ECE519B/496A Selected Topics

MIMO and UWB Communications

Part 2 Wireless Propagation Channels

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Wireless Channel

- Based on the physical phenomenon of radio wave propagation (by Maxwell and Hertz).
- Propagation mechanisms
  - Direct line of sight (LOS)
  - Reflection, by wall or terrain
  - Diffraction, by edges of objects
  - Scattering, through smaller spaces
- Less signal attenuation when LOS exists, as in microwave and certain indoor applications.

- In non-LOS scenario, signal received through other mechanisms with severe attenuation.
- In general, multiple propagation paths exist.

Bring both opportunities and challenges to the communication community.

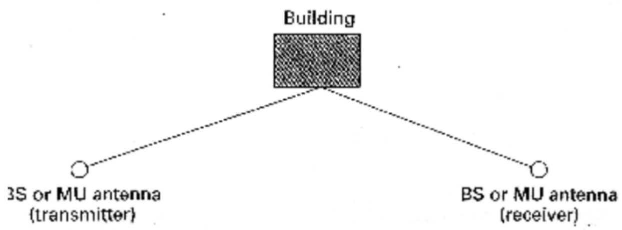


FIGURE 2.2 Reflection of the electromagnetic wave at a boundary.

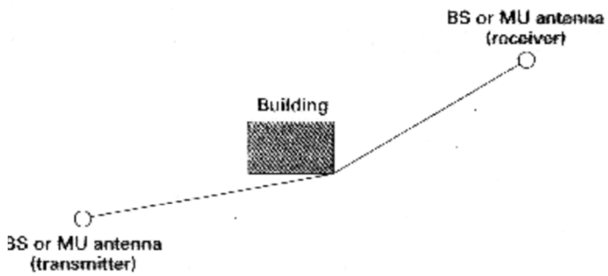


FIGURE 2.3 Diffraction of the electromagnetic wave at the edge of a building

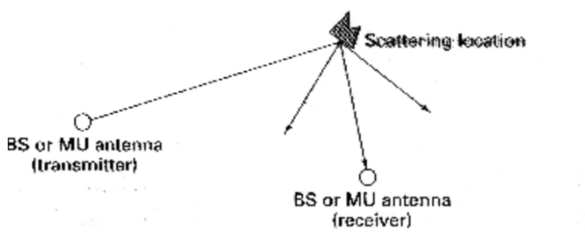
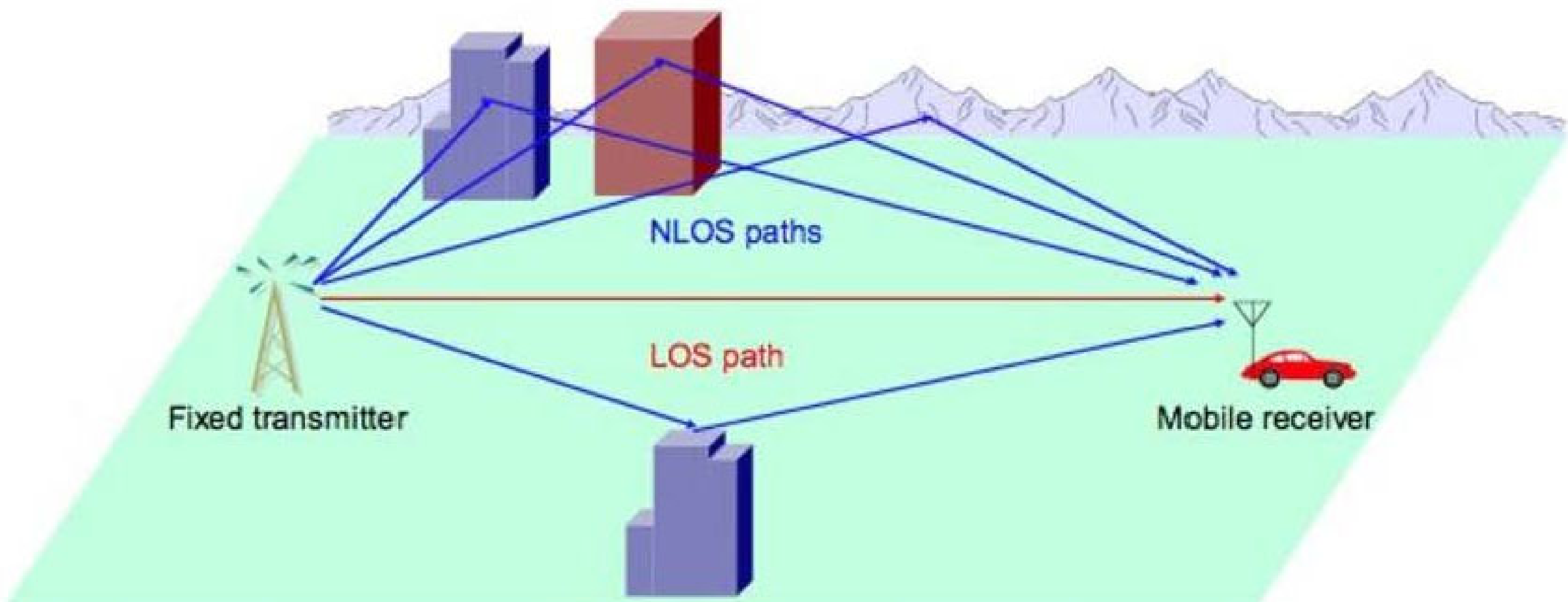


FIGURE 2.4 Scattering of the electromagnetic wave.

These non–line-of-sight (N-LOS) conditions (reflection, diffraction, and scattering) characterize most mobile communication transmissions. The free-space propagation models thus are not suited to calculate the attenuation undergone by the signal being received. The power detected by a receiver (MU or BS) is shown in Figure 2.5.

Observing the power at a separation of several kilometers, we see a steady decrease in power. This is the simple attenuation of power. It does not tell the whole story, however. If we zoom in to a distance of a couple of kilometers, we will see that

Multipath propagation



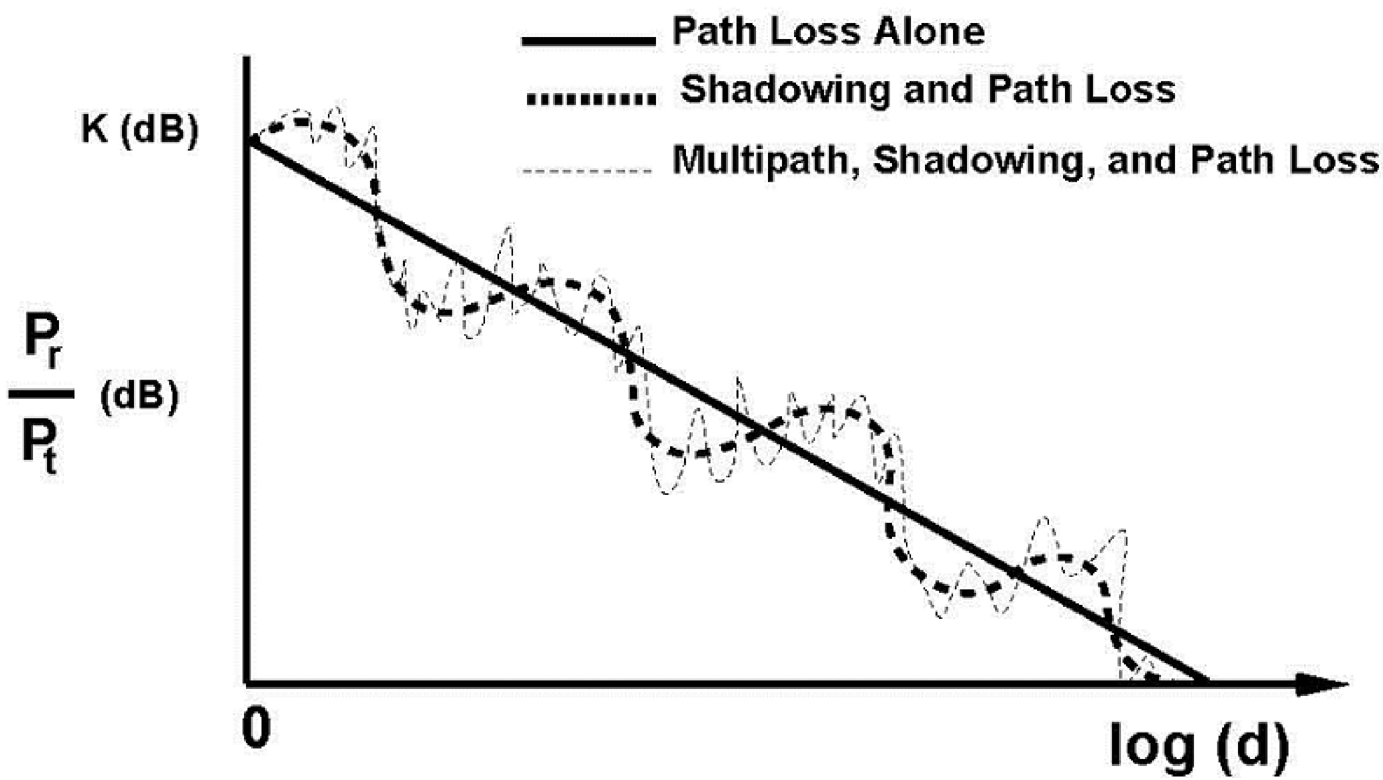


Figure 2.1: Path Loss, Shadowing and Multipath versus Distance.

Two-Ray Model

- In practical environment, at least a ground reflection exists.
- Ray tracing assume known reflector locations and dielectric properties.
- More accurate when receiver is far from the nearest scatterer and the scatterers are large relative to wavelength and smooth.
- Example of ray-tracing models.
- Predict path loss for one LOS path and one ground reflection path case.

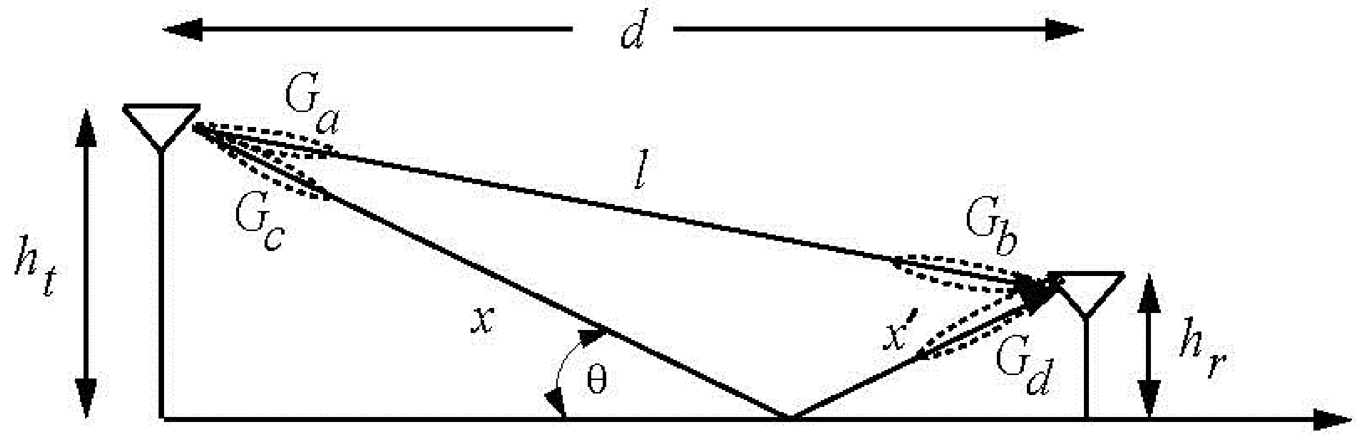


Figure 2.4: Two-Ray Model.

Goldsmith’s book

- Eqs. (2.11), (2.12)
- For smaller distance, received power falls off proportional to d^2, with some nulls.
- When d becomes greater than critical distance $d_c = \frac{4h_t h_r}{\lambda}$, received power is given as

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

where h_t and h_r are transmitter and receiver antenna heights.

- When $d < d_c$, received power falls off proportionally with d^2
- When $d \geq d_c$, received power falls off proportionally with d^4

Ground reflection approximately cancels LOS path above the critical distance.

- Ex. 2.2
- General ray tracing model is more complicated but computer packages available.

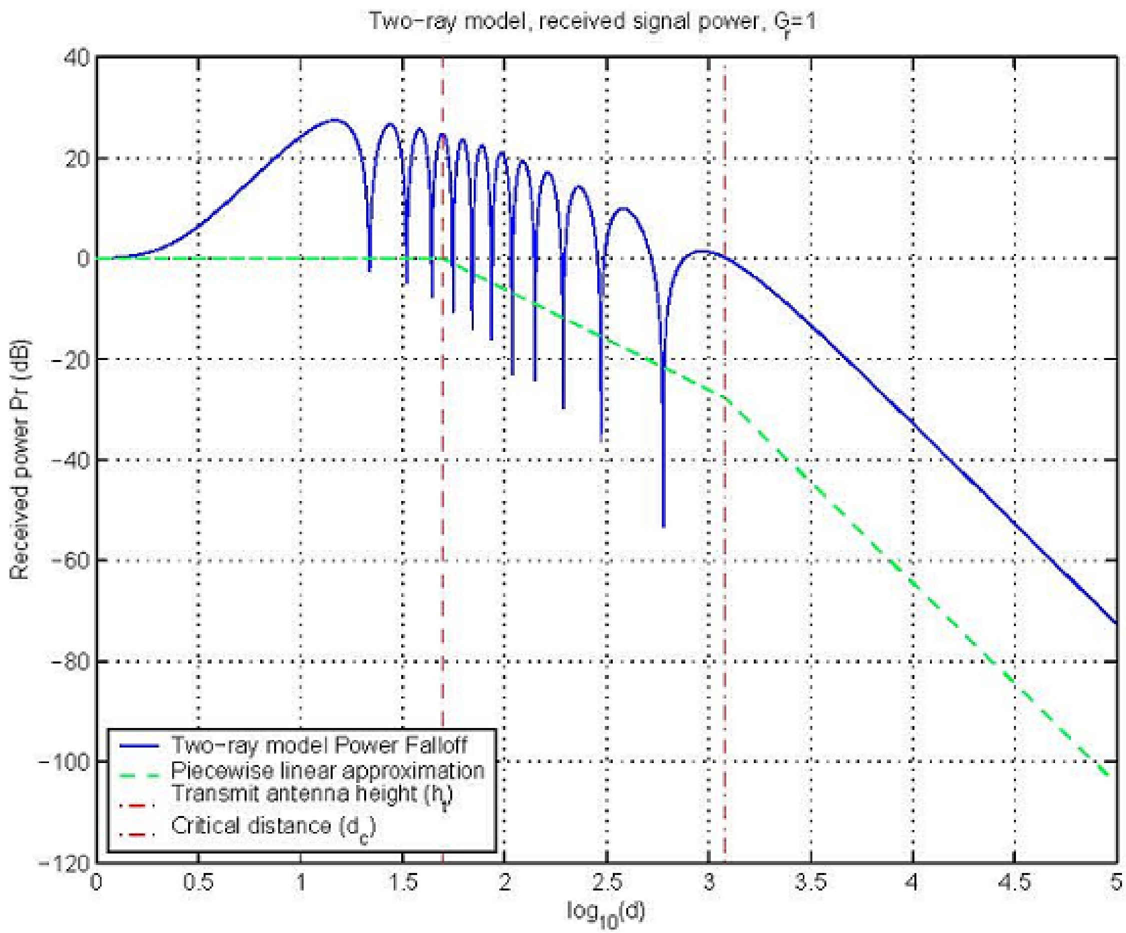


Figure 2.5: Received Power versus Distance for Two-Ray Model.

$$P_r = \begin{cases} P_t \dfrac{\lambda^2 G_l}{4\pi^2 d^2} \sin^2 \dfrac{2\pi h_t h_r}{\lambda d} & h_t < d < d_c \\ P_t \dfrac{G_l h_t^2 h_r^2}{d^4} & d > d_c \end{cases}$$

Wireless Channel Modeling

- Model signal propagation without resorting to Maxwell's equations.
- Characterized by three effects: Fig. 2.1 of Goldsmith
  - Path loss, caused by power dissipation.
  - Shadowing, due to obstacles in the propagation path.
  - Fading, resulted from multipath propagation.

Note: Path loss and shadowing are called large-scale propagation effects whereas fading is small-scale effect.

- Path loss specifies the mean of shadowing.
- Path loss/shadowing jointly determine the mean of fading process.
- In general, coverage and interference analysis is based on path loss and shadowing whereas transmission scheme design is based on fading.

Path Loss

- Power attenuation as distance increases.
- Ignore the variation due to location-specific environment and multipath effect.
- Linear path loss is defined as the ratio of transmitted power and received power

$$PL = P_t / P_r$$

- In dB scale, $PL = 10 \log_{10}(P_t/P_r)$ dB.

- Popular models to predict path loss
  - Free space model: too simple.
  - Ray-tracing model (two-ray here): requires site-specific information.
  - Empirical models: not always generalizable.
  - Log-distance (simplified) model: good for high-level analysis.

Free Space Model

- Predict received signal power over the line-of-sight (LOS) path, i.e. directly from transmit antenna to receive antenna.
- Governed by Friis equation

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

where G_t, G_r are transmit and receive antenna gains, λ is the carrier wavelength and d is the distance, in meters.

- Path loss based on free space model:

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

Notes: 1) $PL \propto d^2$; 2) $PL \propto \lambda^{-2}$.

- The exponent of d^2 is called the path loss exponent or path loss factor. In free space, the path loss exponent is 2.
- EIRP=$P_t G_t$ Equivalent isotropically radiated power

Okumura-Hata model

- Example of empirical models.
- Hata developed a set of formula based on Okumura's measurement data in Tokyo.
- Valid over frequency range of 150-1500 MHz.
- For urban area, median path loss

$$
\begin{aligned}
PL_{median}\, dB &= 69.55 + 26.16 \log_{10}(f_c) \\
&- 13.82 \log_{10}(h_t) - a(h_r) \\
&+ (44.9 - 6.55 \log_{10}(h_t)) \log_{10}(d)
\end{aligned}
$$

- In larger cities with f_c > 300 MHz,

$$a(h_r) = 3.2(\log_{10}(11.75h_r))^2 - 4.97\ \text{dB}$$

- Correction terms for suburban and rural also available.
- COST 231 model extends Hata model to 2 GHz. *Widely used in cellular system simulations.*

Log-Distance Model

- Simplified path loss model for system design.
- Note that in all three earlier models, *PL* in dB at distance *d* is of the form $x+y \log_{10}(d)$.
- Predict path loss using the following formula

$$PL(d) \text{ dB} = -K \text{ dB} + 10\,\gamma \log_{10}(d/d_0)$$

  where d_0 is reference distance, $-K = PL(d_0)$ dB is path loss at $d0$ and γ is a constant.
- d_0 is usually set to 1-10 m for indoor and 1 km for outdoor application.

- K dB calculated from free space model,

$$K = - PL(d_0) \text{ dB} = 20 \log_{10}(\lambda/4\pi d_0)$$

- γ, usually known as path loss exponent, depends on the propagation environment.
- γ can be obtained by minimizing the mean square error (MSE) between model and measurement data.

Typical path-loss exponents

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

Example 2.3

- Path-loss measurements

Distance from transmitter	$M=P_r/P_t$
10 m	-70 dB
20 m	-75 dB
50 m	-90 dB
100 m	-110 dB
300 m	-125 dB

More on Path Loss

- Piecewise linear model
  - Multiple slopes or path-loss exponents
  - Fig. 2.9
- Other indoor attenuation factors

$$P_r \text{ dBm} = P_t \text{ dBm} - PL(d) - \sum_i Floor_i - \sum_j Wall_j$$

Shadowing

- Characterize effects of surrounding large objects.
- Employ statistical model as location, sizes, and properties of objects generally unknown.
- Log-normal shadowing model: most popular and empirically confirmed.
  - Path loss in dB at a distance *d*, ψ_{dB}, is a Gaussian (normal) random variable with distribution function

$$p_{\psi_{\mathrm{dB}}}(x) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{dB}}} \exp\left(-\frac{(x-\mu_{\mathrm{dB}})^2}{2\sigma_{\mathrm{dB}}^2} \right)$$

- μ_{dB} is the mean path loss at distance *d*, usually predicted using proper path loss models.
- σ_{dB} is the standard deviation of ψ_{dB}, ranging from 4 to 13 dB.

Note: If ψ_{dB} is a Gaussian random variable, then path loss in linear scale ψ is a log-normal random variable.

Combined Path Loss and Shadowing

- Apply log-distance model to determine dB

$$\mu_{dB} = PL(d)\text{ dB} = -K + 10\,\gamma\log_{10}(d/d_0)$$

- With shadowing, path loss at distance *d* is a Gaussian random variable with mean *PL*(*d*) dB and variance σ^2_{dB}, estimated as MMSE.
- Path loss with random shadowing

$$\psi_{\text{dB}} = P_t\text{ dB} - P_r\text{ dB} = -K + 10\gamma\lg(d/d_0) + \tilde{\psi}_{\text{dB}}$$

$$\psi_{dB} \sim N(\mu_{dB}, \sigma_{dB}) \qquad \tilde{\psi}_{dB} \sim N(0, \sigma_{dB})$$

Application: Outage probability

- Target minimum received power level $P_{\min}$.
- Because of shadowing, $P_r = P_t - \psi_{\text{dB}}$ is random and may be smaller than $P_{\min}$ for any distance d.
- Outage probability, $P_{\text{out}}(P_{\min}, d)$, defined as the probability that received power at distance d falls below $P_{\min}$:

$$P_{\text{out}}(P_{\min}, d) = \Pr[P_r(d) = P_t - \psi_{\text{dB}} < P_{\min}]$$
$$= Q\left(\frac{P_t - P_{\min} + K - 10\gamma \log_{10}(d/d_0)}{\sigma_{\text{dB}}}\right)$$

Cell Coverage

- Percentage of area in a cell where $P_r > P_{\min}$.
- Due to shadowing, $P_r = P_t - \psi_{dB}$ dB is *random*.
- Design problem: determine P_t for radius R.
  - Taking an incremental area at distance r.
  - Determine cover probability $1-P_{out}(P_{\min}, r)$.
  - Average over all incremental area in the cell

$$C = \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R [1 - P_{\text{out}}(P_{\min}, r)] r dr d\theta$$

$$= Q(a) + \exp\left(\frac{2 - 2ab}{b^2}\right) Q\left(\frac{2 - ab}{b}\right)$$

Where $$a = \frac{P_{\min} - P_t + PL(d_0)\mathrm{dB} + 10\gamma\log_{10}(R/d_0)}{\sigma_{\mathrm{dB}}}$$

$$= \frac{P_{\min} - \overline{P}_r(R)}{\sigma_{\mathrm{dB}}}$$

$$b = \frac{10\gamma\log_{10}(e)}{\sigma_{\mathrm{dB}}}$$

Note: *C* increases as σ_{dB} decreases.

$\overline{P}_r(R)$ is the average received power at the cell boundary (due to path loss only).

- The outage probability of the cell is the percentage of area within the cell that does not meet its minimum power requirement $P_{\min}$

$$P_{out}^{cell} = 1 - C$$