Signal Propagation and Path Loss Models

Lecture Outline

- **Overview of Signal Propagation**
- **Free Space Path Loss Model**
- **Two-Ray Model**
- **Generalized Ray Tracing Model**
- **Single-Slope Path Loss Exponent Model**
- **mmWave Propagation Models**
- **Empirical Models (not covered in lecture, HW, or exams)**
- **Standards-based Models for WiFi and Cellular (not covered in lecture, 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:** $s(t) = \mathrm{Re}\{u(t)e^{j(2\pi f_c t)}\} = s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t)$, where f_c is the carrier frequency and $u(t) = s_I(t) + js_Q(t)$ is the equivalent lowpass signal of $s(t)$ with bandwidth B_u, power P_u, in-phase component $s_I(t) = \mathrm{Re}\{u(t)\}$ and quadrature component $s_Q(t) = \mathrm{Im}\{u(t)\}$. The phase of $u(t)$ includes any carrier phase offset.
   - **Received signal:** $r(t) = \mathrm{Re}\{v(t)e^{j(2\pi f_c t)}\}$; $v(t) = u(t) * c(t)$ for $c(t)$ the equivalent lowpass channel impulse response for $h(t)$.
   - Doppler frequency shift $f_D = (v/\lambda)\cos(\theta)$ may also be introduced in the received signal. We will ignore for now as it has little impact on path loss (big impact on fading).

3. **Free space path loss model:**
   - Typically used for unobstructed LOS signal path.
   - Received signal is
   $$r(t) = \Re\{\frac{u(t)\sqrt{G_t G_r}\lambda e^{j2\pi d/\lambda}}{4\pi d} e^{j(2\pi f_c t)}\}$$
   - Receiver power is
   $$P_r = P_t\left[\frac{\sqrt{G_t G_r}\lambda}{4\pi d}\right]^2 \Rightarrow \frac{P_r}{P_t} = G_t G_r \left[\frac{\lambda}{4\pi d}\right]^2.$$
   - Power falls off proportional to $(1/d)^2$ and to $\lambda^2 = (1/f_c)^2$. This dependence on the inverse of the square of the carrier frequency is due to the effective aperture of the receiver.

- Power falls off proportional to net antenna gain $G_t G_r$ which combines the transmit and receive antenna gains G_t and G_r, respectively.
- *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

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

where G approximates the combined transmit and receiver gains of both multipath components.
- 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. **Single-Slope Path Loss Exponent Model**

- Capture main characteristics of ray tracing using single-slope path loss exponent model: $P_r = P_t K \left[\frac{d_r}{d}\right]^\gamma$, where K is a constant factor $(P_r(d_r)/P_t)$, d_r 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. **Measurement-Based Propagation Models:**

   - Irregular terrain, like in cities or inside buildings, doesn't lend itself to simple analytical path loss models.
   - Measurement-based path loss models are based on extensive measurements, with curve-fitting or analytical models fit to the data.
   - A number of measurement-based path loss models have been developed over the years by researchers as well as standards bodies to model path loss in typical wireless environments.
   - These models are generally based on large empirical measurement campaigns that can range over a variety of distances, frequency ranges, geographical regions for outdoor models, and building types for indoor models. These models have the highest accuracy when they are applied to propagation conditions similar to those under which the empirical measurements that the models are based on were made.
   - The course reader describes the most common analytical path loss models based on empirical measurements for both indoor and outdoor systems.

9. **Standards-based Models for WiFi (802.11) and Cellular (3GPP):**

   - The standards bodies for cellular (3GPP) and WiFi (802.11) have developed 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.
   - The reader describes cellular 3GPP and 5G channel models as well as WiFi 802.11n and 802.11ac models. New models for future cellular and WiFi systems are under development.

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.