CHAPTER

2 Radio Signal Propagation and Models

ACRONYMS

- LOS : Line of Sight
- DG : Diffraction Gain
- V : Fresnel–Kirchoff Diffraction Parameter
- SNR : Signal to Noise Ratio
- N : Path Loss Exponent
- XV : Zero-mean Gaussion Distributed Random Variable
- U(V) : Percentage of Useful Service Area
- JRC : Joint Radio Committee
- RTSD : Roof-to-street Diffraction
- ML : Multiscreen Loss

2.1 INTRODUCTION

This chapter focuses on those aspects of wireless transmission which are necessary to understand the problems faced by higher layers in atmosphere as well as the obstacles in the transmission path.

In vacuum, transmission path is in simply line of sight but it varies greatly in atmosphere due to the obstacles that are present in the path of transmission. These may be large mountains, high rise buildings, trees, etc. These obstacles may create some losses in the strength of signal because the path is no longer line-of-sight now but waves actualy reach the receiver by following multipaths. Several other effects also occur during transmission which are reflection, diffraction, scattering, shadowing, refraction etc. Therefore, radio channels are externally random and do not offer easy analysis. To predict the signal strength from transmitter to receiver, some propagation models are used. The detail of path loss, propagation effects and models are given insight.

2.2 SIGNAL PROPAGATION

Signal propagation in wireless communication needs two points (like wired communication), one to generate the signal and other to detect the signal. But in wireless networks, the signal has no wire to determine the direction of propagation.

In case of wired (or PSTN) connection, one can precisely determine the behavior of a signal travelling along this wire while in wireless connection, this predictable behavior is only valid in a vacuum. Practically radio transmission has to contend with our atmosphere, mountains, buildings, moving senders and receivers etc. Refer Fig. 2.1 in reality, the three circles refere to ranges for transmission, detection and interference of signals.

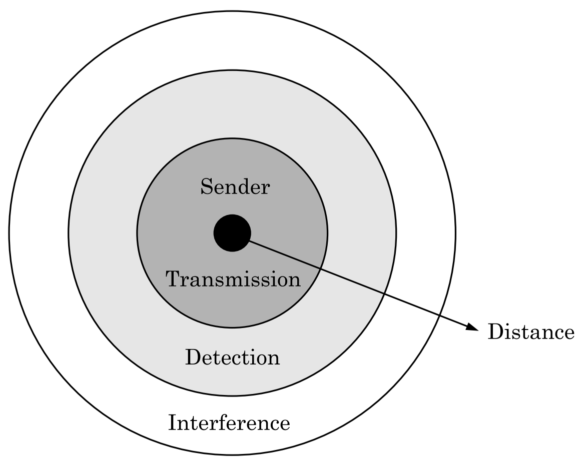


Fig. 2.1 *Ranges for transmission, detection and Interference of Signals*

- **Transmission Range:** It is possible within a certain radius of the sender transmission. In this range, a receiver receives the signals with an error rate low enough to able to be communicate and can also act as sender to establish a new connection.
- **Detection Range:** It lies within second radius of the sender transmission side. In this range, the transmitted power is large enough to be differentiated from background noise. However, the error rate is too high to establish connection in this range.

- **Interference Range :** This range lies within a third even larger radius. The sender may interfere with other transmission by adding a background noise. A receiver will not be able to detect the signals under this range.

2.3 ADDITIONAL SIGNAL PROPAGATION EFFECTS

In free space, signals propagate quite similar to how light does i.e. they follow a straight line-of-sight path. But in real life, we rarely have a line-of-sight between the sender and receiver of radio signals. Before reaching upto receiver, signals have to face a lot of disturbances like, mountains, valleys, big buildings etc. Here several effects occur in addition to the attenuation caused by the distance between sender and receiver. These effects are

1. Shadowing or Blocking
2. Reflection
3. Refraction
4. Scattering
5. Diffraction

All these effects are shown in Fig. 2.2.

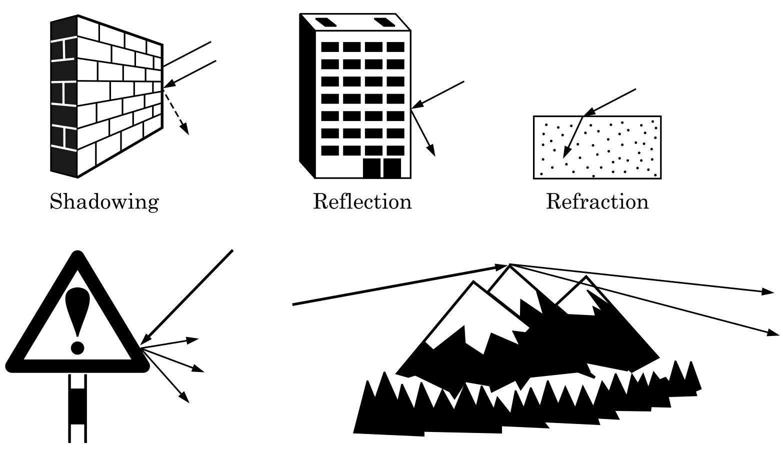


Fig. 2.2

For more clarity, all these effects are described in brief :

1. **Shadowing :** An extreme form of attenuation is blocking or shadowing of radio signals due to large obstacles. Large objects create their shadow which may penetrate or block the signal. The higher the frequency of a signal, the more

it behaves like light. Even small obstacles like a simple wall, a bus on the stop or trees etc. may block the signal.

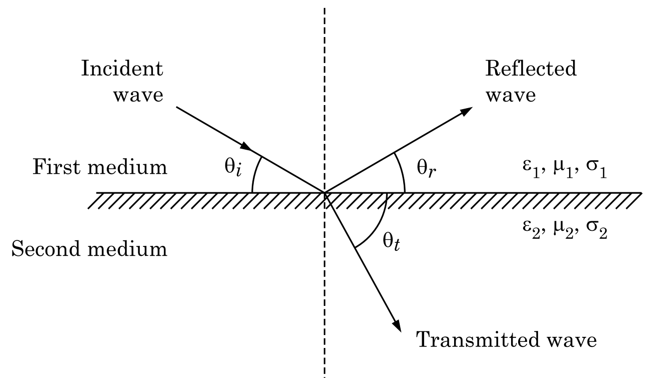
2. **Reflection :** This effect occurs if the object is large compared to the wavelength of the transmitted signal, e.g. huge buildings, mountains or surface of the earth etc. After striking with such object, the signal gets reflected in different directions. In this effect, some power of the signal gets absorbed by the object therefore the reflected signal is not as strong as original. The more often the signal is reflected, the weaker it becomes.
3. **Refraction :** This effect occurs because the velocity of EM waves depends on the density of the medium through which it travels. Those waves which travel into a denser medium are bent towards the medium. This is the reason for line of sight radio waves being bent towards the earth because the density of the atmosphere is higher closer to the ground.
4. **Scattering :** While Shadowing and Reflection are caused by the objects much larger than the wavelength of the signal, the scattering occurs due to obstacles i.e. in order of the wavelength or less. We can say that if the obstacle size is much less than the wavelength of transmitted signal then waves can be scattered. An incoming signal is scattered into several weaker outgoing signals.
5. **Diffraction :** This effect shows the wave character of radio signals. This effect means that the radio waves will be deflected at an edge and propagated in different directions. The results of diffraction are patterns with varying signal strengths depending on the location of the receiver.

Note: Reflection, scattering and diffraction are more prominant propagation mechanisms which impact propagation in mobile communication systems. These mechanisms are explained in detail in next section.

2.4 REFLECTION

The basic concept of reflection, has already been studied in previous section. In this section we will study the effect of medium on reflection.

When a propagating wave in one medium impinges upon another medium then the wave may be partially reflected and partially transmitted and there is no loss of energy by absorption. If the second medium is a perfect conductor then all the incident energy is reflected back into the first medium without any loss. The reflection coefficient depends on many parameters such as material properties, angle of incidence, frequency of propagation wave etc.



$\theta_i \rightarrow$ angle of incident wave with the plane
$\theta_r \rightarrow$ angle of reflected wave with the plane
$\theta_t \rightarrow$ angle of transmitted wave with the plane

Fig. 2.3 *Wave travelling through one medium to another medium*

The angle at which no reflection occurs in the medium of origin is known as '**Brewster angle**'. It means all the waves will be transmitted into second medium. No reflection in origin medium occurs when the incident angle θ_B is such that the reflection coefficient ($\Gamma_{||}$) is equal to zero. The Brewster angle is given by

$$\text{Sin } (\theta_B) = \sqrt{\frac{\varepsilon_1}{\varepsilon_1 + \varepsilon_2}} \quad ...(2.1)$$

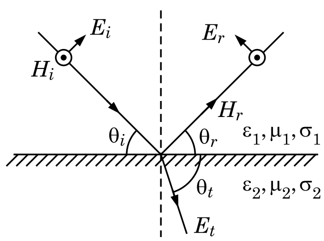
If first medium is free space and second medium has a relative permittivity (ε_r). Then equation (2.1) will be

$$\text{Sin } (\theta_B) = \frac{\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r^2 - 1}} \quad ...(2.2)$$

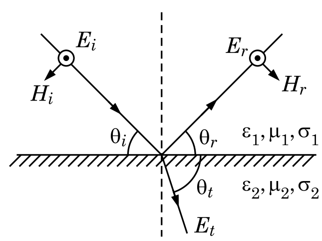
This angle occurs only for vertical polarization, which means when the incident wave is vertically polarized having no coefficient in the horizontal direction. Reflection also depends on the medium at which the wave is striking. The medium may be a dielectric or perfect conductor. The reflection theory for different medium is described in the following subsections.

2.4.1 Reflection from Dielectrics

In general, electromagnetic or radio waves are polarized, meaning they have instantaneous electric field components in the orthogonal directions in space. A polarized wave may be represented as the sum of vertical and horizontal orthogonal components or left hand and right hand circularly polarized components. For an arbitrary polarization, superposition may be used to compute the reflected fields from a reflecting surface. Fig. 2.4 shows two cases of *E*-field polarization in the plane of incidence. **Plane of incidence** is defined as the plane containing incident, reflected and transmitted wave. In Fig. 2.4 (*a*), the E-field has a vertical polarization with respect to the reflecting surface or we can say the E-field polarization is parallel with the plane of incidence while in Fig. 2.4(*b*), the *E*-field polarization is perpendicular to the plane of incidence or the E-field is parallel to the reflecting surface.



(*a*) E-field is parallel to the plane of incidence



(*b*) E-field is perpendicular to the plane of incidence

Fig. 2.4 *Reflection coefficients between two dielectric*

Here, the subscript *i*, *r*, *t* refer to the incident, reflected and transmitted fields, respectively. And ε, μ, σ represents the permittivity, permeability and conductance of different media.

The dielectric constant of a perfect dielectric is

$$\varepsilon = \varepsilon_0\, \varepsilon_r \qquad \text{...(2.3)}$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m (Constant)

and ε_r = Relative permittivity

Whereas, the dielectric constant of a lossy dielectric material is

$$\varepsilon = \varepsilon_0\, \varepsilon_r - j\varepsilon' \qquad \text{...(2.4)}$$

where $\varepsilon' = \dfrac{\sigma}{2\pi f}$

σ is the conductivity of material.

The reflection co-efficients for the two cases of parallel and perpendicular E-field polarization at the boundary of two dielectrics are given by,

Parallel reflection coefficient

$$\Gamma_{||} = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_t - \eta_1 \sin\theta_i}{\eta_2 \sin\theta_t + \eta_1 \sin\theta_i} \qquad ...(2.5)$$

Perpendicular reflection coefficient

$$G_{\wedge} = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_i - \eta_1 \sin\theta_t}{\eta_2 \sin\theta_i + \eta_1 \sin\theta_t} \qquad ...(2.6)$$

where η_i is the intrinsic impedance of the ith medium (i = 1, 2, ...) and given by $\sqrt{\mu_i / \varepsilon_i}$.

The velocity of an electromagnetic wave is given by $\frac{1}{\left(\sqrt{\mu\varepsilon}\right)}$. The boundary conditions at the surface of incidence obeys Shell's law which is given by,

$$\sqrt{\mu_1 , \varepsilon_1} \sin (90^\circ - \theta_i) = \sqrt{\mu_2 \varepsilon_2} \sin (90^\circ - \theta_t) \qquad ...(2.7)$$

The boundary conditions from Maxwell's equations are used to derive equations (2.5) and (2.6) as well as Equations 2.8, 2.9 and 2.10.

$$\theta_i = \theta_r \qquad ...(2.8)$$

and

$$E_r = \Gamma E_i \qquad ...(2.9)$$

$$E_t = (i + \tau) Ei \qquad ...(2.10)$$

where Γ is either $\Gamma_{||}$ or $\Gamma_{\perp}$, depending on whether the E-field is in parallel or perpendicular to the plane of incidence.

For the case when the first medium is free space and $\mu_1 = \mu_2$. The reflection coefficients can be simplified as,

$$\Gamma_{||} = \frac{-\varepsilon_r \sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}{\varepsilon_r \sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}} \qquad ...(2.11)$$

an d

$$\Gamma_{\perp} = \frac{\sin\theta_i - \sqrt{\varepsilon_r - \cos^2\theta_i}}{\sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}} \qquad ...(2.12)$$

For elliptical polarized waves, the wave may be broken down (depolarized) into its vertical and horizontal E components and then superposition principle may be applied to determine transmitted and reflected wave.

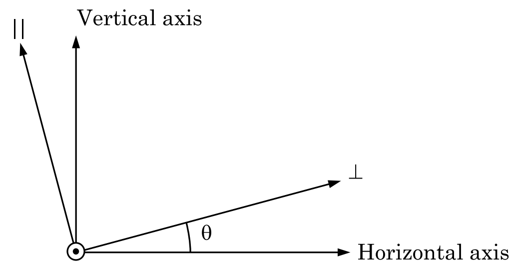


Fig. 2.5 *Axis of orthogonally polarized components. Wave is propagating out of the page (toward the reader)*

The parallel and perpendicular components are related to the horizontal and vertical spatial coordinates. The vertical and horizontal field components at a dielectric boundary may be related by,

$$\begin{bmatrix} E_H^d \\ E_V^d \end{bmatrix} = R^T D_c R \begin{bmatrix} E_H^i \\ E_V^i \end{bmatrix} \qquad \text{...(2.13)}$$

where,

$E_H{}^d$ = Depolarized field component in the horizontal direction

$E_V{}^d$ = Depolarized field component in the vertical direction

$E_H{}^i$ = Horizontally polarized component of the incident wave

$E_V{}^i$ = Vertically polarized component of the incident wave.

A transformation matrix (R) maps vertical and horizontal polarized components to components which are perpendicular and parallel to the plane of incidence. The transformation matrix (R) is given by

$$R = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

where θ = angle between the two sets of axes (see Fig. 2.5)

The depolarization matrix (DC) is given by

$$\text{DC} = \begin{bmatrix} D_{\perp\perp} & 0 \\ 0 & D_{||} \end{bmatrix} \qquad \text{...(2.14)}$$

where $D_{xx} = \Gamma_x$ for the case of **reflection** and

$D_{xx} = T_x = 1 + \Gamma_x$ for the case of **transmission**

Fig. 2.6 shows reflection coefficient as angle of incidence for the case when a wave propagates in free space ($\varepsilon_r = 1$) and the reflection surface has (*a*) $\varepsilon_r = 4$ and (*b*) $\varepsilon_r = 12$.

Through this figure, we are able to study parallel polarization and perpendicular polarization at various relative permittivity.

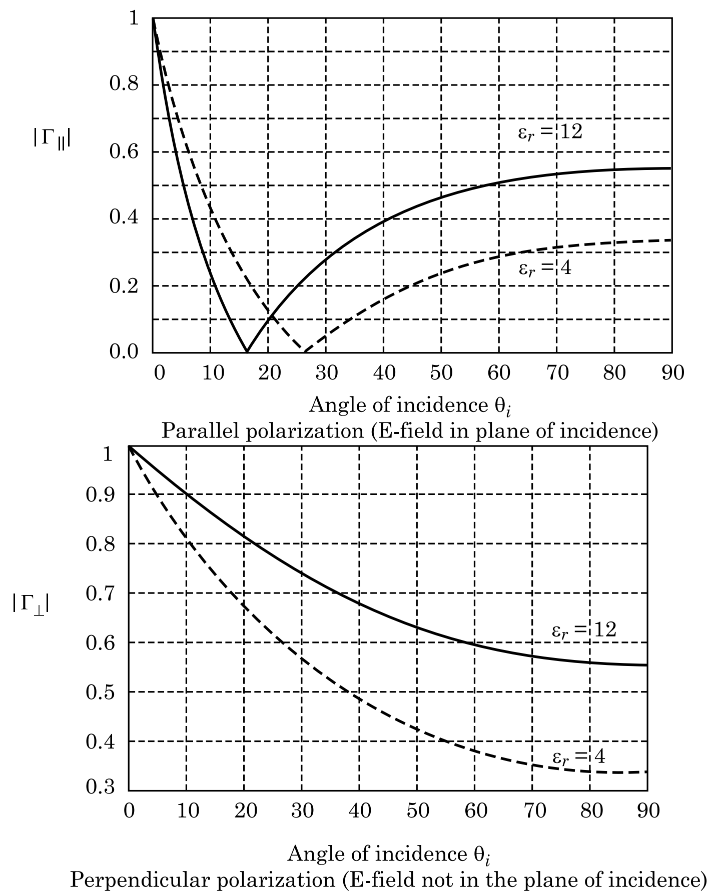


Fig. 2.6 *Reflection coefficients vs angle of incidence*

2.4.2 Reflection from Perfect Conductors

The wave impinges on a perfect conductor is completely reflected because electro megnatic energy cannot pass through a perfect conductor. The reflected wave must be equal in magnitude to the incident wave.

For the case when E-field polarization is vertically polarized the boundary condition requires that

$$\theta_i = \theta_r \quad \text{...(2.15)}$$

and $E_i = E_r$ (E-field parallel to the plane of incidence) ...(2.16)

Similarly, when E-field is horizontally polarized, the boundary condition requires that

$$\theta_i = \theta_r \quad \text{...(2.17)}$$

and $$E_i = -E_r$$

(E-field perpendicular to the plane of incidence) ...(2.18)

Therefore, by referring above equations, we may conclude that for a perfect conductor, the reflection coefficient parallel and perpendicular to the plane of incidence is :

$$\tau_{||} = 1$$

and

$$\tau_{\perp} = -1,$$

2.5 SCATTERING

In addition to reflection, another property of EM wave is that when a radio wave impinges on a rough surface, then the reflected energy get spread in all directions. This is due to the scattering property. Objects which have dimension less than the wavelength of EM wave, tend to scatter energy in all directions, therefore providing additional radio energy at receiver.

Generally, the dimensions of flat surfaces is much larger than the wavelength of the wave. Different propagation effects depend on surface flatness and roughness. Surface roughness is often tested using the Rayleigh criterion. According to Rayleigh criterion the critical height (h_c) of surface protuberances (Swelling or bulge) for a given angle of incidence θ_i, given by

$$\boxed{h_c = \frac{\lambda}{8 \sin \theta_i}} \quad \text{...(2.19)}$$

A surface is considered smooth if its minimum to maximum swelling (height) h is less than h_c ($h < h_c$) and it is considered rough if h is greater than h_c ($h > h_c$). To find out the diminished reflected field for rough surfaces, the flat surface reflection coefficient is multiplied with scattering loss factor (ρ_s), where ρ_s is given by,

$$\rho_s = \exp\left[-8\left(\frac{\pi \sigma_h \sin \theta_i}{\lambda}\right)^2\right] \quad \text{...(2.20)}$$

here, σ_h = Standard deviation of the surface height about the mean surface height

λ = wavelength of wave

and θ_i = angle of incidence of wave at surface.

The reflected E-fields for $h > h_c$ can be solved for rough surfaces using a modified reflection coefficient given as

$$T_{rough} = \rho_s \cdot \tau \quad \text{...(2.21)}$$

2.5.1 Radar Cross Section Model

This model is used to accurately predict the scattered signal strengths. As we know that the received signal varies in strength due to scattering by distant objects. A knowledge of the physical location of such objects is used to find out the approximated signal strength at that point.

The received power for urban mobile radio systems is computed using **bistatic radar equation**. This equation describes the propagation of a wave traveling in free space which impinges (Strikes) on a distant scattering object, and is then reradiated in the direction of the receiver, given by

$$P_R(dBm) = P_T(dBm) + G_T(dBi) + 20\ \log(\lambda) + RCS(dBm^2) - 30\ \log\ (4\pi) - 20\ \log\ d_T - 20\ \log\ d_R \quad \text{...(2.22)}$$

where,

dT = Distance from transmitter to scattering object

dR = Distant from receiver to scattering object

RCS = Radar Cross Section

Equation (2.22) is useful for predicting receiver power which scatters off large objects such as buildings, mountains etc. which are for both the transmitter and receiver.

2.6 DIFFRACTION

It is a significant effect for terrestrial propagation. In physics, diffraction refers to the phenomenon whereby, when e.m. waves are forced to travel through a small slit, they tend to spread out on the far end of the slit as shown in Fig. 2.7.

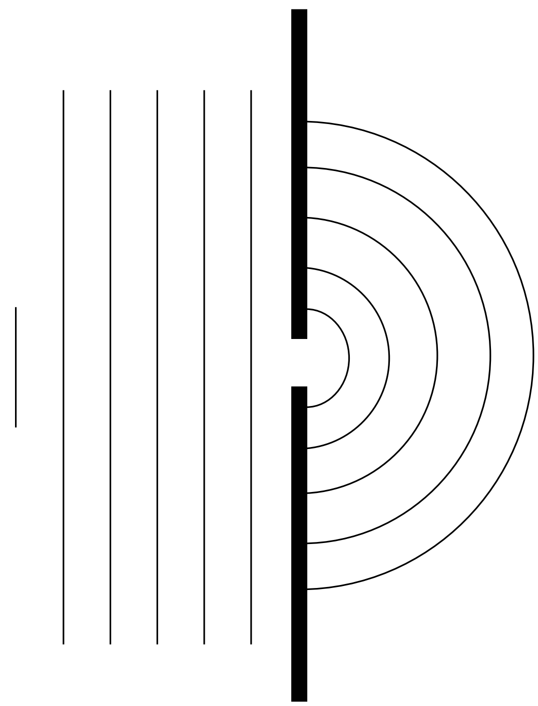


Fig. 2.7 *Plane passing through a slit left to right*

The diffraction mechanism is often explained by Hugen's principle, which may be stated as follows–

"Each point on a wave form acts as a point source for further propagation. However, the point source does not radiate equally in all directions, but favours the forward direction of the front".

This principle is generally used to explain the reason, why e.m. waves bend over hills and around buildings.

The diffraction property of radio signal enables it to propagate even after the line-of-sight (LOS) or around the curved surface of the earth. Although the received field strength decreases rapidly when the receiver moves deeper into the shadowed region. Differection is basically caused by the propagation of secondary wavelets from a wave front into the shadowed region.

The field strength of a diffracted wave in the shadowed region is the vector sum of the electric field components of all the secondary wavelets in the space around the obstacle.

2.6.1 Fresnel Zone Geometry

According to this geometry, the phase difference between a direct line-of-sight path and diffracted path is a function of height and position of the obstacle (may be building, mountain etc.) as well as the location of transmitter and receiver.

Let, a sharpedge (or knife edge) obstacle of height h is placed between transmitter and receiver. The distance of this obstruction from transmitter and receiver is d_1 and d_2 respectively. (See Fig. 2.8) Then the difference between the direct path (LOS Path) and diffracted path is the excess path length denoted by Δ, and given as

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

The corresponding phase difference is

$$\phi = \frac{2\pi\Delta}{\lambda}$$

$$= \frac{2\pi}{\lambda}\cdot\frac{h^2}{2}\frac{(d_1 + d_2)}{d_1 d_2} \qquad \text{...(2.23)}$$

when $\tan x \approx x$ then $\alpha = \beta + \gamma$ (from Fig. 2.7(c)) and

$$\alpha \approx h\left(\frac{d_1 + d_2}{d_1 d_2}\right)$$

Equation (2.23) can be more minimized using the dimensionless Fresnel-Kirchoff diffraction parameter v which is given by

$$v = \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} = \alpha\sqrt{\frac{2d_1 d_2}{\lambda(d_1 + d_2)}} \qquad \text{...(2.24)}$$

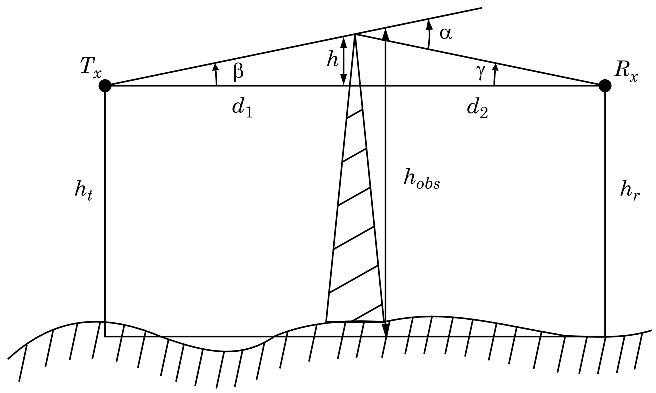
where a is shown in Fig. 2.7.

Put the value of v in equation (2.23)

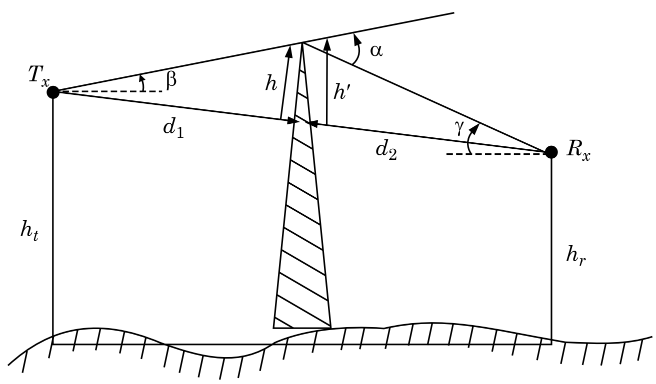
$$\phi = \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{(d_1 + d_2)}{d_1 d_2}$$

$$\phi = \frac{\pi}{2}v^2 \qquad \text{...(2.25)}$$

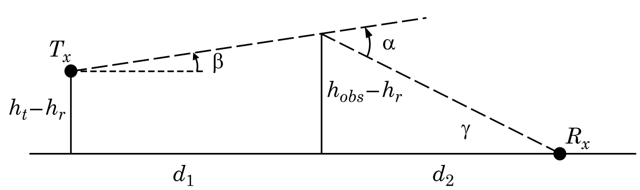
Hence, it is proved that the phase difference between a direct LOS path and diffracted path is a function of height and the position of the obstacle from the transmitter and receiver. In practical diffraction problems. All the heights are reduced by a constant without changing the values of the angles as shown in Fig. 2.8(*c*).



(*a*) Knife-edge diffraction geometry. The point T_x denotes the transmitter and R_x denote the receiver, with an infinite knife-edge obstruction blocking the line-of-sight path.



(*b*) Knife-edge diffraction geometry when the transmitter and receiver are not at the same height. Note that if α and β are small and $h <<$ d_1 and d_2, then h and h' are virtually identical and the geometry may be redrawn as shown in Fig. 2.7*c*.



(*c*) Equivalent knife-edge geometry where the smallest height (in this case h_r) is subtracted from all other heights.

Fig. 2.8 *Knife-edge geometry to minimize the antenna height.*

The **Fresnel Zones** define the concept of diffraction loss as a function of path difference around an obstacle.

Fresnel zones represent successive regions where secondary waves path length is $n\lambda/2$ greater than the total path length of a line-of-sight path. Fig. 2.9 a transparent plane lacted between transmitter and receiver.

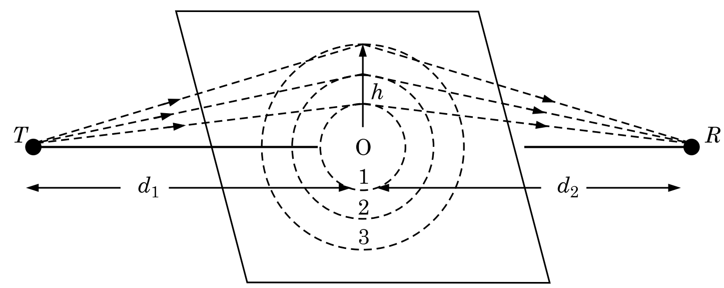


Fig. 2.9 *Concentric circles defining boundaries of Fresnel Zones*

The radius of the *n*th Fresnel Zone is denoted by r_n

$$r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \quad [\text{for } d_1 d_2 >> r_n] \quad ...(2.26)$$

The circles of the plane are called **Fresnel Zones.** The total path length increases by λ/z for sccessive circles. The successive Fresnel Zones have the elffect of alternately providing constructive and destructive interference to the total received signal.

Each successive circle represents the excess path length travelled by the ray compared to line-of-sight path. For example if $n = 1$ then ray has to travel excess path length of $\lambda/2$. If $n = 2$ then length is λ and so on. Depending on the geometry of obstruction, the received energy will be a vector sum of all unobstructed (cleared) Freshnel zones energy.

2.6.2 Knife-edge Diffraction Model

To find out the field strength in a given service area, it is required to estimate the various diffraction losses very precisely.

When shadowing is caused by a single knife edged object (hill or mountain) then the attenuation caused by diffraction can be estimated. This is the simplest diffraction model as shown in Fig. 2.10.

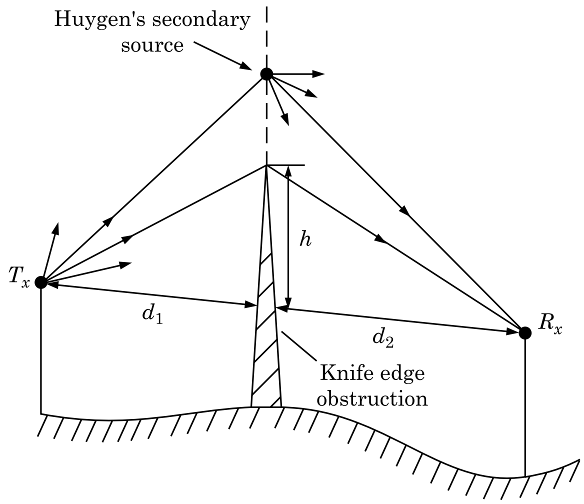


Fig. 2.10 *Knife-edge diffraction model geometry. The receiver R_x is located in the shadow region*

The field strength (E_d) of a diffracted wave at receiver (R_x) which is located in the shadowed region (diffraction zone), is the vector sum of the fields due to secondary sources in the plane above the knife edge.

$$E_d = E_o \cdot F(\nu)$$

or,
$$\frac{E_d}{E_o} = F(V) = \frac{(1+j)}{2}\int_{\nu}^{\infty} exp\,((-j\pi t^2)/2)\,dt \quad ...(2.27)$$

where, E_o = Free space field strength in absence of knife edge

and $F(\nu)$ = Complex Fresnel integral

The diffraction gain due to knife edge is

$$G_d(dB) = 20 \log |F(\nu)| \quad ...(2.28)$$

An approximate solution of equation (2.28) for different values of ν is given–

$G_d(dB) = 0$ for $\nu \le -1$

$G_d(dB) = 20 \log(0.5 - 0.62\,\nu)$ for $-1 \le \nu \le 0$

$G_d(dB) = 20 \log[0.5 \exp(-0.95\nu)]$ for $0 \le \nu \le 1$

$G_d(dB) = 20 \log[0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2}]$ for $1 \le \nu \le 2.4$

$G_d(dB) = 20 \log\left(\frac{0.225}{\nu}\right)$ for $\nu > 2.4$

Fig. 2.11 shows a graphical representation of diffraction gain (G_d) as a function of Fresnel-Kirchoff diffraction parameter (ν).

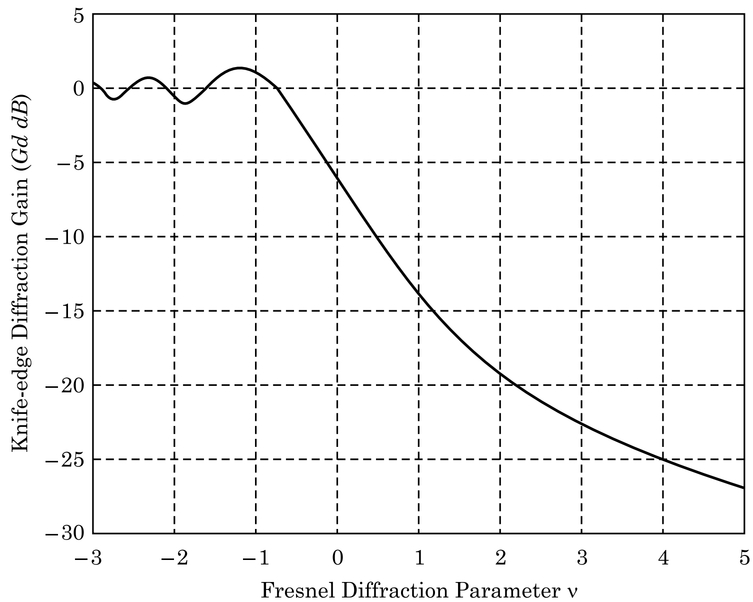


Fig. 2.11 *Graphical representation of diffraction gain as a function of Fresnel diffraction parameter*

2.6.3 Multiple Knife-edge Diffraction Model

In the previous model, we considered only a single knife-edge obstruction in between the path of transmitter and receiver but practically the propagation path may consist of more than one obstruction.

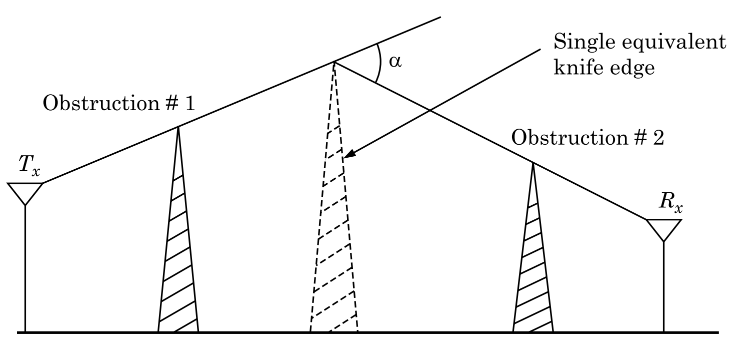


Fig. 2.12 *Multiple Knife-edge diffraction model*

After the researches to calculate the losses provided by multiple obstructions it is being suggested that the series of obstacles can be replaced by a single equivalent obstacle to compute the path-losses easily. This method is shown in Fig. 2.12. The main advantage of this method is that it provides very optimistic estimates of the received signal strength.

2.7 PATH LOSS OF RADIO SIGNALS

In free space, radio signals follow a straight line. The propagation of radio signals is same as light in free space. If such a straight line exists (or establishes) between a transmitter and a receiver then it is said as line-of-sight communication. Even if the signals are propagating in vaccum in LOS path, still the signals experience the **Free Space Loss.**

The signal power (P_r) received at receiver is inversely proportional to the square of the distance (d) between the transmitter and the receiver.

$$P_r \,\alpha\, \frac{1}{d^2}$$

In addition to the distance between transmitter and receiver, the signal power (P_r) also depends on the wavelength and gain of receiver and transmitter antennas.

The received power calculation gets more complex when signal transmission takes place through the atmosphere (not through vaccum). Now, the radio signal has to face a lot of factors (conditions) like rain, snow, air, fog, dust, smog etc.

Now, the attenuation of power in the signal path is known as **path loss** which influences transmission over long distances. Due to this loss or absorption of energy in atmosphere may cause a established link to get break down.

2.8 PROPAGATION BEHAVIOUR

Depending on the frequency, radio waves can also penetrate objects. The lower the frequency, the better the penetration. Generally, radio waves can exhibit three fundamental propagation behaviours depending on their frequency.

1. Ground wave (for $<$ 2 MHz)
2. Sky wave (for 2 – 30 MHz)
3. Line of sight propagation ($>$ 30 MHz)

A brief description of these propagation behaviours is given below:

1. Ground wave: This propagation is suitable for the broadcast at low frequencies. Waves with low frequencies follows the earth's surface and can propagate over long distances. It is useful for communication at very low frequency (VLF), low frequency (LF) and mid frequency (MF) range. These waves are used in submarine communication, AM radio communication etc.

Note: The prime drawback of ground wave propagation is that ground wave signals are suitable for propagation only upto few kilometers range.

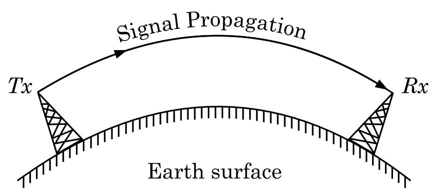


Fig. 2.13 *Ground Wave Propagation (< 2MHz)*

2. Sky wave: In this propagation, the signal reception is by reflection of the waves from the 'Ionosphere'. These waves travel around the globe by bouncing back and forth between the ionosphere and the earth's surface as shown in Fig. 2.14.

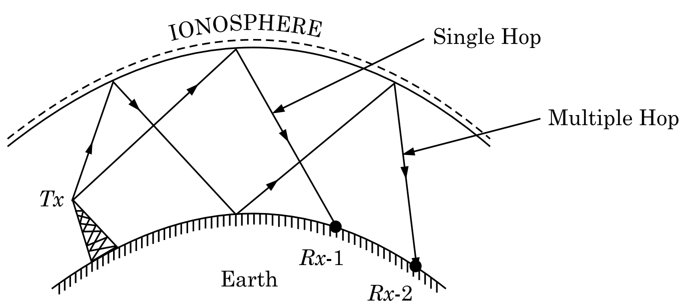


Fig. 2.14 *Sky wave propagation through Ionosphere*

Note: *Ionosphere* is an ionised region, ranging between 60 km to 450 km in the earth's atmosphere. The sky waves are reflected from some of the ionized layers of ionosphere and return back to earth in single hop or multiple hops. [See Fig. 2.14]

In sky wave propagation, for a single hop, the electromagnetic waves cover a distance upto 400 km. Therefore it is best suited for long distance and international broadcasts.

3. Line-of-Sight (LOS): LOS propagation is also known as space wave propagation space waves generally travel in straight line. These waves use LOS propagation because the wavelength of space waves are too short for reflection from the ionosphere. This propagation uses higher frequency range (> 30 MHz). These higher frequency waves follows line of sight path. This enables direct communication with satellite. These are generally used by mobile phone systems, satellite systems, cordless telephones etc.

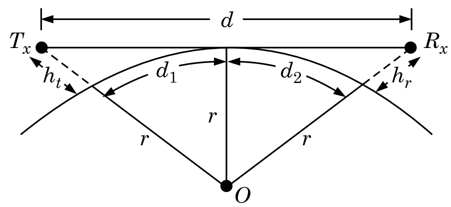


Fig. 2.15 *LOS Propagation*

2.9 FREQUENCY BANDS AND THEIR PROPAGATION MODES

Table 2.1 show frequency bands along with their mode of propagation.

Table 2.1

Band	*Abbreviation*	*Frequency range*	*Mode of Propagation*
ELF	Extra Low Frequency	30 – 300 Hz	Ground wave
VF	Voice Frequency	300 – 3000 Hz	Ground Wave
VLF	Very Low Frequency	3 – 30 KHz	Ground Wave
LF	Low Frequency	30 – 300 KHz	Ground wave
MF	Mid Frequency	300 – 3000 KHz	Ground wave
HF	High Frequency	3 – 30 MHz	Sky wave
VHF	Very High Frequency	30 – 300 MHz	LOS
UHF	Ultra High Frequency	300 – 3000 MHz	LOS
SHF	Super High Frequency	3 – 30 GHz	LOS
EHF	Extra High Frequency	30 – 300 GHz	LOS
Infrared		300 GHz – 400 THz	LOS
Visible light		400 THz – 900 THz	LOS

2.10 PRACTICAL LINK BUDGET DESIGN USING PATH LOSS MODELS

The level of received signal gets changed as distance changes. This decides the coverage of mobile systems and is used in designing of mobile communication systems. Over time, some classical propagation models have emerged which are now used to predict large scale coverage for mobile communication system design. All these models use path loss estimation techniques to accurately predict the signal strength and signal to noise ratio (SNR). Some practical path loss estimation techniques are given below.

2.10.1 Log-Distance Path Loss Model

As we know that the signal strength gets diminished as signal travels from transmitter to receiver. The signal strength decreases logarithmically as distance increases.

The average large-scale path loss for an arbitrary transmitter-receiver separation is expressed as a function of distance by using a path loss exponent n

$$\overline{PL}(d) \times \left(\frac{d}{d_o}\right)^n \qquad \text{...(2.29)}$$

or

$$\overline{PL}(dB) = \overline{PL}(d_o) + 10n\log\left(\frac{d}{d_o}\right) \qquad \text{...(2.30)}$$

where n = Path loss exponent indicates the rate at which the path loss increases with distance.

d_o = Close in reference distance which is determined from measurements close to the transmitter.

d = Transmitter receiver separation distance.

When the graph is plotted on a log-log scale, then the modulated path loss shows a straight line with a slope equal to 10 n dB per decade. The value of path loss exponent (n) varies in different environments as given in Table 2.2.

The selection of reference distance should always be in the far field of the antenna so that near field effects do not alter the path loss. In large coverage mobile systems, 1 km reference distances are commonly used whereas in microcellular systems, 100 m or 1m distances are used.

Table 2.2 *Estimation of path loss (n) for different environments*

Environment	*Path Loss Exponent, n*
In building line of sight	1.6 to 1.8
Free space	2.0
Obstructed in factories	2.0 to 3.0
Urban area Cellular radio	2.7 to 3.5
Shadowed urban Cellular radio	3.0 to 5.0
Obstructed in buildings	4.0 to 6.0

2.10.2 Log-normal Shadowing Model

In the previous equation (2.30), the effect of clutter at same transmitter-receiver separation is not being considered. Note that the clutter may be vastly different at two different locations having same transmitter receiver separation as shown in Fig. 2.16.

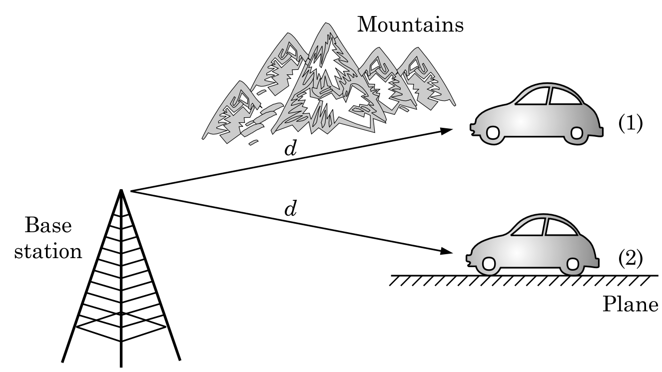


Fig. 2.16 *Clutter variation at different locations.*

For first mobile, the clutter will be high due to mountains, with respect to the second mobile while both are at same distance to the transmitter. Therefore, the measured signal at receiver (mobile 1 and 2) will be different than the average value predicted by equation (2.30).

Measurements have shown that at any value of d, the path loss $PL(d)$ at a particular location is random and distributed log-normally (normal in dB) about the mean distance dependent value – that is,

$$PL(d)\ [dB] = \overline{PL}(d) + X_\sigma$$

$$= \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \qquad ...(2.31)$$

and $$P_r(d)\ [dBm] = Pt[dBm] - PL(d)\ [dB] \qquad ...(2.32)$$

where, X_σ = Zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB)

This logarithmic distribution describes the random shadowing effects which occur at different locations having same transmitter-receiver separation distnace but varying clutter levels. This phenomenon is known as log-normal shadowing.

This model may be used in computer simulation to provide received power levels for random locations in communication system design and analysis.

2.10.3 Determination of Percentage of Coverage Area

In the previous section, we have studied the random effect of shadowing. Due to this effect, the signal strength at some locations within a coverage area will become below a particular desired threshold level.

Let, there be a circular coverage area having radius R from the base station and the desired received signal threshold is assumed as γ. Then the percentage of useful service area $U(\gamma)$ provides a known likelihood of coverage at the cell boundary. Here, useful service area $U(\gamma)$ is the area at which the received signal strength is equal to or greater than γ. Letting $d = r$ represents the radial distance from the transmitter at which the received signal exceeds the threshold γ within an incremental area dA, then $U(\gamma)$ can be found by

$$U(\gamma) = \frac{1}{\pi R^2}\int P_r\,[P_r\,(r) > \gamma]\,dA \qquad ...(2.33)$$

$$= \frac{1}{\pi R^2}\int_0^{2\pi}\int_0^{R} P_r\,[P_r(r) > \gamma]\,r\,d_r\,d\theta \qquad ...(2.34)$$

But at the cell boundary $r = R$, the path loss exponent will be

$$\overline{PL}(r) = 10n\log\left(\frac{R}{d_0}\right) + 10n\log\left(\frac{r}{R}\right) + \overline{PL}(d_0) \qquad ...(2.35)$$

After solving these equations, the useful service area will be

$$U(\gamma) = \frac{1}{2}\left[1 + \exp\left(\frac{1}{b^2}\right)\left(1 - erf\left(\frac{1}{b}\right)\right)\right] \quad \ldots(2.36)$$

where, *erf* error function

and $b = (10n \log e)/\sigma\sqrt{2}$.

2.11 PROPAGATION MODELS

Propagation models are used to determine how many cell sites are required to provide the coverage requirements for the network. The propagation model helps to determine where the cell sites should be located to achieve an optimal position in the network.

The coverage requirement is coupled with the traffic loading requirement which rely on the propagation model chosen to determine the traffic distribution and the off-loading from the existing cell site to new cell sites as part of a capacity relief program. Propagation models are also useful for interference predictions.

Although no propagation model can account for all variations experienced in the real world. Therefore, it is essential that one should use one or several models for determining the path losses in the network. Generally, propagation models are divided into two parts:

1. Outdoor propagation models

2. Indoor propagation models

The detailed classification of propagation models is given in Fig. 2.17.

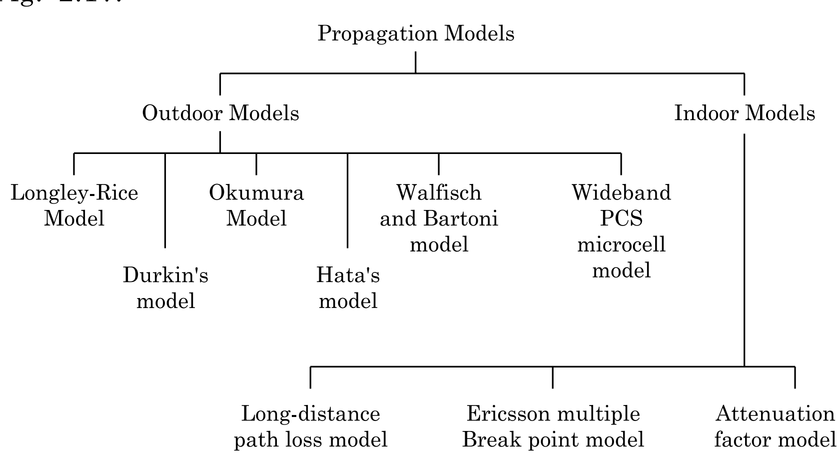


Fig. 2.17 *Classification of Propagation Models.*

2.12 OUTDOOR PROPAGATION MODELS

These models are related with the outside environment. These models aim to predict signal strength at a particular receiving point or in a specific local area (called a Sector). The irregular terrain like presence of trees, buildings and other obstacles generate path loss thereby the signal strength fluctuates at different points. Most of these models are based on a systematic interpretation of measurement data obtained in the service area. Some commonly used models are given below :

2.12.1 Longley-Rice Model

- This model is also referred to as ITS irregular terrain model.
- It is applicable in the frequency range from 40 MHz to 100 GHz over different kinds of terrain (means series of obstacles like buildings mountains etc.)
- In this model, two-ray ground reflection model is used to predict the signal strength within the radio horizon.
- Fresnel-Kirchoff knife-edge model is used to estimate diffraction losses.
- This model operates in two models :
  1. When the terrain path profile detail is available then the path specific parameters can be easily determined and such a prediction is called as **'Point-to-Point'** Prediction.
  2. When the terrain path profile detail is not available then some techniques are used to determine the path specific parameters and such a prediction is called on **'area made'** prediction.
- For a given transmission path, a lot of parameters are used to calculate the path losses (transmission losses), for e.g. polarization, ground conductivity, ground dielectric constant, surface refractivity, effective radius of earth, antenna heights, transmission frequency, path length and climate etc.

2.12.2 Durkin's Model

- This model was developed by Durkin and Edward.

- This model consists of a computer simulator, for predicting field strength over irregular terrain.
- This was adopted by joint radio committee (JRC) in the U.K. for the estimation of mobile coverage area.
- The simulator predicts large-scale phenomena (i.e. path loss) and the losses caused by obstacles in a radio path.
- The execution of path loss simulator consists two parts:
  1. The first part access the tropographic data base of a proposed service area and reconstructs the ground profile information.
  2. The second part calculates the expected path loss along the radial.
- This model is very attractive because it can read in a digital elevation map and perform a site specific propagation computation on the elevation data.
- The main drawback of this model is that it can not accurately predict propagation effects due to foliage, buildings etc. and it does not account for multipath propagation (other than ground reflection).

2.12.3 Okumura's Model

- This model is widely used for signal prediction in urban areas.
- It is applicable in the frequency range from 150 MHz to 1920 MHz.
- It can be used for distances from 1 km to 100 km from transmitter to receiver.
- It can be applied for base station antenna heights ranging from 30 meter to 1000 meter.
- To determine the path loss using Okumura's model, the equation can be expressed as :

$$L_{50}(d_B) = L_F + A_{mu}(f, d) - G(h_{te}) - G(h_{re}) - G_{AREA} \quad ...(2.37)$$

where, L_{50} = $50th$ percentile (i.e. median) value of propagation path loss

L_F = Free space propagation loss

A_{mu} = Median attenuation relative to free space

$G(h_{te})$ = Base station antenna height gain factor

$G(h_{re})$ = Mobile antenna height gain factor

- This model is completely based on measured data and does not provide any analytical explanation.
- This model is considered as best in terms of accuracy in path loss prediction in cluttered environments.
- The main drawback of Okumura's model is that it does not response sufficiently quick to rapid changes in radio path profile or in terrain. Therefore, this model is good in urban and suburban areas but not as good in rural areas.

2.12.4 Hata's Model

- Hata's Model does not account for any of the path-specific corrections used in Okumura's model.
- Hata's model is an experimental formulation of the geographical path loss data provided by Okumura.
- This model is valid from 150 MHz to 1500 MHz.
- Hata's model is applicable in urban, suburban and open areas.
- This model is well suited for large cell mobile systems, but not personal communication systems (PCS) which have cells of the order of 1 km radius.
- This model predicts the median path loss in three types of environment: urban, suburban and rural areas. The median path loss in dB for these three environments are given by the equations

$$L_{50} = A + B \log_{10} d \quad \text{(dB) Urban} \quad ...(2.38)$$

$$L_{50} = A + B \log_{10} d - C \quad \text{(dB) Suburban} \quad ...(2.39)$$

$$L_{50} = A + B \log_{10} d - D \quad \text{(dB) Open} \quad ...(2.40)$$

where d is the range in kilometers from BS to MS. The parameters in these equations depend on the frequency of operation f_c, the height of transmitting station, h_{te} and the height of the receiving station, h_{re}. These parameters are given by the empirical formulas

$$A = 69.55 + 26.16 \log_{10} f_c - 13.82 \log_{10} h_{te} - a(h_{re})$$

$$B = 44.9 - 6.55 \log_{10} h_{te}$$

$$C = 5.4 + 2[\log_{10}(f_c/28)]^2$$

$$D = 40.94 + 4.78(\log_{10} f_c)^2 - 18.33 \log_{10} f_c$$

where f_c is measured in MHz, h_{te} and h_{re} are in meters and $a(h_{re})$ is a correction factor for mobile antenna height. This model is valid for the following ranges–

$$f_c \Rightarrow 150\text{ MHz} - 1000\text{ MHz}$$
$$h_{te} \Rightarrow 30\text{ m} - 200\text{ m}$$
$$h_{re} \Rightarrow 1\text{ m} - 10\text{ m}$$
$$d \Rightarrow 1\text{ km} - 20\text{ km}$$

Fig. 2.18 shows path loss predictions with Hata Model for 30 m Base antenna and 1 m mobile antenna for a midsized city.

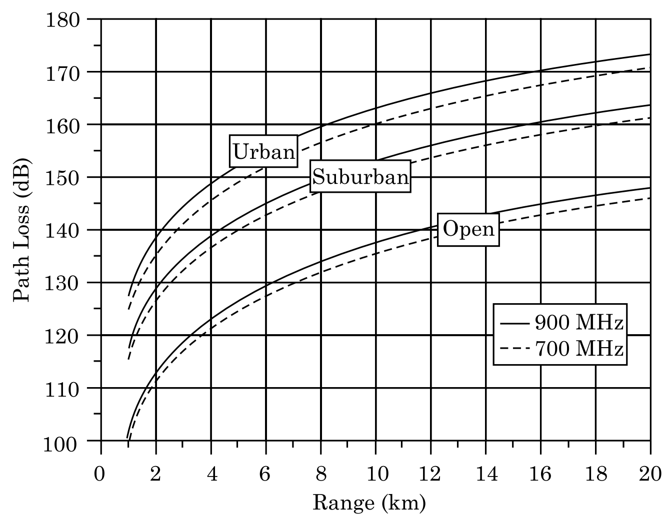


Fig. 2.18 *Path loss predictions with Hata propagation model for a midsized city [Base antenna – 30 m, Mobile antenna – 1 m]*

2.12.5 Walfisch and Bertoni's Model

- This model is a combination of experimental (empirical) and deteministic models for estimating the path loss in an urban environment over the frequency range of 800–2000 MHz.
- This model was used primarily for GSM systems and in some propagation models in the united states.
- This model contains three elements; free-space loss, roof-to-street diffraction and scatter loss, and multiscreen loss (*i.e.* diffraction and scatter loss from other structures).

- The expression of median path loss in this model is given by

$$L_{50} = L_f + L_{rts} + L_{ms} \text{ dB}$$

where, L_f = free-space loss

L_{rts} = roof–to–street diffraction and scatter loss

and L_{ms} = multiscreen loss

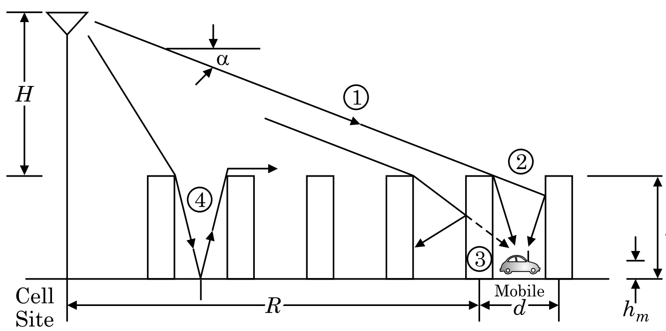


Fig. 2.19 *Propagation geometry of Walfisch and Bertoni's Model.*

2.12.6 Wideband Personal Communication System Microcell Model

- This model assumes omnidirectional vertical antennas and predicts average path loss as

$$\overline{PL}(d) = \begin{cases} 10\eta_1 \log(d) + P_1 & \text{for } 1 < d < d_f \\ 10\eta_2 \log(d/d_f) + 10n_1 \log d_f + P_1 & \text{for } d > d_f \end{cases} \quad ...(7.41)$$

where, $P_1 = \overline{PL}(d_o)$ *i.e.* the path loss in decibels at the reference distance of d_0 = 1m

d = distance from transmitter to receiver in meter

d_f = distance of first Fresnel zone clearance

n_1 and n_2 = Path loss exponents as a function of transmitter height.

- This model used a 20 MHz pulsed transmitter at 1900 MHz to measure path loss, outage and delay spread in cellular systems.
- Using base station antenna heights of 3.7 m, 8.5 m and 13.3 m and a mobile receiver with an antenna height of 1.7 m above ground, statistics for path loss, multipath

and coverage area were developed from extensive measurements in line-of-sight (LOS) and obstructed environment.

2.13 INDOOR PROPAGATION MODELS

These models characterize the radio propagation inside buildings. These are much different from the outdoor models because in indoor radio channels the distances covered are much smaller and the variations in environment is much greater.

Indoor propagation (Inside the building) is highly influenced by the building layout, the construction material used, etc. Again the study of reflection, diffraction and scattering is quite important for indoor propagation models as was used for outdoor propagation models. Inside the building the signal strength may vary from door to door as we so towards inner side of building. It also depends on whether the door is open or close.

Experimental studies have shown that the signal strength received inside a building increases with height of a building. At the lower floors of a building, the urban cluster induces greater attenuation and thereby reduces the level of penetration. While on higher floors, the LOS path may exist, thus causing a stronger signal at the exterior wall of the building.

One major loss known as **Partition loss** that is due to inside partitions of a building. Partition may be of two types :

1. **Hard Partition :** Which are formed as part of building structure and not movable.
2. **Soft Partition :** Which do not connected with the ceiling and may be moved.

Partition losses also occur between floors. These are based on the external dimensions and materials of a building, number of windows in a building etc.

In general, the indoor channels may be classified either as line–of–sight (LOS) or obstructed (OBS) with varying degree of clutter. Given below are some key models used for indoor propagation.

2.13.1 Log-distance Path Loss Model

Indoor path loss obey the distance power law as given

$$PL(dB) = PL(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma \qquad \text{...(2.42)}$$

where, n = depends on surroundings and building type

X_σ = Normal random variable (dB) having a standard deviation of σ dB.

Table 2.3. Shows typical values of n and σ for various buildings.

Table 2.3 *Path Loss Exponent and Standard Deviation measured in Different Buildings*

Building	*Frequency (MHz)*	*n*	*σ(dB)*
Retail Stores	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory LOS			
Textile/Chemical	1300	2.0	3.0
Textile/Chemical	4000	2.1	7.0
Paper/Cereals	1300	1.8	6.0
Metalworking	1300	1.6	5.8
Suburban Home			
Indoor Street	900	3.0	7.0
Factory OBS			
Textile/Chemical	4000	2.1	9.7
Metalworking	1300	3.3	6.8

2.13.2 Ericsson Multiple Breakpoint Model

- This model was obtained by measurements in a multi-floor office building.
- This model is divided into four breakpoints.
- This model also assumes that there is 30dB attenuation at reference distance d_0 = 1m.
- This model provides a deterministic limit on the range of path loss at a particular distance.

2.13.3 Attenuation Factor Model

- It is an in building site specific propagation model that includes the effect of building type as well as the variations caused by obstacles.

- This model is used to reduce the standard deviation between measured and predicted path loss nearly around $4dB$. This was $13dB$ in case of log-distance model.
- The attenuation factor model is given by,

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n_{SF} \log\left(\frac{d}{d_0}\right) + FAF + \sum PAF \ dB \quad ...(2.43)$$

where n_{SF} = Exponent value for the same floor.

FAF = Floor attenuation factor

PAF = Partition attenuation factor

- The FAF may be replaced by an exponent which already considers the effects of multiple floor separation :

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n_{MF} \log\left(\frac{d}{d_0}\right) \sum PAF \ dB \quad ...(2.44)$$

where, n_{MF} represents the path loss exponent based on measurements through multiple floors.

SUMMARY

- The propagation of radio signals is categorized into three ranges, transmission, detection and interference range.
- In free space, the radio signals exhibit the same characteristics as light does.
- Signal faces some losses when propagate through atmosphere.
- Shadowing is a form of attenuation of radio signals due to large obstacles.
- Reflection occurs when the signal strike with an obstacle which dimension is large compared to the wavelength of the signal.
- Refraction occurs when signal travels through one medium to other medium whose density is change than first medium.
- Scattering occurs when the dimension of the obstacle is in order of the wavelength of signal or less.
- Diffraction occurs when the radio wave strikes at an edge of the obstacle and propagated in different directions.
- The Fresnel zone defines the concept of diffraction loss as a function of path difference around an obstacle.
- The attenuation of power in the signal path is known as path loss.
- Propagation models are used to determine the exact cell site location, coverage, interference prediction, path loss exponent etc.
- Outdoor propagation model deals with external environment while indoor propagation models are used inside buildings.
- The angle at which no reflection occurs in the medium of origin is known as **'Brewster Angle'**, which is defined by

$$\sin(D_B) = \sqrt{\frac{\varepsilon_1}{\varepsilon_1 + \varepsilon_2}}$$

- For a perfect conductor, the reflection coefficient parallel and perpendicular to the plane of incidence is:

$$\tau_{11} = 1$$

and $$\tau_{\perp} = -1$$

REVIEW QUESTIONS

1. What are the different ranges of signals in propagation theory?

2. Explain the following in brief :

(*a*) Reflection

(*b*) Diffraction

(*c*) Scattering

(*d*) Shadowing

(*e*) Refraction

3. How reflection depends on the medium? Explain reflection from perfect conductors.

4. Explain Radar cross section model of scattering.

5. What do you understand by Fresnel Zone geometry?

6. Explain knife-edge diffraction model in detail.

7. What do you mean by the term 'Path loss'?

8. Explain the log distance path loss model in practical link budget design.

9. What are the purposes for which propagation models are used in wireless communication? Explain the basic difference between outdoor and indoor propagation models.

10. Explain Hata's outdoor propagation models and find the median path loss for urban, suburban and rural areas.

11. What do you understand by partition losses in indoor propagation models? Explain attenuation factor model in detail.

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