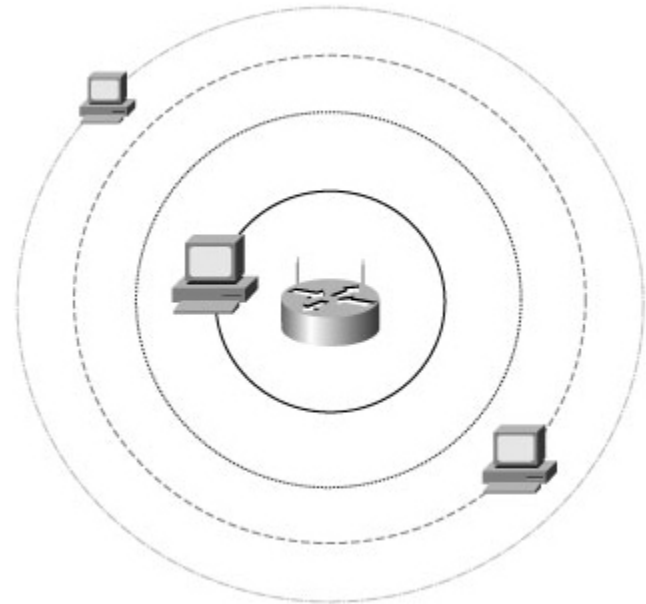


Lecture 2 Outline

- **Signal Propagation Overview**
- **TX and RX Signal Models**
 - **Complex baseband models**
- **Path Loss Models**
 - **Free-space Path Loss**
 - **Ray Tracing Models**
 - **Simplified Path Loss Model**
 - **Empirical Models**
- **Log Normal Shadowing**
- **Combined Path Loss and Shadowing**
- **Model Parameters from Measurements**

Pass Loss

- **Pass loss: degradation of receive power with respect to the increasing transmitter-receiver distance**

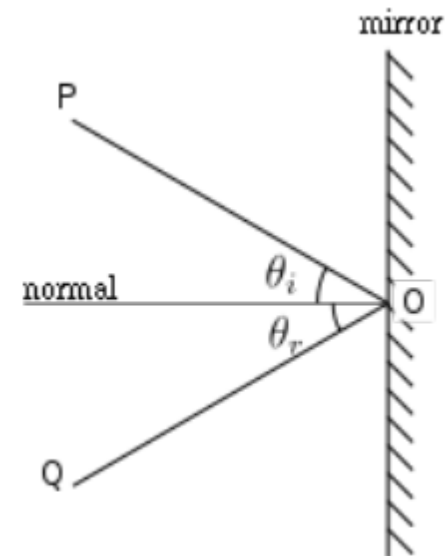


EM wave encounters an obstacle

- **Reflection**
- **Diffraction**
- **Scattering**
- **Absorption**

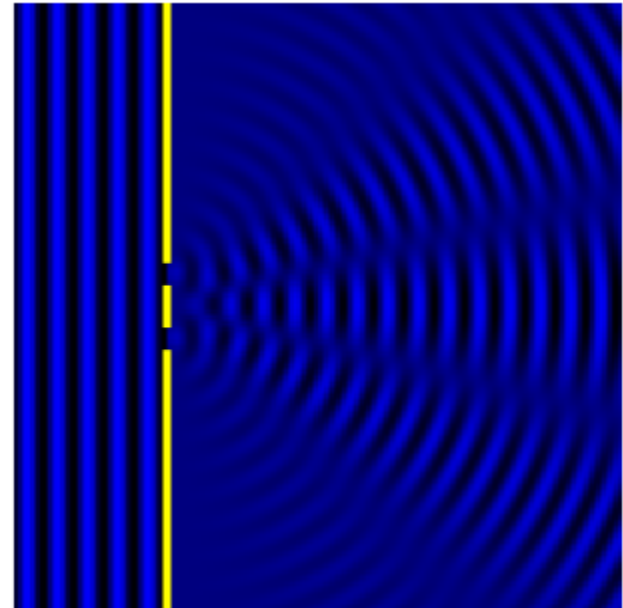
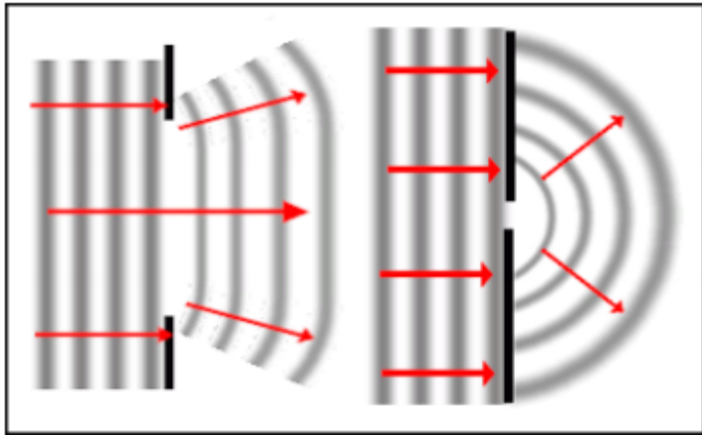
Reflection

- Wave hits an object with dimension much larger than the radio wavelength will be partially reflected off the surface of the object



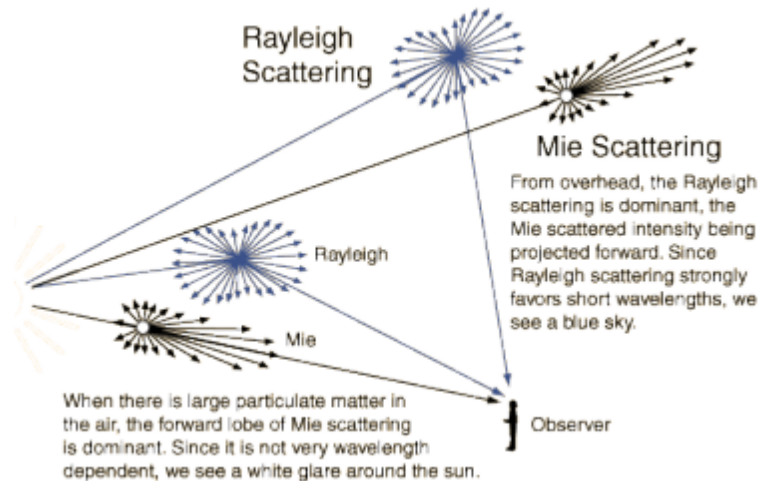
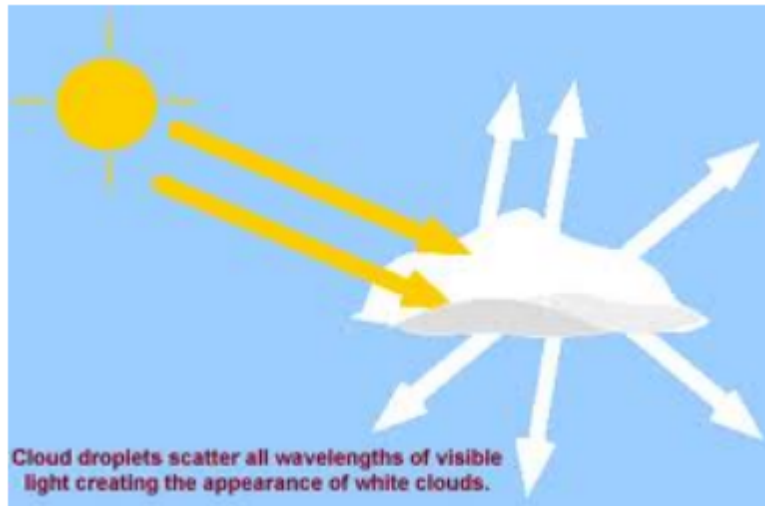
Diffraction

- Apparent bending of waves around small obstacles and the spreading out of waves past small openings



Scattering

- EM wave scattered by particles that are much smaller in diameter than the wavelength

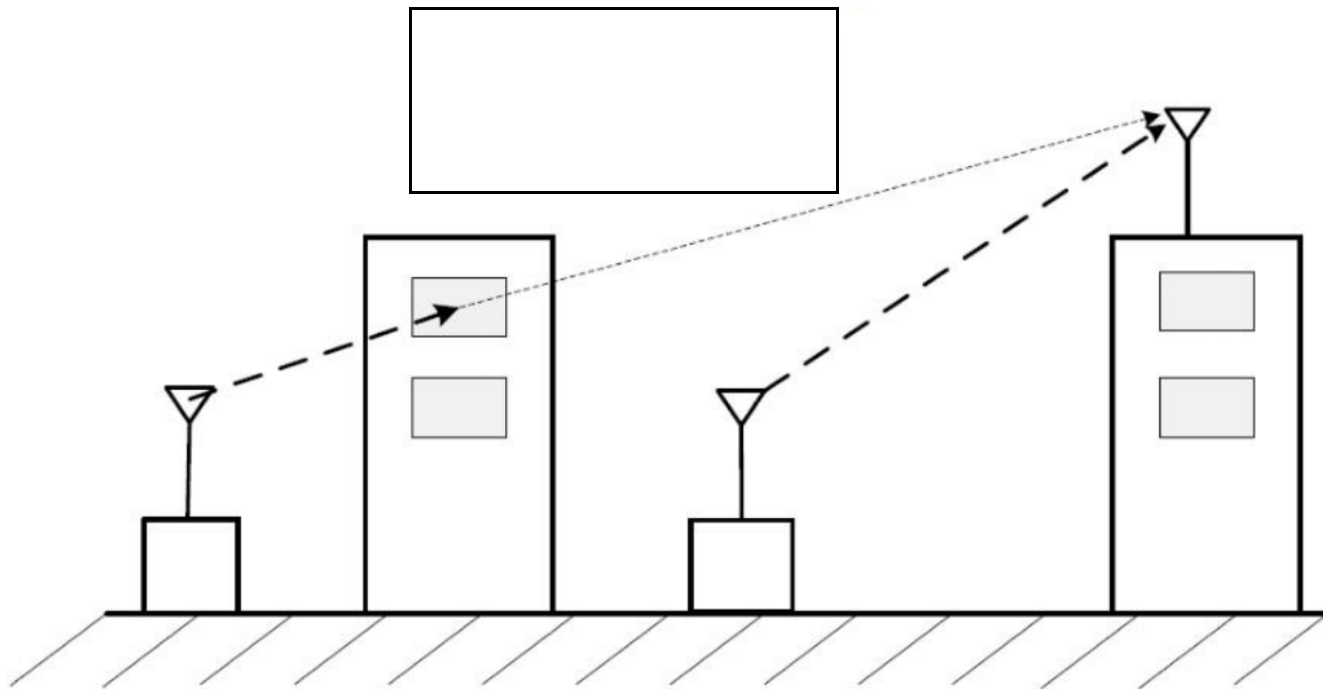


Absorption

- The absorption of EM wave is often called attenuation
- The energy of EM wave is taken up by some matter and transformed to other forms of energy, e.g., heat

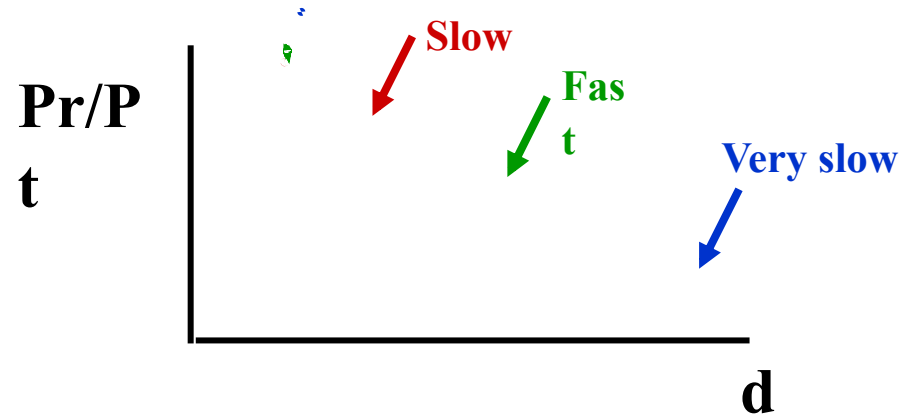
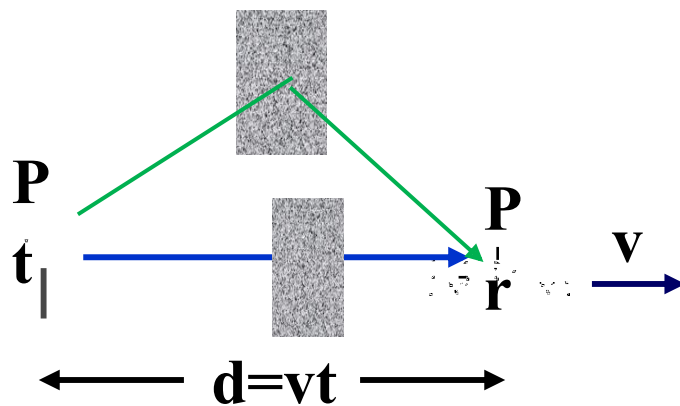
Shadowing

- **Shadowing: variation of receive signal power due to obstacles**



Propagation Characteristics

- Path Loss (includes average shadowing)
- Shadowing (due to obstructions)
- Multipath Fading -- small-scale propagation effect



Path Loss Modeling

- **Maxwell's equations**
 - Complex and impractical
- **Free space path loss model**
 - Too simple
- **Ray tracing models**
 - Requires site-specific information
- **Simplified power falloff models**
 - Main characteristics: good for high-level analysis
- **Empirical Models**
 - Don't always generalize to other environments

Representation of Bandpass Signals

- **Bandpass signal:**

$$s(t) = s_I(t) \cos(2\pi f_c t) - s_Q(t) \sin(2\pi f_c t)$$

- **$s_I(t)$ is in-phase component, $s_Q(t)$ is quadrature component**

- **Define a complex signal:** $u(t) = s_I(t) + js_Q(t)$

$$s(t) = \operatorname{Re}\{u(t)\} \cos(2\pi f_c t) - \operatorname{Im}\{u(t)\} \sin(2\pi f_c t) = \operatorname{Re}\{u(t)e^{j2\pi f_c t}\}$$

- **$u(t)$ is called equivalent lowpass signal for $s(t)$**

Free Space (LOS) Model

- Path loss and path gain:

- Path loss:

$$P_r = P_t - \text{Path Loss (dB)} = 10 \log \left(\frac{P_r}{P_t} \right)$$

- Path gain:

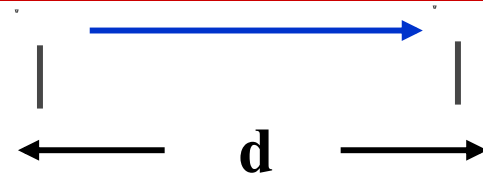
- Power falls off: $P_r = P_t - \text{Path Loss (dB)} = 10 \log \left(\frac{P_r}{P_t} \right)$

$$s(t) = \text{Re}\{u(t)e^{j2\pi f_c t}\}$$

$$r(t) = \text{Re}\left\{\frac{\lambda\sqrt{G_l}e^{-j2\pi d/\lambda}}{4\pi d}u(t)e^{j2\pi f_c t}\right\}$$

$$\frac{P_r}{P_t} = \left[\frac{\sqrt{G_l}\lambda}{4\pi d}\right]^2$$

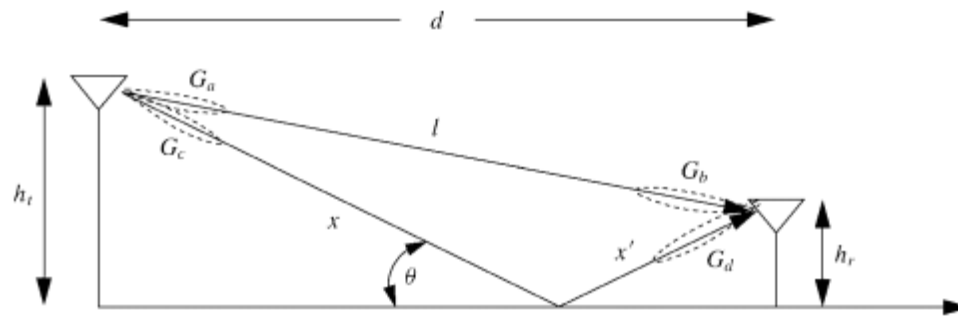
- G_l is the product of tx and rx antenna field radiation pattern in the LOS direction
- Proportional to $1/d^2$



Ray Tracing Approximation

- Rx contains multipath signal components
- Ray tracing:
 - Assume a finite number of reflectors with known location and dielectric property
 - Then, the received signal from each signal component can be calculated
 - Typically includes reflected rays, can also include scattered and diffracted rays.
- Accurate for rural area, city street and indoor environment

Two Path Model



- Path loss for one LOS path and one ground (or reflected) bounce
- Delay spread: $(x+x'-l)/c$

$$P_r = P_t \left[\frac{\lambda}{4\pi} \right]^2 \left| \frac{\sqrt{G_l}}{l} + \frac{R\sqrt{G_r}e^{-j\Delta\phi}}{x+x'} \right|^2, \quad \Delta\phi = \frac{2\pi(x+x'-l)}{\lambda} \approx \frac{4\pi h_t h_r}{\lambda d}$$

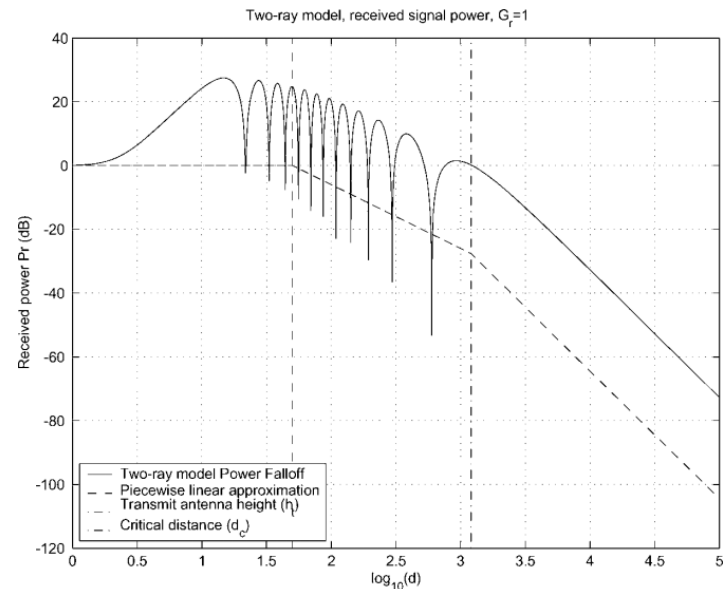
$$P_r \approx \left[\frac{\lambda\sqrt{G_l}}{4\pi d} \right]^2 \left[\frac{4\pi h_t h_r}{\lambda d} \right]^2 P_t = \left[\frac{\sqrt{G_l} h_t h_r}{d^2} \right]^2 P_t$$

Two Path Model

- Ground bounce approximately cancels LOS path above critical distance

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

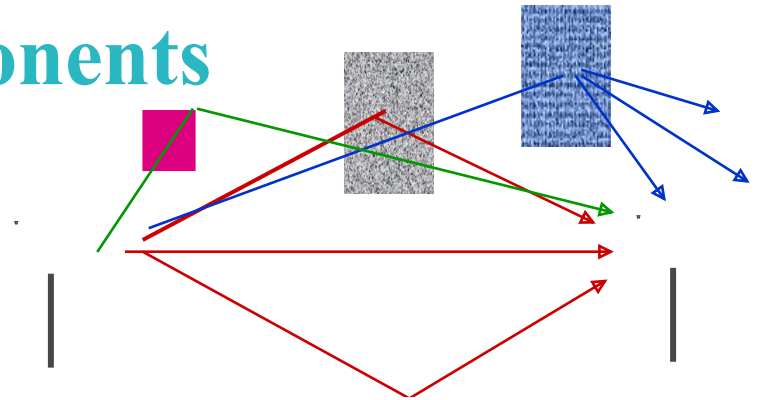
- Power falls off
 - Proportional to d^2 (small d)
 - Proportional to d^4 ($d > d_c$)
 - Independent of l (f)



General Ray Tracing

- Models all signal components

- **Reflections**
- **Scattering**
- **Diffraction**



- Requires detailed geometry and dielectric properties of site
 - Similar to Maxwell, but easier math.
- Computer packages often used

Simplified Path Loss Model

- Used when path loss dominated by reflections.
- Most important parameter is the path loss exponent γ , determined empirically.

$$P_r = P_t K \left[\frac{d_0}{d} \right]^\gamma$$

where $K \text{ dB} = 20 \log_{10} \frac{\lambda}{4\pi d_0}$, is achieved from free-space model

Indoor Propagation Model

- Indoor model differ widely in the materials used for walls and floors, the layout of rooms, windows and obstructing objects
- Difficult to find generic models

$$P_r \text{ dBm} = P_t \text{ dBm} - P_L(d) - \sum_{i=1}^{N_f} \text{FAF}_i - \sum_{i=1}^{N_p} \text{PAF}_i$$

FAF: floor attenuation factor (8-20dB)

PAF: partition attenuation factor

Table 2.1: Typical partition losses

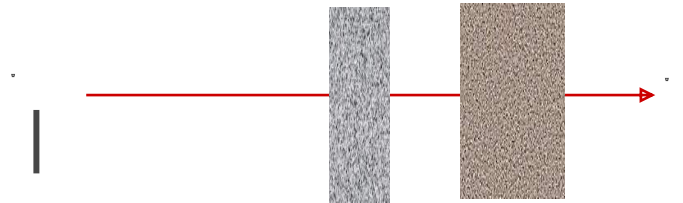
Partition type	Partition loss (dB)
Cloth partition	1.4
Double plasterboard wall	3.4
Foil insulation	3.9
Concrete wall	13
Aluminum siding	20.4
All metal	26

Empirical Channel Models

- **Cellular Models: Okumura model and extensions:**
 - Empirically based (site/freq specific)
 - Awkward (uses graphs)
 - Hata model: Analytical approximation to Okumura
 - Cost 231 Model: extends Hata to higher freq. (2 GHz)
 - Walfish/Bertoni: extends Cost 231 to include diffraction
- **WiFi channel models: TGn**
 - Empirical model for 802.11n developed within the IEEE standards committee. Free space loss up to a breakpoint, then slope of 3.5. Breakpoint is empirically-based.

Commonly used in cellular and WiFi system simulations

Shadowing



- Models attenuation from obstructions
- Random due to random # and type of obstructions

$$p(\psi_{\text{dB}}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{\text{dB}}}} \exp\left[-\frac{(\psi_{\text{dB}} - \mu_{\psi_{\text{dB}}})^2}{2\sigma_{\psi_{\text{dB}}}^2}\right]$$

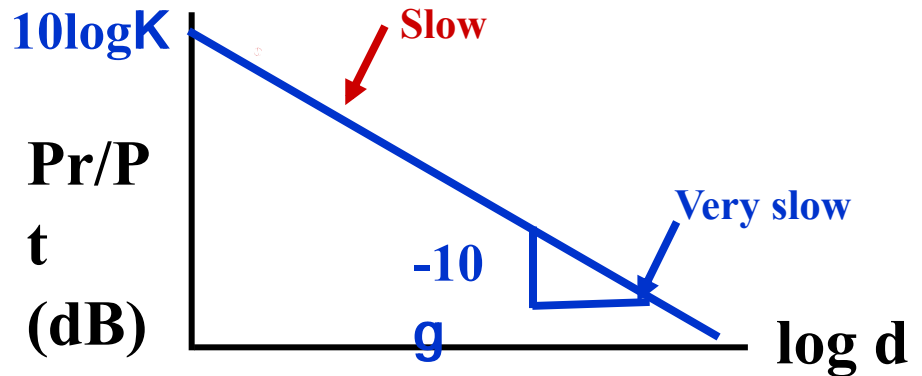
$$p(\psi) = \frac{\xi}{\sqrt{2\pi}\sigma_{\psi_{\text{dB}}}\psi} \exp\left[-\frac{(10\log_{10}\psi - \mu_{\psi_{\text{dB}}})^2}{2\sigma_{\psi_{\text{dB}}}^2}\right], \quad \psi > 0,$$

- Typically follows a log-normal distribution
 - dB value of power is normally distributed
 - $m=0$ (mean captured in path loss), $4\text{ dB} < s < 13\text{ dB}$ (empirical)
 - Central limit theorem can be used to explain this model

Combined Path Loss and Shadowing

- Linear Model: y lognormal

$$\frac{P_r}{P_t} = K d^{-\alpha}$$



- dB Model

$$\frac{P_r}{P_t} (dB) = 10 \log_{10} K - 10 \log_{10} d^{\alpha}$$

Outage Probability

- Path loss: circular cells
- Path loss + shadowing: amoeba cells
 - Tradeoff between coverage and interference
- Outage probability
 - Probability received power below given minimum

$$P_{\text{out}}(P_{\text{min}}, d) = p(P_r(d) < P_{\text{min}})$$

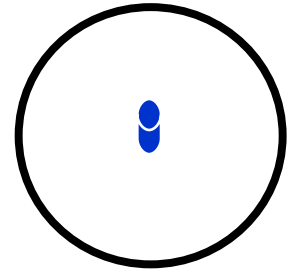
$$p(P_r(d) \leq P_{\text{min}}) = 1 - Q\left(\frac{P_{\text{min}} - (P_t + 10 \log_{10} K - 10\gamma \log_{10}(d/d_0))}{\sigma_{\psi \text{ dB}}}\right)$$

$$Q(z) \triangleq p(X > z) = \int_z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy.$$

Cell Coverage Area

- Cell coverage area

- % of cell locations at desired power
- Increases as shadowing variance decreases
- Large % indicates interference to other cells



Main Points

- Path loss models simplify Maxwell's equations
- Models vary in complexity and accuracy
- Power falloff with distance is proportional to d^2 in free space, d^4 in two path model
- Main characteristics of path loss captured in simple model $P_r = P_t K [d_0/d]^g$
- Empirical models used in simulations
 - Low accuracy (15-20 dB std)
 - Capture phenomena missing from formulas
 - Can be awkward to use in analysis

Main Points

- Random attenuation due to shadowing modeled as log-normal (empirical parameters)
- Combined path loss and shadowing leads to outage and amoeba-like cell shapes
- Cellular coverage area dictates the percentage of locations within a cell that are not in outage

Assignment

- Read Chapter 2
- Homework: 2-2, 2-13, 2-17, 2-19