Signal Propagation and Path Loss Models

Lecture Outline

- **Overview of Signal Propagation**
- **Free Space Path Loss Model**
- **Ray Tracing Path Loss Models**
- **Simplified Path Loss Model**
- **Empirical Path Loss Models**
- **Log-Normal Shadowing**

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 we assume $u(t)$ real for propagation model analysis.
   - **Received signal:**$r(t) = \Re\{v(t)e^{j(2\pi f_c t)}\}$, where $v(t) = u(t)*c(t)$ 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. The 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. **Ray tracing approximation:**
   - Represent wavefronts as simple particles.
   - Simplest models only determine reflections.
   - Scattering and defraction can also be included.

5. **Two path 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.*

6. **General Ray Tracing:**
   - Incorporates 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.*

7. **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.*

8. **Empirical Models:**
   - Irregular terrain, like in cities, doesn't lend itself to simple analytical path loss models.
   - Empirical path loss models based on extensive measurements.
   - Local mean attenuation: empirical measurements of local received power.
   - Okumura Model: Empirical model for irregular terrain.

- 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 simulations.
- Piecewise linear models capture multiple slopes associated with path loss.
- *Models not accurate and don't generalize well to other environments.*

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.
- Empirical models widely used to study cellular system performance via simulation. These models have poor accuracy (15-20 dB STD error), but capture phenomena missing from formulas. Typically awkward for analysis