Topic 2: Propagation Characteristics of Wireless Channels

Content:

1) Introduction to Radio Wave Propagation
   - Basic propagation mechanisms
   - Effects of propagation mechanisms

2) Characterization (modeling) of Wireless Channels
   - Distance dimension: Path loss, shadowing loss, and multipath fading
   - Time dimension: Delay spread (time dispersion)
   - Frequency dimension: Doppler spread (frequency dispersion)

3) Simulation of multipath (Rayleigh) fading channel

Topic 2 Learning Outcomes

At the end of this Topic, you will be able to:

- Define the propagation mechanisms that characterize wireless channels
- Determine the effects of the propagation mechanisms
- Develop mathematical and simulation models for characterizing the wireless channels

Introduction to Radio Wave Propagation

Basic Propagation Mechanisms:

1) Reflection

- occurs when an ElectroMagnetic (EM) wave hits an object whose dimension is much larger than the wavelength of the propagating wave

Example: reflections occur from the surface of the earth and from buildings & walls (page 4)

2) Diffraction

- occurs when an EM wave is obstructed by a surface that has sharp irregularities (edges), giving rise to the bending of the wave

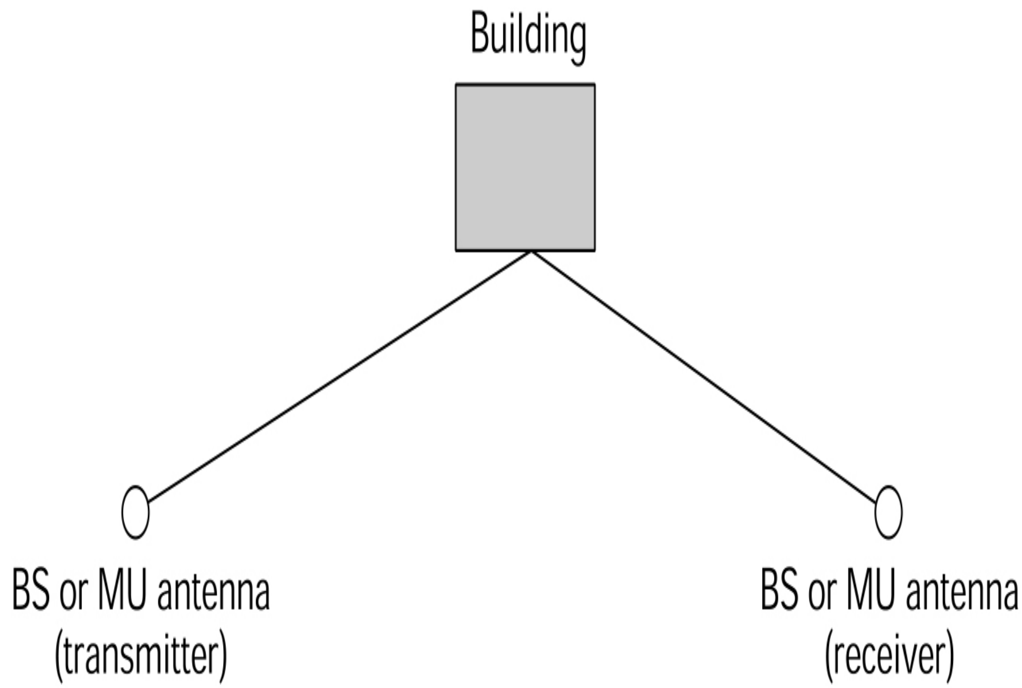
Example: diffraction occurs at the edges of buildings (page 5)

3) Scattering

- occurs when an EM wave hits a number of objects whose dimensions are smaller than or comparable to the wavelength of the propagating wave

Example: scattering is produced by foliage, street signs & lamp posts (page 6)

Reflection of an EM Wave

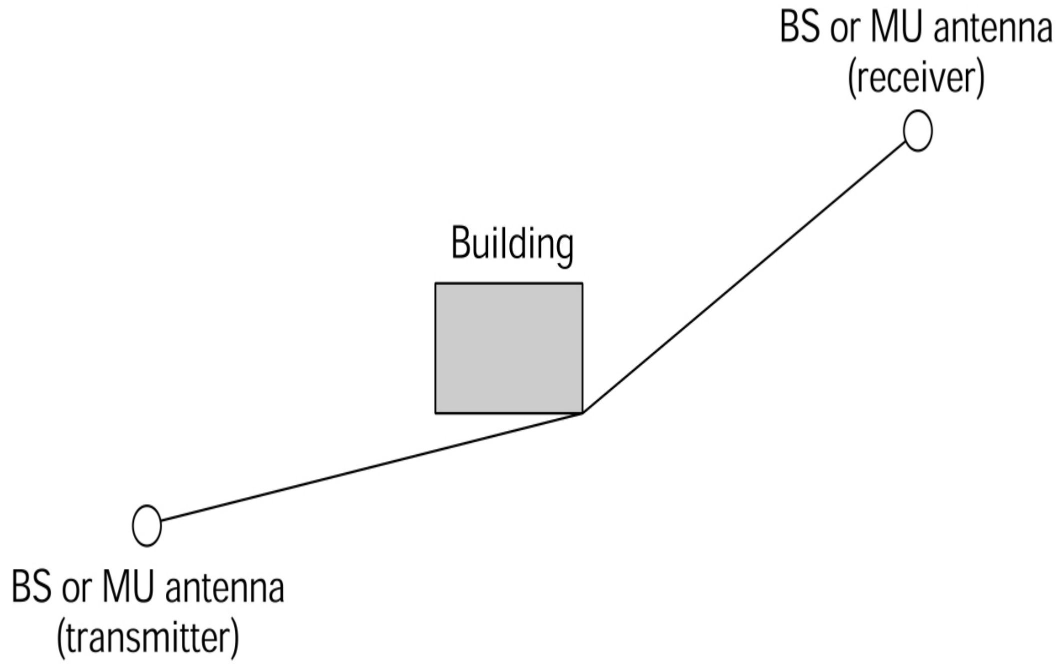


BS: Base Station

MU: Mobile Unit

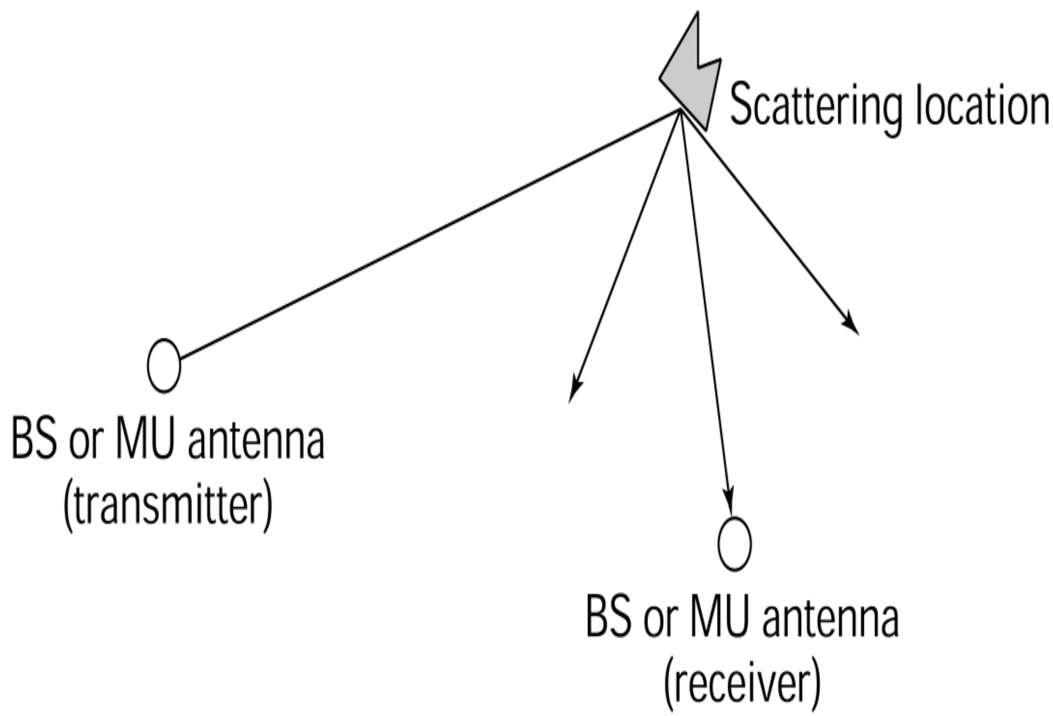
Effect of Reflection: Loss of EM energy - energy is lost during the reflection process

Diffraction of an EM Wave



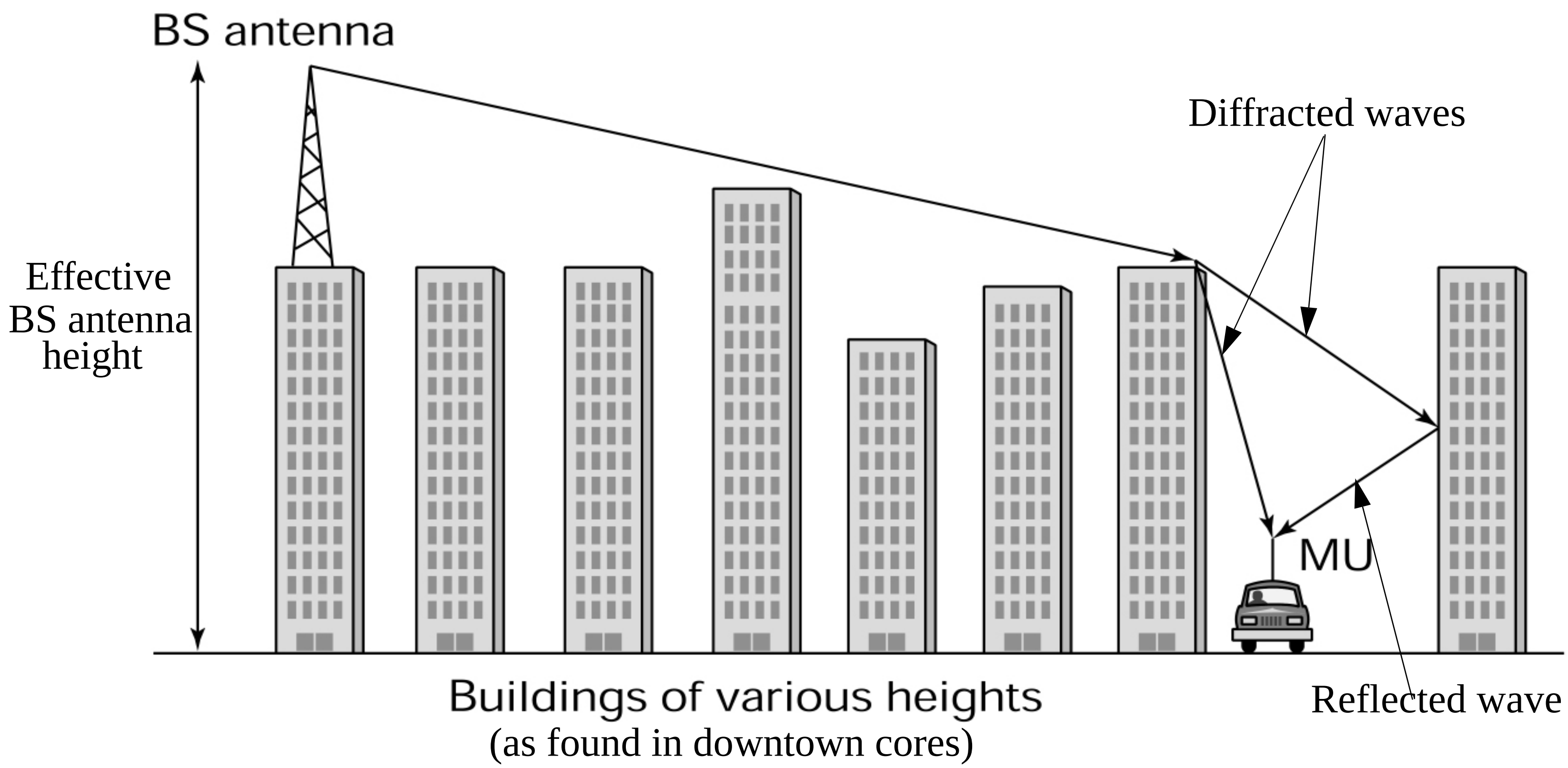
Effect of Diffraction: Loss of EM energy - energy is lost during the bending process

Scattering of an EM Wave



Effect of Scattering: Loss of EM energy - energy is lost because the original signal is split into multiple low-energy signals

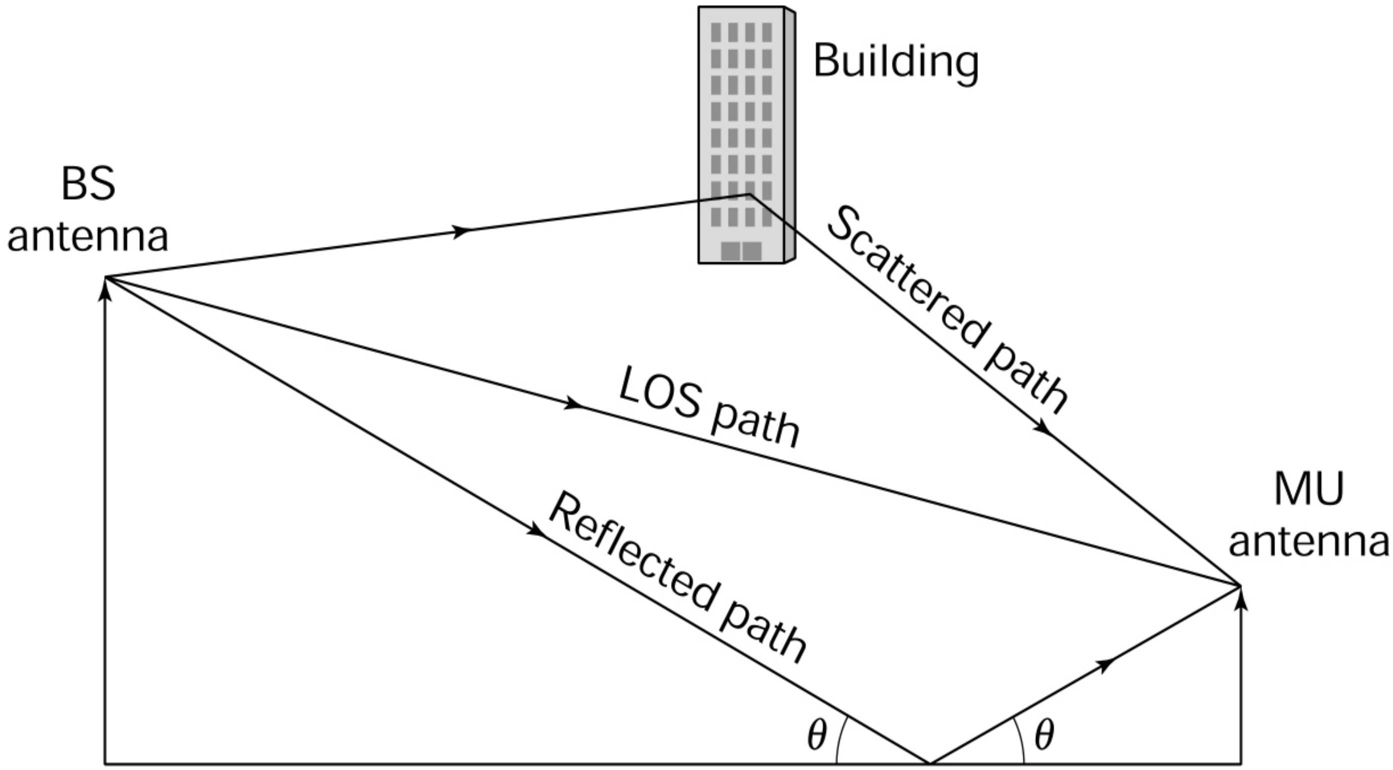
Illustration of Reflected and Diffracted Waves



BS = Base Station; MU = Mobile Unit

<u>*Message:*</u> The type and number of waves arriving at the MU antenna depends on the type of radio environment and the location of the MU relative to the BS antenna

Illustration of LOS, Reflected and Scattered Waves



LOS = Line-of-Sight;   BS = Base Station;   MU = Mobile Unit

Message: The type and number of waves arriving at the MU antenna depends on the type of radio environment and the location of the MU relative to the BS antenna

Note: The diffracted, scattered and reflected paths are referred to as non-line-of-sight (NLOS) paths

Effects of Propagation Mechanisms

Effects of reflection, diffraction and scattering:

1) Path loss or attenuation:

   - mean received power decreases steadily as the distance between Tx and Rx increases

2) Large-scale fading:

   - received power fluctuates about a mean value due to the clutter around the Rx
   - fluctuations have a long period, i.e., slow variation
   - phenomenon is referred to as “long-term” or “large-scale” fading or lognormal shadowing

3) Small-scale fading:

   - the instantaneous received power fluctuates very rapidly due to the vector sum of a random number of signals arriving from different directions
   - fluctuations have a very short period, i.e., fast variation
   - phenomenon is referred to as “short-term” or “small-scale” or Rayleigh fading

Characterization of Wireless Channels

Three Categories of Channel Models:

1) Distance: How does the channel vary with increasing distance between the transmitter and the receiver?

   Distance domain Models: Path loss, shadowing loss, and multipath fading

   (referred to as *Propagation Loss Models*)

2) Time: How does the channel vary with *frequency* due to multipath*?*

   Time domain Model Parameter: Multipath delay spread (time dispersion)

3) Frequency: How does the channel vary with *time* due to relative motion betwen the transmitter and the receiver?

   Frequency domain Model Parameter: Doppler spread (frequency dispersion)

Distance Dimension Characterization of Wireless Channels: Propagation Loss Models

What is a Propagation Loss Model?

- a mathematical formula that characterizes the effects of the propagation mechanisms
- predicts the received signal power at the receiver or the amount of attenuation (loss) between the transmitter and receiver
- models are either theoretical (using EM theory) or empirical (curve-fitting to measured data)

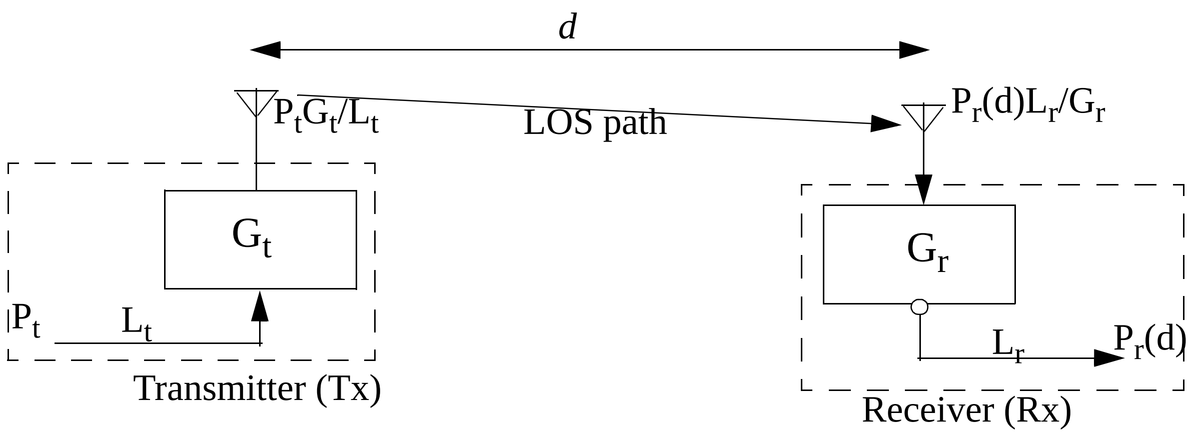
Types of Propagation Loss Models in a Terrestrial wireless system:

1. Path Loss Models: Free space (1-ray), Plane earth (2-ray), log-distance (n-ray), Okumura, Hata
2. Shadowing Loss Model: Lognormal
3. Multipath Fading Models: Rayleigh, Rician

Free-Space Attenuation Model

<u>Main Assumptions:</u> 1. The Rx is in direct line-of-sight (LOS) of the Tx (e.g., sub-urban & open areas)

2. Propagation is via only ONE ray (path)



P_t: Power Amplifier output power

G_t: Tx antenna Gain

P_tG_t/L_t: Effective Isotropic Radiated Power (EIRP)

P_r: received power @ antenna output port

G_r: receiver antenna gain

L_t (L_r): Tx (Rx) cable loss

Friis free-space equation: theoretical formula for calculating the received power at a Rx in LOS with and at radial distance d ($d > 0$) from the Tx

$$P_r(d) = \frac{P_tG_tG_r\lambda^2}{(4\pi)^2d^2L_tL_r}$$

$P_r(d)$ is inversely proportional to d^2

where L_t (L_r) = cable losses at the Tx (Rx), and λ = operating wavelength

Free-Space Attenuation Model

Let PL_{free} denote the free space loss, measured from the Tx Antenna output to Rx Antenna input

Definition:

$$PL_{free} \triangleq \frac{effective\ isotropic\ radiated\ power}{power\ at\ receive\ antenna\ input}$$

From the Friis free space equation on Page 12:

$$PL_{free} = \frac{(P_t G_t)/L_t}{(P_r(d) L_r)/G_r} = \left(\frac{4\pi}{\lambda}\right)^2 d^2 = \left(\frac{4\pi f}{c}\right)^2 d^2$$

Note: $\lambda = \frac{c}{f}$, where c = velocity of light and f = carrier frequency

Conclusions:

1. Free-space attenuation increases with frequency squared
2. Free-space attenuation increases with distance squared

Free-Space Attenuation Model (in dB units)

Let:

$PL_{free,dB}$ = free space path loss, expressed in dB units

$$PL_{free,\,dB} = 10log\left(\frac{P_tG_tG_r}{P_rL_tL_r}\right) = 10log\left(\frac{(4\pi)^2f^2d^2}{c^2}\right) = 20log\left(\frac{4\pi fd}{c}\right) \text{ (in dB)}$$

Notes:

1. *log(.)* = logarithm notation with respect to base 10
2. When the frequency f is in MegaHertz (i.e. f_{MHz} x 10^6 Hz) and radial distance d is in kilometers (i.e., d_{km} x 10^3 meters), the above expression simplifies to:

$$PL_{free,\,dB} = 20log\left(\frac{4\pi(10^6 \times 10^3)}{c}\right) + 20log(f_{MHz}) + 20log(d_{km}) \text{ (in dB)}$$

Set $c = 3 \times 10^8$ meters/sec and the above equation becomes:

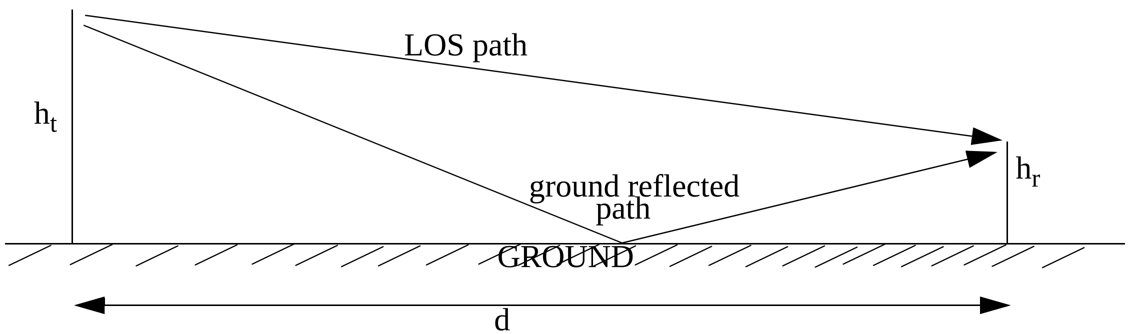
$$PL_{free,\,dB} = 32.44 + 20log(f_{MHz}) + 20log(d_{km}) \text{ (in dB)}$$

Note: If the carrier freq is known, the second term becomes a constant and $PL_{free,dB} = f(distance)$

Two-ray Path (Plane-Earth) Loss Model

Assumption: Transmitted signal arrives at the receiver via 2 paths

- LOS path
- ground reflected path



h_t: Tx antenna height, h_r: Rx antenna height, $d >> h_t$, $d >> h_r$

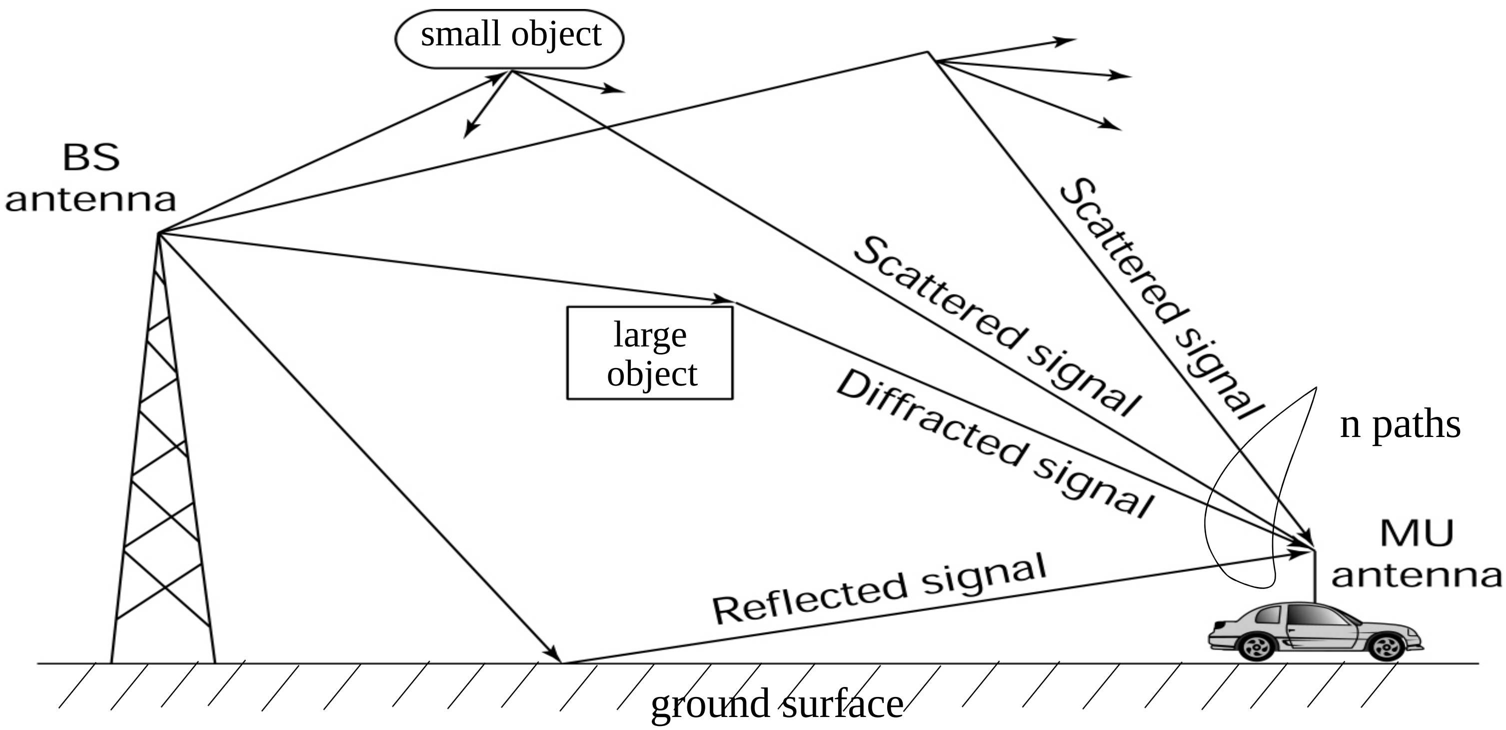
$$PL_{2-ray} = a\frac{d^4}{h_t^2 h_r^2}$$

where the constant "*a*" is a correction factor that depends on the carrier frequency *f*.

Conclusion: Two-ray path loss increases with distance raised to power 4. Clearly, $PL_{2\text{-}ray} > PL_{free}$.

n-ray or Generalized Path Loss Model

- In a typical mobile radio environment, signal reception is via multiple paths comprising reflected, diffracted and scattered paths
- n-ray model applies to the scenario when Tx and Rx are non-line-of-sight (NLOS)



Log-distance Path Loss Model

- For the NLOS environment with n rays, the path loss exponent $\gamma > 2$ and the average path loss at distance d from the Transmitter is:

$$\overline{PL}(d) = \frac{P_t}{P_r(d)} = \frac{P_t}{P_r(d_{ref})(d_{ref}/d)^{\gamma}} = \overline{PL}(d_{ref})\left(\frac{d}{d_{ref}}\right)^{\gamma} \quad \text{(dimensionless quantity)}$$

where $P_r(d_{ref}) = \dfrac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_{ref}^2 L_t L_r}$ (from Friis free space formula)

and

$\overline{PL}(d_{ref})$ = Path loss at reference distance, d_{ref}

Mathematically, $\overline{PL}(d_{ref}) = \dfrac{P_t}{P_r(d_{ref})}$

Taking the logarithm of $\overline{PL}(d)$ with respect to base 10 gives the Log-distance Path Loss Model

Log-distance Path Loss Model

Average Path loss $\overline{PL}(d)_{dB}$ (expressed in *dB* unit) is referred to as the *log-distance* path loss model:

$$\overline{PL}(d)_{dB} = 10log\left(\overline{PL}(d_{ref})\left(\frac{d}{d_{ref}}\right)^{\gamma}\right) = \overline{PL}(d_{ref})_{dB} + 10\gamma log\left(\frac{d}{d_{ref}}\right) \quad \text{(in dB)}$$

where

$\overline{PL}(d_{ref})_{dB}$ is the reference path loss (in *dB*) at the reference distance d_{ref}, and

$\gamma \geq 2$ when $d > d_{ref}$

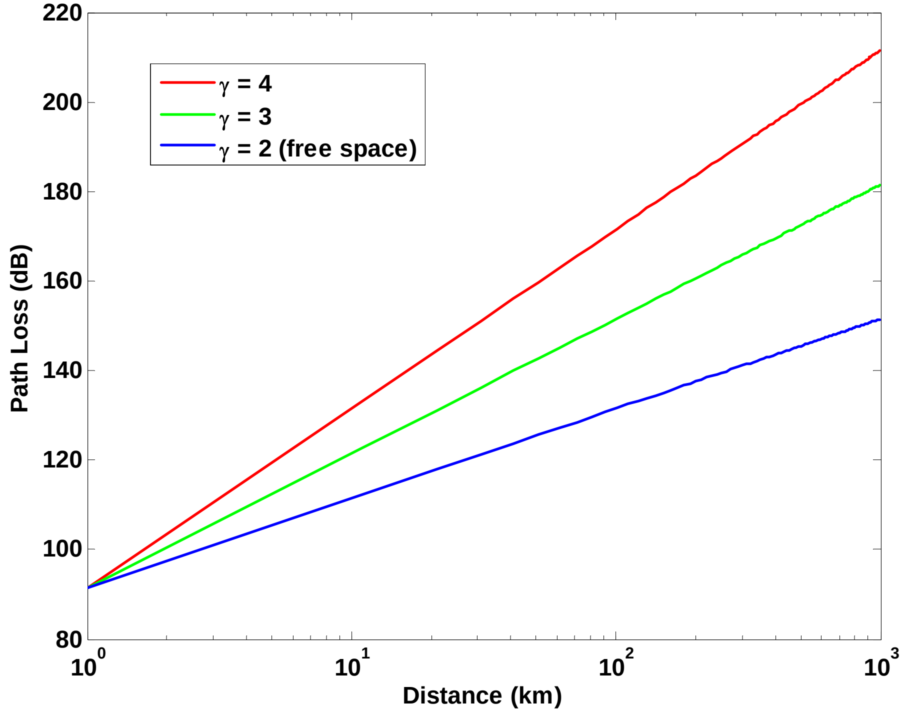
Example Path Loss Exponent Values for Different Propagation Environments:

Propagation Environment	**Path loss exponent, γ**
Free space	2
Urban area - cellular radio	2.7 to 3.5
Shadowed urban area - cellular radio	3 to 5
In-buiding - LOS	1.6 to 1.8
In-buiding - Obstructed	4 to 6
Factories - Obstructed	2 to 3

Path Loss Profile

Path loss profile: Average path loss versus distance, with γ (path loss exponent) being the parameter

<u>*Given:*</u> d_{ref} = 1 km and f = 900 MHz



Class Example

Problem Statement:

The power amplifier (PA) output power of a base station (BS) transmitter is 1 Watt. The transmitter antenna gain is unity while the receiver gain is 2. Cable loss factor, $L_t = L_r$, is unity and the reference distance d_{ref} is 100 meters

a) Find the received power in dBm at a distance of 5 km from the BS transmitter operating at 900 MHz in free space.

b) What is the free space path loss (in dB unit) at a distance of 5 km?

c) If the propagation environment is characterized by a path loss exponent $\gamma = 4$, what is the path loss in dB at a distance of 5 km. What is the excess loss in dB compared to free space?

Empirical Path Loss Models

- Impacting factors:

  i) terrain profile - e.g., simple curved earth profile, mountainous profile, flat profile

  ii) Topography - presence of trees, buildings and other obstacles

- Model categories:

  - dense urban, e.g., downtown core
  - urban, e.g., residential areas
  - sub-urban, e.g., city outskirts
  - rural areas, e.g., villages

- Examples:

  - Okumura model
  - Hata model

Okumura Model

- Graphical plot of median attenuation relative to free space, $A_{ma}(f, d)$ in dB versus frequency f (Data collected for $150 \le f \le 1920$ MHz, $1 \le d \le 100$ km; $h_{bs} = 200$ m; $h_{ms} = 3$ m, urban area)

- Median (i.e., 50th percentile) path loss in dB unit, $PL_m(d)_{dB}$ is predicted by the formula:

$$PL_m(d)_{dB} = PL_{free,\,dB} + A_{ma}(f, d)_{dB} - G(h_{bs})_{dB} - G(h_{ms})_{dB} - G_{AREA,\,dB}$$

where d is BS - MS separation distance in kilometers and the correction factors are

$G(h_{bs})_{dB}$: base station antenna height gain factor in dB

$G(h_{ms})_{dB}$: mobile station antenna height gain factor in dB

$G_{AREA,dB}$: gain due to type of environment in dB

- Okumura model is good for urban and sub-urban areas

Limitation of Okumura Model:

- Difficult to use because of the need to calculate the correction factors when system parameter values (i.e., f, h_{bs}, and h_{ms}) differ from those used for $A_{ma}(f, d)$

Hata Model

- Predicts median path loss $PL_m(d)$ (in dB) in urban areas (large, small & medium cities):

$$PL_{m,\,urban}(d_{km}) = 69.55 + 26.16log(f_{o,\,MHz}) + (44.9 - 6.55log(h_{bs}))log(d_{km}) - 13.82log(h_{bs}) - a(h_{ms})$$

where

$a(h_{ms})$ for large cities is given by:

$$a(h_{ms}) = 3.2[log(11.75h_{ms})]^2 - 4.97$$

$a(h_{ms})$ for small & medium cities is given by:

$$a(h_{ms}) = [1.1log(f_o) - 0.7]h_{ms} - [1.56log(f_o) - 0.8]$$

$f_{o,MHz}$ is the carrier frequency in *MHz*, d_{km} is distance in *km*, h_{bs} and h_{ms} are in meters

Hata Model (Cont'd)

- Predicts median path loss in <u>sub-urban</u> areas:

$$PL_{m,\,suburban}(d) = C - [1.1log(f_o) - 0.7]h_{ms} + [1.56log(f_o) - 0.8] - 2\left[log\left(\frac{f_o}{28}\right)\right]^2 - 5.4$$

- Predicts median path loss in <u>rural</u> areas:

$$PL_{m,\,rural}(d) = C - [1.1log(f_o) - 0.7]h_{ms} + [1.56log(f_o) - 0.8] - 4.78[log(f_o)]^2 + 18.33[logf_o] - 40.94$$

where $C = 69.55 + 26.16log(f_o) + (44.9 - 6.55log(h_{bs}))log(d) - 13.82log(h_{bs})$

- Hata model formulas are valid for $150 \le f_o \le 1500\ MHz$ and for $d > 1\ km$

- Hata model is widely used for Cellular Network planning because of its simplicity

Practical Significance of Path Loss Models

Coverage Design: Find R, the maximum range for correct reception of the transmitted signal

Design Specifications:

- Required signal-to-noise ratio for correct reception at the receiver, SNR_{th}
- Transmit power, P_t
- Path loss model for the environment, $PL(d)$ (see pp. 13, 14, 15, 17, 18, and 22 - 24)
- Operating frequency, f
- Bandwidth of the system, B

Design Steps:

1) Calculate the required received power for correct reception
2) Calculate the maximum allowable path loss
3) Set the given path loss model to the maximum allowable path loss and solve for the range R

Note: The above is a brief introduction. Coverage design will be studied in more detail in Topic 5.