Semi-Empirical Models

Simple theoretical models (i.e., free-space, ideal ground, etc.) do not fit well into real-life scenarios (bad accuracy, disregard of many factors). Practical models are based on combination of measurement and theory (i.e., semi-empirical).

Semi-empirical models: try to make sense of massive measurements based on a few theoretical principles.

Important effects (difficult for theoretical modeling):

- Rough terrain
- Buildings, LOS blockage due to Earth curvature
- Refection
- Moving user (vehicle)

A simple, but popular, generalization of the two-ray model:

$$L_P = \left(\frac{d}{d_0}\right)^v L_0 \leftrightarrow L_P[\text{dB}] = L_0[\text{dB}] + 10v\lg\left(\frac{d}{d_0}\right) \qquad (3.1)$$

d_0 is the reference distance, L_0 is the path loss at d_0, v is the path loss exponent (can assume different values at different scenarios). d_0 is selected in such a way that there is an LOS Tx-Rx path (e.g. d_0=1 m).

d_0, L_0, v are obtained from measurements or from theory.

Equivalently, the received power P_r is:

$$P_r = \left(\frac{d_0}{d}\right)^v P_{r0} \leftrightarrow P_r[\text{dBm}] = P_{r0}[\text{dBm}] + 10v\lg\left(\frac{d}{d_0}\right) \quad (3.1a)$$

where P_{r0} is the Rx power at reference distance d_0.

Example: $v=2$ for free space; $v=4$ for ideal ground (2-ray model). In practice, $2 \le v \le 8$.

Q.: find L_0, P_{r0} for free-space and two-ray models.

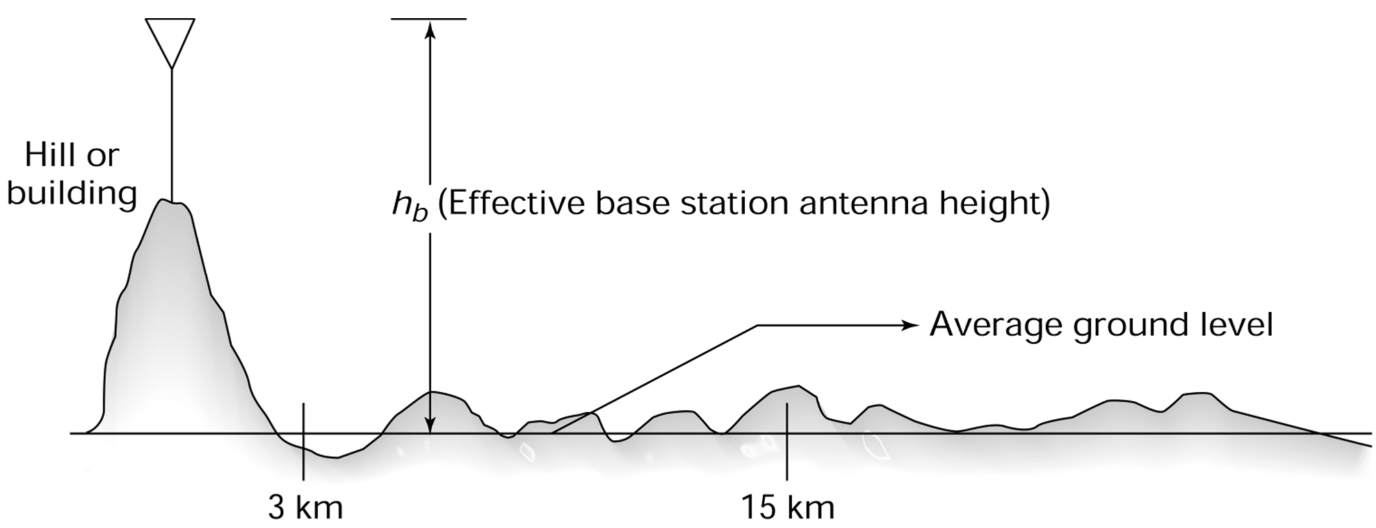
Okumura-Hata Model

Correction factors are introduced to account for:

- Terrain profile (urban/suburban, rural, hilly etc.)
- Antenna heights
- Building profiles (height, type, concentration)
- Street shape/orientation
- Lakes

Okumura-Hata model is a very popular one.

- Generalization of Okumura measurements (1968) by Hata (analytical presentation of graphs) (1980).
- Predicts average (median) path loss (attenuation).
- Terrain profile is taken into account



P.M. Shankar, Introduction to Wireless Systems, Wiley, 2002.

Average (median) path loss in <u>urban areas</u>:

$$L_p(dB) = 69.55 + 26.16\lg(f) + (44.9 - 6.55\lg h_b)\lg(d) - 13.85\lg h_b - a(h_{mu}) \tag{3.2}$$

where: f is the carrier frequency (MHz);
d is the distance (km);
h_b is the BS antenna height (m) (effective);
h_{mu} is the MU antenna height (m) (above ground);
$a(h_{mu})$ is the correction factor;

The correction factor $a(h_{mu})$ is

$$a(h_{mu}) = \begin{cases} 3.2(\lg(11.75 h_{mu}))^2 - 4.97, & \text{large city}, f \ge 300 MHz \\ 8.29(\lg(1.54 h_{mu}))^2 - 1.1, & \text{large city}, f < 300 MHz \\ (1.1 \cdot \lg(f) - 0.7)h_{mu} - (1.56\lg f - 0.8), & \text{small and medium} \end{cases} \tag{3.3}$$

<u>Limits of validity:</u>

$$\begin{aligned} &150 \le f \le 1500(MHz) \\ &30 \le h_b \le 200(m) \\ &1 \le d \le 20(km) \\ &1 \le h_{mu} \le 10(m) \end{aligned} \tag{3.4}$$

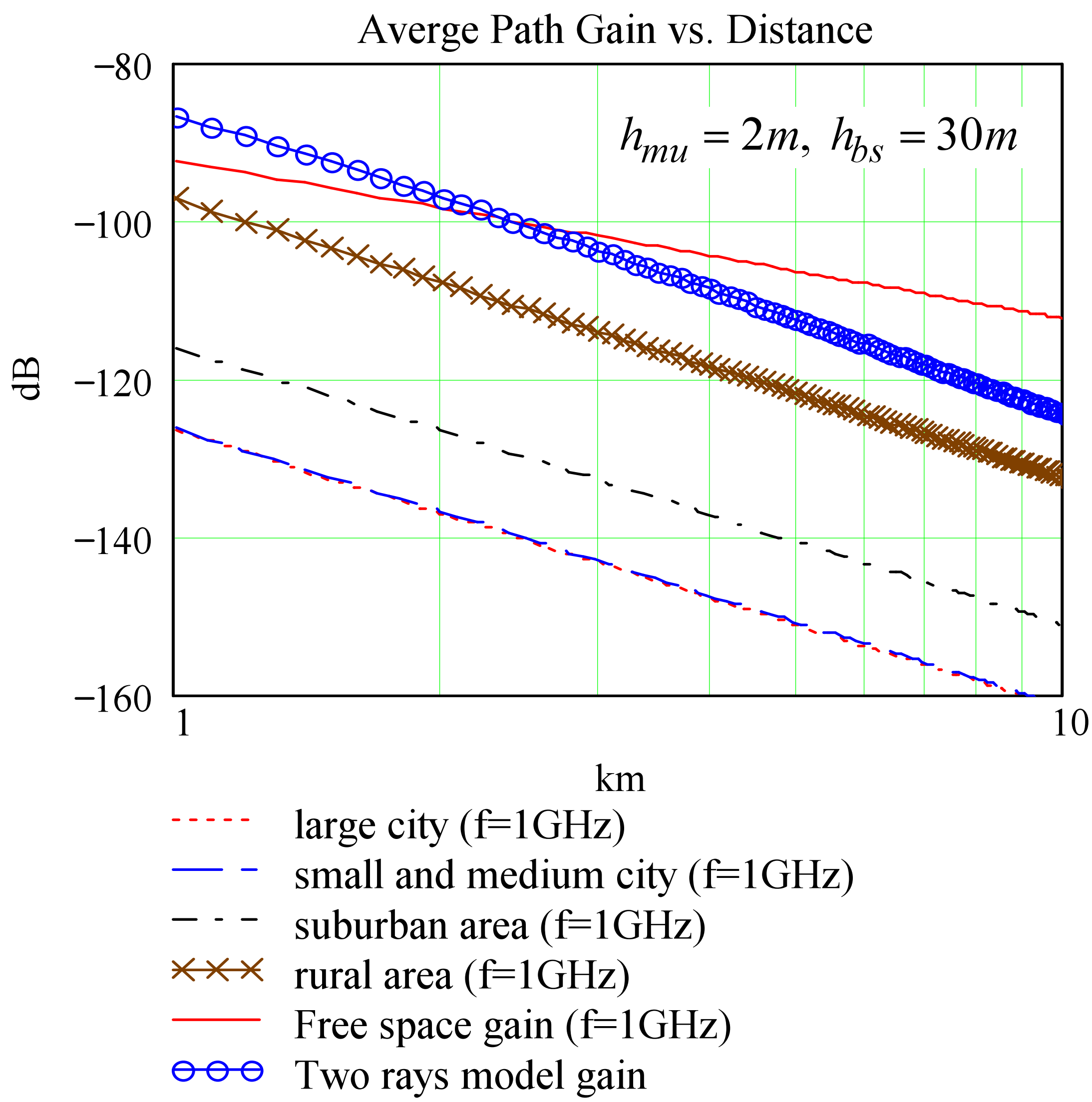
Suburban areas:

$$L_{sub} = L_P - 2\left(\lg\frac{f}{28}\right)^2 - 5.4 \qquad (3.5)$$

where L_P is the path loss in small to medium cities.

Rural areas

$$L_{rur}(dB) = L_P - 4.78(\lg f)^2 + 18.33\lg f - 40.94 \qquad (3.6)$$



Question: Compare to the free-space and two-ray models, what is the path loss exponent?

An Extension

Cost-231 extension of the Hata model:

$$L_P(dB) = 46.3 + 33.93\lg f - 13.82\lg h_b - a(h_{mu}) + (44.9 - 6.55\lg h_b)\lg d + c \quad (3.7)$$

where c is a correction factor :

$$c = \begin{cases} 0dB, & \text{medium city and suburban areas} \\ 3dB, & \text{metropolitan areas} \end{cases}$$

<u>Limits:</u> the same as for the Hata model, except for $1500 \le f \le 2000 MHz$.

<u>Major limitation</u> of the 2 models above: $d \ge 1km$

The model does not take into account building's profile, street type/orientation etc.

Many other models are available.

COST-Walfisch-Ikegami Model

Includes 3 components: free-space loss, roof-to–street diffraction loss (scattering) and multiscreen loss.

The average path loss for **non-LOS** (NLOS):

$$L_P[\text{dB}] = L_{fs} + L_{rts} + L_{ms} \tag{3.8}$$

where:

$L_{fs}[\text{dB}] = 32.4 + 20\lg d + 20\lg f = (\text{free} - \text{space loss})$

L_{rts} is the roof-to-street diffraction loss

L_{ms} is the multiscreen loss (rows of buildings)

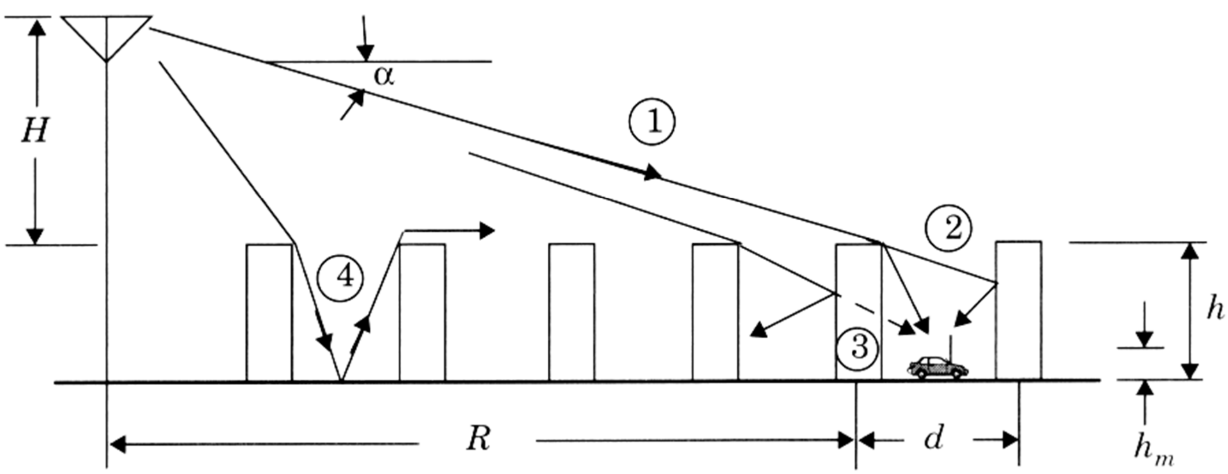


Figure 4.25 Propagation geometry for model proposed by Walfisch and Bertoni [from [Wal88] © IEEE].

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

LOS path loss (in a street canyon):

$$L_P[\text{dB}] = 42.6 + 26\lg d + 20\lg f \quad (\text{d} \geq 0.02\text{km}) \quad (3.11)$$

where d is in km, and f is in MHz.

Limits:

$$800 \leq f \leq 2000 MHz$$
$$4 \leq h_b \leq 50m$$
$$1 \leq h_{mu} \leq 3m$$
$$0.02 \leq d \leq 5km$$

Accuracy: mean error is about 3dB with standard deviation of 4-8dB.

Applications: 3G and later, macrocells and microcells.

Recent Activities: LTE (4G) Pathloss Models

General system parameters		
System parameters	Bandwidth 10MHz; Carrier Frequency 2GHz; CP type - Normal	
Antenna System	Pico: 5 dBi, 2D, Omni, 2TX & 2RX	UE: 0dBi, 2D, Omni, 1TX, 2RX
Noise Figure	Pico: 13dB	UE: 9 dB
Max Power	Pico: 24dBm	UE: 23dBm
Uplink Power control	Open Loop Power Control: P0: –76dBm; α = 0.8.	
Propagation characteristics		
Shadowing Pico-Pico	Pico: 6dB	
Shadowing Pico-UE	3dB for LOS and 4dB for NLOS	
Penetration loss	0dB	
Pico-Pico pathloss (R in km)	if R <= 2/3, $PL_{LOS}(R) = 98.4+20\log_{10}(R)$; else $PL_{LOS}(R) = 101.9+40\log_{10}(R)$	$PL_{NLOS} = 40\log_{10}(R)+169.36$
	$P_{LOS}(R) = 0.5\text{-}\min(0.5, 5\exp(-0.156/R))+\min(0.5, 5\exp(-R/0.03))$	
Pico-UE pathloss (R in km)	$PL_{LOS}(R) = 103.8+20.9\log10(R)$	$PL_{NLOS}(R) = 145.4+37.5\log_{10}(R)$
	$P_{LOS}(R) = 0.5\text{-}\min(0.5, 5\exp(-0.156/R))+\min(0.5, 5\exp(-R/0.03))$	
UE-UE pathloss (R in km)	if R <= 50m, $PL = 98.45+20\log_{10}(R)$; else $PL = 55.78+40\log_{10}(R)$	
Small scale fading	Pico-UE: ITU UMi UE-UE and Pico-Pico: not modeled	

Z. Shen et al, Dynamic Uplink-Downlink Configuration and Interference Management in TD-LTE, IEEE Communications Magazine, Nov. 2012, pp. 51-59.

Recent Activities: 5G & related models

1. T. S. Rappaport et al., “Overview of millimeter wave communications for fifth-generation (5G) wireless networks — with a focus on propagation models,” IEEE Trans. Antennas Propag., vol. 65, no. 12, pp. 6213–6230, Dec. 2017.

2. S. Sun et al., “Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications,” IEEE Trans. Veh. Techl., vol. 65, no. 5, pp. 2843–2860, May 2016.

3. S. Sun, T.S. Rappaport, et al, Propagation Models and Performance Evaluation for 5G Millimeter-Wave Bands, IEEE Trans. Veh. Tech., vol. 67, no. 9, pp. 8422-8439, Sep. 2018.

4. K. Briggs, A. Shojaeifard, Coverage Regions Under Multi-Slope Pathloss Propagation, IEEE Trans. Veh. Tech., vol. 69, no. 10, pp. 11786-11789, Oct. 2020.

5. Study on Channel Model for Frequencies from 0.5 to 100 GHz (Release 16), TR 38.901, 3GPP, Sophia Antipolis, France, 2019.

Recent Activities: 5G & related models

General form of L_P[dB] for UMa/UMi/RMa (see [1]-[3][5]):

$$L_P[\text{dB}] = L_0[\text{dB}] + 10v \lg\left(\frac{d}{d_0}\right), \qquad L_0[\text{dB}] = 20\lg\left(\frac{4\pi d_0}{\lambda}\right)$$

Usually, $d_0 = 1$ m (LOS). Equivalently,

$$L_P[\text{dB}] = 32 + 10v \lg d + 20\lg f_c$$

f_c in GHz, $d \geq d_0 = 1$ m;
$10v$ [dB] = extra loss per decade of d

LOS (street canyon): $v = 2...2.1$
NLOS: $v = 3...4$

Also: multi-break-point model [5]. You can use its simplified form:

$$L = \max\{L_{2-ray}, L_{FS}, L_{\min}, G_t G_r\}, \quad L_{\min} \approx 10^2$$

Note: do not forget to check the LOS distance!

$$d < d_{LOS} \approx 4\left(\sqrt{h_t} + \sqrt{h_r}\right) \text{ [km]}$$

Non-LOS (NLOS) Propagation: Diffraction

Diffraction: penetration of EM waves into non-LOS area ("ray bending").

Any obstruction of LOS path will result in diffraction. While the diffracted field is much weaker than LOS, it can still be important.

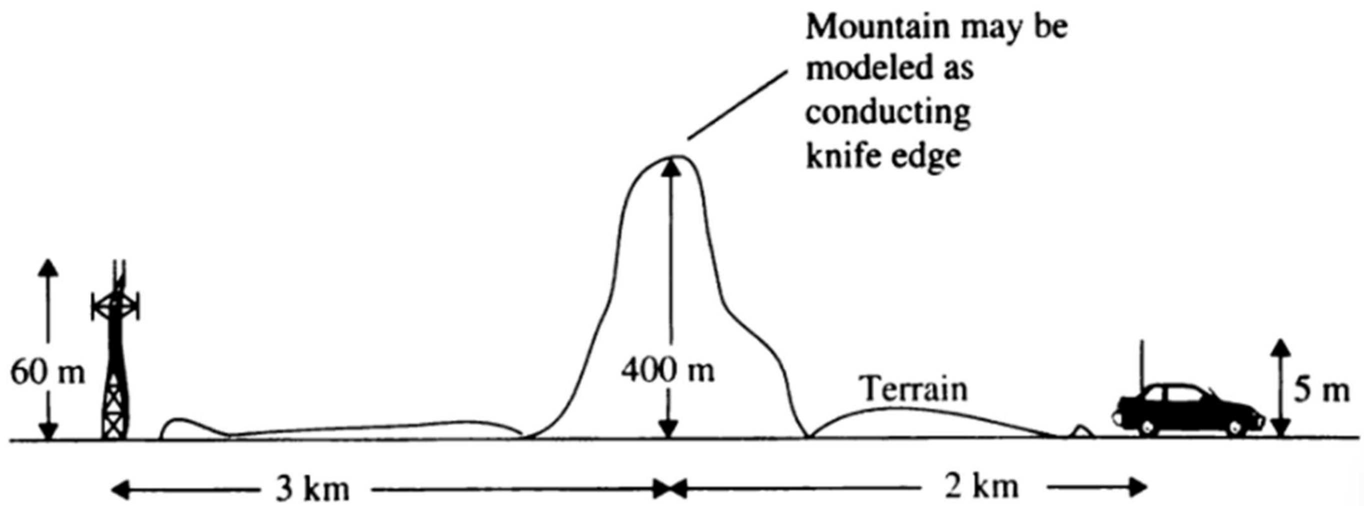


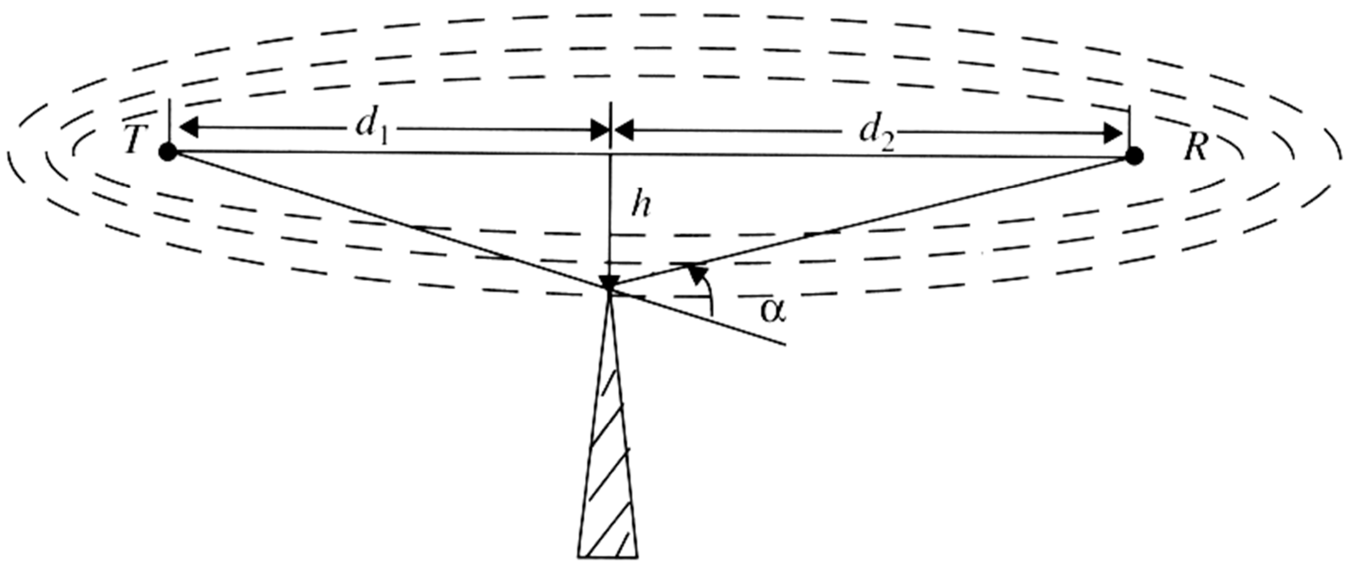
Figure P4.19 Knife-edge geometry for Problem 4.19.

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Fresnel Zones and Diffraction

Fresnel zones: define the space essential for EM wave propagation.

n-th Fresnel zone: region of space where the path length is $[(n-1)\lambda/2, n\lambda/2]$ larger than LOS path length. The zone boundaries are the circles; the path length through each circle is $n\lambda/2$.



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

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Fresnel zone radius:

$$r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \tag{3.12}$$

where $d_1, d_2 >> r_n$.

Diffraction and Fresnel zones can be explained using Huygen's principle (secondary sources).

Contribution of each successive zone is less than the previous one. Blockage of some zones results in diffraction.

Area essential for EM wave propagation

There is no disturbance to the wave propagation along a certain path provided that 1st Fresnel zone is cleared.

Rule of thumb for LOS microwave link design: ~50% of 1st zone must be kept clear.

Knife-Edge Diffraction

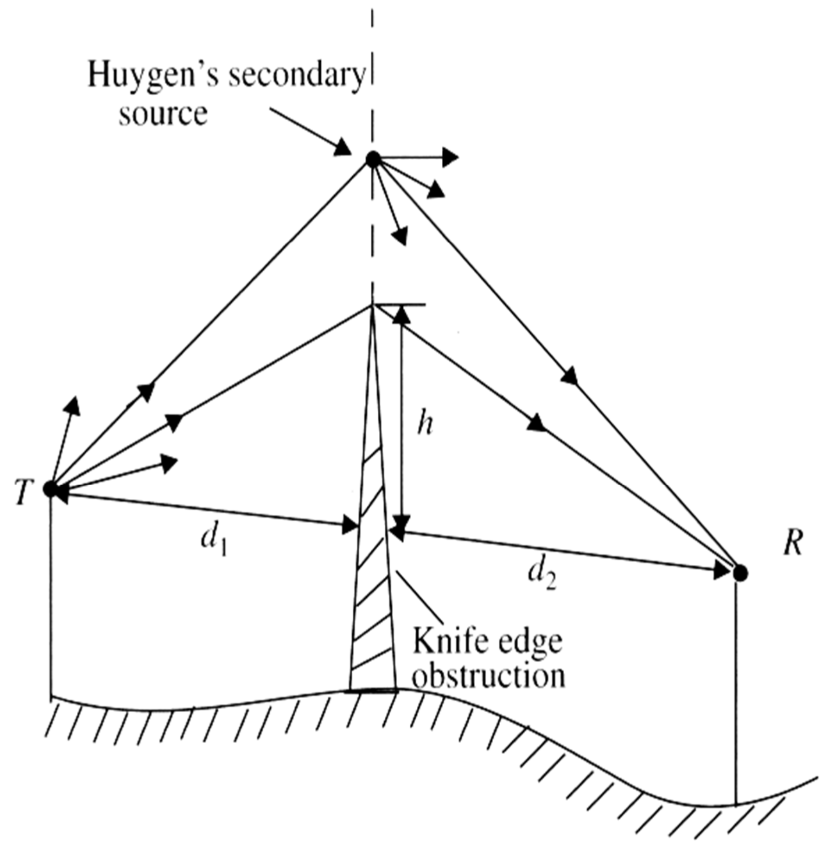


Figure 4.13 Illustration of knife-edge diffraction geometry. The receiver R is located in the shadow region.

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Fresnel-Kirchoff diffraction parameter

$$v = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = h\sqrt{2}/r_1 \qquad (3.13)$$

The field is given by Fresnel integral

$$\frac{E}{E_0} = F(v) = \frac{1+j}{2}\int_v^\infty \exp(-j\pi t^2/2)dt \qquad (3.14)$$

where E_0 is the LOS field (no obstruction).

The field has oscillating behavior w.r.t. h. This is a simple model (approximation). Yet, it is good enough to model many obstacles (buildings, mountains, etc.). Generalizations are possible: multiple knife-edge models.

Another representation: introduce Fresnel integrals,

$$C(x) = \int_0^x \cos\left(\frac{\pi}{2}t^2\right)dt, \ \ \mathrm{S}(x) = \int_0^x \sin\left(\frac{\pi}{2}t^2\right)dt \qquad (3.15)$$

Then,

$$F(\nu) = \frac{1}{2} - \frac{1+j}{2}\left[C(\nu) - jS(\nu)\right] \qquad (3.16)$$

Note that $C(\infty) = S(\infty) = \frac{1}{2}$.

The total path loss is

$$L_p = L_0 L_d \qquad (3.17)$$

where $L_0 = (4\pi R/\lambda)^2$ is the free-space path loss,

$L_d = |F(\nu)|^{-2}$ is the diffraction loss.

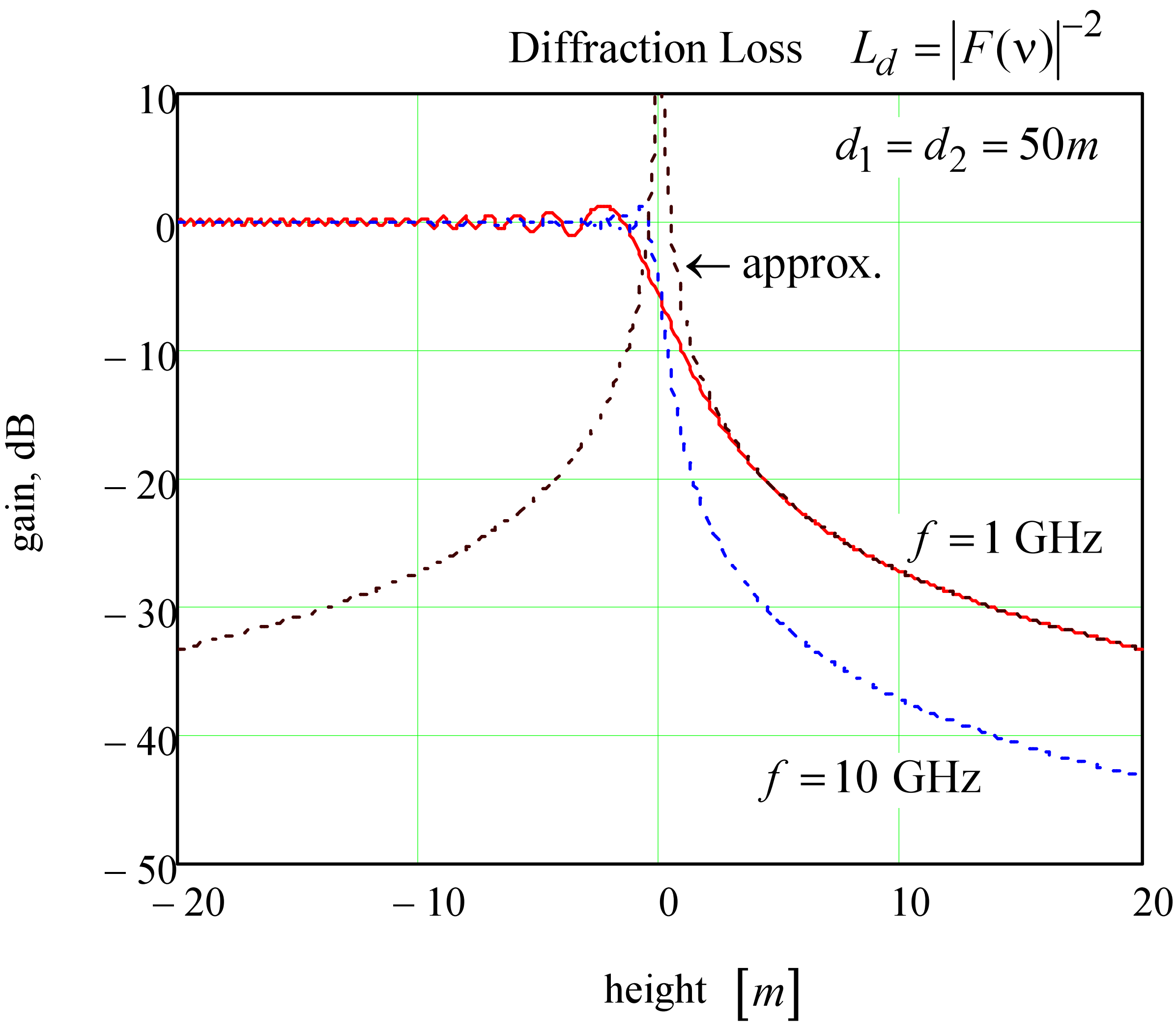
An Approximation[1]

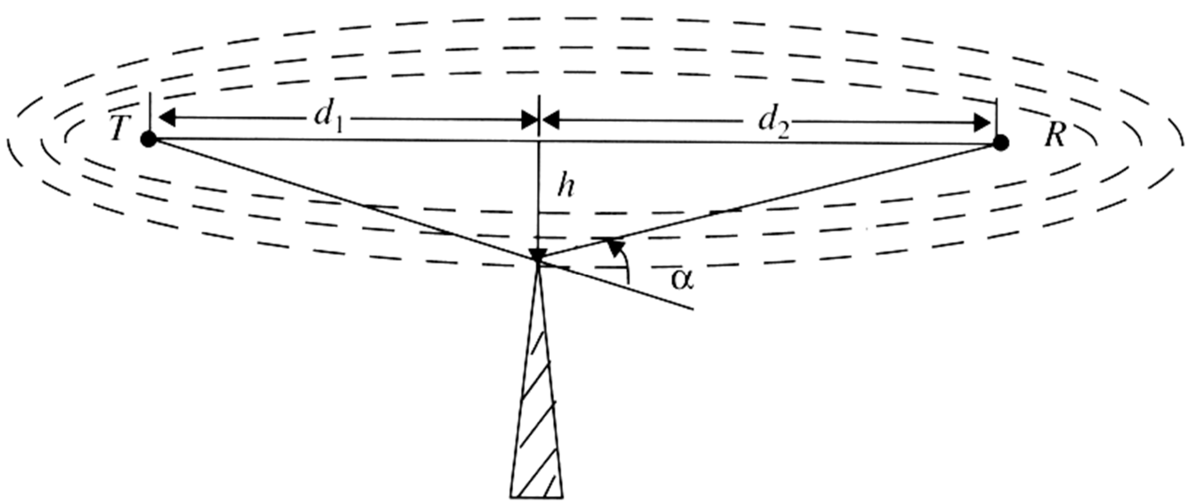
If $d_1, d_2 >> h >> \lambda$:

$$\frac{1}{L_d} = \left|F(\nu)\right|^2 = \left|\frac{E}{E_0}\right|^2 \approx \frac{\lambda}{4\pi^2 h^2} \frac{d_1 d_2}{d_1 + d_2}$$

Note: if the edge is not sharp but rounded, expect 10-20 dB more loss.

[1] see Kraus, Fleish, Electromagnetics with Applications, 5th Edition, McGraw Hill, 1999. (p.235-236).





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

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Summary

- Average (median) path loss. Semi-empirical models.
- Okumura-Hata model. Extension to PCS environments.
- COST-Walfisch-Ikegami Model.
- Fresnel zones and diffraction. Knife-edge diffraction.

Reading:

- Rappaport, Ch. 4.

References:

- S. Salous, Radio Propagation Measurement and Channel Modelling, Wiley, 2013. (available online)
- J.S. Seybold, Introduction to RF propagation, Wiley, 2005.
- Other books (see the reference list).

Note: Do not forget to do end-of-chapter problems. Remember the learning efficiency pyramid!