Lecture 2 - EE 359: Wireless Communications - Autumn 2017

Signal Propagation and Path Loss Models

Lecture Outline

- **Overview of Signal Propagation**
- **Free Space Path Loss Model**
- **Two-Ray Model**
- **Generalized Ray Tracing Model**
- **Simplified Path Loss Model**
- **mmWave Propagation Models**
- **Empirical Models (not covered in lecture, not on HW or exams)**
- **Standards-based Models for WiFi and Cellular (not covered in lecture, not on HW or exams)**

1. **Signal Propagation Characteristics:**
    - Path loss: power falloff relative to distance
    - Shadowing: random fluctuations due to obstructions
    - Flat and frequency selective fading: caused by multipath

2. **Transmitted and received signals:**
    - **Transmitted Signal:**, with power P_t, is $s(t) = \Re\{u(t)e^{j(2\pi f_c t)}\} = s_I(t)\cos(2\pi f_c t+\phi_0) - s_Q(t)\sin(2\pi f_c t+\phi_0)$, where $u(t) = s_I(t) + js_Q(t)$ is the complex baseband signal with bandwidth B, f_c is the carrier frequency, and ϕ_0 is the initial phase. For simplicity, assume $u(t)$ real for propagation analysis.
    - **Received signal:** $r(t) = \Re\{v(t)e^{j(2\pi f_c t)}\}$; $v(t) = u(t) * c(t)$ for $c(t)$ the baseband channel model.
    - Doppler frequency shift $f_D = (v/\lambda)\cos(\theta)$ may also be introduced in the received signal

3. **Free space path loss model:**
    - Typically used for unobstructed LOS signal path.
    - Received signal is
    $$r(t) = \Re\{\frac{u(t)\sqrt{G_l}\lambda e^{j2\pi d/\lambda}}{4\pi d}e^{j(2\pi f_c t+\phi_0)}\}$$
    with received power
    $$P_r = P_t\left[\frac{\sqrt{G_l}\lambda}{4\pi d}\right]^2.$$
    - Power falls off proportional to the ratio of wavelength over distance squared. This inverse frequency dependence is due to the effective aperture of the receiver.
    - Power falls off proportional to net antenna gain G_l.
    - *Model not accurate for general environments.*

4. **Two ray model:**
    - One LOS path, one reflected path.

- At small distances, power falls off proportional to d^2 (free space loss on both paths).
- Above some critical distance d_c, received power given by

$$P_r \approx P_t \left[\frac{\sqrt{G_l} h_t h_r}{d^2}\right]^2.$$

- Above d_c, power falls off proportional to d^4 and is independent of signal wavelength (frequency)
- *Model not generally accurate for cities or indoors.*

5. **Generalized Ray Tracing:**

- Represent wavefronts as simple particles (geometry vs. Maxwell's differential equations).
- Can incorporate all signal components: reflections, scattering, and diffraction.
- Reflected rays have power falloff proportional to d^2 by free space path loss model. Scattered and refracted rays have power falloff that depends on exact distance of scattering or refractive object from transmitter and receiver.
- If objects are more than a few wavelengths from receiver, typically neglect scattering and refraction.
- Most computer packages for channel simulation in indoor/outdoor environments use general ray tracing for path loss.
- *Model requires detailed site information.*

6. **Simplified path loss model:**

- Capture main characteristics of ray tracing using simplified model $P_r = P_t K \left[\frac{d_0}{d}\right]^\gamma$, where K is a constant factor $(P_r(d_0)/P_t)$, d_0 is a reference distance, and γ is the path loss exponent.
- Path loss exponent is function of carrier frequency, environment, obstructions, etc. Typically ranges from 2 to 8 (at around 1 GHz).
- *Model captures main characteristics of ray tracing: good for high-level analysis.*

7. **mmWave Propagation Models:**

- mmWave communication consists of carrier frequencies in the 60-100 GHz range. All commercial systems today fit in a fraction of this band, and it is lightly/not regulated
- mmWave propagation models are still maturing. There are extensive measurements but few analytical models.
- Path loss proportional to λ^2, very high at these frequencies. Can be compensated by massive MIMO (will cover later in the course).
- In addition, measurements indicate heavy oxygen absorption from the atmosphere and heavy attenuation at 60 GHz (also at 120 GHz and 180 GHz) due to chemical structure of oxygen. Measurements also indicate that attenuation due to shadowing from objects more severe at these frequencies and shadowing can also cause scattering of directed beams.
- Bottom Line: mmWave communications will either be short range or require large antenna arrays (MIMO) to get larger range, leading to the dynamic duo of mmWave Massive MIMO

8. **Empirical Models:**
    - Irregular terrain, like in cities, doesn't lend itself to simple analytical path loss models.
    - Empirical path loss models for early cellular systems were based on extensive measurements.
    - Okumura Model: Empirical model for irregular terrain outdoors.
    - Hata Model: Analytical approximation to Okumura model.
    - Cost 231 Extension to Hata Model: Extends Hata model to 2 GHZ and to lower mobile antenna heights. Widely used in 2G cellular simulations.
    - Piecewise linear models capture multiple slopes associated with path loss.
    - Models have poor accuracy (15-20 dB STD error), especially in environments different from those upon which the empirical models are based. Models capture phenomena missing from analytical formulas but are typically awkward for analysis.

9. **Standards-based Models for WiFi (802.11) and Cellular (3GPP):**
    - The standards bodies for cellular (3GPP) and WiFi (802.11) develop classes of propagation models (e.g. indoor, outdoor high speed, outdoor low speed) which are used to evaluate different technology proposals to the standard.
    - Simulation packages often integrate these models into their software for ease of simulations.
    - Cellular 3GPP models: The LTE model was developed for under 6 GHz carrier frequencies. It has detailed path loss models for user equipment (3GPP TS 36.101) and base stations (3GPP TS 36.104) for different amounts of multipath delay spread, user speeds (from pedestrian walking to high speed trains), and MIMO antenna correlations. The 5G model is being standardized now to include higher frequencies (up to 100 GHz). More details at http://www.3gpp.org.
    - WiFi 802.11n and 802.11ac models: Developed by the IEEE Standards Body for 802.11 with MIMO. 802.11n model consisted of multiple models for indoor and outdoor systems with up to 4x4 antenna configurations, up to 40 MHz channels, and different amounts of multipath. Path loss model is free-space model up to a breakpoint, then a 3.5 path loss exponent. The breakpoint is empirically-based. The 802.11ac addendum extended this model to include higher order MIMO (more than 4x4), multi-User MIMO with more than 4 access point antennas, bandwidths greater than 40 MHz, and OFDMA. More details at https://mentor.ieee.org/802.11/dcn/09/11-09-0308-00-00ac-tgac-channel-model-ad.

Main Points

- Path loss models simplify Maxwell's equations. The models vary in complexity and accuracy.
- Power fallof with distance is proportional to d^2 in free space model, d^4 in two path model.
- General ray tracing requires detailed site specific information. Typically generated with computer packages.
- Main characteristics of ray tracing models captured in simplified path loss model.
- mmWave a promising frequency band. Propagation not well understood and likely needs "massive MIMO" for reasonable range.
- Empirical models widely used to study cellular and WiFi performance via simulation. The 802.11 WiFi and 3GPP cellular models are not very accurate and aren't easy to analyze. Mainly used for comparisons of standards proposals.