Unit-II

Large Scale Fading

WEEK1 : Introduction to Radio wave Propagation, Large scale and small scale fading, Friis transmission equation- Free space propagation model - pathloss model, Two Ray model

WEEK2 : Two Ray model (Contd), Simplified pathloss model, Emperical model - Okumara, Emperical model - Hata model, Walfish and bertoni model, Piecewise linear model - log normal model

WEEK3 : Shadowing, Combined pathloss and shadowing, Outage ProbabilIty, Cell Coverage Area, Solving problems – Brewster angle, Solving problems –empirical model, Solving problems – friis transmission formula

Text books, references:

1. Rappaport T.S, "Wireless Communications: Principles and Practice", Pearson education
2. Andrea Goldsmith, "Wireless Communications", Cambridge University Press, Aug 2005

Introduction to Radio wave Propagation

There are two basic ways of transmitting an electro-magnetic (EM) signal, through a guided medium or through an unguided medium. Guided mediums such as coaxial cables and fiber optic cables, are far less hostile toward the information carrying EM signal than the wireless or the unguided medium. It presents challenges and conditions which are unique for this kind of transmissions. A signal, as it travels through the wireless channel, undergoes many kinds of propagation effects such as reflection, diffraction and scattering, due to the presence of buildings, mountains and other such obstructions. Reflection occurs when the EM waves impinge on objects which are much greater than the wavelength of the traveling wave. Diffraction is a phenomena occurring when the wave interacts with a surface having sharp irregularities. Scattering occurs when the medium through the wave is traveling contains objects which are much smaller than the wavelength of the EM wave. These varied phenomena's lead to large scale and small scale propagation losses. Due to the inherent randomness associated with such channels they are best described with the help of statistical models. Models which predict the mean signal strength for arbitrary transmitter receiver distances are termed as large scale propagation models. These are termed so because they predict the average signal strength for large Tx-Rx separations, typically for hundreds of kilometers.

Basic Propagation Mechanisms

Line of sight The line-of-sight (LOS) propagation is the wave propagation in which the EM ray follows a straight line from the transmitter to the receiver. It is shown as a direct ray in the next figure.

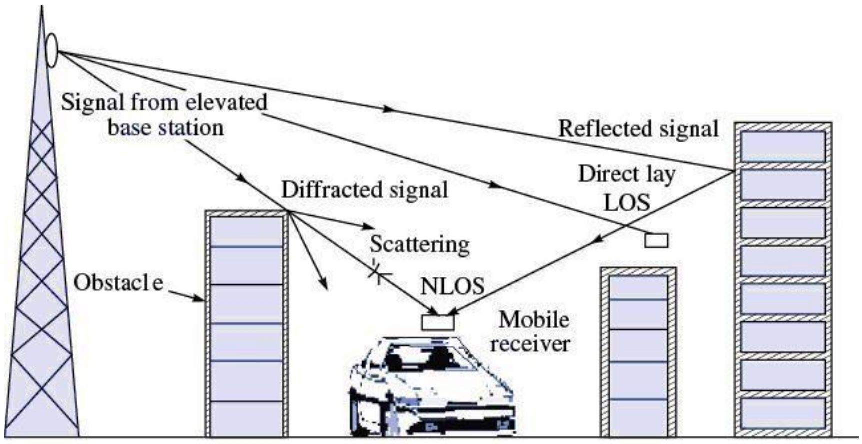
Non-line of sight The non-line-of-sight (NLOS) propagation mechanism is based on and is the resultant of the following mechanisms:

Reflection This occurs when the propagating wave impinges on an object that is larger than its wavelength. Examples of such objects are the surface of the earth, buildings, and walls.

Diffraction This occurs when the radio path between the transmitter and the receiver is obstructed by a surface with sharp irregular edges, which results in the waves bending around the obstacle. Diffraction is more with low- frequency (LF) signals than with high-frequency (HF)

Scattering This occurs when the propagating wave is obstructed by objects that are smaller than its wavelength. Examples of such objects are lamp posts, foliage, street signs, and particles in the air.

Refraction Due to variations in the refractive index of the atmospheric layers, the EM wave bends (in



the cases other than satellite communication).

Fig.1.Radio wave propagation

Propagation Channel Effects

Attenuation It is the drop in the signal power when it is being transmitted from one point to another. It is caused by the transmission path length, obstructions in the signal path, and multipath effect.

Fading As there are obstacles and reflectors in the wireless propagation channel, the transmitted signal arrives at the receiver from various directions over multiple paths. Such a phenomenon is called multipath. Fading is the result of multipath in which the signal strength varies continuously with respect to distance and with time from the transmitter to the receiver along with the attenuation

Shadowing This occurs whenever there is an obstruction between the transmitter and the receiver, and it can be observed in long-distance as well as short distance communication. It is generally caused by buildings and hills.

Free Space Propagation Model

The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. Satellite communication systems and microwave line-of-sight radio links typically undergo free space propagation. As with most large-scale radio wave propagation models, the free space model predicts that received power decays as a function of the T-R separation distance raised to some power (i.e. a power law function). The free space power received by a receiver antenna which is separated from a radiating transmitter antenna by a distance d, is given by the **Friis free space equation**

$P_r(d)= P_tG_tG_r\lambda^2/(4\pi d)^2$

Where P_t is the transmitted power, P_r (d) is the received power which is a function of the T-R separation, G_t is the transmitter antenna gain, Gr is the receiver antenna gain, d is the T-R separation distance in meters and λ is the wavelength in meters. The gain of an antenna is related to its effective aperture, A_e by,

$G=4\pi A_e/\lambda^2$

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

$\lambda = c/f= 2\pi c/\omega c$

where f is the carrier frequency in Hertz, ωc is the carrier frequency in radians per second and c is the speed of light given in meters/s. An isotropic radiator is an ideal antenna which radiates power with unit gain uniformly in all directions, and is often used to reference antenna gains in wireless systems. The effective isotropic radiated power (EIRP) is defined as EIRP = P_tG_t

it represents the maximum radiated power available from a transmitter in the direction of maximum antenna gain, as compared to an isotropic radiator. In practice, effective radiated power (ERP) is used instead of EIRP to denote the maximum radiated power as compared to a half-wave dipole antenna (instead of an isotropic antenna).

The path loss, which represents signal attenuation as a positive quantity measured in dB, is defined as the difference (in dB) between the effective transmitted power and the received power, and may or may not include the effect of the antenna gains. The path loss for the free space model when antenna gains are included is given by

P_L (dB) = $10\log (P_t/P_r) = -10\log [GtGr\lambda^2/(4\pi d)^2]$

When antenna gains are excluded, the antennas are assumed to have unity gain, and path loss is given by

P_L (dB) = $10\log (P_t/P_r) = -10\log[\lambda^2/(4\pi d)^2]$

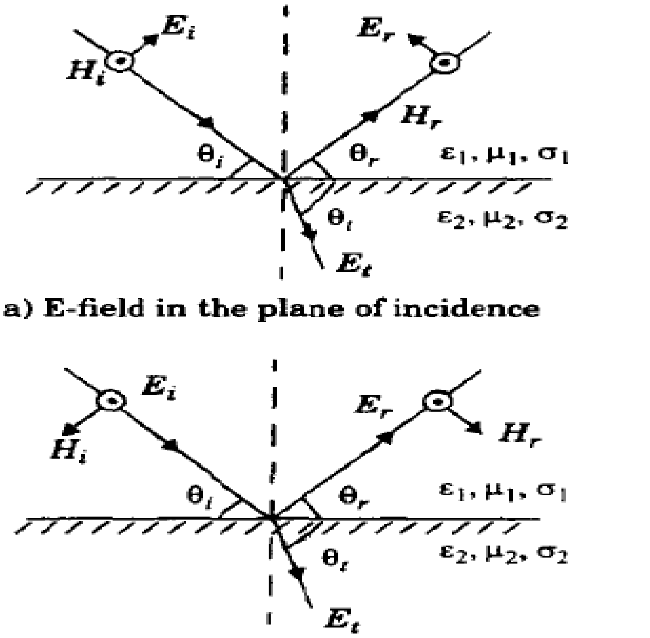
The **Friis free space model** is only a valid predictor for P_r for values of d which are in the far-field of the transmitting antenna. The far-field or Fraunhofer region of a transmitting antenna is defined as the region beyond the far-field distance df, which is related to the largest linear dimension of the transmitter antenna aperture and the carrier wavelength. The Fraunhofer distance is given by df = $2D^2/\lambda$

Where D is the largest physical linear dimension of the antenna. The far-fieldregion df must satisfy

df >> Ds

Reflection:

When a radio wave propagating in one medium impinges upon another medium having different electrical properties, the wave is partially reflected and partially transmitted. If the plane wave is incident on a perfect dielectric, part of the energy is transmitted into the second medium and part of the energy is reflected back into the first medium, and there is no loss of energy in absorption. lf the second medium is a perfect conductor, then all incident energy is reflected back into the first medium without loss of energy. The electric field intensity of the reflected and transmitted waves may be related to the incident wave in the medium of origin through the Fresnel reflection coefficient (Γ). The reflection coefficient is a function of the material properties, and generally depends on the wave polarization, angle of incidence, and the frequency of the propagating wave.



(b) E-field normal to the plane of incidence

Figure 3.4
Geometry for calculating the reflection coefficients between two dielectrics.

Reflection from Dielectrics:

Figure 3.4 shows an electromagnetic wave incident at an angle θ_i with the plane of the boundary between two dielectric media. As shown in the figure, part of the energy is reflected back to the first media at an angle θ_r, and part of the energy is transmitted (refracted) into the second media atan angle θ_t. The nature of reflection varies with the direction of polarization of the E-field. The behavior for arbitrary directions of polarization can be studied by considering the two distinct casesshown inFigure The plane of incidence is defined as the plane containing the incident, reflected, and transmitted rays. In Figure 3.4a, the E—field polarization is parallel with the plane of incidence (that is, the E- field has a vertical polarization, or normal component, with respect to the reflecting surface) and in Figure 3.4b, the E-field polarization is perpendicular to the plane of incidence (that is, the incident E-field is pointing out of the page towards the reader, and is perpendicular to the page and parallelto the reflecting surface).

Because of superposition, only two orthogonal polarizations need be considered to solve general reflection problems. The reflection coefficients for the two cases of parallel and perpendicular E- field polarization at the boundary of two dielectrics are given by

$$\Gamma_{\parallel} = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_t - \eta_1 \sin\theta_i}{\eta_2 \sin\theta_t + \eta_1 \sin\theta_i} \quad \textbf{(E-field in plane of incidence)}$$

$$\Gamma_{\perp} = \frac{E_r}{E_i} = \frac{\eta_2 \sin\theta_i - \eta_1 \sin\theta_t}{\eta_2 \sin\theta_i + \eta_1 \sin\theta_t} \quad \textbf{(E-field not in plane of incidence)}$$

Where η is the intrinsic impedance of the respective medium.

Where ε is the permittivity of the respective medium.

Brewster Angle:

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

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

The Brewster angle is the angle at which no reflection occurs in the medium of origin. It occurs when the incident angle BB is such that the reflection coefficient Γ| | is equal to zero. The Brewster angle is given by the value of θ_B which satisfies

$\mathrm{Sin}\ (\theta_B) = \sqrt{(\varepsilon 1)}/\sqrt{(\varepsilon 1+\varepsilon 2)}$

For the case when the first medium is free space and the second medium has a relative permittivity εr, above equation can be expressed as

$\mathrm{Sin}(\theta_B) = \sqrt{(\varepsilon_r-1)}/\sqrt{(\varepsilon_r^2-1)}$ Note that the Brewster angle occurs only for vertical (i.e. parallel) polarization.

Ground Reflection (2-ray) Model:

In a mobile radio channel, a single direct path between the base station and a mobile is seldom the only physical means for propagation, and hence the free space propagation model is in most cases inaccurate when used alone. The 2-ray ground reflection model shown in Figure 3.7 is a useful propagation model that is based on geometric optics, and considers both the direct path and a ground reflected propagation path between transmitter and receiver. This model has been found to be reasonably accurate for predicting the large-scale signal strength over distances of several kilometers for mobile radio systems that use tall towers (heights which exceed 50 m), as well as for line of-sight, microcell channels in urban environments.

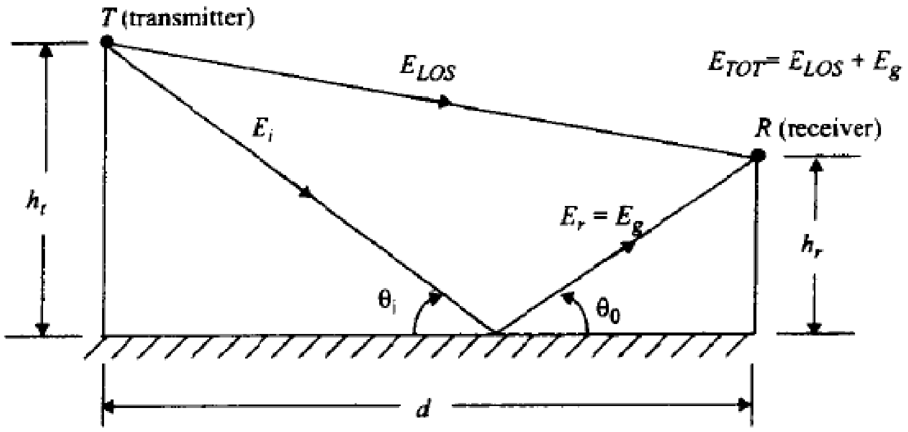


Figure 3.7
Two-ray ground reflection model.

Referring to Figure 3.7, h_t is the height of the transmitter and h_r is the height of the receiver. lf E_O is the free space E-field (in units of V/m) at a reference distance do from the transmitter, then for d > d_o , the free space propagating E—field is given by

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

Two propagating waves arrive at the receiver: the direct wave that travels a distance d'; and the reflected wave that travels a distance d”.

The electric field E_{TOT}(d, t) can be expressed as the sum of equations for distances d’ and d” (i.e. direct wave and reflected wave).

$$\bar{E}_{TOT}(d,t) = \left(\frac{E_0 d_0}{d'}\right)\cos\left(\omega_c\left(t-\frac{d'}{c}\right)\right) + \Gamma\left(\frac{E_0 d_0}{d''}\right)\cos\left(\omega_c\left(t-\frac{d''}{c}\right)\right)$$

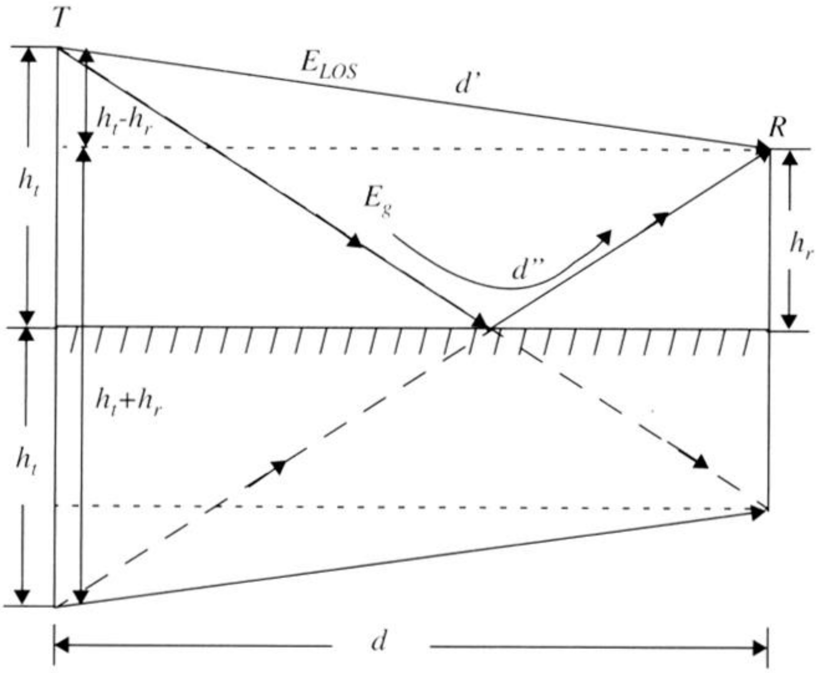
for large T−R separation : θ_i goes to 0 (angle of incidence to the ground of the reflected wave) and Γ = −1 (perfect horizontal E field polarization and ground wave reflection)

Phase difference can occur depending on the phase difference between direct and reflected E fields

The phase difference is θ_Δ due to Path difference , $\Delta = d'' - d'$, between $\bar{E}_{LOS}$ and $\bar{E}_g$

Method of Images

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



The method of images is used to find the path difference between the LOS and the ground reflected paths

Δ can be expanded using a Taylor series expansion

$$
\begin{aligned}
f(x) = \sqrt{1+x} &= f(0) + xf'(0) + \frac{x^2}{2!}f''(0) + \cdots \\
&= 1 + x\frac{1}{2}(1+0)^{-1/2} + \frac{x^2}{2!}\left(-\frac{1}{4}\right)(1+0)^{-3/2} + \cdots \\
&= 1 + \frac{1}{2}x - \frac{1}{8}x^2 + \cdots
\end{aligned}
$$

$$\text{if } x \text{ is small} \quad f(x) \approx 1 + \frac{1}{2}x$$

$$
\begin{aligned}
\Delta = d'' - d' &= \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \\
&= d\sqrt{\left(\left(\frac{h_t + h_r}{d}\right)^2 + 1\right)} - d\sqrt{\left(\left(\frac{h_t - h_r}{d}\right)^2 + 1\right)} \\
&\approx d\left(1 + \frac{1}{2}\left(\frac{h_t + h_r}{d}\right)^2\right) - d\left(1 + \frac{1}{2}\left(\frac{h_t - h_r}{d}\right)^2\right) \\
&\approx \frac{1}{2d}\left((h_t + h_r)^2 - (h_t - h_r)^2\right) \\
&\approx \frac{1}{2d}\left(\left(h_t^2 + 2h_t h_r + h_r^2\right) - \left(h_t^2 - 2h_t h_r + h_r^2\right)\right) \\
&\approx \frac{2h_t h_r}{d}
\end{aligned}
$$

which works well for d >> (ht + hr), which means $\left(\frac{h_t+h_r}{d}\right)^2$; and $\left(\frac{h_t-h_r}{d}\right)^2$ are small

note that the magnitude is with respect to a reference of E_0=1 at d_0=100 meters, so near 100 meters the signal can be stronger than E_0=1

the second ray adds in energy that would have been lost otherwise

for large distances $d >> \sqrt{h_t h_r}$ it can be shown that $\bar{E}_{TOT}(d)| \approx \frac{4\pi E_0 d_0 h_t h_r}{\lambda d^2}$

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

Two-ray path loss model:

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

Now d^4 instead of d^2 for free space

$$P_r \propto \frac{1}{d^4}$$

$$\boxed{\bullet \quad P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^4}$$

Simplified path loss model:

For general trade-off analysis of various system designs it is better to use a simple model that captures the essence of signal propagation

Thus, the simplified model for path loss as a function of distance is commonly used for system design

$$P_r = P_t\ K\ [d_0/d]^\gamma$$

The dB attenuation is thus

$$P_r\ \text{dBm} = P_t\ \text{dBm} + K\ \text{dB} - 10\gamma \log_{10}[d/d_0]$$

K is a unitless constant that depends on the antenna characteristics and the average channel attenuation, d0 is a reference distance for the antenna far field, and γ is the pathloss exponent.

When the simplified model is used to approximate empirical measurements, the value of K < 1 is sometimes set to the free-space path gain at distance d0 assuming omnidirectional antennas

$$K\ \text{dB} = 20 \log [\lambda/(4\pi d_0)]$$

and this assumption is supported by empirical data for freespace path loss at a transmission distance of 100 m.

The Value of K can be determined by measurement at d0 oroptimized (alone or together with γ) to minimize the mean-square error (MSE) between the model and the empirical measurements.

The value of γ depends on the propagation environment: for propagation that approximately follows a free-space or two-ray model, γ is set to 2 or 4 (respectively).

The value of γ for more complex environments can be obtained via a minimum mean-square error (MMSE) fit to empirical measurements as you can see in table given below

- where d_0 is typically assumed to be 1-10 m indoors and 10-100 m outdoors.

Environment	γ range
Urban macrocells	3.7-6.5
Urban microcells	2.7-3.5
Office Building (same floor)	1.6-3.5
Office Building (multiple floors)	2-6
Store	1.8-2.2
Factory	1.6-3.3
Home	3

- Path loss exponents at higher frequencies tend to be higher
- path loss exponents at higher antenna heights tend to be lower

OUTDOOR PROPAGATION MODELS

Based on the coverage area, the Outdoor propagation environment may be divided into three categories

1. Propagation in Macro cells

2. Propagation in Micro cells

3. Propagation in street Micro cells

Outdoor radio transmission takes place over an irregular terrain. The terrain profile must be taken into consideration for estimating the path loss.

e.g. trees buildings and hills must be taken into consideration

Longley-Ryce Model:

The Longley-Ryce model is applicable to point-to-point communication systems in the frequency range from 40 MHz to 100 GHz, over different kinds of terrain. The median transmission loss is predicted using the path geometry of the terrain profile and the refractivity of the troposphere. Geometric optics techniques (primarily the 2-ray ground reflection model) are used to predictsignal strengths within the radio horizon. Diffraction losses over isolated obstacles are estimated using the Fresnel-Kirchoff knife- edge models. Forward scatter theory is used to make troposcatter predictions over long distances.

The Longley-Ryce method operates in two modes. When a detailed terrain path profile is available, the path-specific parameters can be easily determined and the prediction is called a point-to-point mode prediction. On the other hand, if the terrain path profile is not available, the Longley-Ryce method provides techniques to estimate the path-specific parameters, and such a prediction is called an area mode prediction.

Okumura Model:

Okumura`s model is one of the most widely used models for signal prediction in urban areas. This model is applicable for frequencies in the range 150 MHz to 1920 MHz (although it is typically extrapolated up to 3000 MHz) and distances of 1 km to 100 km. It can be used for base station antenna heights ranging from 30 m to 1000 m. Okumura developed a set of curves giving the median attenuation relative to free space (Amu), in an urban area over a quasi-smooth terrain with a base station effective antenna height (hte) of 200 m and a mobile antenna height (hre) of 3 m. These curves were developed from extensive measurements using vertical omni-directional antennas at both the base and mobile, and are plotted as a function of frequency in the range 100 MHz to 1920 MHz and as a function of distance from the base station in the range 1 km to 100 km. To determine path loss using Okumura`s model, the free space path loss between the points of interest is first determined, and then the value of Amu(f, d) (as read from the curves) is added to it along with correction factors to account for the type of terrain. The model can be expressed as

$L50(dB) = LF + Amu(f, d) - G(te) - G(re) - G_{AREA}$

where L50 is the 50th percentile (i.e., median) value of propagation path loss, L_F is the free space propagation loss, A_{mu} is the median attenuation relative to free space, $G(h_{te})$ is the base station antenna height gain factor, $G(h_{re})$ is the mobile antenna height gain factor, and G_{AREA} is the gain due to the type of environment. Note that the antenna height gains are strictly a function of height and have nothing to do with antenna patterns.

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

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

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

Hata Model:

The Hata model [Hat90] is an empirical formulation of the graphical path loss data provided by Okumura, and is valid from 150 MHz to 1500 MHz. Hata presented the urban area propagation loss as a standard formula and supplied correction equations for application to other situations. The standard formula for median path loss in **urban areas** is given by

$L50(urban)(dB) = 69.55 + 26.16\log f_c - 13.82\log h_{te} - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d$

where fc is the frequency (in MHz) from 150 MHz to 1500 MHz, h_{te} is the effective transmitter (base station) antenna height (in meters) ranging from 30 m to 200 m, h_{re} is the effective receiver (mobile) antenna height (in meters) ranging from 1 m to 10 m, d is the T-R separation distance (in km), and $a(h_{re})$ is the correction factor for effective mobile antenna height which is a function of the size of the coverage area. For a small to medium sized city, the mobile antenna correction factor is given by

$a(h_{re}) = (1.11\log f_c - 0.7)h_{re} - (1.56\log f_c - 0.8)$
dBfor a **large city**, it is given by
$a(h_{re}) = 8.29(\log 1.54h_{re})^2 - 1.1$ dB for $f_c <= 300$ MHz $a(h_{re}) = 3.2(\log 11.75h_{re})2 — 4.97$
dBfor $f_c >= 300$ MHz

To obtain the path loss in a **suburban area** the standard Hata formula in equations are modified as
$L_{50}(dB) = L_{50}(urban) - 2[\log(f_c/28)]^2 - 5.4$

and for path loss in open **rural areas,** the formula is modified
as$L_{50}(dB) = L_{50}(urban) – 4.78(\log f_c)^2 + 18.33\log f_c - 40.94$

PCS Extension to Hata Model

The European Co-operative for Scientific and Technical research (EURO-COST) formed the COST-231 working committee to develop an extended version of the Hata model. COST-231 proposed the following formula to extend Hata's model to 2 GHz. The proposed model for path loss is [EUR91]

$$L_{50}(urban) = 46.3 + 33.9\log f_c - 13.82\log h_{te} - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d + C_M \tag{3.87}$$

where $a(h_{re})$ is defined in equations (3.83), (3.84.a), and (3.84.b) and

$$C_M = \begin{matrix} 0\text{ dB} & \text{for medium sized city and suburban areas} \\ 3\text{ dB} & \text{for metropolitan centers} \end{matrix} \tag{3.88}$$

The COST-231 extension of the Hata model is restricted to the following range of parameters:

f : 1500 MHz to 2000 MHz
h_{te} : 30 m to 200 m
h_{re} : 1 m to 10 m
d : 1 km to 20 km

Walfisch and Bertoni Model

A model developed by Walfisch and Bertoni [Wal88] considers the impact of rooftops and building height by using diffraction to predict average signal strength at street level. The model considers the path loss, S, to be a product of three factors.

$$S = P_0 Q^2 P_1 \tag{3.89}$$

where P_0 represents free space path loss between isotropic antennas given by

$$P_0 = \left(\frac{\lambda}{4\pi R}\right)^2 \tag{3.90}$$

The factor Q^2 gives the reduction in the rooftop signal due to the row of buildings which immediately shadow the receiver at street level. The P_1 term is based upon diffraction and determines the signal loss from the rooftop to the street.

In dB, the path loss is given by

$$S(\mathrm{dB}) = L_0 + L_{rts} + L_{ms} \tag{3.91}$$

where L_0 represents free space loss, L_{rts} represents the "rooftop-to-street diffraction and scatter loss", and L_{ms} denotes multiscreen diffraction loss due to the rows of buildings [Xia92]. Figure 3.25 illustrates the geometry used in the Walfisch Bertoni model [Wal88], [Mac93]. This model is being considered for use by ITU-R in the IMT-2000 standards activities.

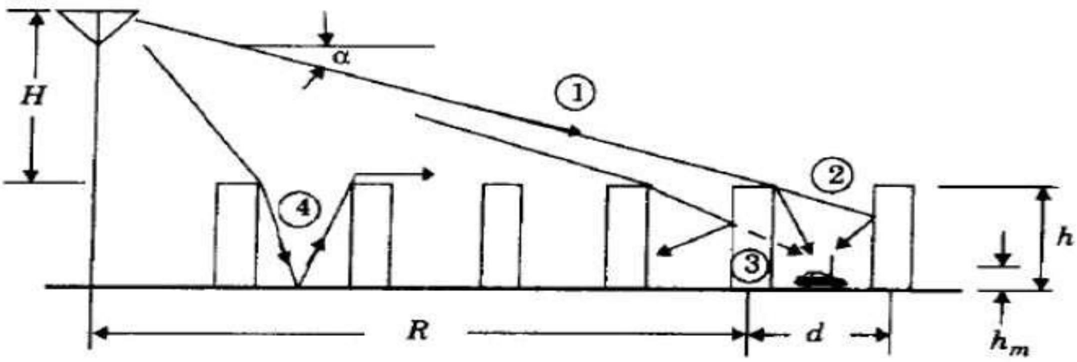


Figure 3.25
Propagation geometry for model proposed by Walfisch and Bertoni [From [Wal88] © IEEE].

Wideband PCS Microcell Model

Work by Feuerstein, et.al. in 1991 used a 20 MHz pulsed transmitter at 1900 MHz to measure path loss, outage, and delay spread in typical microcellular systems in San Francisco and Oakland. 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 (OBS) environments [Feu94]. This work revealed that a 2-ray ground reflection model (shown in Figure 3.7) is a good estimate for path loss in LOS microcells, and a simple log-distance path loss model holds well for OBS microcell environments.

For a flat earth ground reflection model, the distance d_f at which the first Fresnel zone just becomes obstructed by the ground (first Fresnel zone clearance) is given by

$$d_f = \frac{1}{\lambda}\sqrt{(\Sigma^2 - \Delta^2)^2 - 2(\Sigma^2 + \Delta^2)\left(\frac{\lambda}{2}\right)^2 + \left(\frac{\lambda}{2}\right)^4} \tag{3.92.a}$$

$$= \frac{1}{\lambda}\sqrt{16h_t^2h_r^2 - \lambda^2\left(h_t^2 + h_r^2\right) + \frac{\lambda^4}{16}}$$

For LOS cases, a double regression path loss model that uses a regression breakpoint at the first Fresnel zone clearance was shown to fit well to measurements. The model assumes omnidirectional vertical antennas and predicts average path loss as

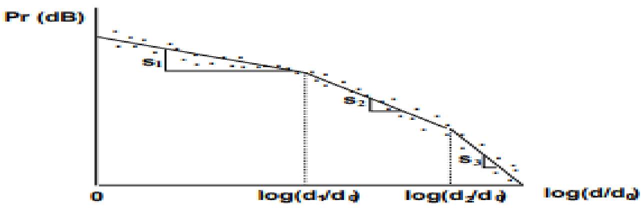
$$PL(d) = \begin{cases} 10n_1 \log(d) + p_1 & \text{for } 1 < d < d_f \\ 10n_2 \log(d/d_f) + 10n_1 \log d_f + p_1 & \text{for } d > d_f \end{cases} \tag{3.92.b}$$

where p_1 is equal to $PL(d_0)$ (the path loss in decibels at the reference distance of $d_0 = 1$ m), d is in meters and n_1, n_2 are path loss exponents which are a function of transmitter height, as given in Figure 3.26. It can easily be shown that at 1900 MHz, $p_1 = 38.0$ dB.

For the OBS case, the path loss was found to fit the standard log-distance path loss law of equation (3.69.a)

$$PL(d)[dB] = 10n\log(d) + p_1 \tag{3.92.c}$$

Piece wise linear model



Piecewise Linear Model for Path Loss.

A piecewise linear model with N segments must specify N − 1 breakpoints d1,...,dN−1 and the slopes corresponding to each segment s1,...,sN .

$$P_r(dB) = \begin{cases} P_t + K - 10\gamma_1 \log_{10}(d/d_0) & d_0 \le d \le d_c \\ P_t + K - 10\gamma_1 \log_{10}(d_c/d_0) - 10\gamma_2 \log_{10}(d/d_c) & d > d_c \end{cases}.$$

INDOOR PROPAGATION MODELS

With the advent of Personal Communication Systems (PCS), there is a great deal of interest in characterizing radio propagation inside buildings. The indoor radio channel differs from the traditional mobile radio channel in two aspects - the distances covered are much smaller, and the variability of the environment is much greater for a much smaller range of T-R separation distances. It has been observed that propagation within buildings is strongly influenced by specific features such as the layout of the building, the construction materials, and the building type. This section outlines models for path loss within buildings.

Indoor radio propagation is dominated by the same mechanisms as outdoor: reflection, diffraction, and scattering. However, conditions are much more variable. For example, signal levels vary greatly depending on whether interior doors are open or closed inside a building. Where antennas are mounted also impacts large-scale propagation. Antennas mounted at desk level in a partitioned office receive vastly different signals than those mounted on the ceiling. Also, the smaller propagation distances make it more difficult to insure far-field radiation for all receiver locations and types of antennas.

Partition Losses (same floor):

Buildings have a wide variety of partitions and obstacles which form the internal and external structure. Houses typically use a wood frame partition with plaster board to form internal walls andhave wood or non-reinforced concrete between floors. Office buildings, on the other hand, often have large open areas (open plan) which are constructed by using moveable office partitions so that the space may be reconfigured easily, and use metal reinforced concrete between floors. Partitions that are formed as part of the building structure are called hard partitions, and partitions that may be moved and which do not span to the ceiling are called soft partitions. Partitions vary widely in their physical and electrical characteristics, making it difficult to apply general models to specific indoor installations.

Partition Losses between Floors:

The losses between floors of a building are determined by the external dimensions and materials ofthe building, as well as the type of construction used to create the floors and the external surroundings. Even the number of windows in a building and the presence of tinting (which attenuates radio energy) can impact the loss between floors. It can be seen that for all three buildings, the attenuation between one floors of the building is greater than the incremental attenuation caused by each additional floor. After about five or six floor separations, very little additional path loss is experienced.

Log-distance Path Loss Model:

According to this model the received power at distance *d* is given by,

$$PL\,(\mathrm{dB}) = PL\,(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma$$

The value of n varies with propagation environments. The value of n is 2 for free space. The value ofn varies from 4 to 6 for obstruction of building, and 3 to 5 for urban scenarios. The important factor is to select the correct reference distance d_0. For large cell area it is 1 Km, while for micro-cell system it varies from 10m-1m.

1. **Log-normal Shadowing:**
   - Statistical model for variations in the received signal amplitude due to blockage.
   - The received signal power with the combined effect of path loss (power falloff model) and shadowing is, in dB, given by

$$P_r(\mathrm{dB}) = P_u(\mathrm{dB}) + 10\log_{10} K - 10\gamma \log_{10}(d/d_0) + \psi(\mathrm{dB}).$$

   - Empirical measurements support the log-normal distribution for ψ:

$$p(\psi_{\mathrm{dB}}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{dB}}}\exp\left[-\frac{(\psi_{\mathrm{dB}} - \mu_{\psi_{dB}})^2}{2\sigma^2_{\psi_{dB}}}\right].$$

   - This empirical distribution can be justified by a LLN argument.
   - The autocorrelation based on measurements follows an autoregressive model:

$$A_\psi(\delta) = \sigma^2_{\psi_{dB}} e^{-\delta/X_c} = \sigma^2_{\psi_{dB}} e^{-v\tau/X_c},$$

     where X_c is the decorrelation distance, which depends on the environment.

2. **Combined Path Loss and Shadowing**
   - Linear Model:

$$\frac{P_r}{P_t} = K\left(\frac{d}{d_0}\right)^\gamma \psi.$$

   - dB Model:

$$\frac{P_r}{P_t}(dB) = 10\log_{10} K - 10\gamma \log_{10}(d/d_0) + \psi_{dB}.$$

3. **Outage Probability under Path Loss and Shadowing**
   - With path loss and shadowing, the received power at any given distance between transmitter and receiver is random.
   - Outage probability $p_{out}(P_{min}, d)$ is defined as the probability that the received power at a given distance d, $P_r(d)$, is below a target P_{min}: $p_{out}(P_{min}, d) = p(P_r(d) < P_{min})$.

- For the simplified path loss model and log normal shadowing this becomes

$$p(P_r(d) \le P_{min}) = 1 - Q\left(\frac{P_{min} - (P_t + 10\log_{10} K - 10\gamma \log_{10}(d/d_0))}{\sigma_{\psi_{dB}}}\right).$$

4. **Cell Coverage Area:**

   - Cellular systems designed for a given average received power $\overline{P}_r(R)$ at cell boundary.
   - Cell coverage area dictates the percentage of locations within the cell with $P_r \ge \overline{P}_r(R)$.
   - Analysis yields:

   $$C = Q(a) + \exp\left(\frac{2-2ab}{b^2}\right) Q\left(\frac{2-ab}{b}\right), \quad a = \frac{P_{min} - \overline{P}_r(R)}{\sigma_{\psi_{dB}}}, \quad b = \frac{10\gamma\log_{10}(e)}{\sigma_{\psi_{dB}}}.$$

   - When the minimum power P_{min} equals the average power at the cell boundary $\overline{P}_r(R)$, $a = 0$, and

   $$C = \frac{1}{2} + \exp\left(\frac{2}{b^2}\right) Q\left(\frac{2}{b}\right).$$

   - Coverage area increases as σ_ψ decreases.
   - Making $\overline{P}_r$ much greater than required received power increases coverage area but causes more intereference between cells.

5. **Model Parameters from Empirical Data:**

   - Constant K obtained from measurement at distance d_0.
   - Power falloff exponent γ obtained by minimizing the MSE of the predicted model versus the data.
   - The resulting path loss model will include average attenuation, so $\mu_{\psi_{dB}} = 0$.
   - The shadowing variance $\sigma^2_{\psi_{dB}}$ obtained by determining MSE of the data versus the empirical path loss model with the optimizing γ.

Solved Examples

Sum:

1) Find the far field distance for an antenna with maximum dimension of 1m is operating frequency of 800 MHZ

Given: Largest dimensions of antenna $D = 1m$

operating frequency $f = 800\,MHZ$

$$\lambda = c/f = \frac{3\times10^8}{800\times10^6} = 0.375$$

The far-field distance df is obtained as

$$d_f = 2D^2/\lambda = \frac{2\times1^2}{0.375} = 5.33m$$

$$\boxed{d_f = 5m}$$

2) A power of 100w is supplied to an isotropic radiator what is the power density at a point 10 km away?

Given $P_t = 100W$ $d = 10\,km = 10\times10^3 m$

$$P_D = \frac{P_t}{4\pi d^2} = \frac{100}{4\pi\times(10\times10^3)^2}$$

$$\boxed{P_D = 79.6\ nW/m^2}$$

3. What will be the far-field distance for a Base station antenna with Largest dimension D=0.5m Frequency of operation fc=900MHz

Sol:

λ=c/f=3*10^8/900*10^6)=0.33m df= 2D^2/ λ =2(0.5)^2/0.33=1.5m

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

Given:
Transmitter power, $P_t = 50$ W.
Carrier frequency, $f_c = 900$ MHz

Using equation (3.9),
(a) Transmitter power,

$$P_t(\text{dBm}) = 10\log[P_t(\text{mW})/(1\text{ mW})]$$
$$= 10\log[50\times10^3] = 47.0\text{ dBm.}$$

(b) Transmitter power,

$$P_t(\text{dBW}) = 10\log[P_t(\text{W})/(1\text{ W})]$$
$$= 10\log[50] = 17.0\text{ dBW.}$$

The received power can be determined using equation (3.1).

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} = \frac{50(1)(1)(1/3)^2}{(4\pi)^2(100)^2(1)} = 3.5\times10^{-6}\text{ W} = 3.5\times10^{-3}\text{ mW}$$

$$P_r(\text{dBm}) = 10\log P_r(\text{mW}) = 10\log\left(3.5\times10^{-3}\text{ mW}\right) = -24.5\text{ dBm.}$$

The received power at 10 km can be expressed in terms of dBm using equation (3.9), where $d_0 = 100$ m and $d = 10$ km

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

5.

Sum:-

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

Given

T-R separation distance = 5 km

E-field at a distance of 1 Km = 10^{-3} V/m

Frequency of operation = f = 900 MHz

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

a) Length of the antenna $L = \lambda/4$

$$= 0.333/4 = 0.0833\ m$$

$$= 8.33\ cm$$

Effective aperture $A_e = G\lambda^2/4\pi$

$$= 2.55\times(0.333)^2/4\pi = 0.016 m^2$$

(b) Since $d >> \sqrt{h_t h_r}$

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

$$= \frac{2\times10^{-3}\times1\times10^3}{5\times10^3}\left[\frac{2\pi\times50\times1.5}{0.33\times5\times10^3}\right]$$

$$= 1131.1\times10^{-6}\ V/m$$

The received power

$$P_r(d) = \frac{(1131.1\times10^{-6})^2}{377}\left[\frac{1.8\times(0.33)^2}{0.33\times5\times10^3}\right]$$

$$P_r(d) = -92.68\ dBm$$

6.

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

The Brewster angle can be found by substituting the values for ε_r in equation

$$\sin(\theta_i) = \frac{\sqrt{(4)-1}}{\sqrt{(4)^2-1}} = \sqrt{\frac{3}{15}} = \sqrt{\frac{1}{5}}$$

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

Thus Brewster angle for $\varepsilon_r = 4$ is equal to $26.56°$.

7.

Find the median path loss using Okumura's model for $d = 50$ km, $h_{te} = 100$ m, $h_{re} = 10$ m in a suburban environment. If the base station transmitter radiates an EIRP of 1 kW at a carrier frequency of 900 MHz, find the power at the receiver (assume a unity gain receiving antenna).

The free space path loss L_F can be calculated using equation (3.6) as

$$L_F = 10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] = 10\log\left[\frac{(3\times10^8/900\times10^6)^2}{(4\pi)^2\times(50\times10^3)^2}\right] = 125.5\ \text{dB}.$$

From the Okumura curves

$$A_{mu}(900\ \text{MHz}(50\ \text{km})) = 43\ \text{dB}$$

and

$$G_{AREA} = 9\ \text{dB}.$$

Outdoor Propagation Models

Using equation (3.81.a) and (3.81.c) we have

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) = 20\log\left(\frac{100}{200}\right) = -6\ \text{dB}.$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right) = 20\log\left(\frac{10}{3}\right) = 10.46\ \text{dB}.$$

Using equation (3.80) the total mean path loss is

$$\begin{aligned} L_{50}(\text{dB}) &= L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \\ &= 125.5\ \text{dB} + 43\ \text{dB} - (-6)\ \text{dB} - 10.46\ \text{dB} - 9\ \text{dB} \\ &= 155.04\ \text{dB}. \end{aligned}$$

Therefore, the median received power is

$$\begin{aligned} P_r(d) &= EIRP(\text{dBm}) - L_{50}(\text{dB}) + G_r(\text{dB}) \\ &= 60\ \text{dBm} - 155.04\ \text{dB} + 0\ \text{dB} = -95.04\ \text{dBm}. \end{aligned}$$