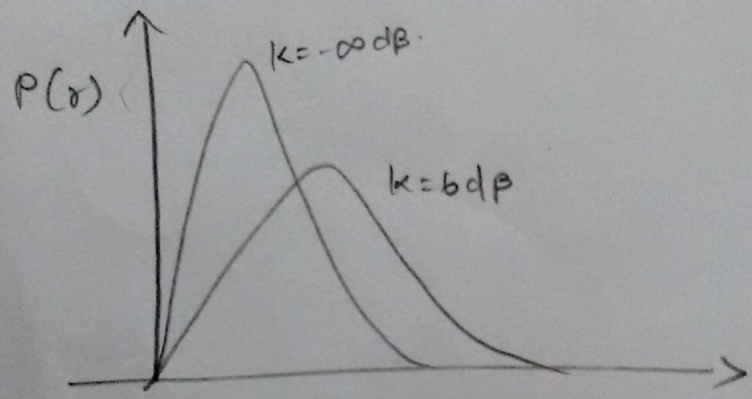
$$\boxed{r_{median} = 1.177\,\sigma}$$

Rayleigh distribution fn.



- **Ricean fading Distribution:**

  - when there is a dominant stationary signal component present, such as a LOS propogation path, small scale fading envelop distribution is Ricean.
  - As dominant signal becomes weaker, composite signal resembles a noise signal - which has an envelop of rayleigh.
  - (i.e) ricean distribution degenerates to rayleigh distribution when dominant component fades away.



Probability density fn of Ricean distribution : k = -∞dB (Rayleigh) and k = 6 dB.

Ricean distribution.

$$\boxed{p(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{(r^2+A^2)}{2\sigma^2}} I_0\left[\frac{Ar}{\sigma^2}\right] & \text{for } (A \geq 0, r \geq 0) \\ 0 & \text{for } (r < 0) \end{cases}}$$

- A - denotes the peak amplitude
- $I_0(\cdot)$ is the modified Bessel fn.

Ricean distribution described using parameter k

$$K = \frac{A^2}{2\sigma^2}$$ $\frac{[\text{deterministic signal}]}{\text{Variance}}$

Where k is the ricean factor.

as $A \longrightarrow 0$, $k \longrightarrow \infty$ dB (ie) ricean becomes rayleigh distribution.