

## WIRELESS COMMUNICATION TECHNOLOGIES

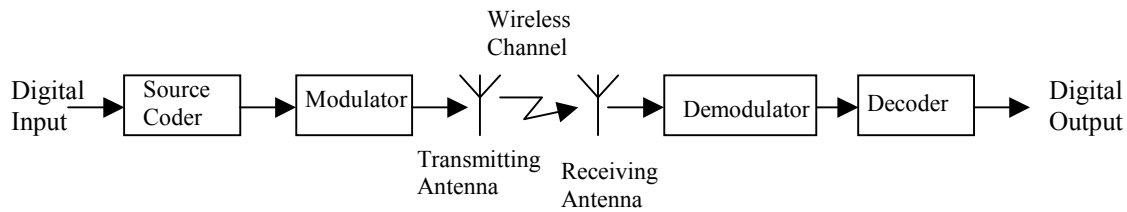
Rutgers University – Dept. of Electrical and Computer Engineering (ECE)  
Course No. 16:332:559:01 (Advanced Topics in Communications Engineering)

Spring 2001

Professor Narayan Mandayam

### **Lecture #1 – Wednesday, January 17, 2001**

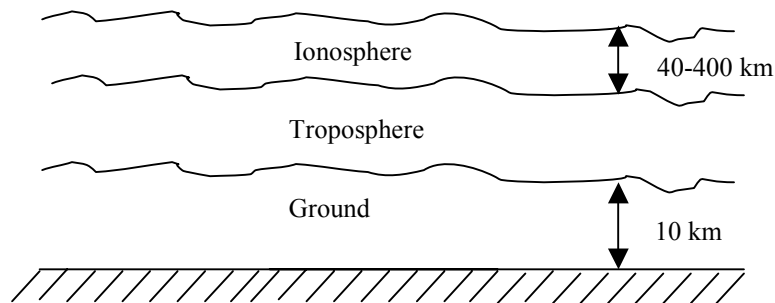
Summary by Michael Weiss



**Fig. 1: Block Diagram of a Typical Wireless Communication System**

Figure 1 depicts a typical wireless communication system. As we begin our study, the feature of interest is the **wireless channel**. Communication between the sending and receiving parties is accomplished by the propagation of electromagnetic "radio" waves through the ground and atmosphere. As all wireless systems operate in this fashion, they all share the same channel. Thus, in principle, each is subject to interference from every other. Such interference can be avoided by implementing geographic and/or frequency separation.

### Overview of Radio Propagation



**Fig. 2: Atmospheric Layers Relevant to Radio Wave Propagation**

Figure 2 depicts the two lowest layers of the atmosphere and their approximate distances from the Earth. These are the only layers of the atmosphere which play a significant role in radio wave propagation.

In the simplest model of wave propagation, we view the transmitted wave as two components—the **ground wave**, which propagates along the surface of the earth, and the **sky wave**, which propagates in space and can return to the earth by reflection in either the troposphere or ionosphere. The degree of reflection is function of wavelength.

### Radio Spectrum Classification

The radio spectrum is divided into sub-bands based on each frequency range's suitability for a given set of applications. Suitability is determined as a function of the atmospheric propagation characteristics of the given frequencies as well as system aspects, such as required antenna size and power limitations.

Based on these considerations, the radio spectrum has been divided into the following sub bands:

- |   |  |
|---|--|
| 1) <b>Extremely Low Frequency (ELF)</b> | 300 - 3000 Hz ( $\lambda=1000 - 100$ km) |
| <b>Very Low Frequency (VLF)</b>         | 3 - 30 kHz ( $\lambda=100 - 10$ km)      |

*Propagation Characteristics:* Propagates between the surface of the Earth and the Ionosphere. Can penetrate deep underground and underwater. As the required antenna size is proportional to the wavelength, the large wavelength in this case mandates the use of large antennas.

*Applications:* mining, underwater communication (submarines), SONAR

- |                              |                                     |
|------------------------------|-------------------------------------|
| 2) <b>Low Frequency (LF)</b> | 30 - 300 kHz ( $\lambda=10 - 1$ km) |
|------------------------------|-------------------------------------|

*Propagation Characteristics:* The sky wave can be separated from the ground wave for frequencies above 100 kHz. This enables communication over large distances by reflecting the sky wave off the atmosphere.

*Applications:* broadcasting, radio navigation

- |                                 |  |
|---------------------------------|--|
| 3) <b>Medium Frequency (MF)</b> | 300 - 3000 kHz ( $\lambda=1000 - 100$ m) |
|---------------------------------|--|

*Propagation Characteristics:* The sky wave separates from the ground wave in this range. Ground wave gives usable signal strength up to 100 km from transmitter.

*Applications:* AM radio broadcasting (550 - 1600 kHz)

- |                               |                                    |
|-------------------------------|------------------------------------|
| 4) <b>High Frequency (HF)</b> | 3 - 30 MHz ( $\lambda=100 - 10$ m) |
|-------------------------------|------------------------------------|

*Propagation Characteristics:* The sky wave is the main propagation mode. The ground wave is used for communication over shorter distances than the sky wave. As propagation loss increases with frequency increases, the use of repeaters is required.

*Applications:* Broadcasting over large areas, amateur radio (ham), citizens band (CB) radio

5) **Very High Frequency (VHF)** 30 - 300 MHz ( $\lambda=10 - 1$  m)

*Propagation Characteristics:* Diffraction (bending of waves due to obstruction) and reflection give rise to communication beyond the horizon. Propagation distances are thousands of kilometers. The diffraction and reflection enables reception within buildings.

*Applications:* broadcast TV, FM radio (88 - 108 MHz), radio beacons for air traffic control

6) **Ultra High Frequency (UHF)** 300 - 3000 MHz ( $\lambda=1$  m - 10 cm)

*Propagation Characteristics:* Reflections from atmospheric layers are possible. Effects of rain and moisture are negligible.

*Applications:* broadcasting, satellite (TV) broadcasting, all (1G to 3G) land mobile phones, cordless phones, some air traffic control

7) **Super High Frequency (SHF)** 3 - 30 GHz ( $\lambda=10 - 1$  cm)

*Propagation Characteristics:* Range becomes limited by obstacles as frequency increases. Propagation is limited by absorption by rain and clouds.

*Applications:* Satellite service for telephony and TV, mobile services in the future

8) **Extremely High Frequency (EHF)** 30 - 300 GHz ( $\lambda=10 - 1$  mm)

*Propagation Characteristics:* Very high losses due to water, oxygen, vapor.

*Applications:* communications at short distances (within line of sight), broadcast satellite for HDTV (for communication between satellites in space, not space to earth)

## **Propagation**

Propagation in free space is the ideal. When propagation takes place close to obstacles, the following propagation mechanisms occur:

- a) **Reflection** – Occurs when a radio wave strikes an object with dimensions that are large relative to its wavelength, i.e. buildings.
- b) **Diffraction** – Occurs when a radio wave is obstructed by surfaces with irregularities. Secondary waves arise from the obstructing surface and give rise to the bending of waves around and behind obstacles.

c) **Scattering** – Occurs when a radio wave travels through a medium containing lots of small (compared to wavelength) objects.

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### **Lecture #2 – Monday, January 22, 2001**

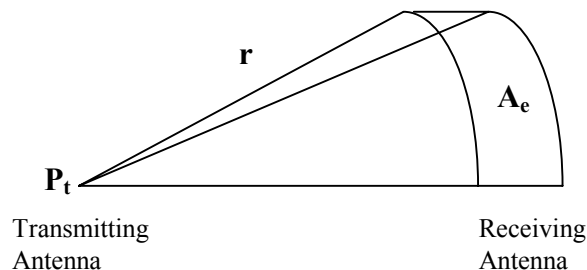
Summary by Michael Weiss

## PATH LOSS

### Path Loss in Free Space

In the last lecture, we defined 3 phenomena relevant to radio wave propagation in the presence of obstacles—namely reflection diffraction, and scattering. Let us begin our subsequent investigation by first considering propagation in free space, in which the influence of obstacles is neglected.

Consider an isotropic radiating source (antenna), emitting a total power  $P_t$ : ("Isotropic" means that energy flows with equal strength in all directions.)



**Fig. 1: Propagation in Free Space**

**Question:** How much power will reach a receiving antenna of area  $A_e$  at a distance  $r$  from the source?

Due to the isotropic nature of the radiating source, the power,  $P_t$  is uniformly distributed over the entire surface of the sphere of radius  $r$  centered at the source. Thus, the power density on the sphere is:

$$S_r = \frac{P_t}{4\pi r^2} \frac{W}{m^2} \quad (1)$$

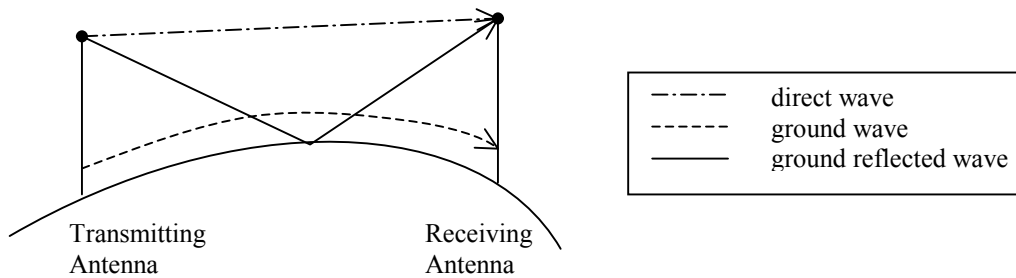
The received power depends on the size of the receiving antenna. Assuming this antenna is lossless and has effective aperture (area)  $A_e$ , the received power is:

$$P_r = S_r A_e = \frac{P_t A_e}{4\pi r^2} \quad (2)$$

Thus, we may model path loss in free space as  $P_r \propto P_t r^{-2}$ —the received power decays as the square of the distance traveled.

As free space represents an ideal situation far from our actual conditions, let us use this result to characterize path loss under somewhat more realistic circumstances.

### Propagation Close to the Earth's Surface

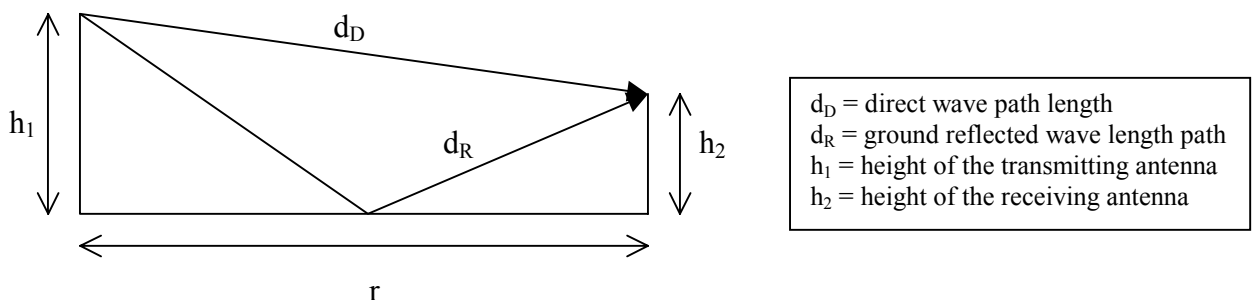


**Fig. 2: Propagation Close to the Earth's Surface**

As depicted in figure 2, propagation close to the Earth's surface occurs by means of the following three mechanisms (we will not consider atmospheric reflections):

- 1) direct wave
- 2) ground wave
- 3) ground reflected wave

In the analysis which follows, we shall neglect the ground wave, as the antenna height is large as compared with the wavelength. Ignoring the curvature of the Earth, as is reasonable for small distances, we may represent the situation with an equivalent model as follows:



**Fig. 3: Equivalent Model of Propagation Close to the Earth's Surface**

First, note that due to its shorter path length, the direct wave will arrive sooner than the ground reflected wave.

Let  $\Delta t$  represent the transit time difference between a wave travelling along the reflected path and one travelling the direct path.

As a result of the reflection, the wave experiences a *change in phase*, as well as a *loss of energy (attenuation)*.

We may model the received waveform,  $E(t)$ , as the superposition of the direct and reflected waves:

$$E(t) = \underbrace{E_0 \cos(\omega t)}_{\text{direct-wave}} + \underbrace{\rho E_0 \cos(\omega(t - \Delta t) + \phi)}_{\text{reflected-wave}} \quad (3)$$

where  $E_0$  = field strength (amplitude) of direct wave under free space propagation model

$\rho$  = attenuation factor

$\phi$  = phase shift

We shall assume that the reflected wave experiences perfect loss-free mirror reflection. This implies that  $\phi = \pi$ .

Let us further assume that the difference in path lengths between the two components is much less than the distance between the antennas ( $d_R - d_D \ll r$ ). Coupled with the assumption of loss-free reflection, this implies that  $\rho \approx 1$ .

Therefore, we may write:

$$E(t) = E_0 \cos(\omega t) + E_0 \cos(\omega(t - \Delta t) + \pi) \quad (4)$$

$$= \underbrace{2E_0 \sin\left(\frac{\omega\Delta t}{2}\right)}_{\text{amplitude-of-received-wave}} \cos(\omega t + \psi) \quad (5)$$

where  $2E_0 \sin\left(\frac{\omega\Delta t}{2}\right)$  represents the amplitude of the received wave (field strength), and  $\psi$

denotes the appropriate phase angle. We wish to determine this field strength in terms of the geometric parameters in figure 3 in order to compute the received power.

Let us determine  $\Delta t$  in terms of the geometry:

$$d_D = \sqrt{r^2 + (h_2 - h_1)^2} \approx r \left( 1 + \frac{1}{2} \left( \frac{h_2 - h_1}{r} \right)^2 \right) \quad (6)$$

$$d_R = \sqrt{r^2 + (h_2 + h_1)^2} \approx r \left( 1 + \frac{1}{2} \left( \frac{h_2 + h_1}{r} \right)^2 \right) \quad (7)$$

where we have used the approximation  $(1+x)^{\frac{1}{2}} \approx 1 + \frac{1}{2}x$  for small  $x$  (in this case,  $h_1, h_2 \ll r$ )

$$\therefore \Delta d = d_R - d_D \approx \frac{2h_1h_2}{r} \quad (8)$$

$$\Delta t = \frac{\Delta d}{c} \quad \omega = 2\pi f = \frac{2\pi c}{\lambda} \quad (9, 10)$$

From (5), the magnitude of the field strength is:

$$|E| = 2E_0 \left| \sin\left(\frac{\omega\Delta t}{2}\right) \right| = 2E_0 \left| \sin\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \right| \quad (11)$$

Therefore, the received power is:

$$P_r = 4E_0^2 \sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \quad (12)$$

Lastly, as  $E_0$  represents the received field strength in the case of free space propagation, we may return to eq. 2 and equate  $E_0^2$  with the received power in the free space case. Thus,

$$E_0^2 = P_{r_{free\ space}} = \frac{P_t A_e}{4\pi r^2} \quad (13)$$

and substituting (13) into (12),

$$P_r = \frac{P_t A_e}{\pi r^2} \sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \quad (14)$$

If we assume that antenna elevations are small compared to the distance between antennas, i.e.  $h_1 h_2 \ll \frac{\lambda r}{4}$ , we may make use of the approximation  $\sin x \approx x$  for small angles.

Therefore,

$$\boxed{P_r \approx \frac{P_t A_e}{\pi r^2} \cdot \frac{4\pi^2 (h_1 h_2)^2}{\lambda^2 r^2} = \frac{4\pi P_t A_e (h_1 h_2)^2}{\lambda^2 r^4}} \quad (15)$$

and we may conclude that under our various assumptions, that the received power decays as the 4<sup>th</sup> power of the transmission distance ( $P_r \propto P_{tr}^{-4}$ ) for propagation close to the Earth's surface (typically, actual measurements yield exponent values between 3 and 4.)

Clearly this result is worse than that derived in eq. 2, in which  $P_r \propto P_t r^{-2}$ . Thus we may conclude, as one might expect, that received power decays more rapidly with distance in the case of propagation close to the Earth's surface than in propagation in free space.

### **Friis Free Space Equation**

The effective aperture of an antenna,  $A_e$  is typically related to its gain as:

$$G = \frac{4\pi A_e}{\lambda^2} \quad (16)$$

Substituting for  $A_e$  in eq. 2, we obtain the equivalent free space path loss representation:

$$P_r = \frac{P_t A_e}{4\pi r^2} = P_t G_r \left( \frac{\lambda}{4\pi r} \right)^2 \quad (17)$$

Typically, the transmitter is also associated with a gain,  $G_t$ . Thus, we may write:

$$P_r = P_t G_t G_r \left( \frac{\lambda}{4\pi r} \right)^2 \quad (18)$$

### **Friis Free Space Equation**

This provides a better model for path loss in free space due to its explicit dependence on  $G_r$  and  $\lambda$ .

### **Power Units**

As we can see using the models above, transmitted power can drop by orders of magnitude over operating distances from the source. Thus, increasing transmit power to combat path loss is a very inefficient approach.

Mobile systems typically use very small transmit powers—on the order of milliwatts. This, coupled with the fact that transmitted power can decay by orders of magnitude over a typical coverage area of square km, leads us to choose dBm as the preferred unit to express received power levels.

The unit dBm denotes decibels above one milliwatt [1]. The received power in units of dBm is defined as:

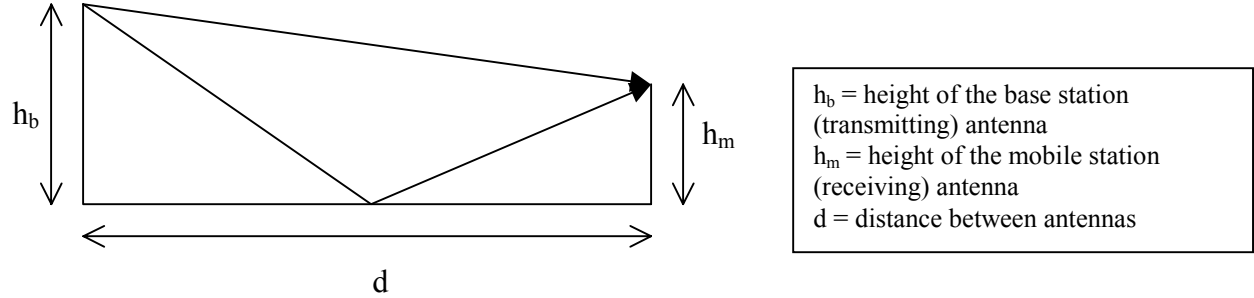
$$P_r \text{ (dBm)} = 10 \log_{10} \left[ \frac{P_r \text{ W}}{\underbrace{0.001 \text{ W}}_{1 \text{ mW}}} \right] = 10 \log_{10} \left[ \frac{P_r}{\text{mW}} \right] \quad (19)$$

in which  $P_r$  is 10 times the base-10 logarithm of the ratio of  $P_r$ , expressed in a given power unit, to 1 milliwatt, expressed in matching units. It is customary to omit the explicit division by 1 mW and implicitly assume that it has happened.

Returning to eq. 18, Friis Free Space Equation, we have:

$$P_r(dBm) = 10 \log_{10} \left[ P_t G_t G_r \left( \frac{\lambda}{4\pi r} \right)^2 \right] \quad (20)$$

### **Propagation Close to the Earth's Surface, Revisited**



**Fig. 4: Equivalent Model of Propagation Close to the Earth's Surface, Revisited**

Returning to eq. 15,

$$P_r \approx \frac{4\pi P_t A_e (h_1 h_2)^2}{\lambda^2 r^4} \quad (15)$$

we may substitute for  $A_e$  from eq. 16,  $G = \frac{4\pi A_e}{\lambda^2}$ , to obtain:

$$P_r \approx P_t G_t G_r \left( \frac{h_b h_m}{d^2} \right)^2 \quad (21)$$

or equivalently,

$$P_r \approx 10 \log_{10} \left[ P_t G_t G_r \left( \frac{h_b h_m}{d^2} \right)^2 \right] \quad dBm \quad (22)$$

Lumping the antenna gains together with the transmitted power, we shall define the *path loss*,  $L_p$  as the ratio of the product of these quantities to the received power:

$$\begin{aligned} L_p \quad (dB) &= 10 \log_{10} \left( \frac{P_t G_t G_r}{P_r} \right) & (23) \\ &= 10 \log_{10} \left( \frac{d^4}{(h_b h_m)^2} \right) \\ &= 40 \log_{10}(d) - 20 \log_{10}(h_b) - 20 \log_{10}(h_m) \end{aligned}$$

We note that the dependence on frequency is not captured in this definition of path loss, as it is absorbed in the antenna gains. The definition in equation 23 is the outgrowth of a model predicated on a series of approximations and assumptions which must hold true for meaningful results. It lacks a real connection to any actual communication environment.

As a contrast to this, several empirical models have been derived for macrocellular systems (a macrocell is a cell typically on the order of kilometers) by curve fitting experimental data. Two of the more useful models for 900 MHz cellular systems are Hata's model based on Okumura's prediction method [2] and Lee's model [3].

### **Path Loss in Macrocells – Hata's Model**

Hata's model is empirically derived based on experimental data collected in Tokyo. As such, it is intended for use in Japanese suburban landscapes and performs poorly for North American suburban terrain. It can distinguish between man-made structures [4] and is known to be accurate within a decibel for transmission distances between 1 and 20 km.

The model is valid within the following operating ranges [10]:

<b>Carrier Frequency:</b>	$100 \text{ MHz} \leq f_c \leq 1500 \text{ MHz}$
<b>Base Station (BS) Antenna Height:</b>	$30 \text{ m} \leq h_b \leq 200 \text{ m}$
<b>Mobile Station (MS) Antenna Height:</b>	$1 \text{ m} \leq h_m \leq 10 \text{ m}$
<b>Transmission Distance:</b>	$1 \text{ km} \leq d \leq 20 \text{ km}$

The path loss in decibels,  $L_p$  (dB) is specified in terms of parameters as follows:

**HATA'S MODEL [10]**

$$L_p \text{ (dB)} = \begin{cases} A + B \log_{10}(d) & \text{for urban area} \\ A + B \log_{10}(d) - C & \text{for suburban area} \\ A + B \log_{10}(d) - D & \text{for open area} \end{cases} \quad (24)$$

where

$$A = 69.55 + 26.16 \log_{10}(f_c) - 13.82 \log_{10}(h_b) - a(h_m)$$

$$B = 44.9 - 6.55 \log_{10}(h_b)$$

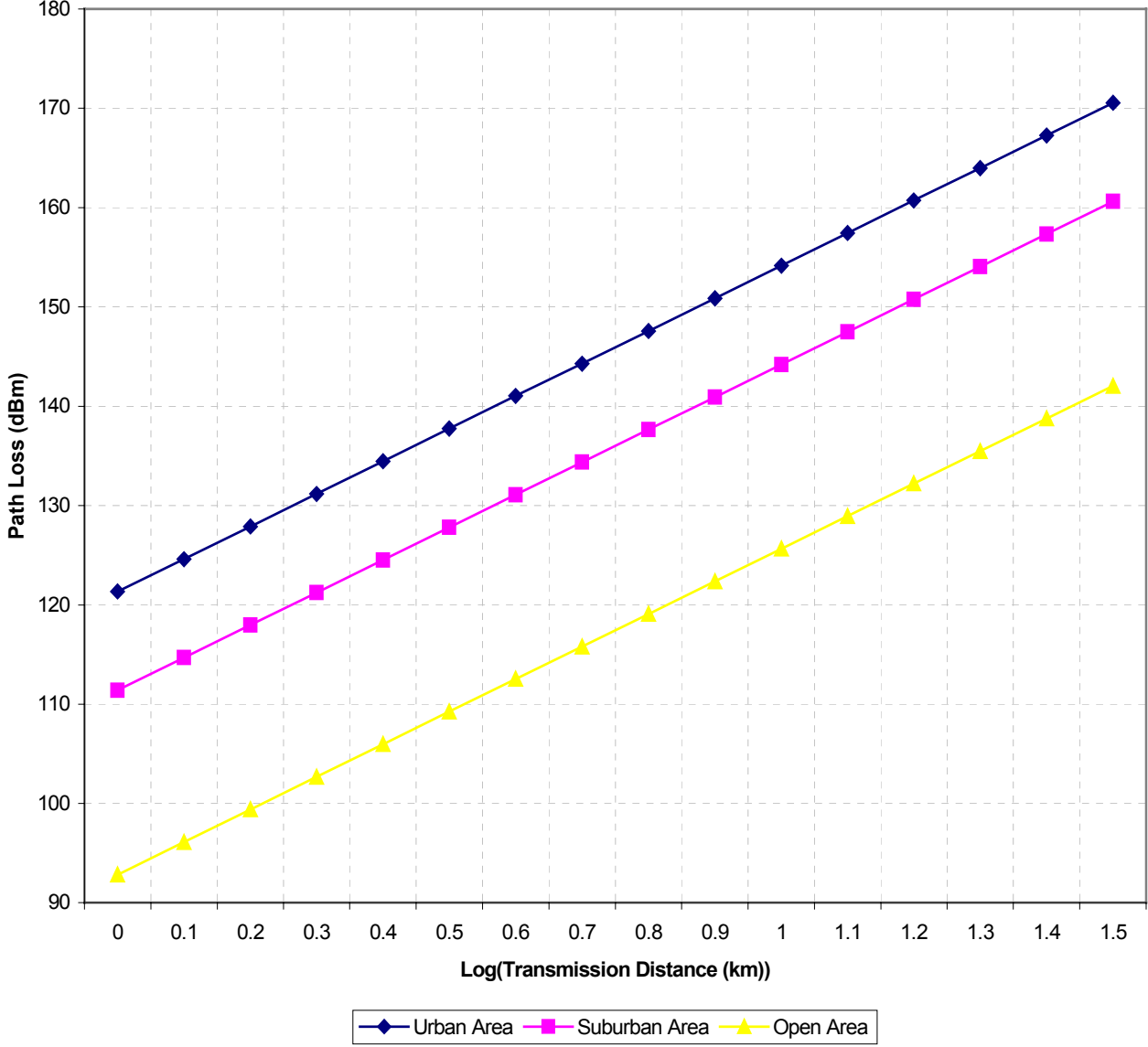
$$C = 5.4 + 2[\log_{10}(f_c / 28)]^2$$

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

and

$$a(h_m) = \begin{cases} [1.1 \log_{10}(f_c) - 0.7]h_m - [1.56 \log_{10}(f_c) - 0.8] & \text{for medium or small city} \\ 8.29[\log_{10}(1.54h_m)]^2 - 1.1 & \text{for large city and } f_c \leq 200 \text{ MHz} \\ 3.2[\log_{10}(11.75h_m)]^2 - 4.97 & \text{for large city and } f_c \geq 400 \text{ MHz} \end{cases}$$

The path loss predicted by Hata's model for the example values ( $h_b=70$  m,  $h_m=1.5$  m,  $f_c=900$  MHz) is depicted in figure 5 below:



**Fig. 5: Example Path Loss as Predicted by Hata's Model**

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### **Lecture #3 – Wednesday, January 24, 2001**

Summary by Michael Weiss

### **Path Loss in Macrocells (continued) – Lee's Model**

Named after W.C.Y. Lee, this empirically derived path loss model is parametrized by  $P_{r_0}$ , the power at the 1-mile point of interception, and  $\gamma$ , an experimentally determined path loss slope. It is indicated for use with *flat terrain* and is specified as follows [3]:

#### **LEE'S MODEL [3]**

$$P_r = 10 \log_{10} \left[ P_{r_0} \left( \frac{r}{r_0} \right)^{-\gamma} \left( \frac{f}{f_0} \right)^{-n} \alpha_0 \right] \text{ dBm} \quad (1)$$

where

$P_r$  = field strength of the received signal at a distance  $r$  from the transmitter

$P_{r_0}$  = received power at 1 mile (1.6 km)

$r$  = distance between MS and BS antennas

$r_0$  = 1 mile (1.6 km)

$\gamma$  = path loss slope (experimentally determined)

$f$  = actual carrier frequency

$f_0$  = nominal carrier frequency, (= 900 MHz)

$n$  = empirically derived exponent. depends on geographical locations and operating frequency ranges.  $2 \leq n \leq 3$ .  
 $n=2$  is recommended for a suburban or open area with  $f < 450$  MHz. Use  $n=3$  for an urban area with  $f > 450$  MHz.

$\alpha_0$  = correction factor—accounts for antenna heights, transmit power, and antenna gains which differ from nominal values

According to Lee, for path-loss prediction it is preferable that "the received signal be predicted in an absolute power level (dBm) and be compared easily and directly with the experimental data. [3]" For this reason, we assume the set of conditions below. The model may be adapted for use with different values by means of the correction factor,  $\alpha_0$ .

**Nominal Values:**

Carrier Frequency:	900 MHz
Base Station (BS) Antenna Height:	30.48 m (100 ft)
BS Transmit Power:	10 Watts
BS Antenna Gain:	6 dB above dipole gain
Mobile Station (MS) Antenna Height:	3 m
MS Antenna Gain:	0 dB above dipole gain

**Correction Factor ( $\alpha_0$ ):**

Note that the actual frequency of the transmitted signal does not explicitly appear in the formulae specifying  $\alpha_0$ . The formula is a general one which is valid for all frequencies greater than 30 MHz.

$$\alpha_0 = \alpha_1 \alpha_2 \alpha_3 \alpha_4 \alpha_5$$

$$\alpha_1 = \left( \frac{\text{new BS antenna height (m)}}{30.48 \text{ m}} \right)^2$$

$$\alpha_2 = \left( \frac{\text{new MS antenna height (m)}}{3 \text{ m}} \right)^v \quad (2)$$

$$\alpha_3 = \frac{\text{new transmitter power (W)}}{10 \text{ W}}$$

$$\alpha_4 = \frac{\text{new BS antenna gain with respect to } \lambda/2 \text{ dipole}}{4}$$

$$\alpha_5 = \text{different antenna - gain correction factor at the mobile unit}$$

The exponent  $v$ , which appears in the expression above for  $\alpha_2$  is also derived from empirical data and is specified as:

$$v = \begin{cases} 2 & \text{for new mobile - unit antenna height } > 10 \text{ m (30 ft)} \\ 1 & \text{for new mobile - unit antenna height } < 3 \text{ m (10 ft)} \end{cases} \quad (3)$$

The following table lists some example values for the empirically derived quantities  $P_r$  and  $\gamma$ :

Propagation Environment	$P_{r_0}$ (dBm)	$\gamma$
Free Space	-45	2
Open Area	-49	4.35
US Suburban Area	-61.7	3.84
Philadelphia, PA (urban)	-70	3.68
Newark, NJ (urban)	-64	4.31
Tokyo, Japan (urban)	-84	3.05

**Table 1: Sample Values for Empirical Constants in Lee's Model**

We may express the path loss  $L_p$  as:

$$L_p \text{ (dBm)} = P_t \text{ (dBm)} - P_r \text{ (dBm)} \quad (4)$$

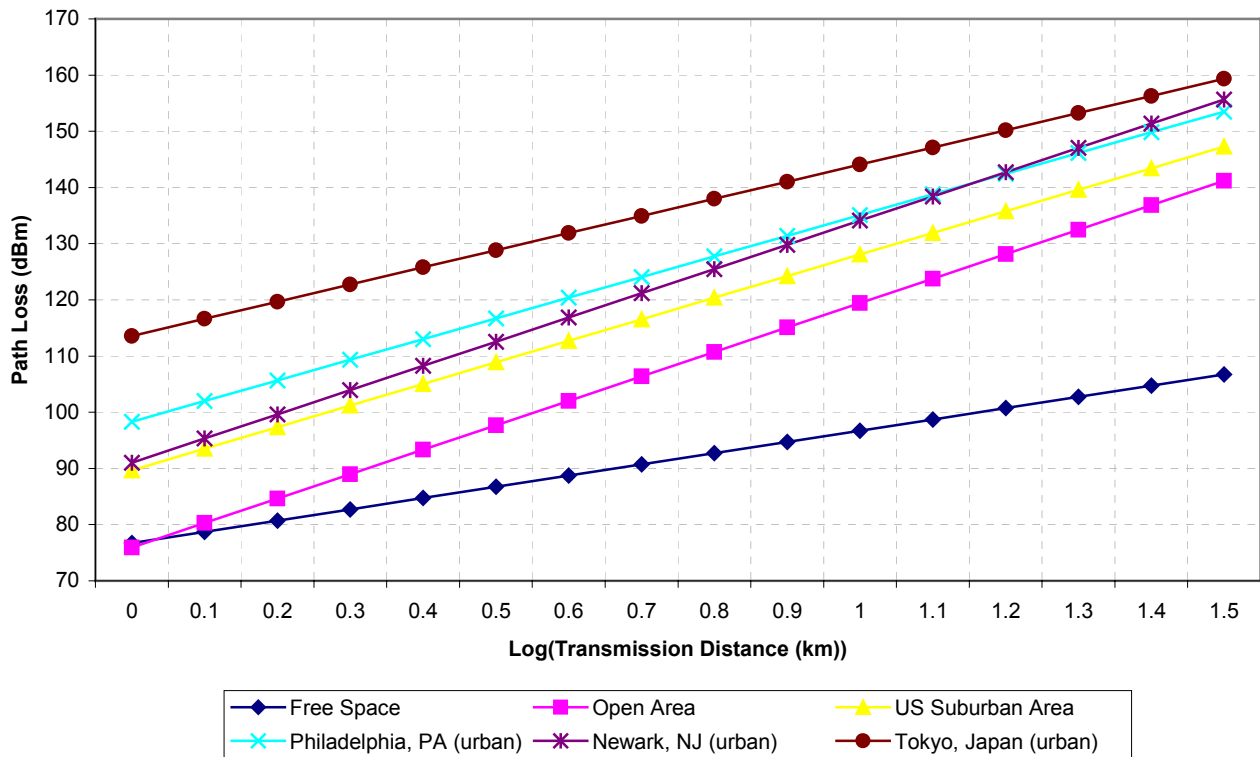
where  $P_t$  is the transmitted power.

Using the data in table 1, we may write path loss expressions for the various environments as follows:

$$L_p \text{ (dBm)} = \begin{cases} 85 + 20 \log_{10} \left( \frac{r}{1.6 \text{ km}} \right) + 10n \log_{10} \left( \frac{f}{900 \text{ MHz}} \right) - \alpha_0 & \text{Free Space} \\ 89 + 43.5 \log_{10} \left( \frac{r}{1.6 \text{ km}} \right) + 10n \log_{10} \left( \frac{f}{900 \text{ MHz}} \right) - \alpha_0 & \text{Open Area} \\ 101.7 + 38.4 \log_{10} \left( \frac{r}{1.6 \text{ km}} \right) + 10n \log_{10} \left( \frac{f}{900 \text{ MHz}} \right) - \alpha_0 & \text{US Suburban Area} \\ 110 + 36.8 \log_{10} \left( \frac{r}{1.6 \text{ km}} \right) + 10n \log_{10} \left( \frac{f}{900 \text{ MHz}} \right) - \alpha_0 & \text{Philadelphia, PA (urban)} \\ 104 + 43.1 \log_{10} \left( \frac{r}{1.6 \text{ km}} \right) + 10n \log_{10} \left( \frac{f}{900 \text{ MHz}} \right) - \alpha_0 & \text{Newark, NJ (urban)} \\ 124 + 30.5 \log_{10} \left( \frac{r}{1.6 \text{ km}} \right) + 10n \log_{10} \left( \frac{f}{900 \text{ MHz}} \right) - \alpha_0 & \text{Tokyo, Japan (urban)} \end{cases} \quad (5)$$

For comparison with Hata's model, the path loss predicted by Lee's model for the example values below is depicted in figure 1, which follows:

Base Station Antenna Height: 70 m  
 Mobile Station Antenna Height: 1.5 m  
 Carrier Frequency: 900 MHz



**Fig. 1: Example Path Loss as Predicted by Lee's Model**

### Path Loss in Outdoor Microcells—The COST231 Study

We now turn our attention to propagation within microcells. Microcells have grown in importance with the rise of PCS, which introduced smaller, more frequently placed base stations than the cellular system it succeeded.

The COST231 study yielded two models for path loss in urban microcellular environments. They are the COST231-Hata model, which extends Hata's model for use with higher frequencies, and the COST231-Walfish-Ikegami model.

### COST231-Hata Model

Most future PCS systems are expected to operate in the 1800-2000 MHz frequency band. It has been shown that path loss can be more dramatic at these frequencies than those in the 900 MHz range. In fact, some studies have suggested that the path loss experienced at 1845 MHz is approximately 10 dB larger than those experienced at 955 MHz, all other parameters being kept constant [5].

The COST231-Hata model extends Hata's model for use in the 1500-2000 MHz frequency range, where it is known to underestimate path loss. The model is expressed in terms of the following parameters:

Carrier Frequency	$f_c$	1500-2000 MHz
BS Antenna Height	$h_b$	30-200 m
MS Antenna Height	$h_m$	1-10 m
Transmission Distance	$d$	1-20 km

The path loss according to the COST231-Hata model is expressed as:

$$L_p \text{ (dB)} = A + B \log_{10}(d) + C \quad (6)$$

where

$$A = 46.3 + 33.9 \log_{10}(f_c) - 13.28 \log_{10}(h_b) - a(h_m)$$

$$B = 44.9 - 6.55 \log_{10}(h_b)$$

$$C = \begin{cases} 0 & \text{for medium city and suburban areas with moderate tree density} \\ 3 & \text{for metropolitan areas} \end{cases}$$

While both the Hata and COST231-Hata models are designed for use with base station antenna heights greater than 30 meters, they may be used with shorter antennas provided that surrounding buildings are well below this height. Neither model should be used to predict path loss in an urban canyon. Lastly, the model should not be used for prediction with transmission distances below 1 km, as path losses become highly dependent on local topography below this range.

### **COST231-Walfish-Ikegami Model**

In the COST231-Walfish-Ikegami model, base station antennas may be above or below the rooftops, but the model predicts poorly when BS antenna heights are close to roof heights.

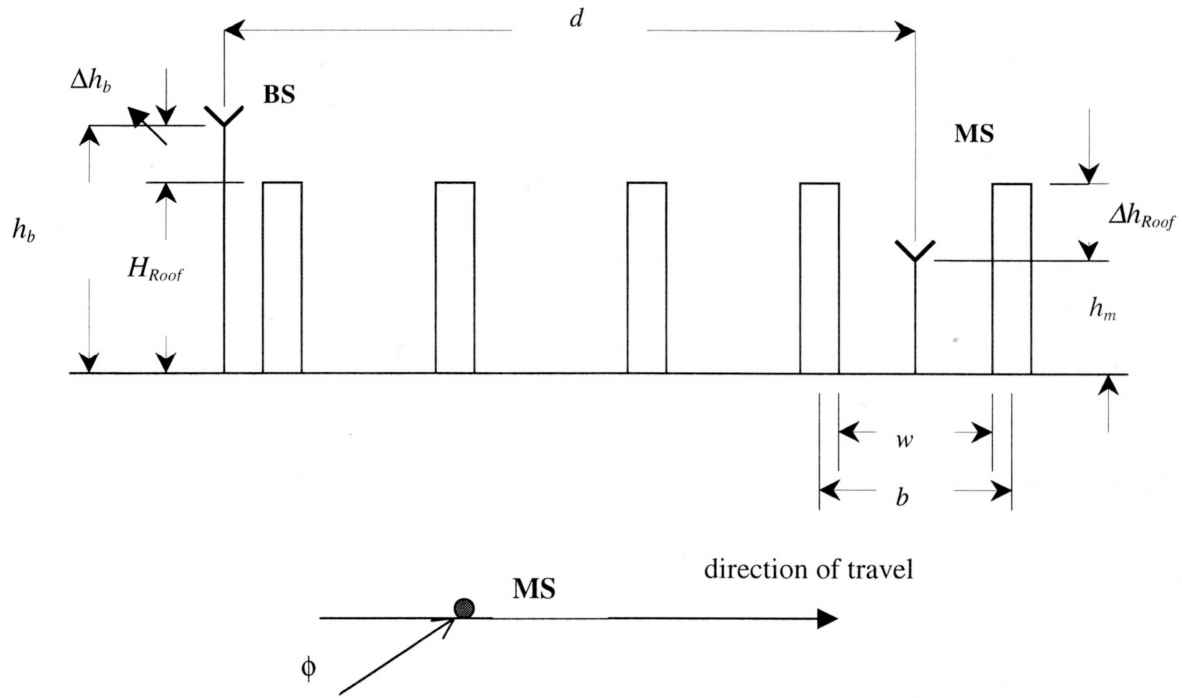
### **Line-of-Sight (LOS) Propagation in a Street Canyon:**

The path loss for line-of-sight (LOS) propagation in a street canyon is specified in terms of the transmission distance,  $d$  (km), and the carrier frequency,  $f_c$  (MHz), as:

$$L_p \text{ (dB)} = 42.6 + 26 \log_{10}(d) + 20 \log_{10}(f_c) \quad d \geq 20 \text{ m} \quad (7)$$

where the first constant is chosen so that at a distance of 20 meters,  $L_p$  is equal to the free space path loss.

## Non-Line-of-Sight (NLOS) Propagation:



**Fig. 2: Parameters used in COST231-Walfish-Ikegami Model**

As depicted in figure 2 above, NLOS path loss is specified in terms of the following parameters:

height of buildings	$h_{\text{roof}}$
building separation	$b$
street width	$w$
road orientation with respect to direct radio path	$\phi$

Path loss in the NLOS case is specified in terms of 3 components, as follows:

$$L_p = \begin{cases} L_0 + L_{rts} + L_{msd} & \text{for } L_{rts} + L_{msd} \geq 0 \\ L_0 & \text{for } L_{rts} + L_{msd} < 0 \end{cases} \quad (8)$$

where  $L_0 \equiv$  free space propagation loss  
 $L_{rts} \equiv$  roof-to-street diffraction and scatter loss  
 $L_{msd} \equiv$  multi-screen diffraction loss

These components are determined as follows:

$$L_0 = 32.4 + 20 \log_{10}(d) + 20 \log_{10}(f_c) \quad (9)$$

$$L_{rts} = -16.9 - 10 \log_{10}(w) + 10 \log_{10}(f_c) + 20 \log_{10} \Delta h_m + L_{ori} \quad (10)$$

where

$$L_{ori} = \begin{cases} -10 + 0.354(\phi) & 0^\circ \leq \phi \leq 35^\circ \\ 2.5 + 0.075(\phi - 35) & 35^\circ \leq \phi \leq 55^\circ \\ 4.0 - 0.114(\phi - 55) & 55^\circ \leq \phi \leq 90^\circ \end{cases} \quad (11)$$

and

$$\Delta h_m = h_{roof} - h_m \quad (12)$$

The multi-screen diffraction loss is:

$$L_{msd} = L_{bsh} + k_a + k_d \log_{10}(d) + k_f \log_{10}(f_c) - 9 \log_{10}(b) \quad (13)$$

where

$$L_{bsh} = \begin{cases} -18 \log_{10}(1 + \Delta h_b) & h_b \geq h_{roof} \\ 0 & h_b < h_{roof} \end{cases}$$

$$k_a = \begin{cases} 54 & h_b > h_{roof} \\ 54 - 0.8h_b & d \geq 0.5 \text{ km and } h_b \leq h_{roof} \\ 54 - \frac{0.8\Delta h_b d}{0.5} & d < 0.5 \text{ km and } h_b \leq h_{roof} \end{cases} \quad (14)$$

$$k_d = \begin{cases} 18 & h_b > h_{roof} \\ 18 - \frac{15\Delta h_b}{h_{roof}} & h_b \leq h_{roof} \end{cases}$$

$$k_f = -4 + \begin{cases} 0.7(f_c / 925 - 1) & \text{medium city and suburban} \\ 1.5(f_c / 925 - 1) & \text{metropolitan area} \end{cases} \quad (15)$$

$$\Delta h_b = h_b - h_{roof} \quad (16)$$

$k_a$  represents the increase in path loss for BS antennas below the rooftops of adjacent buildings.  $k_d$  and  $k_f$  control the dependency of the multi-screen diffraction loss on the distance and frequency, respectively.

The model is valid for the following parameter ranges:

$f_c$	800-2000 MHz
$h_b$	4-50 m
$h_m$	1-3 m
$d$	20 m – 5 km

In the absence of actual measurements, the following default values are recommended:

$$\begin{aligned} b & 20\text{-}50 \text{ m} \\ w & b/2 \\ \phi & 90^\circ \\ h_{\text{roof}} & (3 \times \# \text{ floors in bldg}) + \begin{cases} 3 \text{ m} & \text{pitched roof} \\ 0 \text{ m} & \text{flat roof} \end{cases} \end{aligned}$$

The model works best when  $h_b \gg h_{\text{roof}}$ . As mentioned at the outset, when  $h_b \approx h_{\text{roof}}$ , large errors can be expected. Lastly, the model performs poorly for  $h_b \ll h_{\text{roof}}$  because the terms in equation # do not account for wave guiding in street canyons and diffraction at street corners.

### **Path Loss in Street Microcells—The Two-Slope Model**

We now turn our attention to street microcells, where transmission distances range up to 500 meters and antenna heights are less than 20 meters. Within these ranges, some empirical measurements have shown that LOS propagation along city streets can be accurately described by the two-slope model [6], [7].

According to this model, the received signal strength may be written as:

$$\mu_\Omega = 10 \log_{10} \left( \frac{A}{d^a \left(1 + \frac{d}{g}\right)^b} \right) \text{ dBm} \quad (17)$$

where

- A a constant
- d the distance in meters
- a,b parameters which reflect the propagation environment. For example, at distances close to the base station, free space propagation predominates, and  $a=2$ . At large distances, where we expect an inverse fourth to eighth power law,  $b$  ranges from 2 to 6.
- g breakpoint parameter (150-300 m)  
This represents the distance along the line of sight between antennas at which the Fresnel zone first touches the ground (assuming a flat surface.) This distance is given by:

$$g = \frac{1}{\lambda_c} \sqrt{(\Sigma^2 - \Delta^2)^2 - 2(\Sigma^2 + \Delta^2) \left(\frac{\lambda_c}{2}\right)^2 + \left(\frac{\lambda_c}{2}\right)^4} \quad (18)$$

$$\begin{aligned} \text{where } \Sigma &= h_b + h_m \\ \Delta &= h_b - h_m \end{aligned}$$

Note that  $g$  is frequency dependent.

It may be approximated for high frequencies as  $g = \frac{4h_b h_m}{\lambda}$ .

The parameter values determined by Harley [6] are as follows:

$h_b$ (meters)	$a$	$b$	$g$ (meters)
5	2.3	-0.28	148.6
9	1.48	0.54	151.8
15	0.4	2.10	143.9
19	-0.96	4.72	158.3

**Table 2: Parameter Values for the Two-Slope Model**

### NLOS Propagation—Propagation Around Street Corners

As a mobile station rounds a street corner, the LOS transmission of the previous section gives way to NLOS propagation. The average drop in the received signal from such an event is 25-30 dB over distances as small as 10 meters for low antenna heights in areas with multi-story buildings. For regions with only one or two story buildings, the same drop occurs over a range of 40 to 50 meters.

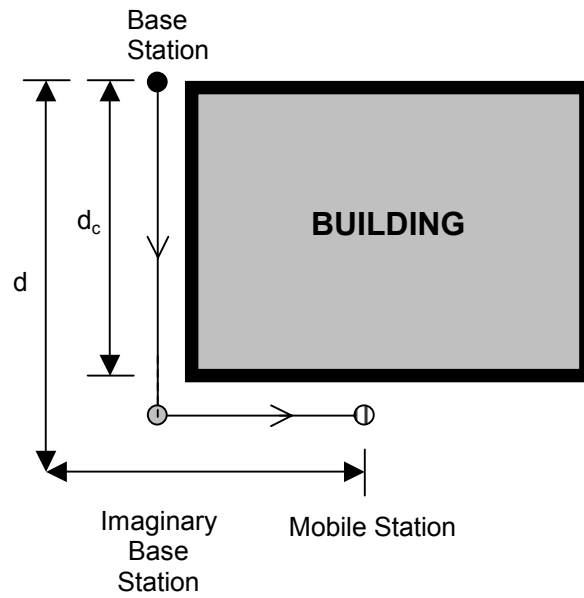
The following model, empirically derived by Grimlund and Gudmundson, is designed to predict received signal power in a rounding-the-street-corner scenario.

The model assumes that the mobile station communicates via LOS with the base station until it reaches the street corner. After rounding the street corner, the NLOS propagation is modeled by assuming LOS propagation between the mobile station and an imaginary base station located at the street corner, whose transmit power is equal to the received power at the street corner from the actual BS.

The received signal strength is given as:

$$\mu_{\Omega} \text{ dbm} = \begin{cases} 10 \log_{10} \left( \frac{A}{d^a \left(1 + \frac{d}{g}\right)^b} \right) & d \leq d_c \\ 10 \log_{10} \left( \frac{A}{d_c^a \left(1 + \frac{d_c}{g}\right)^b} \cdot \frac{1}{(d - d_c)^a \left(1 + \frac{d - d_c}{g}\right)^b} \right) & d > d_c \end{cases} \quad (19)$$

where  $d_c$  (m) is the distance between the actual BS and the corner and  $d$  is the total length of the MS to BS path, wrapping around the corner.



**Fig. #: NLOS Propagation Around a Corner in a Street Microcell**

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