Chapter 4 :

Large scale path loss

قسم هندسة تقنيات الحاسوب

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Chapter 4

4.1 Mobile Radio Propagation

- The transmission path between the transmitter and the receiver can be either Simple line-of-sight (LOS), or Obstructed by buildings, mountains, and foliage.
- The speed of motion impacts how rapidly the signal level fades as a mobile terminal moves.
- The signal strength decreases as the distance between the transmitter and receiver increases.
- Propagation models have focused on predicting the average received signal strength at a given distance from the transmitter.
  a. **Large-scale propagation models**: used for estimating the radio coverage area of a transmitter for large T-R separation distances.
  b. **Small-scale fading models:** models that characterize the rapid fluctuations of the received signal strength over very short travel distances.
- As mobile moves over very small distances, the instantaneous received signal strength may fluctuate rapidly giving rise to small-scale fading. The reason for this is that the received signal is a sum of many rays coming from different directions.

4.2 Free Space Propagation loss

- The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed LOS path between them.
- As with most large-scale radio wave propagation models, the free space model predicts that received power decays as a function of the T-R separation distance raised.

The free space power received by a receiver antenna which is separated from a radiating transmitter antenna by a distance *d*, is given **by the Friis free space equation**,

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

where

P_t is the transmitted power in watts,

$P_r(d)$ is the received power which is a function of the T-R separation in watts,

G_t is the transmitter antenna gain,

G_r is the receiver antenna gain,

d is the T-R separation distance in meters,

L is the system loss factor not related to propagation ($L \geq 1$),

λ is the wavelength in meters.

The gain of an antenna is related to its effective aperture A_e by

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

The effective aperture A_e is related to the physical size of the antenna, and λ is related to the carrier frequency by

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

where

f is the carrier frequency in Hertz (Hz),

ω_c is the carrier frequency in radians per second (rad/s),

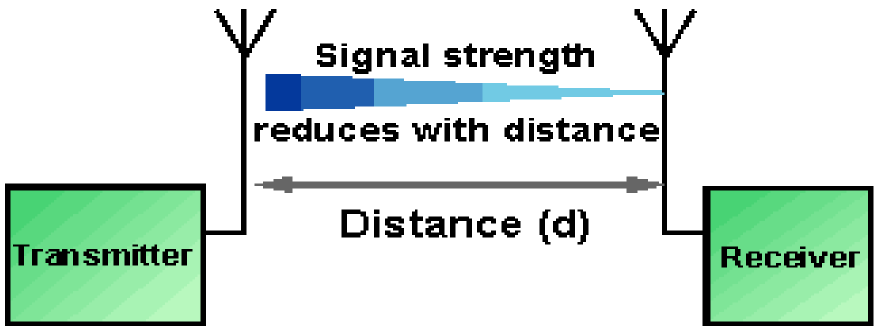
c is the speed of light ($\approx 3\times10^8$ m/s).

- The values for P_t and P_r must be expressed in the same units, and G_t and G_r are dimensionless quantities.
- The losses L ($L \geq 1$) are usually due to transmission line attenuation, filter losses, cable loss, and antenna losses in the communication system.
- A value of $L = 1$ indicates no loss in the system hardware.
- An isotropic radiator is an ideal antenna which radiates power with unit gain uniformly in all directions, and is often used to reference antenna gains in wireless systems.

The effective isotropic radiated power (*EIRP*) is defined as

$$EIRP = P_t\, G_t$$

- In practice, antenna gains are given in units of *dBi* (*dB* gain with respect to an isotropic source) or *dBd* (dB gain with respect to a half-wave dipole).
- The Friis free space model is only a valid predictor for P_r for values of d which are in the far-field of the transmitting antenna.

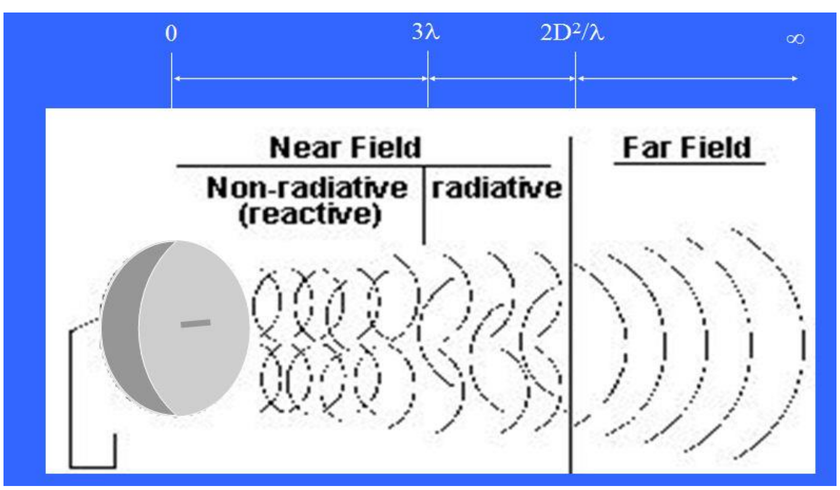


The **path loss** represents signal attenuation as a positive quantity measured in *dB*, is defined as the difference between the transmitted power and the received power.

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

4.2.2 Understanding the Antenna Near Field & Far Field Distances

The fields surrounding an antenna are divided into 3 main regions:



1- **Reactive Near Field**

The reactive near field ad the radiating near field. The reactive near field is the region where the fields are reactive i.e the E and H fields are out of phase by 90 degrees to each other. For propagating or radiating fields, the fields must be orthogonal to each other but in phase.

2- **Radiating Near Field (Fresnel region)**

The radiating near field or Fresnel region is the region between the reactive near and far field. The reactive fields do not dominate in this region. However unlike the far field region, the shape of the radiation pattern varies significantly with distance.

3- **Far Field**

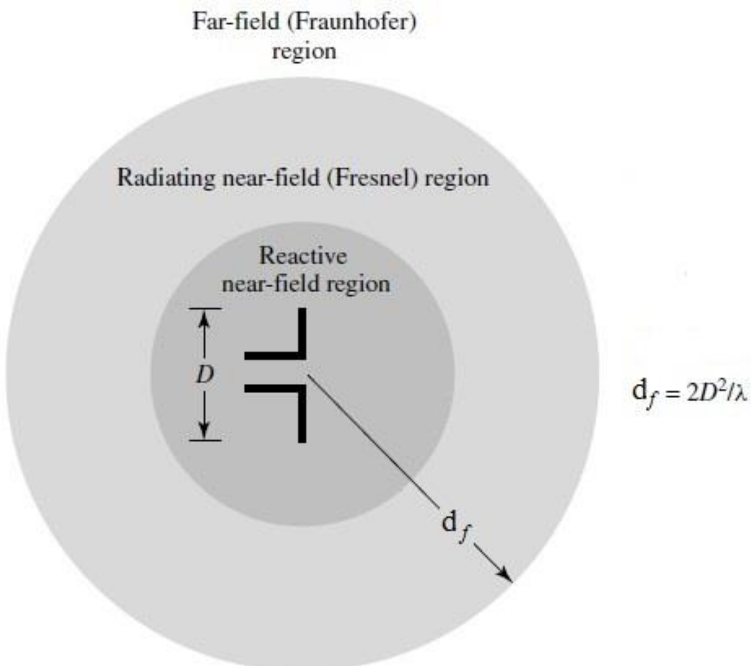
When talking about antennas the far field is the region that is at a large distance from the antenna. In the far field the radiation pattern does not change shape as the distance increases. There are three conditions which must be satisfied to ensure that the antenna is at a distance which qualifies as the far field.

$$\text{Reactive Near Field} \leq 0.62 \times \sqrt{\frac{D^3}{\lambda}}$$

$$\text{Radiating Near Field (Frensel Region)} \leq \frac{2D^2}{\lambda}$$

$$\text{Far Field } \geq \frac{2D^2}{\lambda}$$

$$\lambda = \frac{\text{Speed of Light}}{\text{Frequency}}$$



The far-field distance is given by

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

where D is the largest physical linear dimension of the antenna.

- Friis equation does not hold for $d = 0$. For this reason, large-scale propagation models use a close-in distance, d_0, as a known received power reference point.
- The received power, $P_r(d)$, at any distance $d > d_0$, may be related to P_r at d_0.
- The value $P_r(d_0)$ may be predicted from Friis equation, or may be measured in the radio environment by taking the average received power at many points located at a close-in radial distance d_0 from the transmitter.
- The reference distance must be chosen such that it lies in the far-field region, that is, $d_0 \geq d_f$, and d_0 is chosen to be smaller than any practical distance used in the mobile communication system. Thus, using Friis equation, the received power in free space at a distance greater than d_0 is given by

$$P_r(d) = P_r(d_0).\left(\frac{d_0}{d}\right)^2$$

where $d \geq d_0 \geq d_f$

- Because of the large dynamic range of received power levels, often *dBm* or *dBW* units are used to express received power levels. This is done by simply taking the logarithm of both sides and multiplying by 10.

For example, if P_r is in units of *dBm*, the received power is given by

$$P_r(d)\ dBm = 10\log\left[\frac{P_r(d_0)}{0.001\,W}\right] + 20\log\left(\frac{d_0}{d}\right)$$

where $P_r(d_0)$ is in units of watts.

Example 1

Find the far-field distance for an antenna with maximum dimension of 1*m* and operating frequency of 900 *MHz*.

Solution

Given:

Largest dimension of antenna, $D = 1m$,

Operating frequency, $f = 900\ MHz$,

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{900\times10^6} = 0.33m$$

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

Example 2

If a transmitter produces 50 *watts* of power, express the transmit power in units of

a. *dBm*,
b. *dBW*.

If 50 *watts* is applied to a unity gain antenna with a 900 *MHz* carrier frequency, find the received power in *dBm* at a free space distance of 100*m* from the antenna. What is P_r *(10 km)*? Assume unity gain for the receiver antenna.

Solution:

Given:

$P_t = 50\ W,\ f{=}900\ MHz$

(a)

$$P_t(dBm) = 10\log\left[P_t(mW)/(1\ mW)\right] = 10\log[50\times10^3] = 47\ dBm$$

(b)

$$P_t(dBm) = 10\log\left[P_t(W)/(1\ W)\right] = 10\log\left[50\right] = 17\ dBW$$

The received power is

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

$$P_r(d) = \frac{50\times1\times1}{1}\left(\frac{0.33}{4\pi\times100}\right)^2 = 3.5\times10^{-6} W = 3.5\times10^{-3} mW$$

$$P_r(dBm) = 10\log P_r(mW) = 10\log(3.5\times10^{-3}\ mW) = -24.5\, dBm$$

The received power at 10 *km* can be expressed in terms of *dBm* as

$$P_r(10\, km) = P_r(100) + 20\log\left(\frac{100}{10000}\right) = -24.5\, dBm - 40\, dB = -64.5\ dBm$$

Example 3

Determine the isotropic free space loss at 4 *GHz* for the 3.5 *km* path to a receiver from transmitter.

Solution:

$$\lambda = \frac{c}{f} = \frac{3\times10^{8}}{4\times10^{9}} = 0.075m$$

$$PL(dB) = -20\log\left(\frac{0.075}{4\pi\times3.5\times10^{3}}\right) = 115.4\ dB$$

4.3 Basic Propagation mechanisms

The physical mechanisms that govern radio propagation are complex and diverse, but generally attributed to the following three factors

1. Reflection
2. Diffraction
3. Scattering

1- Reflection

l Occurs when waves impinges upon an obstruction that is much larger in size compared to the wavelength of the signal

Example: reflections from earth and buildings , these reflections may interfere with the original signal constructively or destructively

2- Diffraction

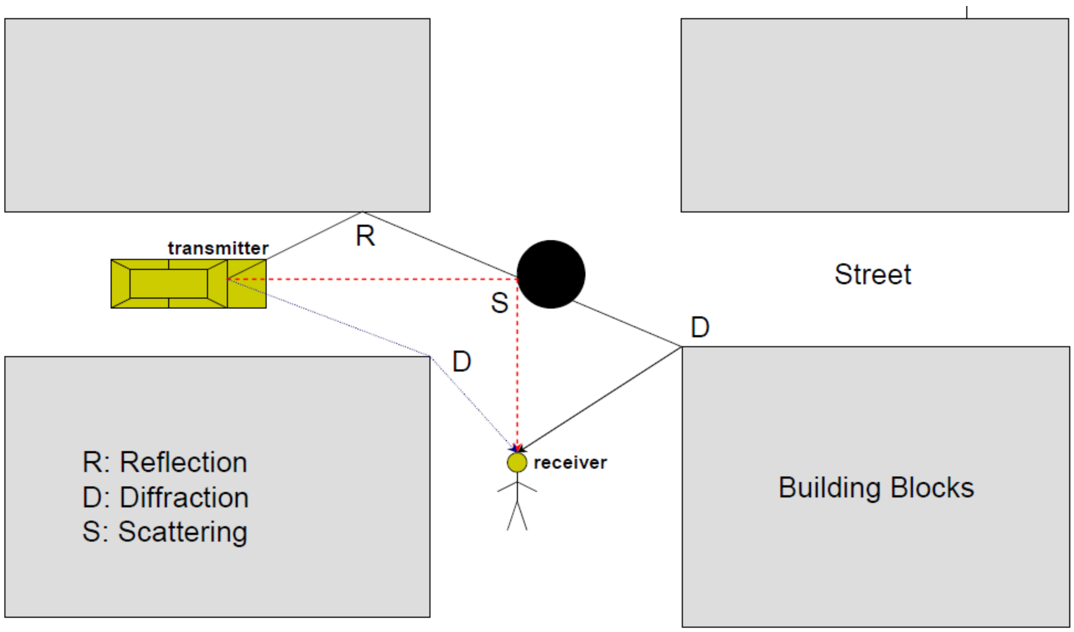
l Occurs when the radio path between sender and receiver is obstructed by an impenetrable body and by a surface with sharp irregularities (edges)

Explains how radio signals can travel urban and rural environments without a line-of-sight path

3- Scattering

l Occurs when the radio channel contains objects whose sizes are on the order of the wavelength or less of the propagating wave and also when the number of obstacles are quite large.

- They are produced by small objects, rough surfaces and other irregularities on the channel
- Follows same principles with diffraction
- Causes the transmitter energy to be radiated in many directions
- Lamp posts and street signs may cause scattering

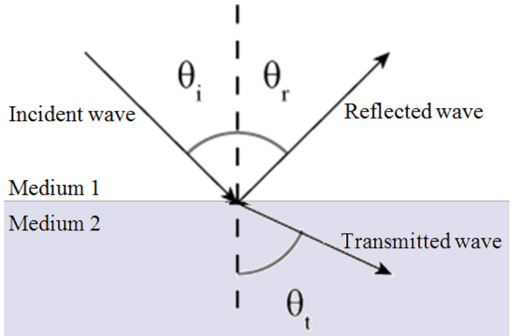


4.3.1 Reflection

Reflection occurs when a propagating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength of the propagating wave. Reflections occur from the surface of the earth and from buildings and walls.

- Interaction of electromagnetic (EM) waves with materials having different electrical properties than the material through which the wave is traveling leads to transmitting of energy.

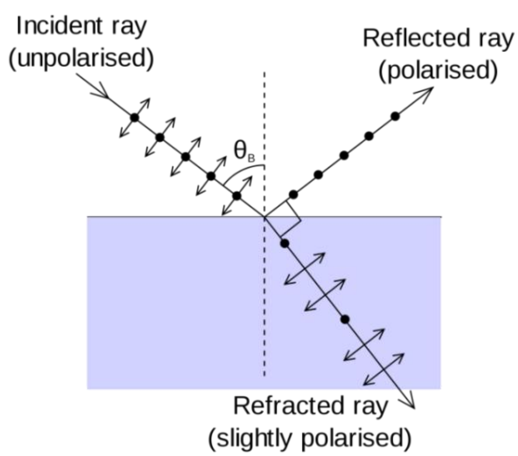
- When a radio wave falls on another medium having different electrical properties, a part of it is transmitted into it, while some energy is reflected back.



If the medium is a **dielectric**, some energy is reflected back and some energy is transmitted.

If the medium is a perfect **conductor**, all energy is reflected back to the first medium.

The amount of energy that is reflected back depends on the polarization of the EM wave.



Brewster's angle (also known as the polarization angle) is an angle of incidence at which wave with a particular polarization is perfectly transmitted through a dielectric surface, with no reflection (reflection coefficient is equal to zero).

- By applying laws of electro-magnetics, it is found to be

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

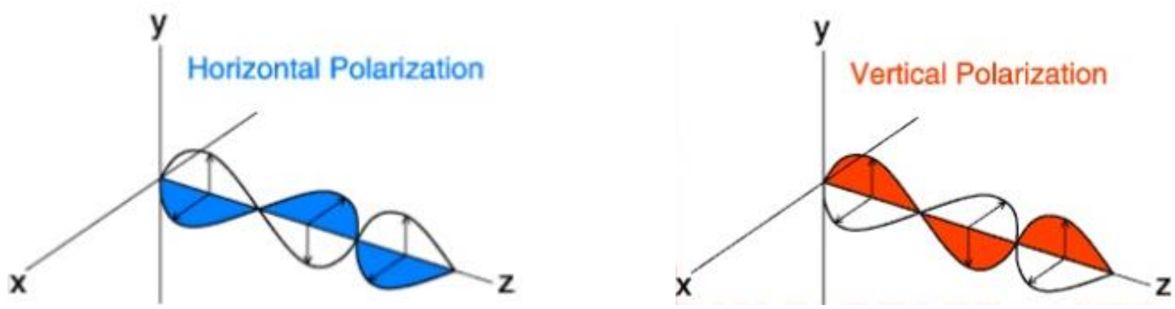
- For the case when the first medium is free space and the second medium has a relative permittivity ε_r, Brewster's angle can be expressed as

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

Note that the Brewster angle occurs only for vertical (i.e. parallel) polarization.

- The reflection coefficient depends on:
  (a) Wave polarization
  (b) Angle of incidence,
  (c) Frequency of the propagating wave.

- For example, as the EM waves cannot pass through conductors, all the energy is reflected back with angle of incidence equal to the angle of reflection and reflection coefficient Γ= −1.
- In general, EM waves are polarized, meaning they have instantaneous electric field components in orthogonal directions in space.



Example 4

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

Solution:

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$$\sin\theta_B = \frac{\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r^2 - 1}} = \frac{\sqrt{4-1}}{\sqrt{4^2 - 1}} = \frac{\sqrt{3}}{\sqrt{15}} = \sqrt{\frac{1}{5}}$$

$$\theta_B = \sin^{-1}\sqrt{\frac{1}{5}} = 26.56^o$$

Reflection from perfect conductor

- The electric field inside the perfect conductor is always zero. Hence all energy is reflected back. Therefore

$$\theta_i = \theta_r$$

a. For vertical polarization, and

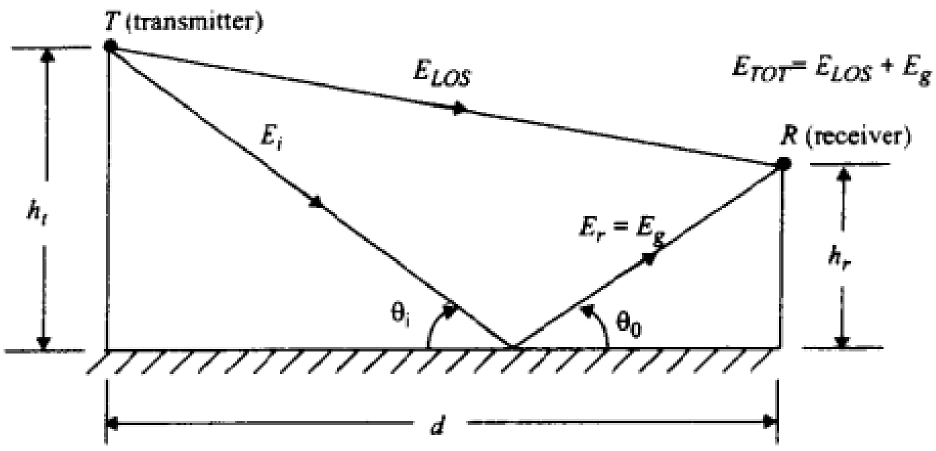
$$E_i = E_r$$

b. For horizontal polarization.

$$E_i = -E_r$$

Ground Reflection (2-ray) Model

- A single direct path between the base station and a mobile is seldom.
- The 2-ray ground reflection model (shown in Figure below) is a useful propagation model that is based on geometric optics, and considers both the direct path and a ground reflected propagation path between transmitter and receiver.
- This model is reasonably accurate for predicting the large-scale signal strength over distances of several kilometers for mobile radio systems that use tall towers (heights which exceed 50*m*), as well as for LOS microcell channels in urban areas.
- In most mobile communication systems, the maximum T-R separation distance is only a few tens of kilometers, and the earth may be assumed to be flat.
- The total received E-field (E_{TOT}) is a result of the direct LOS component (E_{LOS}), and the ground reflected component (E_g).



- Referring to Figure, h_t is the height of the transmitter and h_r is the height of the receiver.
- Two propagating waves arrive at the receiver:
  - The **direct wave** (LOS) that travels a distance *d'*
  - The **reflected wave** that travels a distance *d''*.

- The received E-field at a distance *d* from the transmitter can be approximated as

$$E_{TOT}(d) \approx \frac{2E_0 d_0}{d} \frac{2\pi h_t h_r}{\lambda d} \approx \frac{k}{d^2} \; V/m$$

where

d is the distance over a flat earth between the bases of the transmitter and receiver antennas

k is a constant related to E_0, the antenna heights, and the wavelength.

- The power received power at a distance *d* from the transmitter can be expressed as

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

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As seen from equation above at large distances $d >> \sqrt{h_t h_r}$, the received power falls off with distance raised to the fourth power, or at a rate of 40 dB/decade. This is a much more rapid path loss than is experienced in free space.

Note also that at large values of *d*, the received power and path loss become independent of frequency.

Example 5

A mobile is located 5 *km* away from a base station and uses a vertical *λ/4* monopole antenna with a gain of 2.55 *dB* to receive cellular radio signals. The E-field at 1*km* from the transmitter is measured to be 10^{-3} *V/m*. The carrier frequency used for this system is 900 *MHz*.

a) Find the length and the gain of the receiving antenna.
b) Find the received power at the mobile using the 2-ray ground reflection model assuming the height of the transmitting antenna is 50*m* and the receiving antenna is 1.5*m* above ground.

Solution

Given:

T-R separation distance = 5 *km*

E-field at a distance of 1*km*

Frequency of operation, *f* = 900 *MHz*

a)

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{900\times10^6} = 0.333m$$

Length of the antenna, *L* = *λ/4* = 0.333/4 = 0.0833*m* = 8.33*cm*.

Gain of *λ/4* monopole antenna can be obtained using

$$G = \frac{4\pi A_e}{\lambda^2} = 1.8 = 2.55\ dB.$$

b) Since $d >> \sqrt{h_t h_r}$, the electric field is given by

$$E_{TOT}(d) \approx \frac{2E_0 d_0}{d}\frac{2\pi h_t h_r}{\lambda d} \approx \frac{k}{d^2}\ V/m$$

$$= \frac{2\times10^{-3}\times1\times10^{3}}{5\times10^{3}}\left[\frac{2\pi\times50\times1.5}{0.333\times5\times10^{3}}\right] = 113.1\times10^{-6}\ V/m$$

The received power at a distance *d* can be obtained using

$$P_r(d) = \frac{|E|^2}{120\pi}A_e = \frac{|E|^2}{120\pi}\left(\frac{G\lambda^2}{4\pi}\right)$$

$$P_r(d) = \frac{(113.1\times10^{-6})^2}{377}\left(\frac{1.8\times(0.333)^2}{4\pi}\right)$$

$$= 5.4\times10^{-13}\ W = -122.68\,dBW\ or\ -92.68\,dBm$$

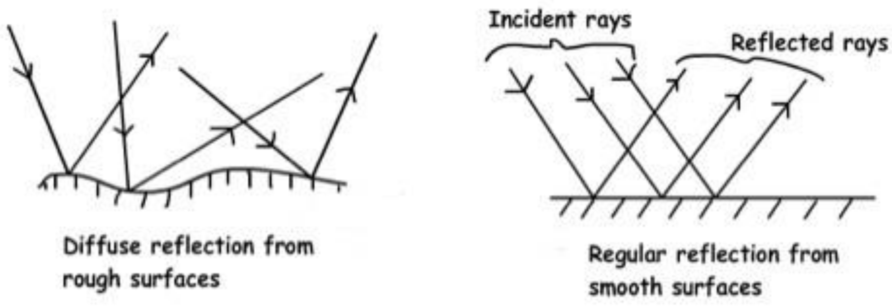
4.3.2 Scattering

- The actual received power at the receiver is stronger than claimed by the models of reflection and diffraction.
- The cause of scattering is that the trees, buildings and lamp-posts scatter energy in all directions. This provides extra energy at the receiver.
- Roughness is tested by a Rayleigh criterion, which defines a critical height h_c of surface protuberances for a given angle of incidence θ_i , given by,

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

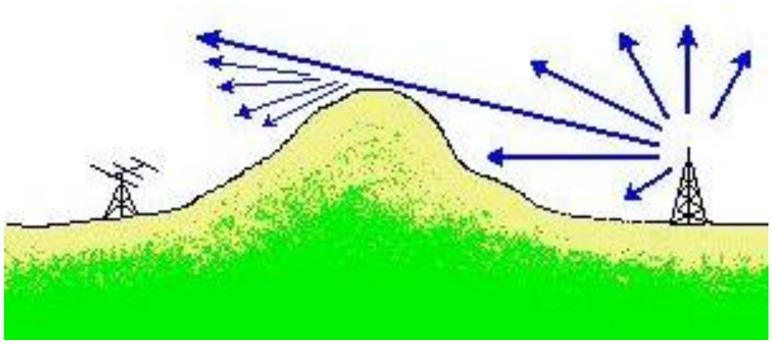
a. The surface is *smooth* if its minimum to maximum protuberance h is less than h_c,

b. The surface is *rough* if protuberance is greater than h_c.



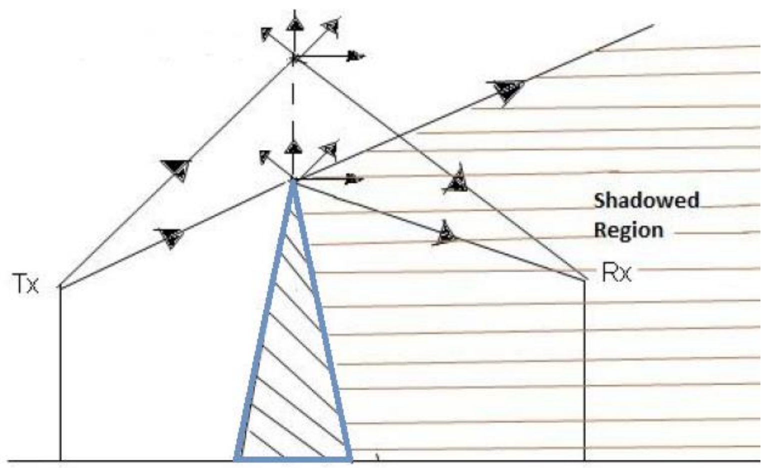
4.3.3 Diffraction

- Diffraction is the phenomena that occur when radio waves encounter obstacles that have sharp irregularities (edges). The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle.



- The radio wave changes in amplitude and phase and penetrates the shadow zone, deviating from a straight line path.

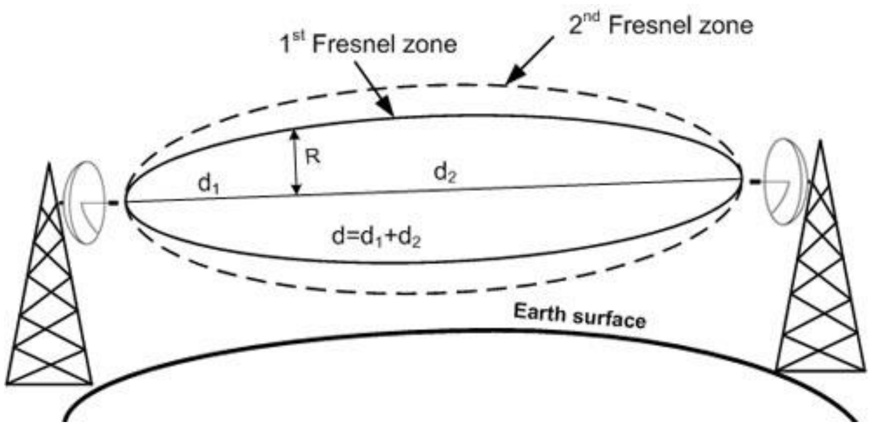
- Diffraction is explained by Huygens-Fresnel principle which states that all points on a wavefront can be considered as the point source for secondary wavelets which form the secondary wavefront in the direction of the prorogation.
- In mobile communication, diffraction, scattering and reflection have a great advantage since the receiver is able to receive the signal even when not in line of sight of the transmitter.
- At high frequencies, diffraction, like reflection, depends on the geometry of the object, as well as the amplitude, phase, and polarization of the incident wave at the point of diffraction.



- Knife-edge diffraction model is one of the simplest diffraction model to estimate the diffraction loss. It considers the object like hill or mountain as a knife edge sharp object.

4.4 Fresnel Zones

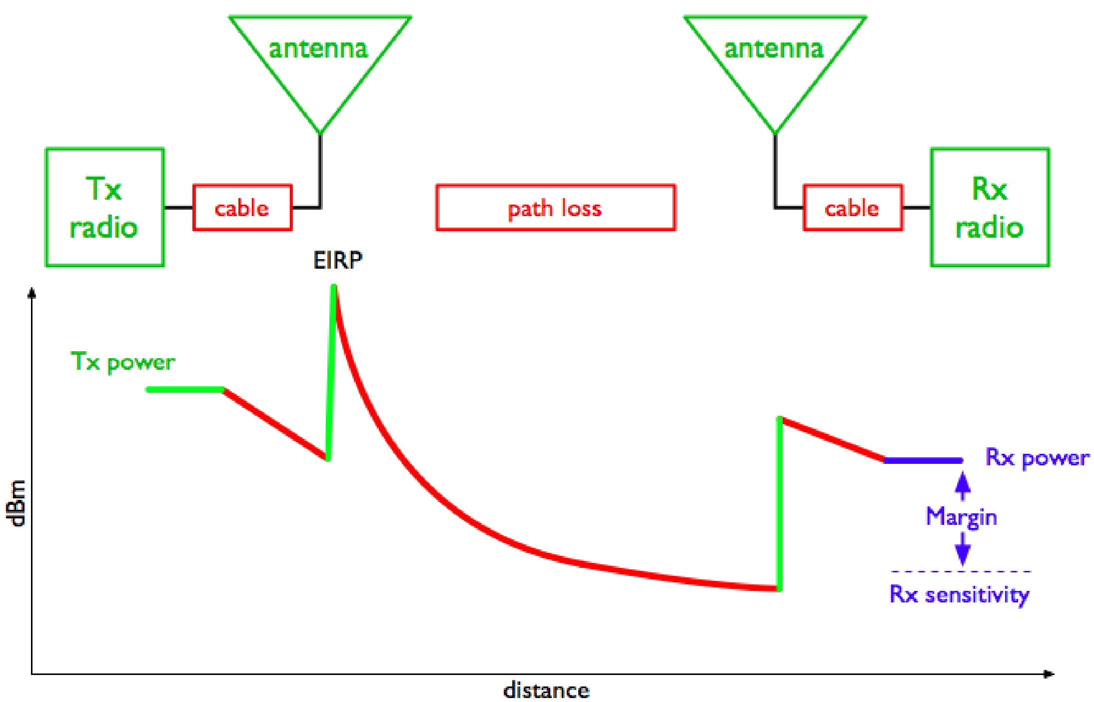
- As mentioned before, the more is the object in the shadowed region greater is the diffraction loss of the signal.
- The effect of diffraction loss is explained by Fresnel zones as a function of the path difference.
- The successive Fresnel zones have phase difference of π which means they alternatively provide constructive and destructive interference to the received the signal.
- The radius of the each Fresnel zone is maximum at middle of transmitter and receiver (i.e. when $d_1 = d_2$) and decreases as moved to either side.



- It is seen that the loci of a Fresnel zone varied over d_1 and d_2 forms an ellipsoid with the transmitter and receiver at its focii.
  a. If there's no obstruction, then all Fresnel zones result in only the direct LOS prorogation and no diffraction effects are observed.
  b. If an obstruction is present, resulting in diffraction and also the loss of energy.
- The height of the obstruction can be positive zero and negative also.
- The diffraction losses are minimum as long as obstruction doesn't block volume of the 1st Fresnel zone.
- Diffraction effects are negligible beyond 55% of 1st Fresnel zone.

4.5 Link Budget Analysis

- The performance of any communication link depends on the quality of the equipment being used.
- ***Link budget*** is a way of quantifying the link performance.
- The received power in an 802.11 link is determined by three factors: ***transmit power***, ***transmitting antenna gain***, and ***receiving antenna gain***.
- If that power, minus the ***free space loss*** of the link path, is greater than the ***minimum received signal level*** of the receiving radio, then a link is possible.
- The difference between the minimum received signal level and the actual received power is called the ***link margin***.
- The link margin must be positive, and should be maximized (should be at least 10dB or more for reliable links).



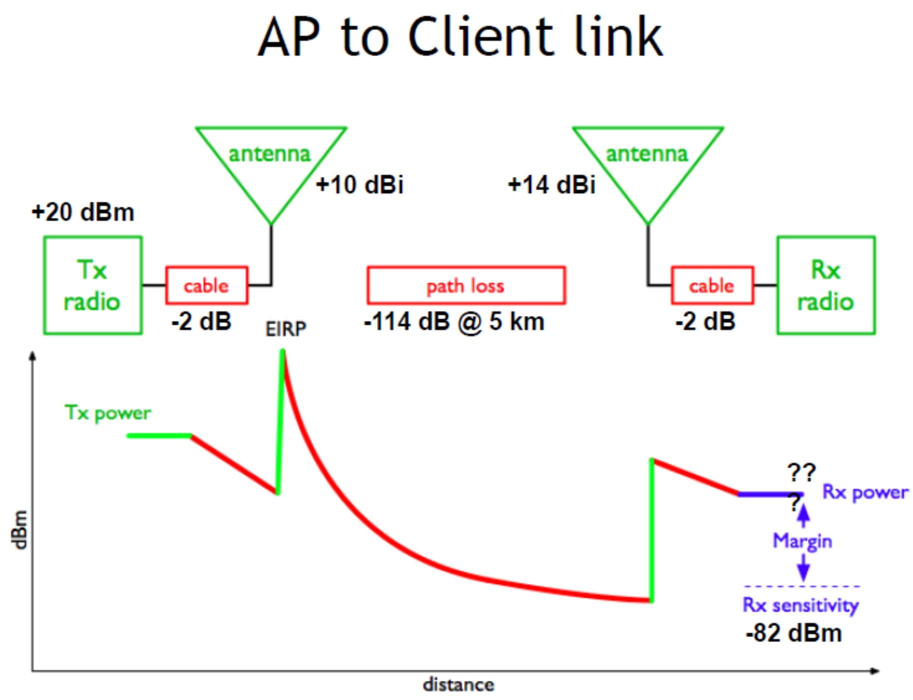
Example link budget calculation

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

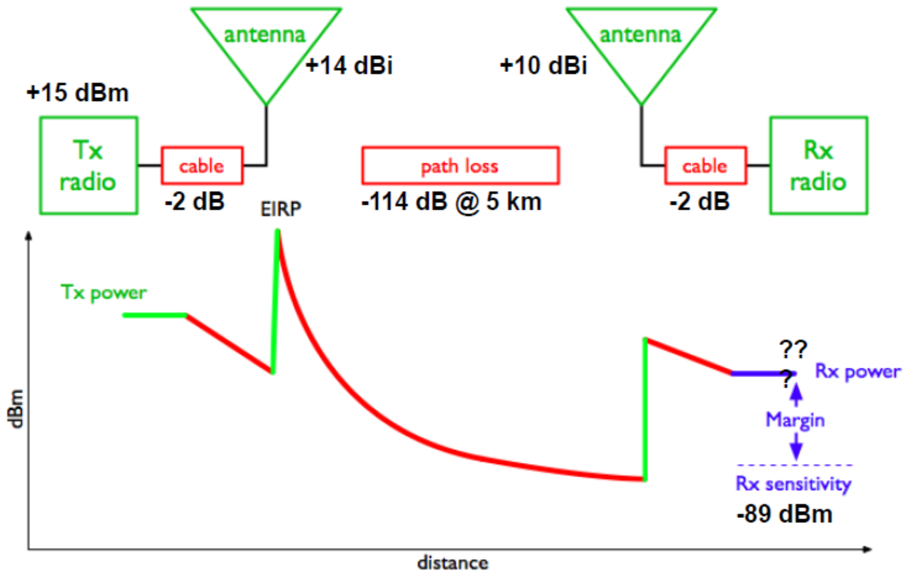
Sol

A) AP to Client link



- Total Gain = 20 dBm (TX Power AP) + 10 dB (Antenna Gain AP) – 2 dB (Cable Losses AP) + 14 dB (Antenna Gain Client) – 2 dB (Cable Losses Client) = 40 dB Total Gain
- expected received signal level = 40 dB Total Gain -114 dB (free space loss @5 km) = -74
- *link margin = -74 dBm (expected received signal level) --82 dBm (sensitivity of Client) = 8 dB (link margin)*

B) : Client to AP link



- Total Gain = 15 dB (TX Power client) + 14 dB (Antenna Gain) - 2 dB (Cable Losses Client) + 10 dB (Antenna Gain AP) - 2 dB (Cable Losses AP) = 35 dB Total Gain
- received signal = 35 dB Total Gain -114 dB (free space loss @5 km) = - 79
- link margin = -79 dB (expected received signal level) - - 89 dBm (sensitivity of AP) = 10 dB (link margin)