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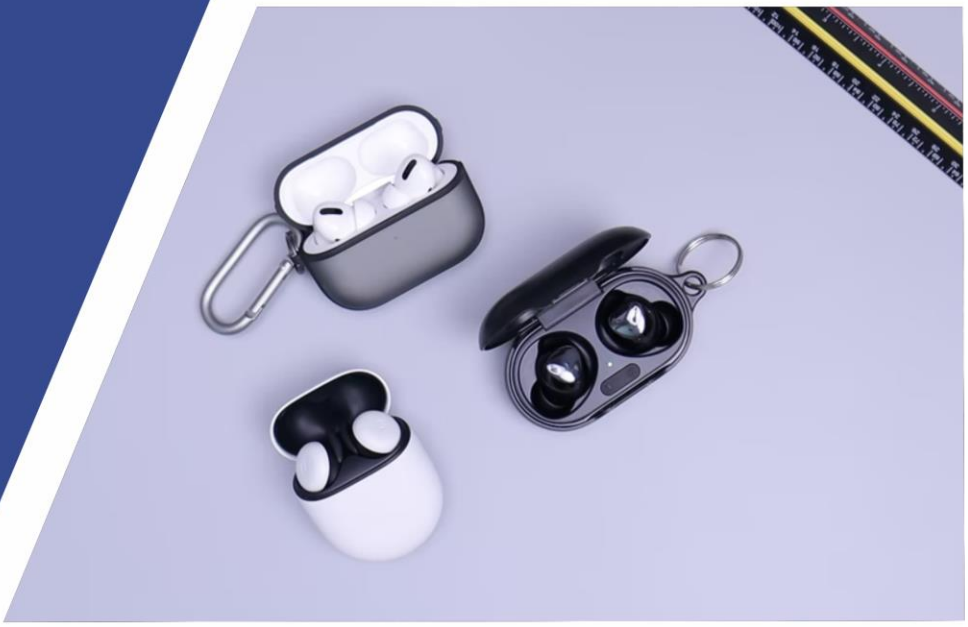
# CIT 855



## Wireless Communication I

## Module 2

# CIT 855 Wireless Communications I Module 2

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# Unit 1 Wireless Channel Model

## 1.0 Introduction

Mobile communication is burdened with particular propagation complications, making reliable wireless communication more difficult than fixed communication between carefully positioned antennas. The antenna height at a mobile terminal is usually very small, typically less than a few meters. Hence, the antenna is expected to have very little 'clearance', so obstacles and reflecting surfaces in the vicinity of the antenna have a substantial influence on the characteristics of the propagation path. Moreover, the propagation characteristics change from place to place and, if the terminal moves, from time to time.

## 2.0 Objectives

At the end of this unit, you should be able to:

- explain the term channel model
- mention the two types of communication channels
- discuss the statistical propagation models
- define a path loss and state its causes
- describe two propagation prediction for a path loss.

## 3.0 Main Content

### 3.1 Channel Model

Channel is the medium between the transmitting antenna and the receiving antenna as shown in Figure 2.1

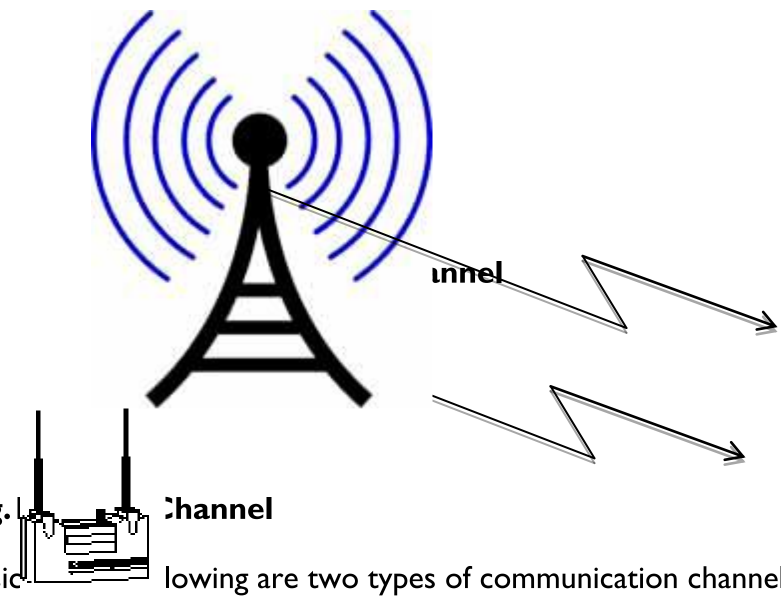


**Fig. [illegible] Channel**

Basic [illegible] lowing are two types of communication channels

- wired channels, and
- radio or wireless channel.

The wired channels are stationary and predictable whereas the radio channels are extremely random and do not offer easy analysis.

The characteristics of wireless signal changes as it travels from the transmitter antenna to the receiver antenna. These characteristics depend upon the distance between the two antennas, the path(s) taken by the signal, and the environment (buildings and other objects) around the path. The profile of received signal can be obtained from that of the transmitted signal if we have a model of the medium between the two. This model of the medium is called **channel model**.

A channel can be modeled physically by trying to calculate the physical processes which modify the transmitted signal. For example in wireless communications, the channel can be modeled by calculating the reflection of every object in the environment. A sequence of random numbers might also be added in to simulate external interference and/or electronic noise in the receiver.

Statistically, a communication channel is usually modeled as a triple consisting of an input alphabet, an output alphabet, and for each pair (i, o) of input and output elements a transition probability p(i, o). Semantically, the transition probability is the probability that the symbol *o* is received given that *i* was transmitted over the channel.

Statistical and physical modeling can be combined. For example in wireless communications, the channel is often modeled by a random attenuation (known as fading) of the transmitted signal, followed by additive noise. The attenuation term is a simplification of the underlying physical processes and captures the change in signal power over the course of the transmission. The noise in the model captures external interference and/or electronic noise in the receiver. If the attenuation term is complex it also describes the relative time a signal takes to get through the channel. The statistics of the random attenuation are decided by previous measurements or physical simulations.

Channel models may be continuous channel models in that there is no limit to how precisely their values may be defined.

A channel model may include:

- noise model, for example, Additive White Gaussian Noise (AWGN).
- distortion model, for example non-linear channel causing intermodulation distortion (IMD).
- interference model, for example cross-talk (co-channel interference) and intersymbol interference (ISI) .
- modeling of underlying physical layer transmission techniques, for example an equivalent baseband model of modulation and frequency response.
- radio frequency propagation model.
  fading model, for example Rayleigh fading, Ricean fading, log-normal shadow fading and frequency selective (dispersive) fading.
- doppler shift model, which combined with fading results in a time-invariant system
- mobility models, which also causes a time-invariant system.

### 3.1.1 Statistical Propagation Models

In generic system studies, the mobile radio channel is usually evaluated from 'statistical' propagation models: no specific terrain data is considered, and channel parameters are modeled as stochastic variables.

Three mutually independent, multiplicative propagation phenomena can usually be distinguished: 'large-scale' path loss, shadowing and multipath fading.

- **Path-loss**
  The 'large-scale' effect causes the received power to vary gradually due to signal attenuation determined by the geometry of the path profile in its entirety. This is in contrast to the local propagation mechanisms, which are determined by terrain features in the immediate vicinity of the antennas.
- **Shadowing**
  This is a 'medium-scale' effect: field strength variations occur if the antenna is displaced over distances larger than a few tens or hundreds of metres.
- **Multipath-Propagation**
  Fading leads to rapid fluctuations of the phase and amplitude of the signal if the vehicle moves over a distance in the order of a wave length or more. Multipath fading thus has a 'small-scale' effect.

### 3.1.2 Basic Concept of Path Loss

Path Loss (or path attenuation) is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space. Path loss may be due to many effects, such as free space loss, refraction, diffraction, reflection, aperture-medium coupling loss, and absorption.

Path loss is also influenced by terrain contours, environment (urban or rural, vegetation and foliage), propagation medium (dry or moist air), the distance between the transmitter and the receiver, and the height and location of antennas.

Path loss model describes the signal attenuation between transmitting and receiving antennas as a function of the propagation distance and other parameters. The simplest channel is the free space line of sight channel with no objects between the receiver and the transmitter or around the path between them. In this simple case, the transmitted signal attenuates since the energy is spread spherically around the transmitting antenna.

#### 3.1.2.1 Causes

Path loss normally includes propagation losses caused by the natural expansion of the radio wave front in free space (which usually takes the shape of an ever-increasing sphere), absorption losses (sometimes called penetration losses), when the signal passes through media not transparent to electromagnetic waves, diffraction

losses when part of the radio wave front is obstructed by an opaque obstacle, and losses caused by other phenomena.

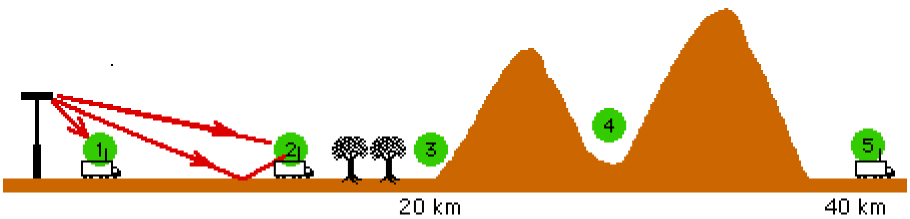
### 3.1.2.2 Propagation Prediction

Calculation of the path loss is usually called prediction. Exact prediction is possible only for simpler cases, such as the above-mentioned free space propagation or the flat-earth model. For practical cases the path loss is calculated using a variety of approximations.

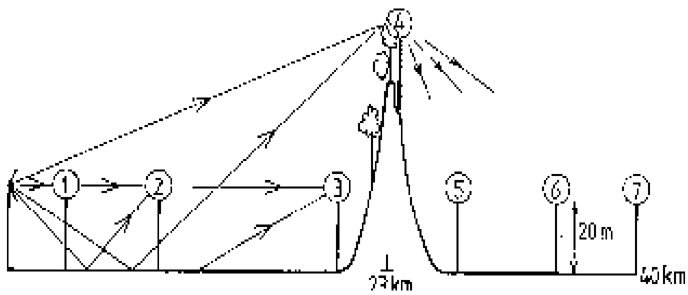
**Statistical methods** (also called stochastic or empirical) are based on measured and averaged losses along typical classes of radio links. Among the most commonly used methods are Okumura-Hata, the cost Hata model, W.C.Y. Lee, etc. These are also known as radio wave propagation models and are typically used in the design of cellular network. For wireless communication in the VHF and UHF frequency band (the bands used Walkie-talkies, police, taxis and cellular phones), one of the most commonly used methods is that of Okumura-Hata as refined by the COST 231 project. Other well-known models are those of Walfisch-Ikegami, W.C.Y. Lee, and Erceg . For FM radio and TV broadcasting, the ITU model is commonly used in predicting the path loss.

**Deterministic methods** based on the physical laws of wave propagation are also used; ray tracing is one of such methods. These methods are expected to produce more accurate and reliable predictions of the path loss than the empirical methods; however, they are significantly more expensive in computational effort and depend on the detailed and accurate description of all objects in the propagation space, such as buildings, roofs, windows, doors, and walls. For these reasons they are used predominantly for short propagation paths. Among the most commonly used methods in the design of radio equipment such as antennas and feeds is the finite-difference time-domain method.

The path loss in other frequency bands such as MW, SW, and Microwave are predicted with similar methods, though the concrete algorithms and formulas may be very different from those for VHF/UHF. Reliable prediction of the path loss in the SW/HF band is particularly difficult, and its accuracy is comparable to weather predictions.




**(a)**




**(b)**

**Fig.1.2: (a) & (b): Illustration of Path Loss**

In the above path profile in Figure 2.2 (a and b), the most appropriate path loss model depends on the location of the receiving antenna.

- At location 1, free space loss is likely to give an accurate estimate of path loss
- At location 2 and 3, a strong line-of-sight is present, but ground reflections can significantly influence path loss. The plane earth loss model appears appropriate
- At location 4, free space loss needs to be corrected for significant diffraction losses, caused by trees cutting into the direct line of sight
- Path loss prediction at location 5, 6 and 7 is more difficult than at the other locations. Ground reflection and diffraction mechanisms interact.

### 3.1.2.3 Received Signal Power and Attenuation

Path loss is one of the mechanisms causing attenuation between the transmitter power amplifier and receiver front end. Some other effects are listed below, with an indication of the order of magnitude in a GSM-like system.

- Losses in the antenna feeder (0 .. 4 dB)
- Losses in transmit filters, particularly if the antenna radiates signal of multiple transmitters (0 .. 3 dB)
- Antenna directionality gain (0 .. 12 dB)
- Losses in duplex filter
- Fade margins to anticipate for multipath (9 .. 19 dB) and shadow losses (5 dB)
- Penetration losses if the receiver is indoors, typically about 10 dB for 900 MHz signals.

**Self-Assessment Exercise**

i. What is meant by path loss
ii. What are the causes of a path loss?

## 4.0 Conclusion

Channel model is the medium between the transmitting antenna and the receiving antenna. The three mutually independent, multiplicative propagation phenomena are ‘large-scale’ path loss, shadowing and multipath fading.

## 5.0 Summary

In this unit you have learnt that:

- channel models may be continuous channel models in that there is no limit to how precisely their values may be defined
- the three mutually independent, multiplicative propagation phenomena are: 'large-scale' path loss, shadowing and multipath fading
- path loss (or path attenuation) is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space
- path loss includes propagation losses caused by the natural expansion of the radio wave front in free space, absorption losses, diffraction losses, etc
- path loss is calculated using a variety of approximations such as statistical and deterministic methods.

## 6.0 Self-Assessment Exercise

i. What do you understand by channel model?
ii. Mention two types of communication channels
iii. Describe two propagation predictions for a path loss
iv. Discuss on the statistical method of propagation prediction

## 7.0 References/Further Reading

Linnartz, J.M.G. (1996). *Wireless Communication*. Baitzer Science Publishers.

Molisch, A. F. (2005): *Wireless Communications*. Wiley and Associate.

Rappaport, T. S. (2005). *Wireless Communication: Principle and Practice.* (2nd ed.). India: Prentice Hall.

# Unit 2 Large Scale Propagation Model

## 1.0 Introduction

Mobile radio channel puts various limitations on the performance of wireless or mobile communication systems. The two fundamental blocks of any communication system are transmitter and the receiver. In wireless communications, the transmission path between the transmitter and receiver can vary from simple line-of-sight to one that is severely obstructed by buildings, mountains and foliage.

## 2.0 Objectives

At the end of this unit, you should be able to:

- define an effective isotropic radiated power
- describe free space propagation model
- compute the power and the magnitude of the E-field at the receiver antenna.

## 3.0 Main Content

### 3.1 Free Space Propagation Model for Mobile Communication

The free space propagation model is a model which is used to predict received signal strength at a particular location when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. For example, satellite communication systems and microwave line-of-sight radio links, typically, undergo free space propagation. Like other large-scale radio-wave propagation models, the free space-radio propagation model predicts that the received power decays as a function of the transmitter-receiver separation distance raised to some power (i.e. a power law function). It states that power falls off proportional to distance (d).

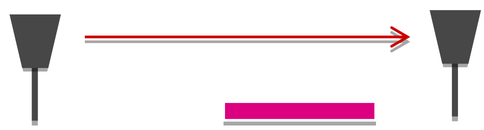


**Fig.2.1: Line-of-sight**

In a radio communication system, the propagation of the modulated signal is accomplished by means of a transmitting antenna, the function of which is twofold:

- to convert the electrical modulated signal into an electromagnetic field. In this capacity, the transmitting antenna acts as an "impedance-transforming" transducer, matching the impedance of the antenna to that of the free space.
- to radiate the electromagnetic energy in desired directions.

At the receiver, we have a receiving antenna whose function is the opposite of that of the transmitting antenna. It converts the electromagnetic field into an electrical signal from which the modulated signal is extracted. In addition, the receiving antenna may be required to suppress radiation originating from directions where it is not wanted.

Typically, the receiver is located in the far-field of the transmitting antenna, in which case, for all practical purposes, we may view the transmitting antenna as a fictitious volumeless emitter or point source.

Let us consider an isotropic source radiating a total power denoted by $P_t$, measured in watts. The radiating power passes uniformly through a sphere of surface area $4\pi d^2$, where d is the distance (in meters) from the source. Therefore, the power density, denoted by P(d), at any point on the surface of the sphere is given by

$$P(d) = \frac{P_t}{4\pi d^2}\, watts/m^2$$

- Free space (Line-of-sight) LOS without obstacles, satellite communications, microwave line-of-sight radio link.
- Friis Free Space Equation: The far-field or Fraunhoher region, of a transmitting antenna may be defined as the region beyond the far field distance $d_f$, which is related to the largest linear dimension of the transmitter antenna aperture and the carrier wavelength. The Fraunhofer distance can be expressed as

$$d_f = \frac{2D^2}{\lambda}$$ , D: the largest physical linear dimension of the antenna

Additionally, to be in the far field region, $d_f$ must satisfy $d_f \gg D$ and $d_f \gg \lambda$

The received signal power is expressed as:

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

where $P_t$ = total power radiated by an isotropic source

$G_t$ = transmitting antenna gain

$G_r$ = receiving antenna gain

d = distance between transmitting and receiving antenna

λ = wavelength of the carrier signal = c/f

c = 3 x $10^8$ m/s, velocity of light

f = carrier frequency

$P_t G_t$ = EIRP

L: system loss factor not related to propagation (L ≥ 1)

Due to transmission line attenuation, filter loss, antenna losses

$G = \frac{4\pi A_e}{\lambda^2}$ , $A_e$ : antenna's effective aperture $\alpha$ physical size of the antenna,

$\lambda = \frac{c}{f} = \frac{2\pi c}{w_c}$ , $f$ : carrier frequency[rad/s], c: speed of light [3 x $10^8$ m/s]

- Received power in Free Space

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \quad , \quad d \geq d_0 \geq d_f$$

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

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

- Maximum radiated power:
- The effective isotropic radiated power (EIRP) is defined as the product of the transmitted power, $P_t$, and the power gain of the transmitting antenna, $G_t$ i.e.

The effective isotropic radiated power (EIRP) = $P_tG_t$ watts

In fact, EIRP represents the maximum radiated power available from a transmitter in the direction of maximum antenna gain, as compared to an isotropic radiator.

In dB, EIRP is equal to sum of the antenna gain, $G_t$ (in dBi) plus the power, $P_t$ (in dBm) into that antenna.

For example, a 12 dBi gain antenna fed directly with 15 dBm of power has an Effective Isotropic Radiated Power (EIRP) of:

12 dBi+ 15dBm = 27 dBm(500 mW).

- ERP: Effective radiated power as compared to a half-wave dipole antenna
- ERP = EIRP – 2.15dB
- Effective Aperture ($A_e$) of an antenna is defined as the ratio of the power available at the antenna terminal to the power per unit area of the appropriately polarized incident electromagnetic wave.

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

- Path loss

Path loss (PL) for the free space model when antenna gains are included can be expressed as

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

when antenna gains are excluded,

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

**Note: Measuring in Decibels: dB, dBm, dBi**

**dB** (Decibel) = 10 log 10 (Pr/Pt)

Log-ratio of two signal levels. Named after Alexander Graham Bell. For example, a cable has 6 dB loss or an amplifier has 15 dB of gain. System gains and losses can be added/subtracted, especially when changes are in several orders of magnitude.

**dBm (dB milliWatt)**

Relative to 1mW, i.e. 0 dBm is 1 mW (milliWatt). Small signals are negative (e.g.-83dBm). Typical 802.11b WLAN cards have +15 dBm (32mW) of output power. They also specified -83 dBm RX sensitivity (minimum RX signal level required for 11Mbps reception).

For example, 125mW is 21dBm and 250mW is 24dBm. (Commonly used numbers)

**dBi (dB isotropic) for EIRP (Effective Isotropic Radiated Power)**

The gain a given antenna has over a theoretical isotropic (point source) antenna. The gain of microwave antennas (above1 GHz) is generally given in dBi.

**dBd (dB dipole)**

The gain an antenna has over a dipole antenna at the same frequency. A dipole antenna is the smallest, least gain practical antenna that can be made. A dipole antenna has 2.14 dB gain over a 0 dBi isotropic antenna.

Thus, a simple dipole antenna has a gain of 2.14 dBi or 0 dBd and is used as a standard for calibration.

The term dBd (or sometimes just called dB) generally is used to describe antenna gain for antennas that operate less than 1GHz (1000Mhz).

### 3.1.1 Relating Power to Electric Field

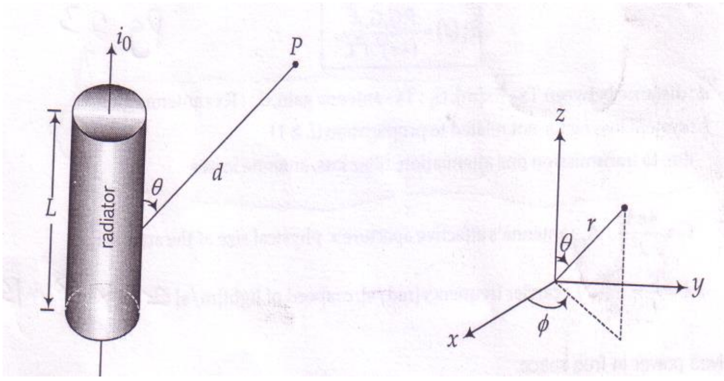



**Fig.2.2: Relating Power to Electric Field**

$$E_r = \frac{I_0 L\cos\theta}{2\pi\varepsilon_0 c}\left(\frac{1}{d^2}+\frac{c}{j\omega_c d}\right)e^{j(\omega_c t - kd)},\quad E_\theta = \frac{I_0 L\sin\theta}{4\pi\varepsilon_0 c^2}\left(\frac{j\omega_c}{d}+\frac{c}{d^2}+\frac{c^2}{j\omega_c d^3}\right)e^{j(\omega_c t-kd)}$$

$$H_\phi = \frac{I_0 L\sin\theta}{4\pi c}\left(\frac{j\omega_c}{d}+\frac{c}{d^2}\right)e^{j(\omega_c t-kd)}\quad , E_\theta = H_r = H_\theta = 0$$

$$As\ d \to \infty, only\ E_\theta, H_\theta\ be\ considered$$

- Power flux density

$$P_d\left[W/m^2\right] = \frac{EIRP}{4\pi d^2} = \frac{P_t G_t}{4\pi d^2} = \frac{E^2}{R_{fs}} = \frac{|E^2|}{\eta_0} = \frac{E^2}{377\Omega},$$

$$\eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 376.7\Omega = 120\pi\Omega$$

$R_{fs}$: intrinsic impendence of free space,

E : electric field at the receiver

$$P_d(d)[W] = P_d A_e = \frac{|E|^2}{120\pi}A_e = \frac{P_t G_t G_r \lambda}{(4\pi)^2 d^2}$$

- Circuit Model for antenna system

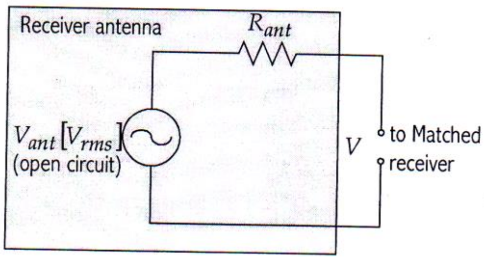



**Fig.2.3: Circuit Model for Antenna System**

$$P_r(d)[W] = \frac{V^2}{R_{ant}} = \frac{[V_{ant}/2]^2}{R_{ant}} = \frac{V_{ant}^2}{4R_{ant}}$$

**Self-Assessment Exercise**

Compute the far field distance for an antenna with maximum dimension of 1m and operating frequency of 900MHz

**Solution:** Given: largest dimension of antenna, D =1m

Operating frequency $f$ = 900MHz,

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

we know that the far-field distance is expressed as

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

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

**Self-Assessment Exercise**

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

**Solution:** Given that

Transmitter power, $P_t = 50W$

Carrier frequency, $f_c$ = 900MHz

$$\lambda = \frac{c}{f} = \frac{3\times10^{8}\ m/s}{900\times10^{6}\ Hz} m = \frac{1}{3} = 0.33$$

i. We know that the transmitter power is given by

$$\mathrm{P_t\ (dBm)} = 10\log\left[\frac{\mathrm{P_t\,(mW)}}{\mathrm{1mW}}\right] = 10\log\left[50\times10^{3}\right] = 47.0dBm$$

ii. Transmitter power in dBW will be given by

$$P_t(dBW) = \left[\frac{P_t(W)}{1W}\right] = 10\ \log[50] = 17.0dBW$$

We know that the received power can be determined using the following expression:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = \frac{50(1)(1)(1/3)^2}{(4\pi)^2 (100)^2 (1)} = (3.5 \times 10^{-6})W = 3.5 \times 10^{-3}\ mW$$

Now, the received power in (dBm) will be given by

$P_r$ (dBm) = 10 log $P_r$ (mW)

= 10 log (3.5 x $10^{-3}$ mW) = -24.5 dBm

Further, the received power at 10km may be expressed in terms of dBm, where $d_0$ = 100m and d = 10km, as under:

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

**Self-Assessment Exercise**

Assume a receiver is located 10km from a 50W transmitter. The carrier frequency is 900MHz, free space propagation is assumed, $G_t$ = 1, and $G_r$ =2, determine (a) the power at the receiver, (b) the magnitude of the E-field at the receiver antenna, (c) the rms voltage applied to the receiver input assuming that the receiver antenna has a purely real impedance of 50Ω and is matched to the receiver.

**Solution**

Given that

Transmitter power, $P_t$ = 50W

Carrier frequency, $f_c$ = 900MHz

Transmitter antenna gain, $G_t$ = 1

Receiver antenna gain, $G_r$ = 2

Receiver antenna resistance = 50 Ω

i. We know that the power received at distance d = 10km is given by

$$P_r(d) = 10\log\left(\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}\right) = 10\log\left(\frac{50 \times 1 \times 2\ (1/3^2}{(4\pi)^2 10000^2}\right) = -91.5dBW = -61.5dBm$$

ii. Again, we know that the magnitude of the received E-field is expressed as

$$|E| = \sqrt{\frac{P_r(d)120\pi}{A_e}} =$$

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

$$|E| = \sqrt{\frac{7\times10^{-10}\times120\pi}{\lambda^2 G_r/4\pi}} = \sqrt{\frac{7\times10^{-10}\times120\pi}{2\times0.33^2/(4\pi)}} = 0.0039\,V/m$$

iii. Also the applied rms voltage at the receiver input (50Ω) is given by

$$V_{ant} = \sqrt{P_r(d)\times4R_{ant}} = \sqrt{7\times10^{-10}\times4\times50} = 0.374mV$$

**Self-Assessment Exercise**

i. What are the two basic types of communication channels?

ii. Define Effective Isotropic Radiated Power (EIRP)

## 4.0 Conclusion

In this unit, we have discussed the free space propagation model and the relating power to electric field.

## 5.0 Summary

In this unit you have learnt that:

- the free space propagation model is a model which is used to predict received signal strength at a particular location when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. For example, satellite communication systems and microwave line-of-sight radio links, typically, undergo free space propagation.
- the free space power received by a receiver antenna situated at a particular location which is separated from a radiating transmitter antenna, by a distance d, is given by the following free space expression

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

## 6.0 Self Assessment Exercise

i. Assume a receiver is located 15m from a 55W transmitter. The carrier frequency is 900MHz, free space propagation is assumed $G_t$ = 1, and $G_r$ =2, find (a) the power at the receiver and (b) the magnitude of the E-field at the receiver antenna.
ii. Describe free space propagation model for mobile radio wave propagation.

## 7.0 References/Further Reading

Linnartz's, J. M. G. (1996). *Wireless Communication*. Baitzer Science Publishers.

Molisch, A. F. (2005). *Wireless Communications*. Wiley and Associate.

Rappaport, T. S. (2005). *Wireless Communication: Principle and Practice.* (2nd ed.), India: Prentice Hall.

Sharma, S. (2007). *Wireless and Cellular Communication*. New Delhi: S. K. Kataria & son

# Unit 3 Radio Propagation Mechanisms

## 1.0 Introduction

Singular information is transmitted with the help of electromagnetic wave. Electromagnetic wave consists of electric and magnetic fields.

As a matter of fact, the mechanisms responsible for electromagnetic wave propagation are:

- reflection
- diffraction and
- scattering

In case of mobile communications, operating conditions are quite severe. The reason is that most cellular radio systems operate in urban areas. In urban areas there is no direct line-of-sight path available between the transmitter and the receiver, and also, the presence of high-rise buildings creates severe diffraction loss.

Further, because of multiple reflections from various objects, the electromagnetic waves travel along different paths having variable lengths. Now, these waves interact with each other and this interaction creates the so-called multipath fading at a particular point location. As a result of this, the strengths of the waves reduce with the increase in distance between the transmitter and receiver.

## 2.0 Objectives

At the end of this unit, you should be able to:

- Explain the three propagation mechanisms
- Describe Ground Reflection Model.

## 3.0 Main Content

### 3.1 The Three Basic Propagation Mechanisms

In order to describe radio propagation, three basic mechanisms are generally considered. These mechanisms are:

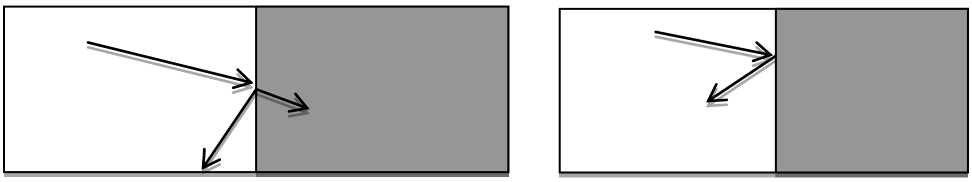
- **Reflection:** occurs when a propagating electromagnetic wave impinges upon an object which is very large in dimensions when compared to the wavelength of the propagation wave e.g. the surface of the earth, buildings, walls, etc. These mechanisms often dominate radio propagation in indoor applications. In outdoor urban areas, this mechanism often loses its importance because it involves multiple transmissions that reduce the strength of the signal to negligible values.

- **Diffraction:** occurs when the radio path between the Transmitter (Tx) and Receiver (Rx) are obstructed by a surface that has irregularities (edges). The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle, giving rise to a bending of waves around the obstacle, even when a line-of-sight path does not exist between transmitter and receiver. 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.

- **Scattering:** occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel. In practice, foliage, street signs, and lamp posts induce scattering in a mobile communications system."

### 3.1.1 Reflection

- Reflection = f(Fresnel reflection coefficient) = f(material property, wave polarisation, angle of incident, frequency)

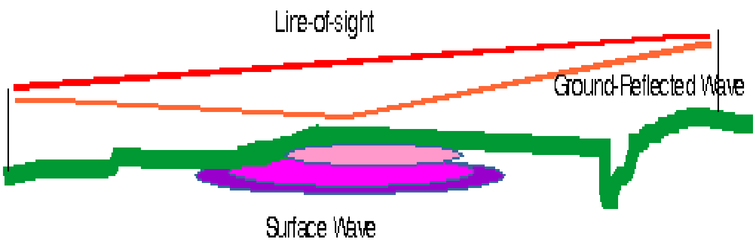


Perfect Perfect dieletric conductor

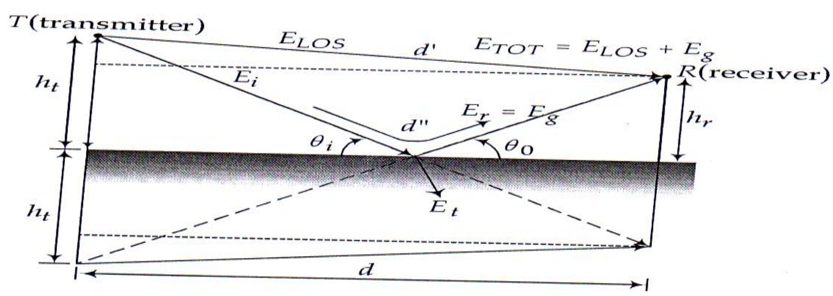
**Fig. 3.1: Reflection**

**Ground Reflection (2-Ray) Model**

- Free space propagation model is inaccurate when used alone.
- 2-ray ground reflection model has been found to be reasonable and accurate for predicting the large-scale signal strength model over distances of several kilometers for mobile radio systems that use tall towers (height which exceed 50m) as well as for line-of-sight (LOS) microcell channels in urban environments.




a.



b. **Fig.3.2 (a & b): The Method of Images is used to find the Path Difference between the Line-of-sight and the Ground Reflected Paths**

- The free space propagation E-field:

From fig. 3.2(b), $h_t$ is the height of the transmitter and $h_r$ is the height of the receiver. If $E_0$ is the free space E-field (in units of V/m) at a reference distance $d_0$ from the transmitter, then for d > $d_0$, the free space propagating E-field is expressed

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

here $|E(d,t)| = \frac{E_0 d_0}{d}$ denotes the envelope of the E-field at d meters from the transmitter. Two propagating waves arrive at the receiver: the direct wave which travels a distance $d'$, and the reflected wave which travels a distance $d''$. The E-field because of the line-of-sight component at the receiver will be given by

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

and the E-field for the group reflected wave, which has a propagation distance of d", will be given by

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

According to laws of reflection in dielectrics, we have $\theta_i = \theta_0$ and
$E_g = \tau E_i \quad , \quad E_t = (1-\Gamma)E_i$ where $\Gamma$ is the reflection coefficient for ground. For small values of $\theta_i \Rightarrow E_g \approx -E_i$ perfect ground reflection $\Gamma = -1, \; E_t = 0$

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

- Path difference between the LOS and the ground reflected paths will be given by
-

$$\Delta = d'' - d' = \sqrt{(h_t + h_r) + d^2} - \sqrt{(h_t - h_r) + d^2}$$

$$if \;\; d >> h_t + h_r \, , h_t - h_r \;\; (1 + x^2)^{1/2} \approx 1 + \frac{1}{2}x^2$$

If d is very large:

$$\Delta = d^{"} - d^{'} \approx \frac{2h_t h_r}{d} \Rightarrow \therefore \theta_\Delta = \frac{2\pi\Delta}{\lambda} = \frac{\Delta\omega_c}{c}, \; and \; \tau_d = \frac{\Delta}{c} = \frac{\theta_\Delta}{2\pi f_c}$$

It must be noted that as d becomes large, the difference between the distances d' and d" become very small, and the amplitudes of $E_{LOS}$ and $E_g$ are virtually identical and differ only in phase i.e.

$$\left|\frac{E_0 d_0}{d}\right| = \left|\frac{E_0 d_0}{d^{'}}\right| = \left|\frac{E_0 d_0}{d^{"}}\right|$$

If the received E-field is evaluated at some time, say at t = d"/c

$$E_{TOT}(d, t = \frac{d"}{c}) = \frac{E_0 d_0}{d^{'}} \cos\left[\omega_c\left(\frac{d" - d^{'}}{c}\right)\right] + (-1)\frac{E_0 d_0}{d^{"}}\cos(0^0)$$
$$= \frac{E_0 d_0}{d^{'}}\cos(\theta_\Delta) - \frac{E_0 d_0}{d^{"}} \approx \frac{E_0 d_0}{d^{'}}[\cos\theta_\Delta - 1]$$

if d>>$h_t h_r$ and $\theta_\Delta << 1, \cos\theta_\Delta \approx 1 + \theta_\Delta$

$$E_{TOT}(d) \approx \frac{E_0 d_0}{d}\cos\theta_\Delta \approx \frac{E_0 d_0}{d}\frac{2\pi}{\lambda}\frac{2h_t h_r}{d} \approx \frac{1}{d^2}\left(\frac{E_0 d_0 4\pi h_t h_r}{\lambda}\right) = \frac{k}{d^2}[V/m]$$

$$P_r(d) = \left[\frac{|E_{TOT}|^2}{120\pi}A_e = \frac{16\pi^2 h_t^2 h_r^2 d_0^2}{\lambda^2 d^4}\frac{|E_0|^2 A_e}{120\pi}\right]$$
$$= \frac{16\pi^2 h_t^2 h_r^2 d_0^2}{\lambda^2 d^4}\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2} = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

Power falls off proportional to distance rose to the fourth powers.

**Self-Assessment Exercise**

It is given that a mobile is located 5km away from a base station and makes use of a vertical λ/4 monopole with a gain of 2.55dB to receive cellular radio signal. The E-field at the transmitter is measured to be $10^{-3}$V/m. The carrier frequency used for this system is 900MHz.

i. Find the length and the effective aperture of the receiving Rx antenna.
ii. Compute the receiver power at the mobile using the 2-ray ground reflection model assuming the height of the transmitting antenna is 50m and the receiving antenna is 1.5m above ground.

**Solution**

Given that T-R separation distance = 5km, E-field at a distance of 1km = $10^{-3}$ V/m Frequency of operation, *f* = 900MHz

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

(a) Antenna length: L = λ/4 = 0.333/4 = 0.833m = 8.33cm

Also, effective aperture of $\lambda$/4 monopole antenna can be obtained as under:

$$\text{Gain} : G = \frac{4\pi A\varepsilon}{\lambda^2} = 2.55dB = 1.8$$

$$A_e = \frac{\lambda^2}{4\pi}G = \frac{0.333^2}{4\times3.1428}\times1.8 = 0.0158(m^2)$$

b. Now, since $d \cong \sqrt{h_t h_r}$ , the electric field will be given by

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

$$E_r = \frac{2\times10^{-3}\times1\times10^3}{5\times10^3}\left[\frac{2\pi(50)(1.5)}{0.333(5\times10^3)}\right] = 113.1\times10^{-6}\ V/m$$

Further, we know that the received power at a distance d can be obtained as below

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

$$P_r(d = 5km) = 5.4\times10^{-13}W$$
$$= -122.68\ dBW = -92.68\ dBm$$

### 3.1.2 Diffraction-Loss

If the direct line-of-sight is obstructed by a single object (of height $h_m$), such as a mountain or building, the attenuation caused by diffraction over such an object can be estimated by treating the obstruction as a diffracting knife-edge.

- Allow radio signals to propagate around the curved surface of the earth
- Huygen's principle

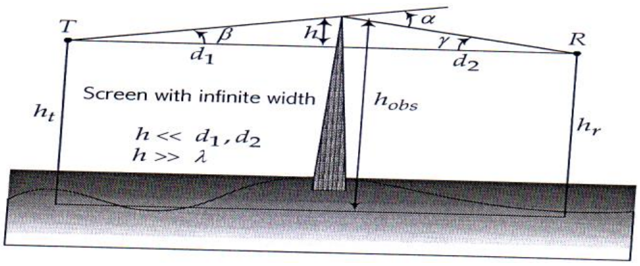



**Fig. 3.3: Knife-edge Geometry**

- Excess path length ($\Delta$)= diffraction path length-direct path length

$$\Delta \approx \frac{h^2(d_1+d_2)}{2d_1d_2} \quad \text{Phase difference} \quad \phi = \frac{2\pi\Delta}{\lambda} \Rightarrow \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{(d_1+d_2)}{d_1d_2}$$

$$\phi = \frac{\pi}{2}\left(h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}}\right)^2 \quad if\ h_t \neq h_r$$

- Fresnel Zones:
- Illustrate how shadowing is sensitive to the frequency as well as the location of obstructions with relation to the Tx or Rx.

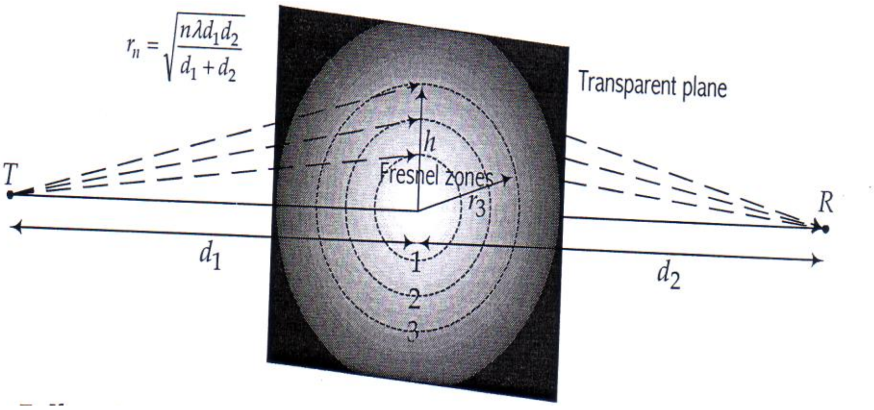



**Fig.3.4 (a): Fresnel Zones**

- If an obstruction does not block the volume contained within the first Fresnel zone, then the diffraction loss will be minimal, and diffraction effect may be neglected.
- For design of LOS microwave links, as long as 55% of the 1st Fresnel zone is kept clear, then further Fresnel zone clearance does not significantly alter the diffraction loss.

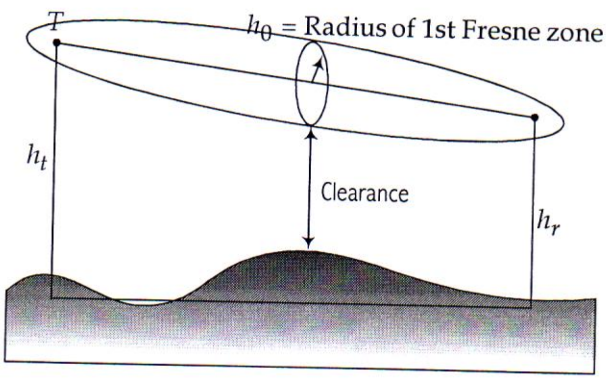



**Fig. 3.4 (b): Fresnel Zones**

- **Knife-Edge Diffraction Model**

The phenomenon by which an electromagnetic waveform diffracts, or bends, as it strikes the sharp edge of an obstacle transverse to its direction of propagation. The portion of the signal that is not cut off by the knife edge continues to propagate, but the edge of the signal bends into the line-of-sight (LOS) shadow region as if to fill the void left by the portion of the signal cut off. Knife-edge diffraction can be used to advantage in radio communications when line-of-sight (LOS) cannot be achieved due to the presence of an obstacle, such as a mountain top or building, that lies in the path of the transmit and receive antennas.

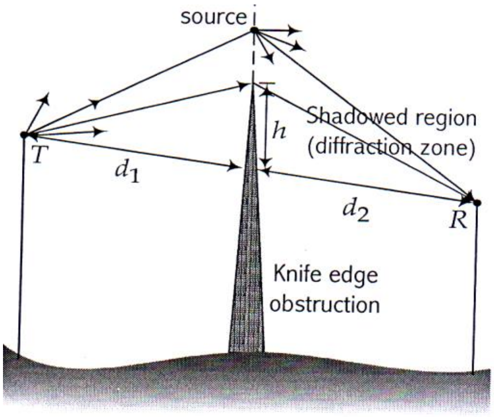



**Fig. 3.5: Knife-edge Diffraction Model**

Diffraction gain due to the presence of knife edge

Gd[dB] = 0, $\upsilon \le -1$

Gd[dB] = 20 log(0.5 – 0.62$\upsilon$), -1 ≤ $\upsilon$ ≤0

$G_d$[dB] = 20 log(0.5exp(-0.95$\upsilon$)), -1 ≤ $\upsilon$ ≤0

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

$$G_d[\mathrm{dB}] = 20\log\left(\frac{0.225}{\upsilon}\right), \upsilon > 2.4$$

$$\upsilon = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} : \textit{Fresnel} - \textit{Kirchoff diffraction parameter}$$

**Self-Assessment Exercise**

Find diffraction loss λ = 1/3m, $d_1$ = 1km, $d_2$ = 1km.

i. h = 25m

$$\upsilon = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} = 25\sqrt{\frac{2(1000+1000)}{(1/3)\times 1000 \times 1000}} = 2.74$$

$$Gd[dB] = 20\log\left(\frac{0.225}{\upsilon}\right), \upsilon > 2.4$$

$$G_d[dB] = 20\log\left(\frac{0.225}{2.74}\right) = -21.7$$

$$\Delta \approx \frac{h^2(d_1+d_2)}{2d_1d_2} = \frac{25^2(1000+1000)}{2\times1000\times1000} = \frac{1{,}250{,}000}{2000{,}000} = 0.625m$$

$$\Delta = \frac{n\lambda}{2} \rightarrow n = \frac{2\Delta}{\lambda} = \frac{2\times0.625}{0.333} = 3.75$$

The tip of the obstruction completely blocks the first three Fresnel zones

ii. h = 0

$$\upsilon = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = 0\sqrt{\frac{2(1000+1000)}{(1/3)\times1000\times1000}} = 0$$

$$Gd[dB] = 20\log(0.5-0.62\upsilon), when -1 \le \upsilon \le 0$$

$$G_d[dB] = 20\log(0.5-0.62\times0) = 20\log 0.5 = -6$$

$$\rightarrow \Delta = 0$$

$$\rightarrow n = 0$$

The tip of the obstruction lies in the middle of the first Fresnel zone

iii. h = -25m

$$\upsilon = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = -25\sqrt{\frac{2(1000+1000)}{(1/3)\times1000\times1000}} = -2.74 \rightarrow G_d[dB] = 0 \rightarrow n = 3.75$$

The diffraction losses are negligible

Multiple Knife-Edge Diffraction

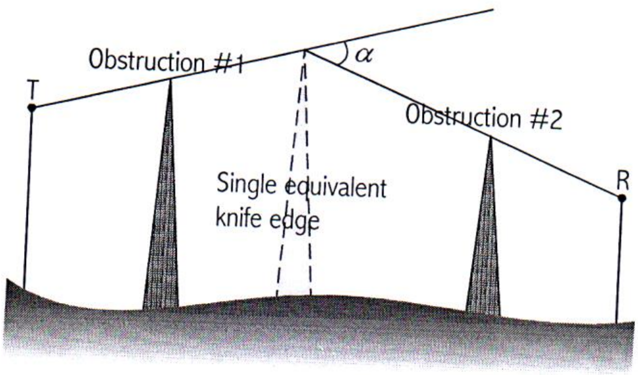



**Fig. 3.6: Multiple Knife-edge Diffraction**

### 3.1.3 Scattering

- Objects such as lamp posts and trees tend to scatter energy in all directions, thereby providing additional radio energy at a receiver.
- Roughness test: Rayleigh criterion

$$\text{Critical height}: h_c = \frac{\lambda}{8\sin\theta_i}, \; \theta_i : angle of\ incidence$$

- Smooth surface: Max to min protuberance $h < h_c$

- Reflection coefficient for rough surface

$$\Gamma_{rough} = p_s \Gamma,\ p_s = \exp\left[-8\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right] I_0\left[8\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right],$$

$\sigma_h$ : standard deviation of the surface height above the mean surface height.

- Radar Cross Section (RCS) Model
- For rough surface

$$\mathrm{RCS[m2]} = \frac{\text{power density of the signal scattered in the direction of receiver}}{\text{power density of the radio wave incident on the scattering object}}$$

- Received power due to scattering: the propagation of wave traveling in free space impinges on a distant scattering object, and is then reradiated in the direction of the receiver

Assumption: scattering object is in the far field (Fraunhofer region)

$$P_R[dBm] = P_T[dBm] + G_T[dBi] + 20\log d_R$$

$d_T(d_R)$: the distance from the scattering object to the Tx(Rx)

dBi: dB gain with respect to an isotropic source

- RCS for medium and large size building located 5-10km away:

$14.1\mathrm{dB.m}^2 \sim 55.7\mathrm{dB.m}^2$

## 3.2 Total Path Loss

The previously presented methods for ground reflection loss and diffraction losses suggest a "Mondriaan" interpretation of the path profile: Obstacles occur at straight vertical lines while horizontal planes cause reflections. That is, the propagation path is seen as a collection of horizontal and vertical elements.

Total loss=Free space loss + Ground reflection loss + Multiple knife-edge diffraction loss

**Self-Assessment Exercise**

i. What are the mechanisms responsible for electromagnetic wave propagation?
ii. Discuss the effect of path loss on the performance of a cellular radio network

# 4.0 Conclusion

The three basic propagation mechanisms are reflection, diffraction, and scattering.

## 5.0 Summary

In this unit, you have learnt that:

- electromagnetic wave consists of electric and magnetic fields.
- reflection occurs when a propagating electromagnetic wave impinges upon an object which is very large in dimensions when compared to the wavelength of the propagation wave
- diffraction occurs when the radio path between the Transmitter (Tx) and Receiver (Rx) are obstructed by a surface that has irregularities (edges)
- scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large.

## 6.0 Self-Assessment Exercise

Describe Ground Reflection (Two-Ray) model for mobile radio wave propagation.

## 7.0 References/Further Reading

Goldsmith, A. (2005). *Wireless Communications*. Cambridge University Press.

Linnartz's, J. M. G. (1996). *Wireless Communication*. Baitzer Science Publishers.

Molisch, A. F. (2005). *Wireless Communications*. Wiley and Associate.

Rappaport, T. S. (2005). *Wireless Communication: Principle and Practice.* (2nd ed.), India: Prentice Hall.

Sharma, S. (2007). *Wireless and Cellular Communication*. New Delhi: S. K. Kataria & Sons

# Unit 4 Path Loss Model

## 1.0 Introduction

In this unit, you are going to learn the various path loss models for predicting radio coverage area when designing a wireless communication system.

## 2.0 Objectives

At the end of this unit, you should be able to:

- Describe Log-distance path model
- List outdoor propagation models
- Mention two indoor propagation models.

## 3.0 Main Content

### 3.1 Empirical Path Loss Model

The primary use of an empirical model such as log-normal shadowing is to predict radio coverage when designing a wireless communication system.

The actual environments are too complex to model accurately. In practice, most simulation studies use empirical models that have been developed based on measurements taken in various real environments.

The commonly used empirical models are: Hata model, Cost 231 Extension to Hata model, COST 231-Walfish-Ikegami Model, Erceg Model etc.

### 3.1.1 Practical Link Budget Design Using Path Loss Models

**What Is Link Budget Calculation?**

A link budget is a rough calculation of all known elements of the link to determine if the signal will have the proper strength when it reaches the other end of the link. To make this calculation, various details are required like total length of transmission cable and loss per unit length at the specified frequency as there will always be some loss of signal strength through the cables.

### 3.1.1.1 Log-Distance Path Loss Model

The log-distance path loss model is a radio propagation model that predicts the path loss a signal encounters inside a building or densely populated areas over distance. In the log-distance path loss model, the path loss is automatically calculated based on the distance between the transmitter and the receiver in the emulator world.

- **Average large-scale path loss for an arbitrary T_R separation:**

$$\overline{\mathrm{PL}}(\mathrm{d})\ \alpha\ (\mathrm{d/d_0})^n,\ \overline{\mathrm{PL}}[dB] = \overline{\mathrm{PL}}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

$d_0$: the close – in reference distance in the far field of the antenna

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

- Uses the idea that both theoretical and empirical evidence suggests that average received signal strength decreases logarithmically with distance.
- Measure received signal strength near to transmitter and approximate to different distances based on above "reference" observation

### 3.1.1.2 Log-Normal Shadowing

The path loss PL(d) at a particular location: log-normal distribution

$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma;\ Normal\ distribution$$

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

$$X_\sigma \sim N(0,\sigma^2): zero-mean\ Gaussian\ distributed\ r.v\ with\ standard\ deviation\ \sigma\ [dB]$$

$$due\ to\ environmental\ surrounding$$

$$\sigma: 4 \sim 12dB, depending\ on\ the\ severity\ of\ the\ shadowiing$$

$$Log-normal\ rv: Y\ e^X,\ X \sim N(m,\sigma^2)$$

- The probability that the received signal level will exceed a certain value

$$P[P_r(d) > \gamma][dB] = Q\left(\frac{\gamma - \overline{P_r}(d)}{\sigma}\right)$$

$$Q(z) = \frac{1}{\sqrt{2\pi}}\int_z^\alpha \exp\left(-\frac{x^2}{2}\right)dx = \frac{1}{2}\left[1 - erf\left(\frac{z}{\sqrt{2}}\right)\right],\ erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$$

### 3.1.1.3 Determination of Percentage of Coverage Area

- U(γ) : Percentage of useful service area – Percentage of area with a received signal that is equal or greater than γ

$$U(\gamma) = 0.5\left(1-\mathrm{erf}(a)+\exp\left(\frac{1-2ab}{b^2}\right)\left[1-erf\left(\frac{1-ab}{b}\right)\right]\right)$$

$R: the radius of\ a\ circular\ coverage area$

$$a = \frac{\left(\gamma - P_t + \overline{PL}(d_0) + 10n\log(R/d_0)\right)}{\sigma\sqrt{2}},\ b = \frac{(10n\ \log e)}{\sigma\sqrt{2}}$$

$\sigma : s\tan dard\ deviation$

## Self-Assessment Exercise

A pass loss model: $PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10n\log(d/d_0) + X_\sigma, d_0 = 100m$

| Distance from Tx | Received Power [dBm] |
|---|---|
| 100m / 200m / 1 km /2 km | 0 / -20 / -35 / -70 |

i. Find the minimum mean square error (MMSE) estimate for the path loss exponent n
ii. Find the standard deviation
iii. Estimate the received power at d = 2km
iv. Predict the likelihood that the received signal level at 2km will be greater than -60dBm.
v. Predict the percentage of area within a 2km radius cell that received signals greater than -60dBm.

**Solution:**

(a) Since

$$PL(d)[dB] = \overline{PL}(d_0) + 10n\log(d/d_0) = \overline{PL}(d_0) - 10n\log(d_i/100m)$$

$$P_r(100m) = P_r(100m) - 0 = 0,$$

$$P_r(200m) = -3n,$$

$$P_r(1km) = -10,$$

$$Pr(3km) = -14.77n$$

$$J(n) = (0-0)^2 + (-20-(-3n))^2 + (-35-(-10n))^2 + (-70-(-14.77n))^2$$

$$= 6525 - 2887.8n + 327.153n^2$$

$$\frac{dJ(n)}{dn} = 654.306n - 2887.8 = 0 \Rightarrow n = 4.4$$

(b) standard deviation

$\sigma^2 = J(n) / 4 = 152.36 / 4 = 38.09 \rightarrow \sigma = 6.17dB$

(c) Pr(2km) = 0 – 10 log(2000/100) = -57.24dBm

(d) $$P[P_r(d) > -60dBm] = Q\left(\frac{\lambda - \overline{P_r(d)}}{\sigma}\right) = Q\left(\frac{-60 + 57.24}{6.17}\right) = 67.4\%$$

(e) 92%

### 3.1.2 Empirical Model for Outdoor Propagation Models

More sophisticated models take into account factors such as terrain. urban clutter, antenna heights, and diffraction e.g. Longley-Rice, Durkin, Okumura, Hata, COST-231, Walfisch & Bertoni etc.

(a) **Longley-Rice Model [1967, 1978]**

- Applicable to point-to-point communication systems in frequency range from 40MHz ~ 100GHz over different kinds of terrains.
- Not considering the effects of buildings and foliage, and the multipath

(b) **Durkin's Model [1969]**

- Adopted by the Joint Radio Committee (JRC) in the U.K for the estimation of effective mobile radio coverage areas
- Modeled LOS and diffraction from obstacles
- Excludes reflections from other surrounding objects and local scatters

(c) **Okumura Model**

- Most widely used models for signal prediction in urban areas
- 150 ~ 1920 MHz
- Distance: 1km ~ 100km
- Base station antenna height: 30m ~ 100m
- Wholly based on measured data and does not provide any analytic explanation
- The simplest and best in terms of accuracy in path loss prediction for mature cellular and land mobile radio systems in clustered environment
- The model is fairly good in urban and suburban areas, but not as good in rural areas
- A standard for system planning in modern land mobile radio system in Japan
- Common standard derivations between predicted and measured path loss: 10dB ~ 14dB
  L50[dB] = LF + Amu(f,d) – G(hte) – G(hre) – GAREA

L50 : the $50^{th}$ percentile (i.e. median) value of propagation path loss

LF: 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

$G_{AREA}$ : the gain due to the type of environment

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

$$G(h_{re}) = 10\log\left(\frac{h_{re}}{3}\right),\quad h_{re} \le 3m,$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right),\ 10m > h_{te} > 3m,$$

---

## Self-Assessment Exercise

Find the median path loss and Pr(d) using Okumura's model.

d = 50km, $h_{te}$ = 100m, $h_{re}$ = 10m (suburban environment). Base station's EIRP: 1kW@900MHz, $G_r$ = 0dB.

**Solution:**

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

Free space loss

$$L_F = 10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] = 125.5dB$$

$$A_{mu}\ (900MHz, 50km) = 43dB, \qquad G_{AREA} = 9dB \text{ from the Okumura curves}$$

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) = -6dB$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right) = 10.46dB$$

$$L_{50}[dB] = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$
$$= 125.5dB + 43dB - (-6)dB - 10.46dB - 9dB = 155.04dB$$

The medium received power:

Pr(d) = EIRP(dBm) - L50[dB] + Gr(dB) = 60dBm – 155.04dB + 0dB = -95.04dBm

(d) **Hata Model [1990]**

- Empirical formulation of the graphical path loss data provided by Okumura
- The model is designed for 150MHz ~ 1500MHz and are applicable to the first generation cellular system
- Median path loss in urban areas

$L_{50}$(urban)[dB] = 69.55 + 26.16log$f_c$ – 13.82log $h_{te}$ -a($h_{re}$) + (44.9 –6.55log $h_{te}$)log d d[km] : Tx – Rx distance = carrier frequency

$h_{te}$ = height of the transmitting (base station) antenna

$h_{re}$ = height of the receiving (mobile) antenna

a($h_{re}$) : correction factor for effective mobile antenna height

$a(h_{re}) = (1.1 \log f_c – 0.7)h_{re} - (1.56 \log f_c - 0.8)dB$: for a small to medium sized city $a(h_{re}) = 8.29(\log 1.54h_{re})^2 – 1.1dB$ : for a large city, $f_c \leq 300Hz$

$a(h_{re}) = 3.2[\log(11.75h_{re})]^2 – 4.97dB$ : for a large city , $f_c \geq 300Hz$

**Self-Assessment Exercise**

Determine the path loss of a 900MHz cellular system operating in a large city from a base station with the height of 100m and mobile station installed in a vehicle with antenna height of 2m. The distance between the mobile and the base station is 4km.

**Solution**

d[km] : 4km, $f_c$ = 900MHz, $h_{te}$ = 100m, $h_{re}$ =

12m $a(h_{re}) = 3.2[\log(11.75h_{re})]^2 – 4.97 = 1.045dB$

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

$=69.55 + 26.16 \log(900) – 13.82 \log(100) - 1.045 + (44.9 – 6.55 \log 100) \log 4 \quad = 137.3dB$

- Path loss in a suburban area

$L_{50}[dB] = L_{50}(urban) – 2[\log(f_c / 28)]^2 – 5.4$

- Path loss in open rural areas

$L_{50}[dB] = L_{50}(urban) – 4.78[\log(f_c)]^2 – 18.33 \log f_c – 40.98$

(e) PCS Extension to Hata Model (COST 231 Extension to Hata Model)

- Extended Hata model for 2GHz PCS by European Co-operative for Science and Technical Research (EUROCOST)

$L_{50}(urban)[dB] = 46.3 + 33.9 \log(f_c) – 13.82 \log(h_{te}) - a(h_{re}) + (44.9 – 6.55 \log(h_{te})) \log d + C_M$

$$C_M = \begin{cases} 0dB, & \text{for meium sized city \& suburban areas} \\ 3dB, & \text{for metropolitan centers} \end{cases}$$

- This model is restricted to the following parameters:

| | |
|---|---|
| Carrier frequency | 1.5GHz to 2GHz |
| Base Antenna Height | 30m to 300m |
| Mobile Antenna Height | 1m to 10m |
| Distance d | 1km to 20km |

- This model is designed for large and small macro-cells, i.e., base station antenna heights above rooftop levels adjacent to base station.

(f) CCIR Model

- An empirical formula for the combined effects of free-space path loss and terrain-induced path loss was published by the CCIR (Comité Consultatif International des Radio-Communication, now ITU-R) and is given by

$$L_{CCIR}(dB) = 69.55 + 26.16\log_{10} f_{MHz} - 13.82\log_{10} h_1 - a(h_2) + (44.9 - 6.55\log_{10} h_1)\log_{10} d_{km} - B$$

where $h_1$ and $h_2$ are base station and mobile antenna heights in meters, respectively, $d_{km}$ is the link distance in kilometers, $f_{MHz}$ is the center frequency in megahertz, and

$$a(h_2) = (1.1\log_{10} f_{MHz} - 0.7)h_2 - (1.56\log_{10} f_{MHz} - 0.8)$$
$$B = 30 - 25\log_{10}(\%\ of\ area\ \text{covered}\ by\ buildings)$$

- This formula is the Hata model for medium–small city propagation conditions, supplemented with a correction factor, B.

- The term B is such that the correction B = 0 is applied for an urban area, one that is about 15% covered by buildings; for example, if 20% of the area is covered by buildings, then

$$B = 30 - 25\log_{10} 20 = -25dB$$

(g) **The Hata-Davidson Model**

- The Telecommunications Industry Association (TIA) recommends in their publication TSB-88A the following modification to the Hata model to cover a broader range of input parameters.

- The modification consists of the addition of correction terms to the Hata model:

$$L_{HD} = L_{Hata} + A(h_1, d_{km}) - S_1(d_{km}) - S_3(f_{MHz}) - S_4(f_{MHz},\ d_{km})$$

in which A and $S_1$ are distance correction factors extending the range to 300 km, $S_2$ is a base station antenna height correction factor extending the range of $h_1$ values to 2500 and $S_4$ are frequency correction factors extending frequency to 1500MHz:

| Distance | $A(h_1, d_{km})$ | $S_1(d_{km})$ |
|---|---|---|
| $d_{km}$ <20 | 0 | 0 |
| 20 ≤ $d_{km}$< 64.38 | $0.62137(d_{km}-20)[0.5+0.15\log_{10}(h_1/121.92]$ | 0 |
| 64.38 ≤$d_{km}$< 300 | $0.62137(d_{km}-20)[0.5+0.15\log_{10}(h_1/121.92]$ | $0.174(d_{km}-64.38)$ |

$$S_2(h_1, d_{km}) = 0.00784|\log_{10}(9.98/d_{km})|(h_1 - 300) \; for \; h_1 > 300$$
$$S_3(f_{MHz}) = f_{MHz}/250\log_{10}(1500/f_{MHz})$$
$$S_4(f_{MHz}, d_{km}) = [0.112\log_{10}(1500/f_{MHz})](d_{km} - 64.38) \; for \; d_{km} > 64.38$$

### 3.1.3 Indoor Propagation Models

There are several causes of signal corruption in an indoor wireless channel. The primary causes are signal attenuation due to distance, penetration losses through walls and floors and multipath propagation.

The indoor signal propagation differs from an outdoor case particularly in distances and in variability of the environment, so these models are site specific and they have to take account of partition losses and surrounding objects which cause multipath propagation.

- Difference from the mobile radio channel
- The distances covered are much smaller.
- The variability of the environment is very high even for small T-R separations e.g. doors closed vs. opens, ceiling vs. desk mounted antennas walls, floors, furniture, people moving around.
- Physical Effects:
- Signal decays much faster
- Coverage contained by walls, etc.
- Walls, floors, furniture attenuate/ scatter radio signals
- Path loss formula:

Path Loss = Unit Loss + 10 n log(d) = k F + l W

where:

Unit loss = power loss (dB) at 1m distance (30 dB)

n = power-delay index

d = distance between transmitter and receiver

k = number of floors the signal traverses

F = loss per floor

l = number of walls the signal traverses

W = loss per wall

**Table 4.1: Measure of Accuracy of Simple Model; the Larger the σ, the Less Accurate the Model**

| Building | Freq (MHz) | n | dB |
|---|---|---|---|
| Retail Stores | 914 | 2.2 | 8.7 |
| Grocery Stores | 914 | 1.8 | 5.2 |
| Office, Hard Partitions | 1500 | 3.0 | 7.0 |
| Office, Soft Partitions | 900 | 2.4 | 9.6 |
| Office, Soft Partitions | 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 to street | 900 | 3.0 | 7.0 |
| Factory OBS | | | |
| Textile/Chemical | 4000 | 2.1 | 9.7 |
| Metalworking | 1300 | 3.3 | 6.8 |

**Source: Prof. Randy H. Katz (Radio Propagation Lecture)**

- **Other Effecting Factors**
- People moving around: Additional multipath induced attenuation of 10 dB.
- Buildings with few metal and hard partitions: RMS delay spread of 30 to 60 ns (several mbps w/o equalization).
- Buildings with metal/open aisles: RMS delay spread of up to 300 ns (100s kbps w/o equalisation)
- Between floors:

i. concrete/steel flooring yields less attenuation than steel plate flooring
ii metallic tinted windows yield greater attenuation
iii 15 dB for first floor separation, 6 - 10 dB for next four floors, 1 - 2 dB for each additional floor of separation

- Received signal strength depends on open plan offices, construction materials, density of personnel, furniture, etc.
- Path loss exponents:
- Narrowband (max delay spread < bit period)

i Vary between 2 and 6, 2.5 to 4 most common
ii Wall losses: 10 dB to 15 dB
iii Floor losses: 12 dB to 27 dB

- Wideband (max delay spread > bit period)
- Delay spread varies between 15 ns and 100 ns
- Can vary up to 250 ns
- Requires sophisticated equalisation techniques to achieve acceptable bit error rates.

- **Example 1**: indoor RF propagation at 2.4GHz (U.C. Berkeley). RF propagation obstacles can be termed hard partitions if they are part of the physical / structural components of a building. On the other hand, obstacles formed by the office furniture and fixed or movable / portable structures that do not extend to a buildings ceiling are considered soft partitions. Radio signals effectively penetrate both kinds of obstacles or partitions in ways that are very hard to predict.
- **Example 2:** indoor RF propagation at 60GHz. The 60 GHz band can be a good candidate for indoor wireless office communication, once RF components and modules become more widely available. Indoor rms delay spreads presumably are on the order of 15 to 50 nsec.

Typical delay profiles show:

- a dominant line-of-sight
- a collection of early reflections with a constant delay profile between 0 and some instant t.-
- an exponential decay beyond t.

For 60 GHz in-office propagation, t is about 50 nanoseconds. Oxygen attenuation is not noticeable for such short-range transmission. With highly directional antennas, the delay spread can be reduced to 5 to 8 nanoseconds. Severe attenuation occurs when signals have to penetrate through glass or wood. This helps to confine cell areas.

Double-glazed windows: 3 - 7 dB, concrete wall: 20-30 dB.

### Self-Assessment Exercise

List three outdoor propagation models.

## 4.0 Conclusion

In this unit, we studied the Empirical path loss, practical link budget design using path loss models, the outdoor and indoor propagation models.

## 5.0 Summary

The main points in this unit include the following:

- the primary use of an empirical model such as log-normal shadowing is to predict radio coverage when designing a wireless communication system
- a link budget is a rough calculation of all known elements of the link to determine if the signal will have the proper strength when it reaches the other end of the link
- the log-distance path loss model is a radio propagation model that predicts the path loss as a signal encounters inside a building or densely populated areas over distance
- the actual environments are too complex to model accurately, so most simulation studies use empirical models such as Hata model, Cost 231 Extension to Hata model, COST 231-Walfish-Ikegami Model, Erceg Model etc
- the primary causes of indoor wireless channels are signal attenuation due to distance, penetration losses through walls and floors and multipath propagation.

## 6.0 Self-Assessment Exercise

i. Describe log-distance path model
ii. What are the causes of signal corruption in an indoor wireless channel.

## 7.0 References/Further Reading

Garg, V. K. & Wilkes J. E. (1996). *Wireless and Personal Communications Systems*. Prentice Hall.

Goldsmith, A. (2005). *Wireless Communications*. Cambridge University Press.

Linnartz's, J. M. G. (1996). *Wireless Communication*, Baitzer Science Publishers.

Molisch, A. F. (2005). *Wireless Communications*, Wiley and Associate.

Rappaport T. S. (2005). *Wireless Communication: Principle and Practice.* (2nd ed.). India: Prentice Hall.

Saunders, S.R. (1999). *Antennas and Propagation for Wireless Communication Systems*. Wiley.

Sharma, S. (2007). *Wireless and Cellular Communication*. New Delhi: S. K. Kataria & Sons.

# Unit 5 Shadowing

## 1.0 Introduction

Shadowing is the effect that the received signal power fluctuates due to objects obstructing the propagation path between transmitter and receiver. These fluctuations are experienced on a local-means power, which is short term averages to remove fluctuations due to multipath fading.

## 2.0 Objectives

At the end of this unit, you should be able to:

- Define a shadowing model
- Illustrate with a diagram a shadowing model.

## 3.0 Main Content

### 3.1 Shadowing Concept

If there are any objects (such buildings or trees) along the path of the signal, some part of the transmitted signal is lost through absorption, reflection, scattering, and diffraction. This effect is called shadowing. As shown below, if the base antenna were a light source, the middle building would cast a shadow on the subscriber antenna, hence the name shadowing.

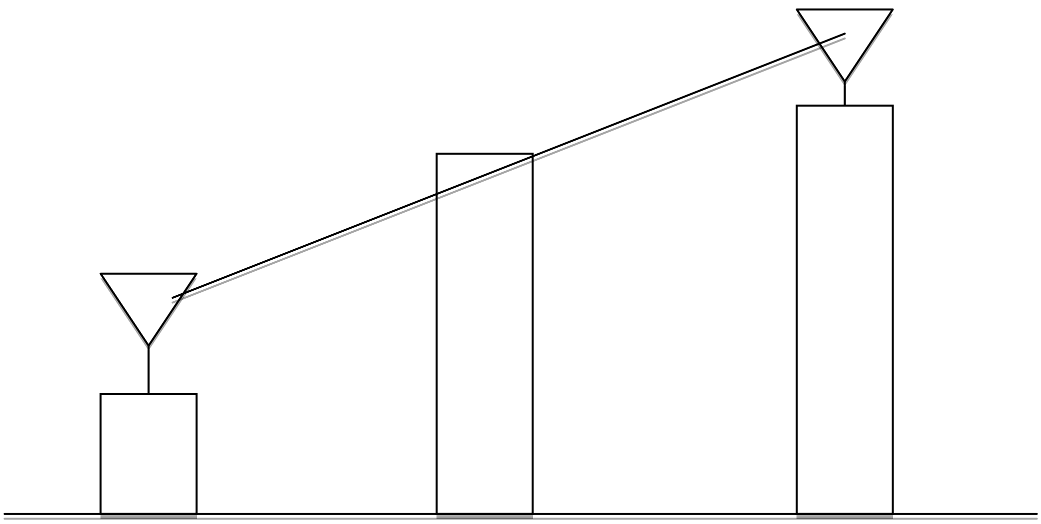


**Fig.5.1: Shadowing**

Experiments reported by Egli in 1957 showed that, for paths longer than a few hundred meters, the received (local-mean) power fluctuates with a 'log-normal' distribution about the area- mean power.

"Log-normal" means that the local-mean power expressed in logarithmic values i.e,

$\bar{P}_{\log} = \ln\left(\frac{\bar{P}}{\bar{\bar{P}}}\right)$ dB or neper has a normal *i.e.*, Gaussian distribution.

- local means is the average over about 40l, to remove multipath fading denoted by a single overline
- area means is the average over tens or hundreds of meters, to remove multipath fading and shadowing denoted by a double overbar.

The probability density function (pdf) of the local-mean power is thus of the form

$$f_{\bar{p}\log}\left(\bar{P}_{\log}\right)=\frac{1}{\sqrt{2\pi\sigma_s}}\exp\left[-\frac{1}{2\sigma_s^2}\left(\bar{P}_{\log}\right)^2\right]$$

where $\Omega_s$ is the logarithmic standard deviation of the shadowing, expressed in natural units. The standard deviation in dB is found from s = 4.34 s. For instance s = 6 dB shadowing is equivalent to s = 1.36. If we convert 'nepers' to 'watts', the log-normal distribution of received (local-mean) power is found

$$f_{\bar{p}\log}\left(\bar{P}_{\log}\right)=\frac{1}{\sqrt{2\pi\sigma_s}}\exp\left[-\frac{1}{2\sigma_s^2}\ln^2\left(\frac{\bar{P}}{\bar{\bar{P}}}\right)\right]$$

Here the factor "1/local-mean power" occurs due to the conversion of the pdf of $P_{Log}$ to local-mean power.

### 3.1.1 Depth of Shadowing

For average terrain, Egli reported a logarithmic standard deviation of about 8.3 dB and 12 dB for VHF and UHF frequencies, respectively. Such large fluctuations are caused not only by local shadow attenuation by obstacles in the vicinity of the antenna, but also by large-scale effects leading to a coarse estimate of the area-mean power.

### 3.1.2 Implications for Cell Planning

Shadowing makes practical cell planning complicated. To fully predict local shadow attenuation, up-to-date and highly detailed terrain data bases are needed. If one extends the distinction between large-area and small-area shadowing, the definition of shadowing covers any statistical fluctuation of the received local-mean power about a certain area-mean power, with the latter determined by (predictable) large-scale mechanisms. Multipath propagation is separated from shadow fluctuations by considering the local-mean powers. That is, the standard deviation of the shadowing will depend on the geographical resolution of the estimate of the area-mean power. A propagation model which ignores specific terrain data produces about 12 dB of shadowing. On the other hand, prediction methods using topographical data bases with unlimited resolution can, at least in theory, achieve a standard deviation of 0 dB. Thus, the standard deviation is a measure of the impreciseness of the terrain description. If, for generic system studies, the (large-scale) path loss is taking a simple form depending only on distance but not on details of the path profile, the standard deviation will necessarily be large. On the other hand, for the planning of a practical network in a certain (known) environment, the accuracy of the large-scale propagation model may be refined. This may allow a spectrally more efficient planning if the cellular layout is optimized for the propagation environment.

### Self-Assessment Exercise

What is meant by shadowing?

## 4.0 Conclusion

Shadowing is attenuation from natural and man-made object (fast). Signals are blocked by obstructing structures.

## 5.0 Summary

In this unit you have learnt that:

- shadowing is the effect that the received signal power fluctuates due to objects obstructing the propagation path between transmitter and receiver.

"log-normal" means that the local-mean power expressed in logarithmic values i.e,
$\bar{P}_{\log} = \ln\left(\frac{\bar{P}}{\bar{\bar{P}}}\right)$ dB or neper has a normal *i.e.*, Gaussian distribution.

- shadowing covers any statistical fluctuation of the received local-mean power about a certain area-mean power, with the latter determined by (predictable) large-scale mechanisms.

## 6.0 Self-Assessment Exercise

Illustrate with a diagram what a shadowing model is.

## 7.0 References/Further Reading

Garg, V. K. & Wilkes J. E. (1996). *Wireless and Personal Communications Systems*. Prentice Hall.

Goldsmith, A. (2005). *Wireless Communications,* Cambridge University Press.

Linnartz's, J. M. G. (1996). *Wireless Communication*. Baitzer Science Publishers.

Molisch, A. F. (2005). *Wireless Communications*. Wiley and Associate.

Rappaport, T. S. (2005). *Wireless Communication: Principle and Practice.* (2nd ed.). India: Prentice Hall.