Wireless Communications

Channel Modeling – Large Scale

Hamid Bahrami
EM Spectrum
Radio Wave

- **Radio wave**: a form of electromagnetic radiation, created whenever a charged object accelerates with a frequency

- How are EM waves produced?

  Charged particle $\rightarrow$ E-field and moving charged particle $\rightarrow$ B-field
Review: Radio Wave Propagation

- Electric field and magnetic fields are orthogonal
- The direction of propagation of the EM wave is orthogonal to both the electric and magnetic fields
  - EM wave is propagating in the z direction
  - $E$ field in orientated along the x axis
  - $B$ field in orientated along the y axis
Radio Wave Propagation

- **Statement of the problem**
  - Path loss, reflection, diffraction, and scattering
  - Lack of direct line-of-sight path between the Tx and Rx
  - Multipath fading

- **Large-scale fading**: transmission over large T-R separation distance (hundreds or thousands of meters)

- **Small-scale fading**: transmission over short travel distance (a few wavelengths) or short time duration (seconds)
Free Space Propagation Model

- To predict received signal strength when the Tx and Rx have a line-of-sight (LOS) path
  - Satellite communication systems
  - Microwave LOS radio links
  - Friis free space equation

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

- Transmitted power
- Transmitter antenna gain
- Received power
- Receiver antenna gain
- Wavelength in meters
- System loss factor \( L = 1 \): no loss
- Distance between the Tx and Rx

\[ \lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c} \]
If 50W is applied to a unity gain antenna with a 900M Hz carrier frequency, find the received power in dBm at a free space distance of 100 m from the antenna. Assume unity gain for the receiver antenna.

\[ P_r(d) = \frac{P_i G_i G_r \lambda^2}{(4\pi)^2 d^2 L} \]

\[ P_r(100) = \frac{(50)(1)(1)(3.0 \times 10^8 / 900 \times 10^6)^2}{(4\pi)^2 (100)^2 (1)} = 3.5 \times 10^{-3} mW \]

\[ 3.5 \times 10^{-3} mW \Rightarrow 10 \log(3.5 \times 10^{-3}) = -24.5 dBm \]
Free Space Propagation Model

- **Path loss**
  - Signal attenuation
  - The difference between the effective transmitted power and the received power
  - May or may not include the effect of the antenna gains
  - Measured in dB

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

\[
 PL(dB) = 10 \log \frac{P_t}{P_r} = -10 \log \frac{\lambda^2}{(4\pi)^2 d^2}
\]
Free Space Propagation Model

- **Review: near-field**
  - The close-in region of an antenna where the angular field distribution is dependent upon the distance from the antenna
  - The region close to a source

- **Review: far-field**
  - The close-in region of an antenna where the angular field distribution is independent upon the distance from the antenna
Free Space Propagation Model

- Far-field (Fraunhofer region)
  - The region beyond the far-field distance \( d_f \)
    
    \[
    d_f = \frac{2D^2}{\lambda}
    \]
    The largest physical linear dimension of the antenna

    \( d_f \gg D, d_f \gg \lambda \)

    Reference point:
    
    \[
    P_r(d) = P_r(d_0) \left( \frac{d_0}{d} \right)^2 \quad d \geq d_0 \geq d_f
    \]

    \[
    P_r(d) \, dBm = 10 \log \frac{P_r(d_0)}{0.001} + 20 \log \left( \frac{d_0}{d} \right) \quad d \geq d_0 \geq d_f
    \]
Example: page 109, Ex. 4.1

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

\[ d_f = \frac{2D^2}{\lambda} \]

Answer:

Largest dimension of antenna, \( D = 1\text{m} \)

Operating frequency, \( \lambda = \frac{c}{f} = \frac{3.0\times10^8}{900\times10^6} = 0.33\text{m} \)

The far-field distance \( d_f = \frac{2D^2}{\lambda} = \frac{2}{0.33} = 6\text{m} \)

\( d_f \gg D \quad d_f \gg \lambda \)
Example: page 109, 4.2

- If 50W is applied to a unity gain antenna with a 900M Hz carrier frequency, find the received power in dBm at a free space distance of 100 m from the antenna. What is \( P_r(10\text{km}) \)? Assume unity gain for the receiver antenna.

Reference point:

\[
P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \quad d \geq d_0 \geq d_f
\]

\[
P_r(d) \text{dBm} = 10 \log \frac{P_r(d_0)}{0.001} + 20 \log \left(\frac{d_0}{d}\right) \quad d \geq d_0 \geq d_f
\]

\[
P_r(d) \text{dBm} = -24.5 + 20 \log \left(\frac{100}{10000}\right) = -64.5 \text{dBm}
\]
Statement of the problem
- Reflection, diffraction, and scattering
- Lack of direct line-of-sight path between the Tx and Rx
- Multipath fading

Large-scale fading: transmission over large T-R separation distance (hundreds or thousands of meters)
Take a look of this case first…
Reflection

- *When* a radio wave propagating in one medium impinges upon another medium have different electrical properties
- The wave is partially reflected
- The reflection coefficient
  - The material properties
  - The wave polarization
  - The angle of incidence
  - The wave frequency
Ground Reflection Model

- Two-Ray model

The path distance between the LOS and the ground reflected path

\[ \Delta = d'' - d' = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \]

\[ \Delta \approx \frac{2h_t h_r}{d}, \text{ when } d \gg h_t + h_r \]

\[ |E_{\text{TOT}}| = |E_{\text{LOS}}| + |E_g| \]
\[ \Delta = \Delta d = d_2 - d_1 = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} = d \sqrt{1 + \left( \frac{h_t + h_r}{d} \right)^2} - d \sqrt{1 + \left( \frac{h_t - h_r}{d} \right)^2} \]

Taylor Series

\[ \sqrt{1 + x} = \sum_{n=0}^{\infty} \frac{(-1)^n (2n)!}{(1 - 2n)n! 4^n x^n} \]

\[
\frac{h_t + h_r}{d} \ll 1 \text{ and } \frac{h_t - h_r}{d} \ll 1
\]

\[ \sqrt{1 + \left( \frac{h_t + h_r}{d} \right)^2} = 1 + \frac{(-1)(2)}{(-1)(4)} \left( \frac{h_t + h_r}{d} \right)^2 \]

\[ \Rightarrow d \sqrt{1 + \left( \frac{h_t + h_r}{d} \right)^2} - d \sqrt{1 + \left( \frac{h_t - h_r}{d} \right)^2} = d \left( 1 + \frac{1}{2} \left( \frac{h_t + h_r}{d} \right)^2 \right) - d \left( 1 + \frac{1}{2} \left( \frac{h_t - h_r}{d} \right)^2 \right) \]

\[ d >> h_t + h_r; \quad d >> h_t - h_r; \quad d >> h\_r h_r \]

\[ \Delta d \equiv d - d + \frac{1}{2d} \left( h_t^2 - h_t^2 + h_r^2 - h_r^2 + 2h_r h_t + 2h_t h_t \right) \equiv \frac{2h_r h_t}{d} \]
Ground Reflection Model

- The received E-field

\[ E_{TOT} \approx \frac{2E_0 d_0}{d} \frac{2\pi h_t h_r}{\lambda d} \]

- The received power at a distance \( d \)

\[ P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \]

\[ PL(dB) = 40 \log d - \left( 10 \log G_t + 10 \log G_r + 20 \log h_t + 20 \log h_r \right) \]
Ground Reflection Model

- **Advantage**
  - Consider both the direct path and a ground reflected propagation path between the Tx and Rx

- **Disadvantage**
  - Oversimplified: does not include factors like terrain profile and surroundings

- **Whether the two-ray model could be applied?**
  - Case 1: $h_t=35$ m, $h_r=3$ m, $d=250$ m
  - Case 1: $h_t=30$ m, $h_r=1.5$ m, $d=450$ m
Review: Radio Wave Propagation

- **Statement of the problem**
  - Reflection, diffraction, and scattering
  - Lack of direct line-of-sight path between the Tx and Rx
  - Multipath fading

- **Large-scale fading**: transmission over large T-R separation distance (hundreds or thousands meters)
Diffraction

- Signals propagate around the curved surface to the earth, beyond the horizon and to propagate behind obstructions.
- Caused by the propagation of secondary wavelets into a shadowed region.
Fresnel Zone Geometry

Excess path length

\[
\Delta d \equiv \frac{h^2}{2d_a} + \frac{h^2}{2d_b} = \frac{(d_a + d_b)h^2}{2(d_a d_b)}
\]

\[
\Delta \theta = \frac{2\pi \Delta d}{\lambda} \approx \frac{2\pi}{\lambda} \times \frac{(d_a + d_b)h^2}{2d_a d_b}
\]

Fresnel-Kirchoff diffraction parameter

\[
\nu = h \sqrt{\frac{2(d_a + d_b)}{\lambda d_a d_b}}
\]

Phase difference:
- Height of the obstruction
- Position of the obstruction
- Position of Tx and Rx
Fresnel Zone Geometry
Fresnel Zone Geometry

- **Diffraction Loss**
  - An function of the path difference around an obstruction
  - An obstruction causes a blockage of energy from some of the Fresnel zones, thus allowing only some of transmitted energy to reach the receiver
  - Design LOS microwave links: 55% of the first Fresnel zone is clear
  - Prediction of the diffraction loss is not easy in a real life due to complex and irregular terrain
Knife-edge Diffraction Model

- The simplest diffraction model
- When shadowing is caused by a single object
- In practice, graphical or numerical solutions are relied upon to compute diffraction gain

\[
G_d (dB) = 20 \log_{10} |F(v)|
\]

\[
G_d (dB)=\begin{cases} 
0 & v \leq -1 \\
20 \log \left( \frac{1}{2} - 0.62v \right), & -1 \leq v \leq 0 \\
20 \log \left( \frac{1}{2} e^{-0.95v} \right), & 0 \leq v \leq 1 \\
20 \log \left( 0.4 - \sqrt{0.1184 - (0.38 - 0.1)^2} \right), & 1 \leq v \leq 2.4 \\
20 \log \left( \frac{0.225}{v} \right), & v > 2.4
\end{cases}
\]
Multiple Knife-edge Diffraction

- More than one obstructive object
- The total diffraction loss due to all of the obstacles must be computed
- Replace all obstacles by a single equivalent one
Scattering

- When a radio wave impinges on a rough surface, the reflected energy is spread out (diffused) in all directions due to *scattering*
- Resulting in the stronger received signal
Example 4.8, pp. 133

- 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. $f=900$ MHz.
Practical Path Loss Model

- Path loss is the loss in signal strength as a function of distance
  - Terrain dependent
  - Site dependent
  - Frequency dependent
  - May or may not depend on line of sight (LOS)
- Commonly used to estimate link budgets, cell sizes and shapes, capacity, handoff criteria, etc.
- Models are approximations of losses derived from measurements
Practical Path Loss Model

- Log-distance path loss model
  - The average received signal power decreases logarithmically with distance

\[
\overline{PL}(d) \propto \left( \frac{d}{d_0} \right)^n
\]

\[
\overline{PL}(dB) = \overline{PL}(d_0) + 10n\log_{10} \left( \frac{d}{d_0} \right)
\]

n: the path loss exponent
d₀: the close-in reference distance
d: the T-R separation distance
Practical Path Loss Model – cont.

- Log-distance path loss model
  - Path loss exponents for different environments

<table>
<thead>
<tr>
<th>Environment</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>3 to 5</td>
</tr>
<tr>
<td>In building LOS</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed buildings</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstructed factories</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>
Practical Path Loss Model

- Log-normal shadowing
  - Considering the different surrounding environmental clutter with the same T-R separation
  - The path loss $PL(d)$ at a particular location is random and distributed log-normally (dB)

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

$X_\sigma$ : a zero-mean Gaussian distributed RV (dB) with standard deviation $\sigma$(dB)
Review: Gaussian Distribution

- Q function or error function (erf)

\[
Q(z) = \frac{1}{\sqrt{2\pi}} \int_{z}^{\infty} \exp\left(-\frac{x^2}{2}\right) dx = \frac{1}{2} \left[1 - \text{erf}\left(\frac{x}{\sqrt{2}}\right)\right]
\]

\[
Q(z) = 1 - Q(-z)
\]

\[
\Pr[\Pr(d) > \gamma] = Q\left(\frac{\gamma - \bar{Pr}(d)}{\sigma}\right)
\]

\[
\Pr[\Pr(d) > \gamma] = Q\left(\frac{\bar{Pr}(d) - \gamma}{\sigma}\right)
\]
Problem 4.21

- During the first month of work, you get an assignment to perform a measurement campaign to estimate the channel path loss exponent for a new wireless product.

- You performed field measurements and collected the following data:
  - Reference path loss: PL (d₀)
  - Path loss measurements: PL (d₁), PL (d₂), …

- Using the path loss exponent model, find an expression for the optimum value of the path loss exponent n, which minimizes the mean square error between measurements and the model.

- Hint: the optimum value of n should minimize the mean square error (MSE) between your predicted path loss and measured path loss.
Outdoor Propagation Models

- Longley-Rice model [ITS Irregular Terrain Model]
  - Point-to-point communication systems
  - Frequency range: 40 MHz ~ 100 GHz
- Techniques
  - The two-ray ground reflection model
  - The Fresnel-Kirchoff knife-edge model
  - Forward scatter theory over long distances
- Shortcomings
  - Does not provide corrections due to environment factors
  - Does not consider multipath
Outdoor Propagation Models

- Durkin’s model
  - Considering the nature of propagation over irregular terrain and losses caused by obstacles in a radio path
  - Typically used for the design of modern wireless systems
  - Durkin path loss simulator
    - Non-LOS
    - LOS, but with inadequate first Fresnel-zone clearance
- Shortcomings
  - Does not consider man-made structures
  - Does not consider multipath
Outdoor Propagation Models

- Okumura model
  - One of the most widely used models in urban areas
  - Frequency range: 150 MHz ~ 1920 MHz
  - Distance: 1km ~ 100 km
  - Station antenna heights: 30m ~ 1000m
  - Wholly based on measured data and does not provide any analytical explanation
- Shortcomings
  - Slow response to rapid changes in terrain
Outdoor Propagation Models

- **Hata model**
  - An empirical formulation of the graphical path loss data
  - Frequency range: 150 MHz ~ 1500 MHz
  
  $$L_{50}(urban)(dB) = 69.55 + 26.16 \log f_c - 13.82 \log h_{re} - a(h_{re}) + (44.9 - 6.55 \log h_{re}) \log d$$

  - Well suited for large cell mobile systems, but not personal communication systems (PCS)

- **Cost-231**
  - PCS extension to Hata model
Indoor Propagation Models

- Differ from the traditional mobile radio channels
  - The distance covered are much smaller
  - The variability of the environment is much greater
  - Relatively new research field
- Partition losses (same floor)
  - Hard partition: partitions are formed as part of the building structure
  - Soft partition: partitions may be moved and do not span to the ceiling
Indoor Propagation Models

- Partition losses between floors
  - The external dimensions
  - Materials of the buildings
  - The type of construction used to create the floors
  - The external surroundings
  - The number of windows
Indoor Propagation Models

- **Log-distance path loss**

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

- **Ericsson multiple breakpoint model**
  - Measurements in a multiple floor office building
  - Four breakpoints
  - Both upper and lower bound on the path loss are considered
Indoor Propagation Models

- **Attenuation factor model**
  - Accurately deploy indoor and campus networks
  - Reduce the standard deviation between measured and predicted path loss to around 4 dB

\[
PL(dB) = PL(d_0) + 10n \log\frac{d}{d_0} + FAF + \sum PAF
\]

FAF: a floor attenuation factor for a specified number of building floors
PAF: the partition attenuation factor for a specific obstruction encountered by a ray drawn between the TX and Rx in 3-D