Mobile Radio Propagation

Large Scale Propagation model

Dr. Abdel-Rahman al-Qawasmi

Wireless Communications

Principles and Practice

Theodore S. Rappaport *SE*

Introduction

-Transmission path between transmitter and receiver obstructed by buildings, and mountains

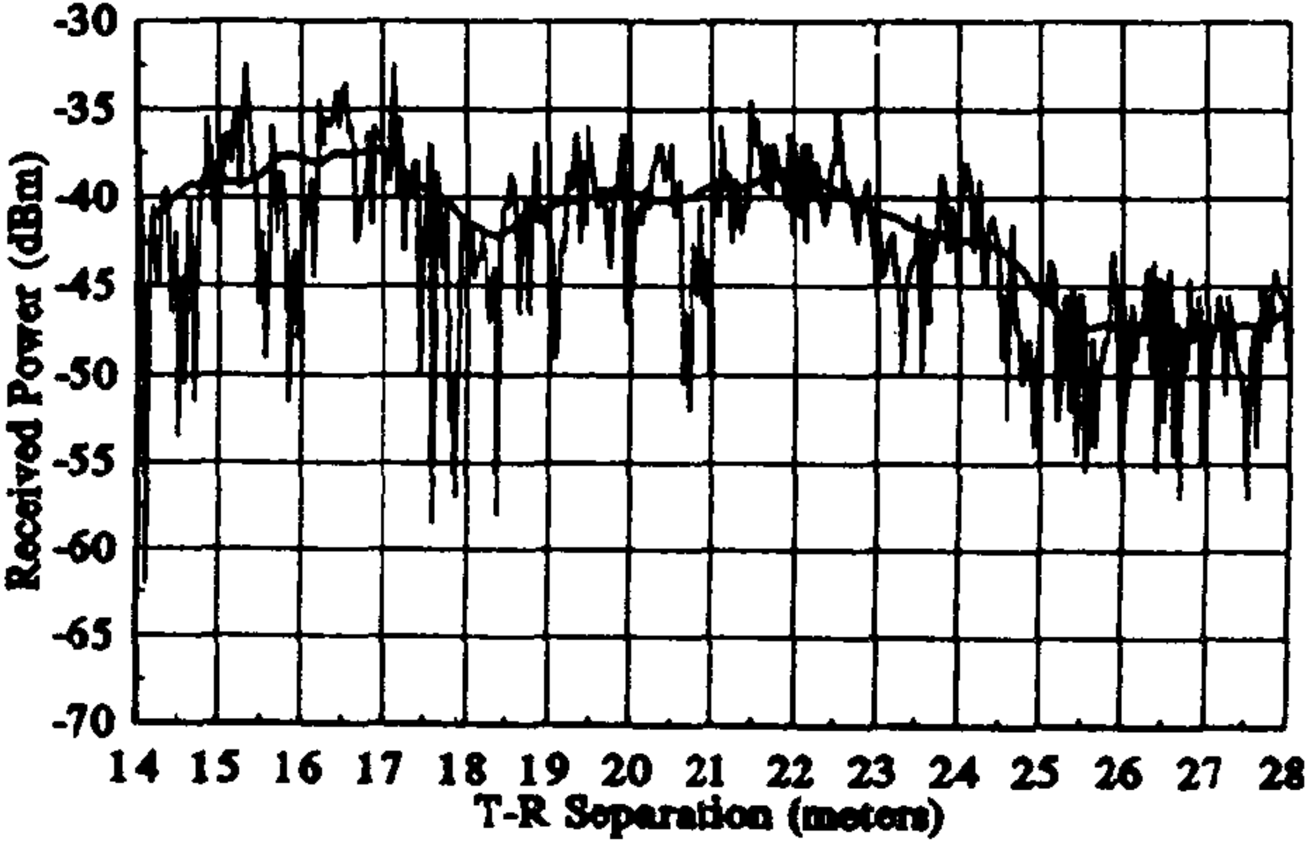
-The main sources of fading is : Reflection, Diffraction and scattering.

-The interaction between different electromagnetic waves arrived from different paths causes multi-path fading.

-If the distance between the transmitter and receiver (T-R) is large then model is called Large-Scale Propagation.

-If the distances between the transmitter and receiver (T-R) is short [few meters] then model is called Small-Scale Propagation

Introduction



Free-Space Propagation Model

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

Antenna Gains

Transmitted Power

Loss factor not related to propagation≥1

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

Received Power

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

Effective aperture

(Physical size of antenna)

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

Free-Space Propagation Model

- Friis implies that the received power decays with distance at a rate of 20 dB

- The **path loss** (PL) represents the signal attenuation and it defines as the difference (in dB) between the effective transmitted power and the received power (gains=1)

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

The received power in free space at a distance greater than the reference d_0 is given by:

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

$$d \geq d_0 \geq d_f$$

↓

Far field region

Free-Space Propagation Model

In units of watts

In dB_m

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

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

The largest physical linear dimension of antenna

Free-Space Propagation Model Example

Example 3.1

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

Solution to Example 3.1

Given:

Largest dimension of antenna, $D = 1$ m

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

Using equation (3.7.a), far-field distance is obtained as

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

Free-Space Propagation Model Example

Example 3.2

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 P_r (10 km) ? Assume unity gain for the receiver antenna.

Solution to Example 3.2

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

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

Reflection form dielectrics

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.

•The Fresnel **reflection coefficient** (Γ) is a function of the material properties, and generally depends on the wave polarization, angle of incidence, and the frequency of the propagating wave.

•**Polarization:** when the wave can be represented as the sum of two spatially orthogonal components in space (vertical and horizontal).

- Relative permittivity

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

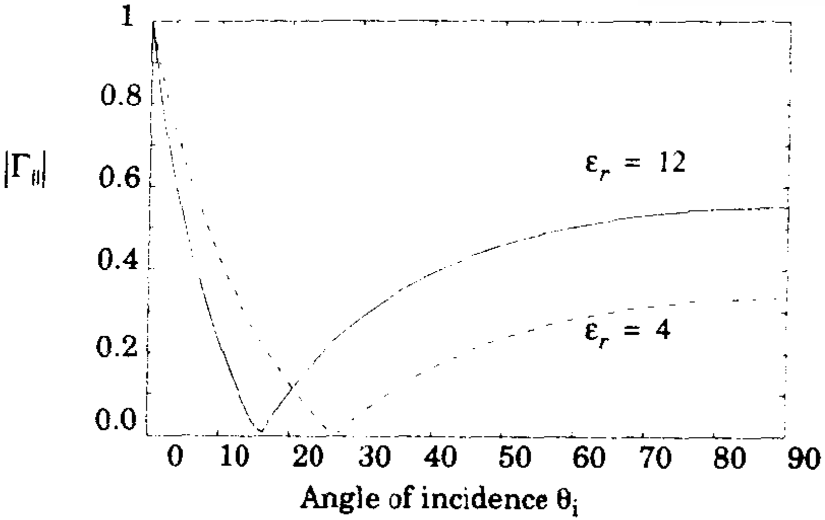
$$\Gamma_{\perp} = \frac{\sin\theta_i - \sqrt{\varepsilon_r - \cos^2\theta_i}}{\sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}}$$

Reflection form dielectrics

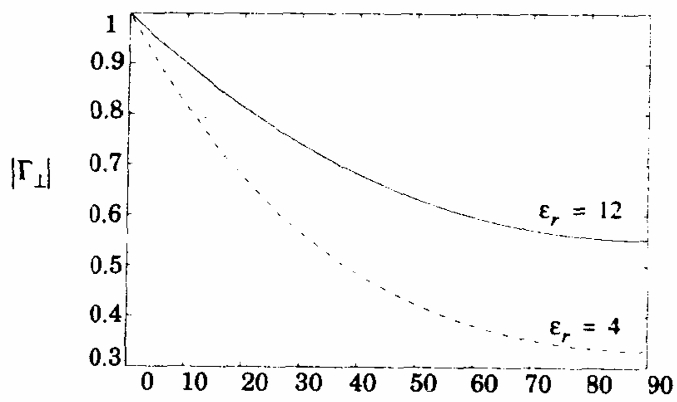
$$\varepsilon' = \frac{\sigma}{2\pi f}$$

Table 3.1 Material Parameters at Various Frequencies

Material	Relative Permittivity ε_r	Conductivity σ (s/m)	Frequency (MHz)
Poor Ground	4	0.001	100
Typical Ground	15	0.005	100
Good Ground	25	0.02	100
Sea Water	81	5.0	100
Fresh Water	81	0.001	100
Brick	4.44	0.001	4000
Limestone	7.51	0.028	4000
Glass, Corning 707	4	0.00000018	1
Glass, Corning 707	4	0.000027	100
Glass, Corning 707	4	0.005	10000



Parallel polarization (E-field in plane of incidence)



Perpendicular polarization (E-field not in plane of incidence)

Example

Example 3.4

Demonstrate that if medium 1 is free space and medium 2 is a dielectric, both $|\Gamma_{\parallel}|$ and $|\Gamma_{\perp}|$ approach 1 as θ_i approaches $0°$ regardless of ε_r.

Solution to Example 3.4

Substituting $\theta_i = 0°$ in equation (3.24)

$$\Gamma_{\parallel} = \frac{-\varepsilon_r \sin 0 + \sqrt{\varepsilon_r - \cos^2 0}}{\varepsilon_r \sin 0 + \sqrt{\varepsilon_r - \cos^2 0}}$$

$$\Gamma_{\parallel} = \frac{\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r - 1}}$$

$$= 1$$

Substituting $\theta_i = 0^o$ in equation (3.25)

$$\Gamma_{\perp} = \frac{\sin 0 - \sqrt{\varepsilon_r - \cos^2 0}}{\sin 0 + \sqrt{\varepsilon_r - \cos^2 0}}$$

$$\Gamma_{\perp} = \frac{-\sqrt{\varepsilon_r - 1}}{\sqrt{\varepsilon_r - 1}}$$

$$= -1.$$

Brewster Angle

The **Brewster Angle**: is an angle when no reflection is occurred in the medium of origin

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

Example 3.5

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

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

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

Reflection from perfect conductors

Electromagnetic energy cannot pass through a perfect conductor. To obey Maxwell's equations, the reflected wave must be equal in magnitude to the incident wave.

For a perfect conductor

$$\theta_i = \theta_r$$

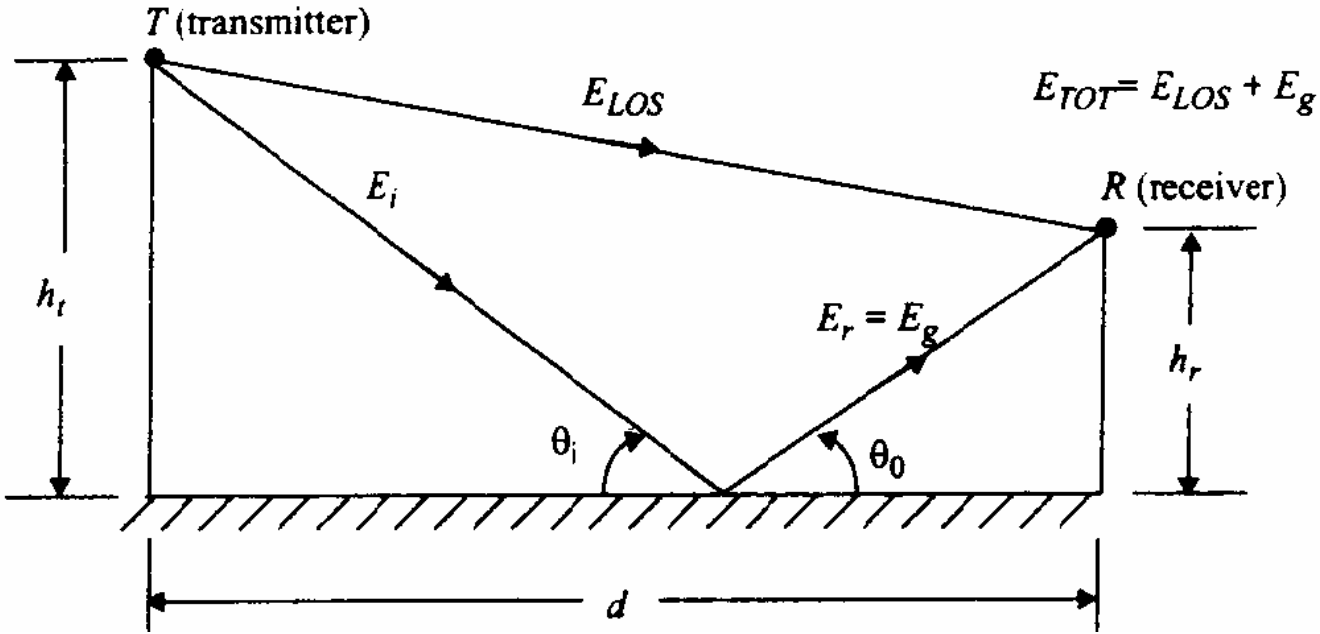
$E_r = E_i$ (parallel E-field polarisation)

$E_r = -E_i$ (perpendicular E-field polarisation)

Ground Reflection (2-ary) Model

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

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



Example

Example 3.6

A mobile is located 5 km away from a base station and uses a 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 is 900 MHz.

(a) Find the length and the gain of the receiving antenna.

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

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

Length of the antenna, $L = \lambda/4$

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

Diffraction

Diffraction allows radio signals to propagate around the curved surface of the earth, beyond the horizon, and to propagate behind obstructions. Although the received field strength decreases rapidly as a receiver moves deeper into the obstructed (shadowed) region, the diffraction field still exists and often has sufficient strength to produce a useful signal.

the *excess path length* (Δ)

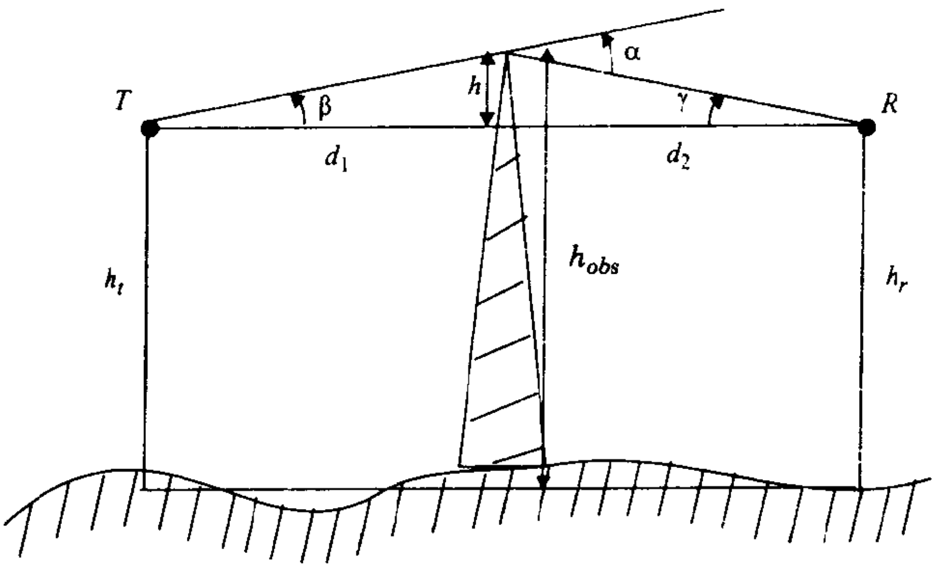
$$\Delta \approx \frac{h^2}{2}\frac{(d_1+d_2)}{d_1 d_2}$$

phase difference

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

or $$\phi = \frac{\pi}{2}v^2$$

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



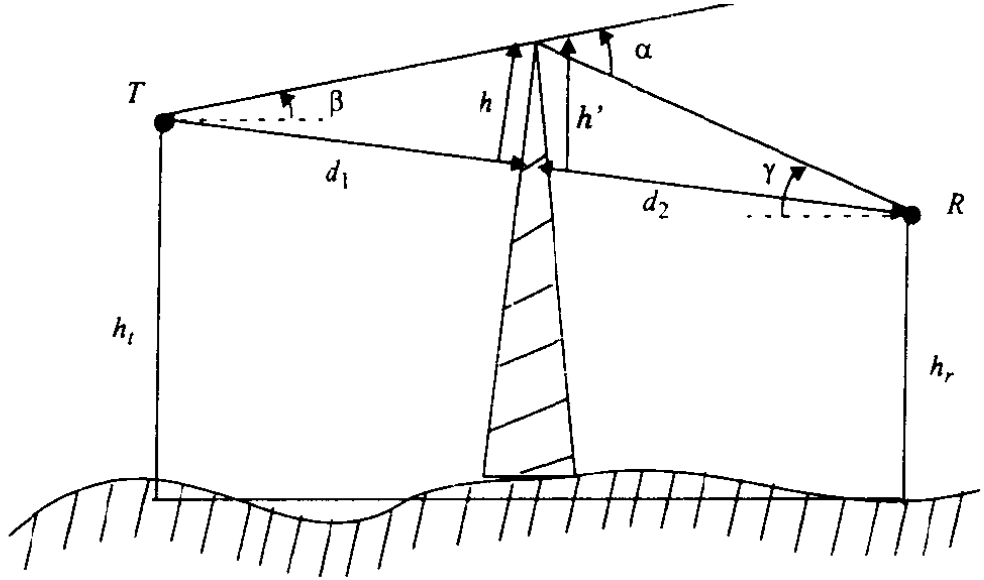
(a) Knife-edge diffraction geometry. The point *T* denotes the transmitter and *R* denotes the receiver, with an infinite knife-edge obstruction blocking the line-of-sight path.

Diffraction

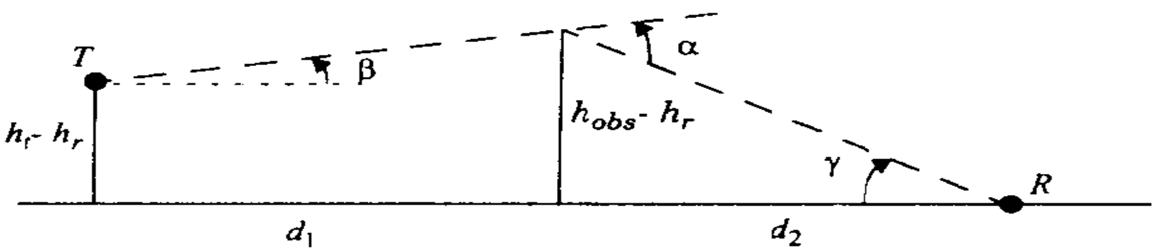
The phase difference between a direct LOS path and diffracted path is a function of height and position of the obstruction, as well as the transmitter and receiver location.

Figure c shows that the geometry is simplified without changing the values of the angles

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



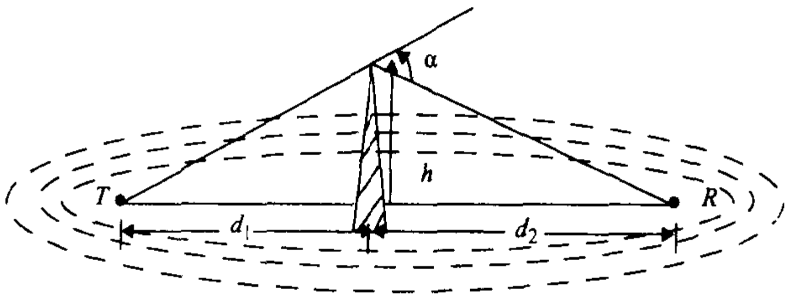
(b) Knife-edge diffraction geometry when the transmitter and receiver are not at the same height. Note that if α and β are small and $h << d_1$ and d_2,then h and h' are virtually identical and the geometry may be redrawn as shown in Figure 3.10c.



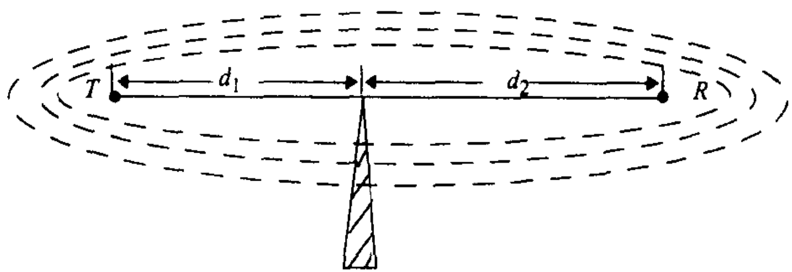
(c) Equivalent knife-edge geometry where the smallest height (in this case h_r) is subtracted from all other heights.

Knife-edge Diffraction model

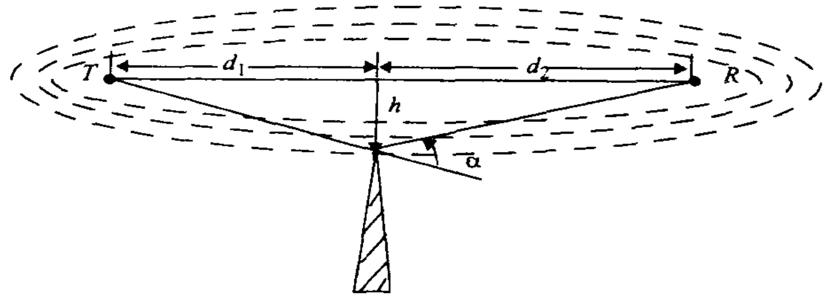
When **Shadowing** is caused by a single object such as a hill or mountain, the attenuation caused by diffraction can be estimated by treating the obstruction as a diffracting knife edge.



(a) α and ν are positive, since *h* is positive



(b) α and ν are equal to zero, since *h* is equal to zero



(c) α and ν are negative, since *h* is negative

Illustration of Fresnel zones for different knife-edge diffraction scenarios.

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

E_0 is the free space field strength and F(v) is the Fresnel integral

v is the Fresnel-Kirchoff parameter.

Knife-edge Diffraction model

The diffracted gain G_d(dB)=20 log|F(υ)|

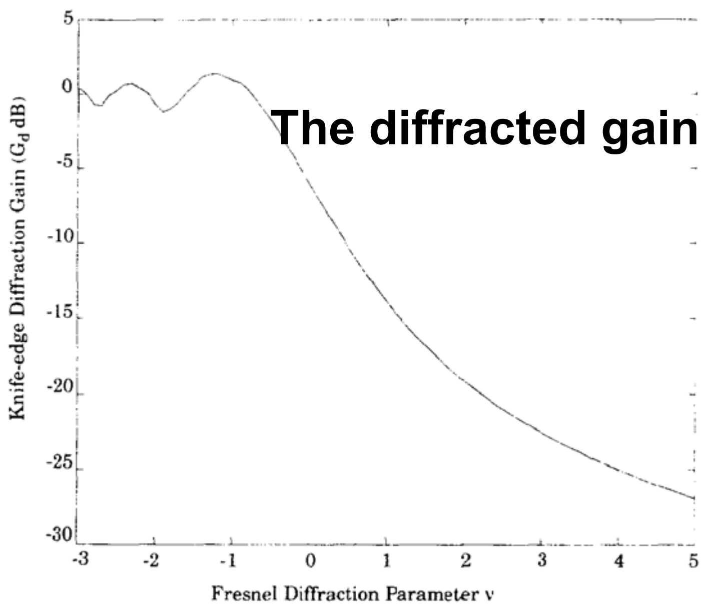


Figure 3.14
Knife-edge diffraction gain as a function of Fresnel diffraction parameter v

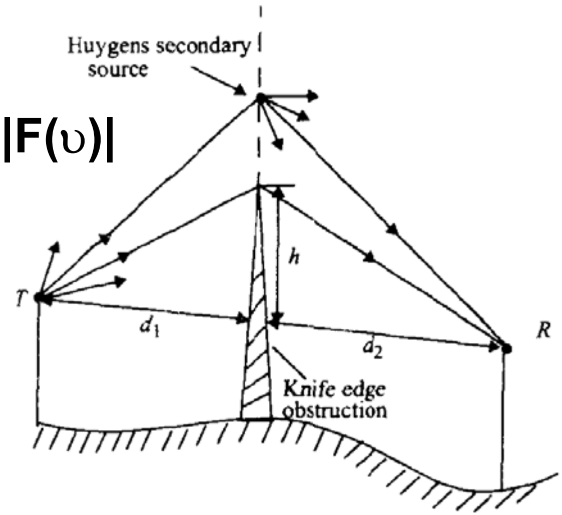


Figure 3.13
Illustration of knife-edge diffraction geometry. The receiver R is located in the shadow region.

$$G_d(dB) = \begin{cases} 0 & v \le -1 \\ 20\log(0.5 - 0.62v) & -1 \le v \le 0 \\ 20\log(0.5e^{-0.95v}) & 0 \le v \le 1 \\ 20\log(0.4 - \sqrt{0.1184 - (0.38 - 0.1v)^2} & 1 \le v \le 2.4 \\ 20\log(\frac{0.225}{\upsilon}) & v > 2.4 \end{cases}$$

Example

Example 3.7

Compute the diffraction loss for the three cases shown in Figure 3.12. Assume $\lambda = 1/3$ m, $d_1 = 1$ km, $d_2 = 1$ km, and (a) $h = 25$ m, (b) $h = 0$ (c) $h = -25$ m. Compare your answers using values from Figure 3.14, as well as the approximate solution given by equation (3.61.a) — (3.61.e). For each of these cases, identify the Fresnel zone within which the tip of the obstruction lies.

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

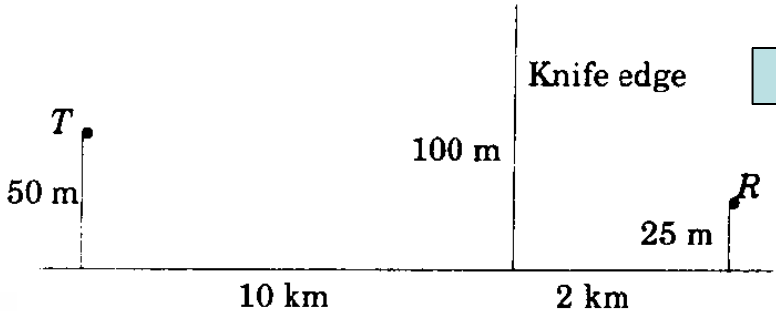
Graph 3-14

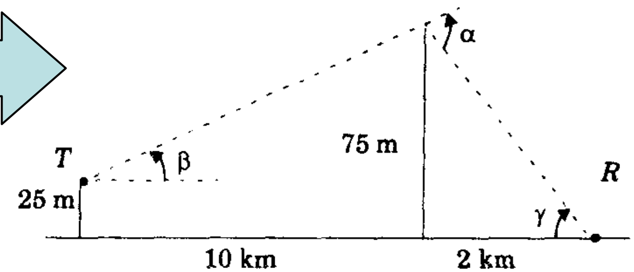
$$G_d(dB) = \begin{cases} 0 & v \le -1 \\ 20\log(0.5-0.62v) & -1 \le v \le 0 \\ 20\log(0.5e^{-0.95v}) & 0 \le v \le 1 \\ 20\log(0.4-\sqrt{0.1184-(0.38-0.1v)^2} & 1 \le v \le 2.4 \\ 20\log(\frac{0.225}{\upsilon}) & v > 2.4 \end{cases}$$

Example

Example 3.8

Given the following geometry, determine (a) the loss due to knife-edge diffraction, and (b) the height of the obstacle required to induce 6 dB diffraction loss. Assume $f = 900$ MHz.





$$\lambda = \frac{c}{f}$$

$$\beta = \tan^{-1}\left(\frac{75-25}{10000}\right) = 0.2865^o$$

$$\gamma = \tan^{-1}\left(\frac{75}{2000}\right) = 2.15^o$$

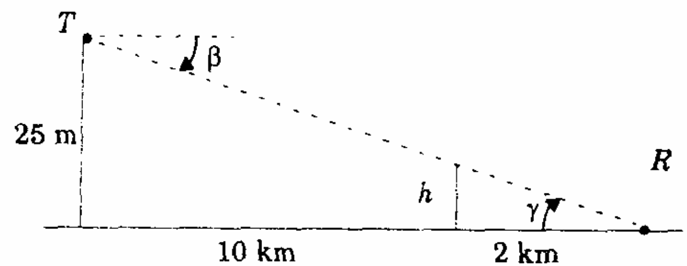
and

$$\alpha = \beta + \gamma = 2.434^o = 0.0424 \text{ rad}$$

Then using equation (3.56)

$$\nu = 0.0424\sqrt{\frac{2 \times 10000 \times 2000}{(1/3) \times (10000 + 2000)}} = 4.24.$$

From Figure 3.14 or (3.61.e), the diffraction loss is 25.5 dB.



It follows that $\frac{h}{2000} = \frac{25}{12000}$, thus $h = 4.16$ m.

Scattering

When the radio wave impinges on a rough surface, the reflected energy is spread out in all directions due to scattering.

Let us define h_c, where any surface could be considered as a smooth if its maximum to minimum protuberance is less than this parameter.

As a modification δc could be rewritten using the Bessel function. where,

I_o= Bessel function of the first kind and zero order

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

$$\delta_c = e^{[-8(\frac{\pi\sigma_h \sin(\theta_i)}{\lambda})^2]} I_o(8(\frac{\pi\sigma_h \sin(\theta_i)}{\lambda})^2)$$

Radar Cross Section (RCS) Model

RCS of scattering object is defined as the ratio of the power density of the signal scattered in the direction of the receiver to the power density of the radio wave incident upon the scattering object (square meters).

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

where d_T and d_R are the distance from the scattering object to the transmitter and receiver, respectively.

This equation may be applied to scatters in the far field of the both transmitter and Receiver and useful for predicting receiver power which scatter off large objects, such as buildings.

Practical Link Budget Design Using Path Loss Models

Models are derived used:

1. Empirical Method: which based on fitting curves or analytical expressions that recreate a set of measured data.
2. Theoretical (Analytical) Method, by using analysis techniques.

Log-Distance Path Loss Model

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

where n is the path loss exponent

It is important to select a free space reference distance that is appropriate for the propagation environment(1km for cellular systems)

Table 3.2 Path Loss Exponents for Different Environments

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

Log-Normal Shadowing

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

where X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB).

Log-distance PL model does not consider the fact that the surrounding environment clutter be vastly different at two different locations having the same T-R separation.

Outdoor Propagation Models

A number of propagation models are available to predict path loss over irregular terrain to predict signal strength at a particular receiving point or in a specific local area (sector).

Longley-Rice Model

Applicable to point-to-point communication terms in the frequency range from 40MHz-100GHz over different kinds of terrain

It operates in two modes

- **Point-to-point prediction**
  The path specific parameters can be easily determined, when a detailed terrain path profile is available.
- **Area mode prediction**
  The path specifications could be estimated, when the path profile is not available

Okumura Model

- Used widely for signal prediction in urban areas
- It's applicable for the frequency range of 150MHz-1920MHz, distances of 1km-100km, and BS antenna heights ranging from 30-1000m.
- The losses could be calculated by

$$L_{50}(dB) = L_F + A_{mu}(f,d) - G(h_{t_e}) - G(h_{r_e}) - G_{AREA}$$

where:

L_{50}(dB)=median value of the propagation path loss

L_F= free space propagation loss

A_{mu}= median attenuation relative to the free space

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

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

G_{AREA}=gain due to the type of environment

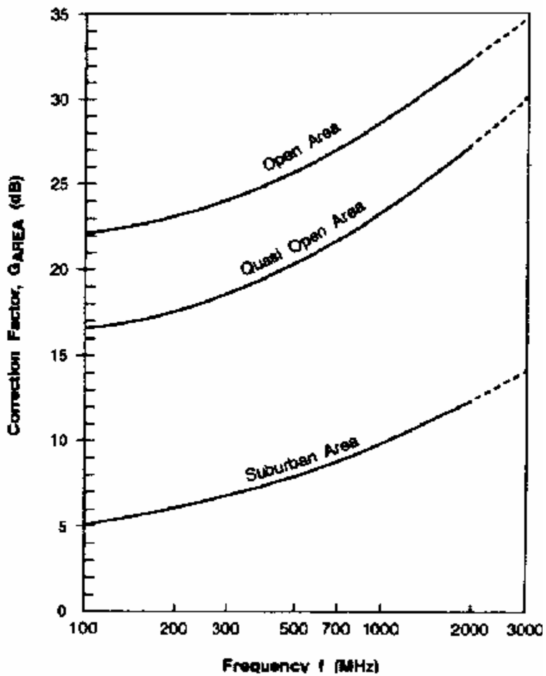
h_{te}= BS effective antenna height of 200m

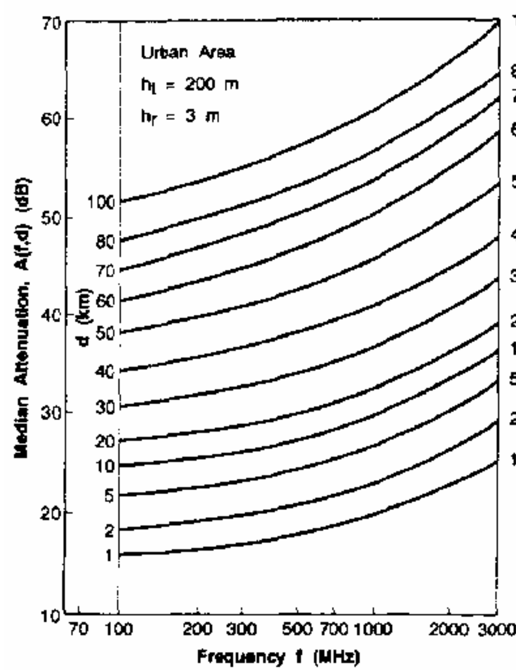
h_{re}= MS effective antenna height of 3m

Okumura Model

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

$$G(h_{r_e}) = \begin{cases} 10\log(\frac{h_{r_e}}{3}) & h_{r_e} \le 3m \\ 20\log(\frac{h_{r_e}}{3}) & 10m > h_{r_e} > 3m \end{cases}$$





Example 3.10

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).

Solution to Example 3.10

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

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

From the Okumura curves

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

and

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

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

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

Outdoor propagation models

- Its an empirical formulation of the graphical path loss data provided by Okumura.
  - Its valid from 150-1500MHz
  - The path loss could be calculated from

$$L_{50}(dB) = \begin{cases} 69.55 + 26.16\log(f_c) - 13.82\log(h_{t_e}) - a(h_{r_e}) + [44.9 - 6.55\log(h_{t_e})]\log(d) & ,urban \\ L_{50,urban} - 2[\log(\frac{f_c}{28})]^2 - 5.4 & ,suburban \\ L_{50,urban} - 4.78[\log(f_c)]^2 - 18.33\log(f_c) - 40.98 & ,rural \end{cases}$$

where:

h_{te}= BS effective antenna height of 30-200m

h_{re}= MS effective antenna height of 1-10m

d= the Tx-Rx separation distance in km

$a(h_{re})$=correction factor of MS antenna height

Hata Model

$$a(h_{r_e}) = \begin{cases} [1.1\log(f_c) - 0.7]h_{r_e} - 1.56\log(f_c) + 0.8 & ,\mathrm{small-to-medium-city} \\ 8.29[\log(1.54h_{r_e})]^2 - 1.1 & , fc \le 300MHz - \mathrm{large\,city} \\ 3.2[\log(1175.54h_{r_e})]^2 - 4.97 & , fc \ge 300MHz - \mathrm{large\,city} \end{cases}$$

Hata model compare very closely with original Okumura model, as long as d>1km. But, its not suitable for personal communication systems (PCS) which have cells on the order of 1km radius and frequency is up to 2GHz.

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

$$where,$$

$$f_c = extended - to - 2GHz$$

$$C_M = \begin{cases} 0dB & \mathrm{medium-sized-cities-and-suburban-areas} \\ 3dB & \mathrm{metro-politan-centers} \end{cases}$$