Wireless Physical Layer Concepts: Part II

Raj Jain
Professor of CSE
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

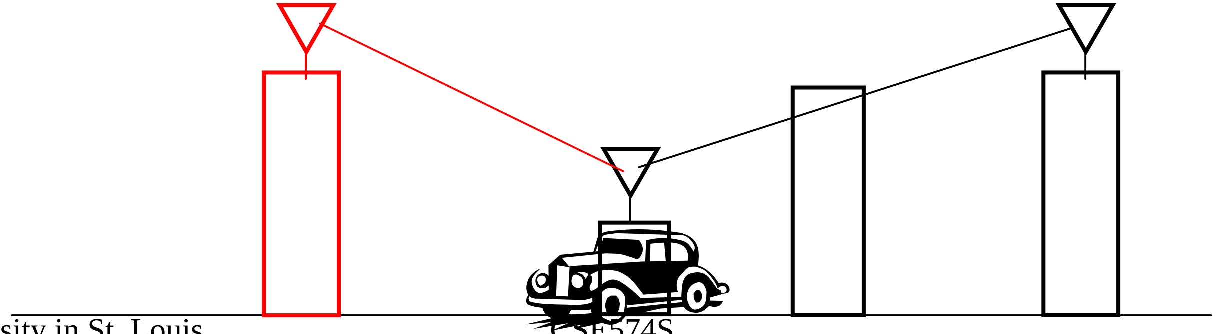
Audio/Video recordings of this lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-10/

Overview

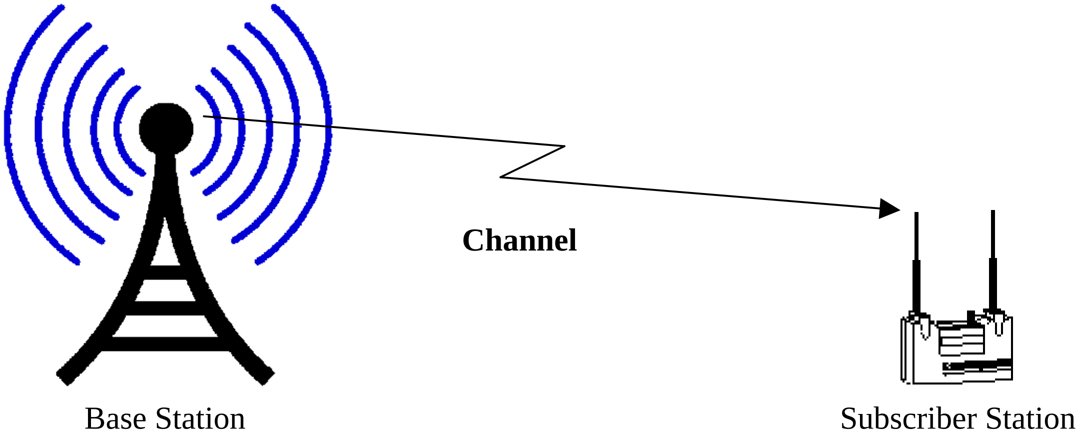
- Channel Model
- Path Loss, Fading, Shadowing, Noise
- d^{-4} Power Law
- Fresnel Zones
- Tapped Delay Line Model
- Doppler Spread

Wireless Radio Channel

- Path loss: Depends upon distance and frequency
- Noise
- Shadowing: Obstructions
- Frequency Dispersion (Doppler Spread) due to motion
- Interference
- Multipath: Multiple reflected waves
- Inter-symbol interference (ISI) due to dispersion



Channel Model



- Power profile of the received signal can be obtained by *convolving* the power profile of the transmitted signal with the impulse response of the channel.
- Convolution in time = multiplication in frequency
- Signal x, after propagation through the channel H becomes y:

$$y(f)=H(f)x(f)+n(f)$$

- Here $H(f)$ is **channel response**, and $n(f)$ is the noise. Note that x, y, H, and n are all functions of the signal frequency f.

Path Loss

- Power is distributed equally to spherical area $4\pi\ d^2$
- The received power depends upon the wavelength
- If the Receiver collects power from area A_R:

$$P_R = P_T G_T \frac{1}{4\pi d^2} A_R$$

- Receiving Antenna Gain

$$G_R = \frac{4\pi}{\lambda^2} A_R$$

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

- This is known as Frii's Law.
  Attenuation in free space increases with frequency.

Path Loss (Cont)

- In practice the distance exponent is higher: 3.5 to 5.5 (after a breakpoint)

$$P_R = P_R(d_{\text{break}}\left(\frac{d}{d_{\text{break}}}\right)^{-n}$$

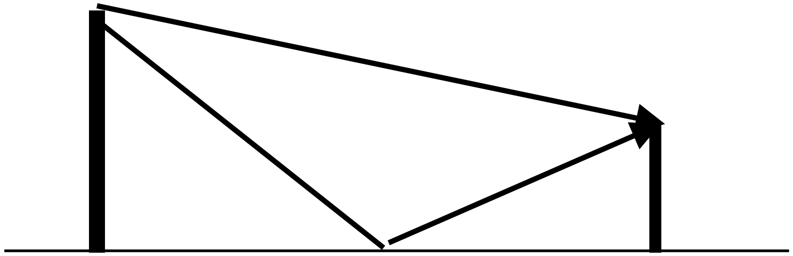
  - n ≈ 3.5 to 5.5

- In log scale:

$$P_R(d=1m) = P_T + G_T + G_R + 20\,log_{10}\left(\frac{\lambda}{4\pi}\right)$$

$$P_R(d) = P_R(1) - 20log_{10}d$$

d^{-4} Power Law



- Using a two-ray model

$$P_R = P_T G_T G_R \left(\frac{h_t h_r}{d^2}\right)^2$$

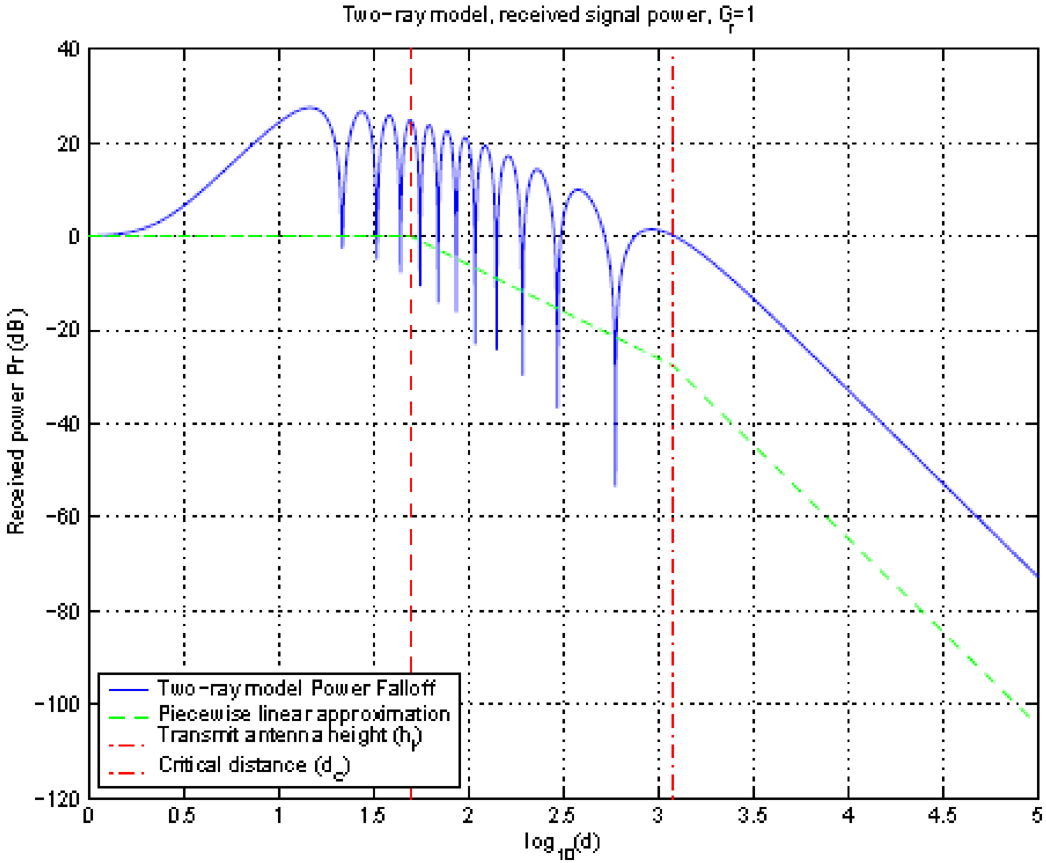
- Here, h_T and h_R are heights of transmit and receive antennas
- It is valid for distances larger than

$$d_{\text{break}} = 4 h_T h_R / \lambda$$

- Note that the received power becomes independent of the frequency.
- Measured results show n=1.5 to 5.5

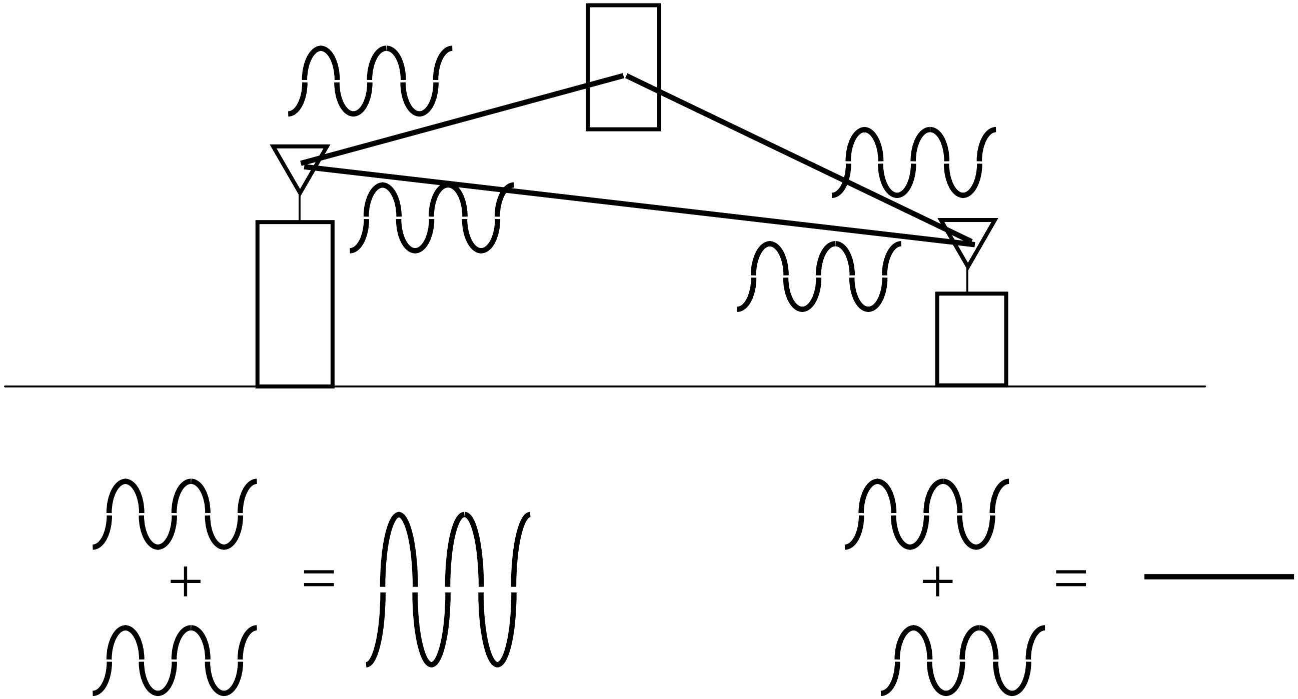
d^{-4} Power Law (Cont)

- The transition happens around 100m



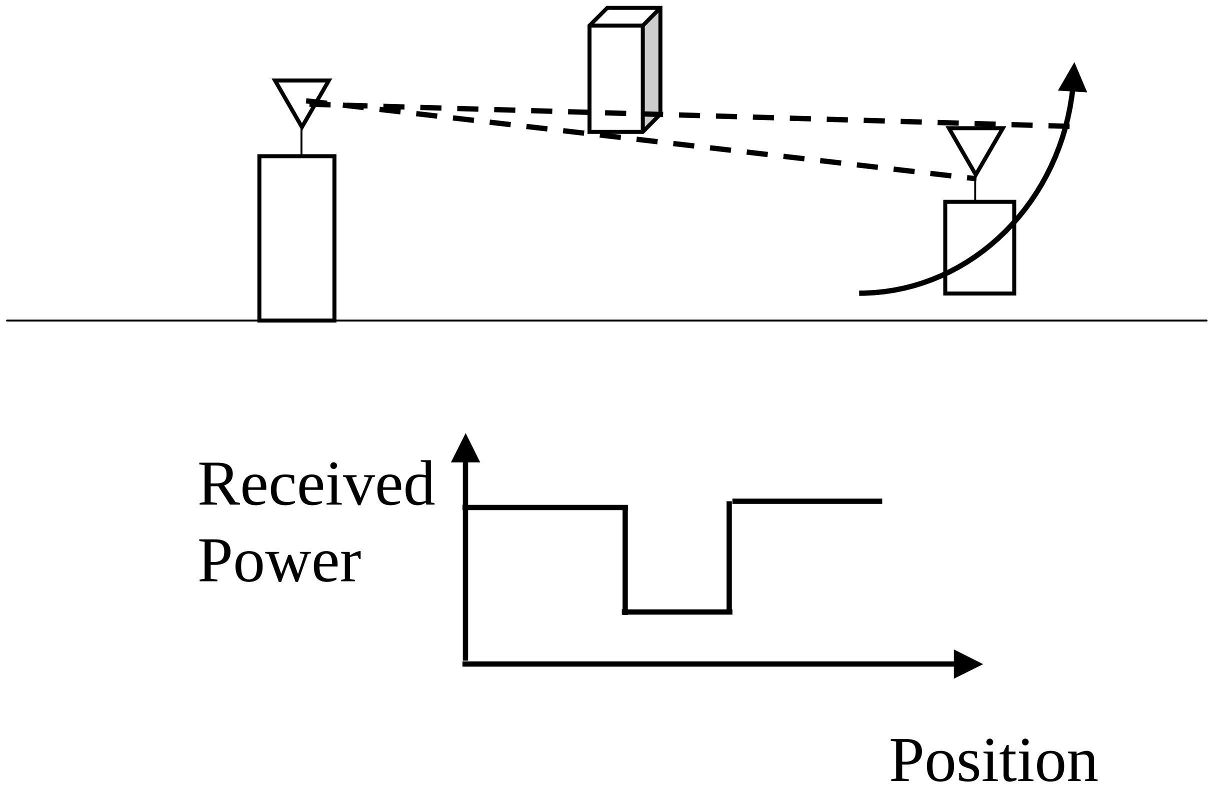
Small Scale Fading

- The signal amplitude can change by moving a few inches ⇒ Small scale fading



Large Scale Fading

- Shadowing gives rise to large scale fading



Shadowing

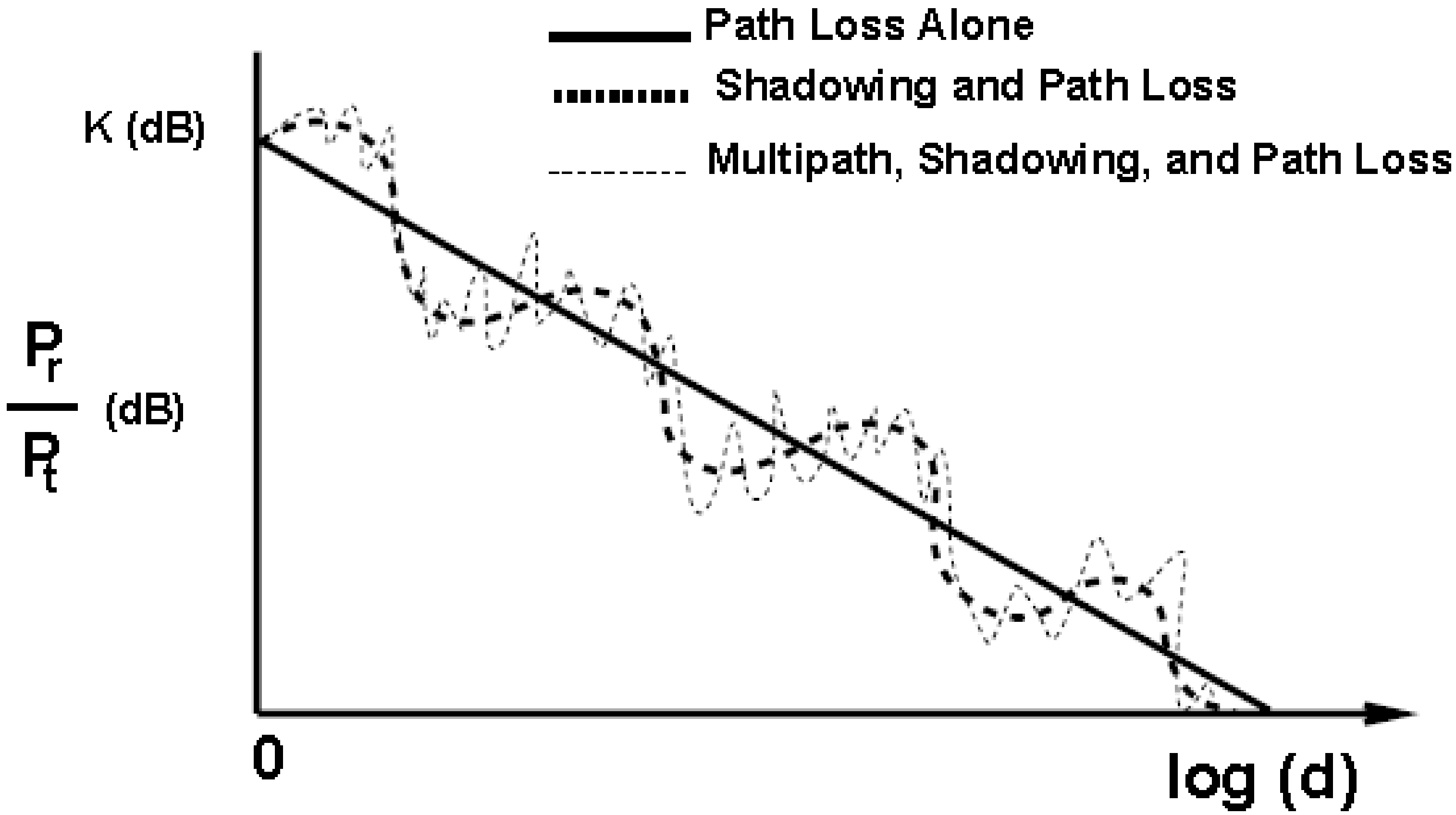
$$PL(d)\,dB = \overline{PL}(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) + \chi$$

- χ is a Gaussian random variable with standard deviation σ^2

χ

- Power received at the same distance may be random and has log normal distribution
- Log Normal Shadowing

Path Loss

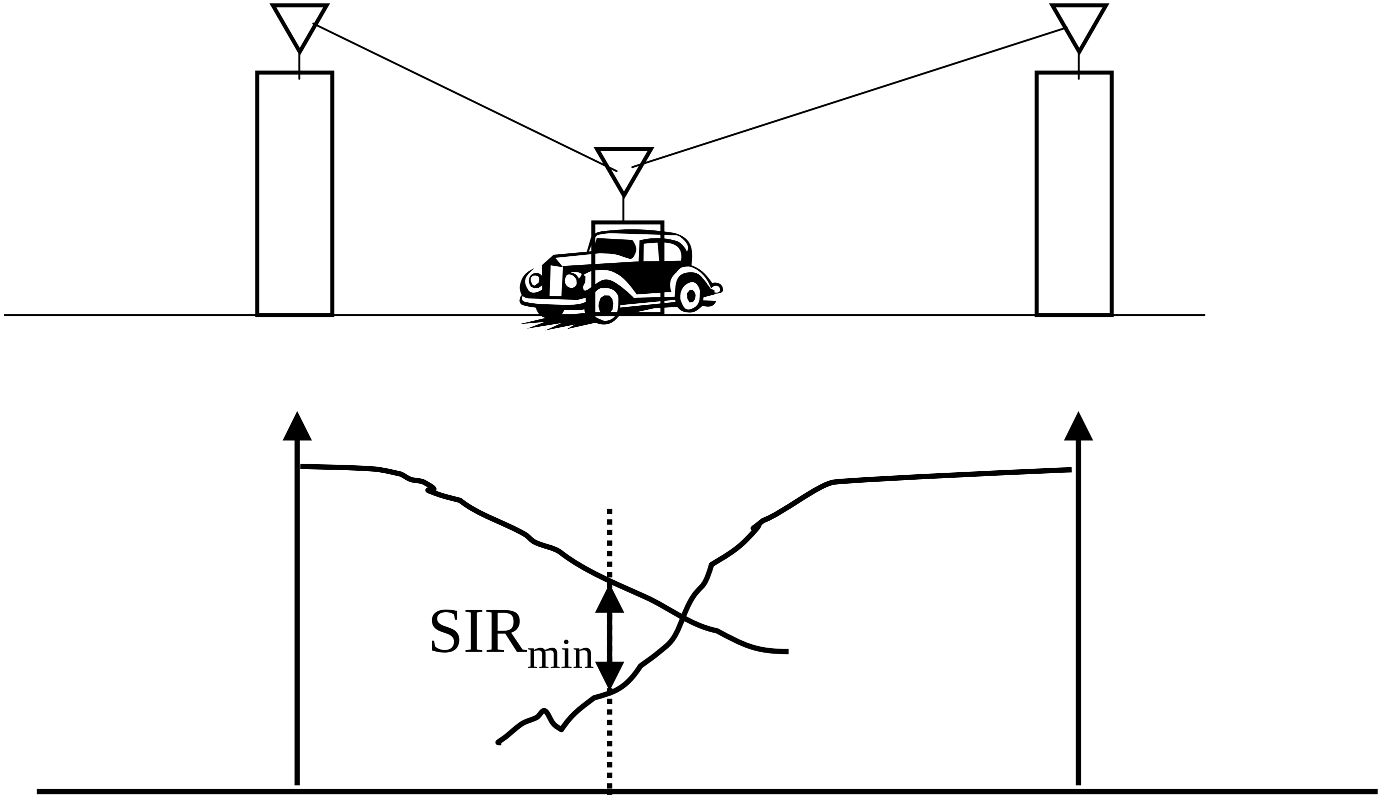

Path Loss Alone
Shadowing and Path Loss
Multipath, Shadowing, and Path Loss
K (dB)
$\frac{P_r}{P_t}$ (dB)
0
log (d)

Noise

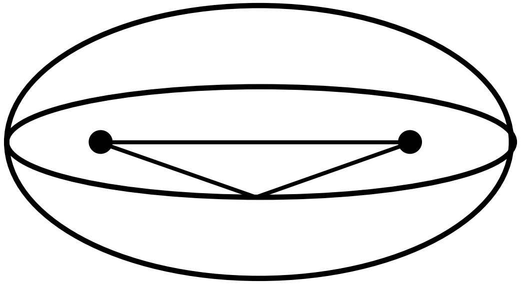
Noise consists of 3 components:

1. Thermal Noise: Proportional to absolute temperature
   - Noise Power Spectral Density $N_0 = k_B T$
   - Where, k_B = Boltzman's constant = 1.38×10^{-23} Joules/Kelvin
   - For a band of width B:
     - Noise Power $P_n = N_0 B = -174 + 10 \log_{10}(B)$ dBm at 300°K
2. Spurious Emissions: Car ignition and Electronic devices Decreases at higher frequencies. More noise in urban areas.
3. Receiver Noise: Amplifiers and mixers add noise.
   - Noise generated before the amplifiers also gets amplified

Interference Limited Systems



Fresnel Zones



- Draw an ellipsoid with BS and MS as Foci
- All points on ellipsoid have the same BS-MS run length
- Fresnel ellipsoids = Ellipsoids for which run length = LoS + iλ/2
- At the Fresnel ellipsoids results in a phase shift of i\pi
- Radius of the ith ellipsoid at distancd d_T from the transmitter and d_R from the receiver is $\sqrt{\frac{\imath\lambda d_T d_R}{d_T+d_R}}$
- Free space (d^2) law is followed up to the distance at which the first Fresnel Ellipsoid touches the ground

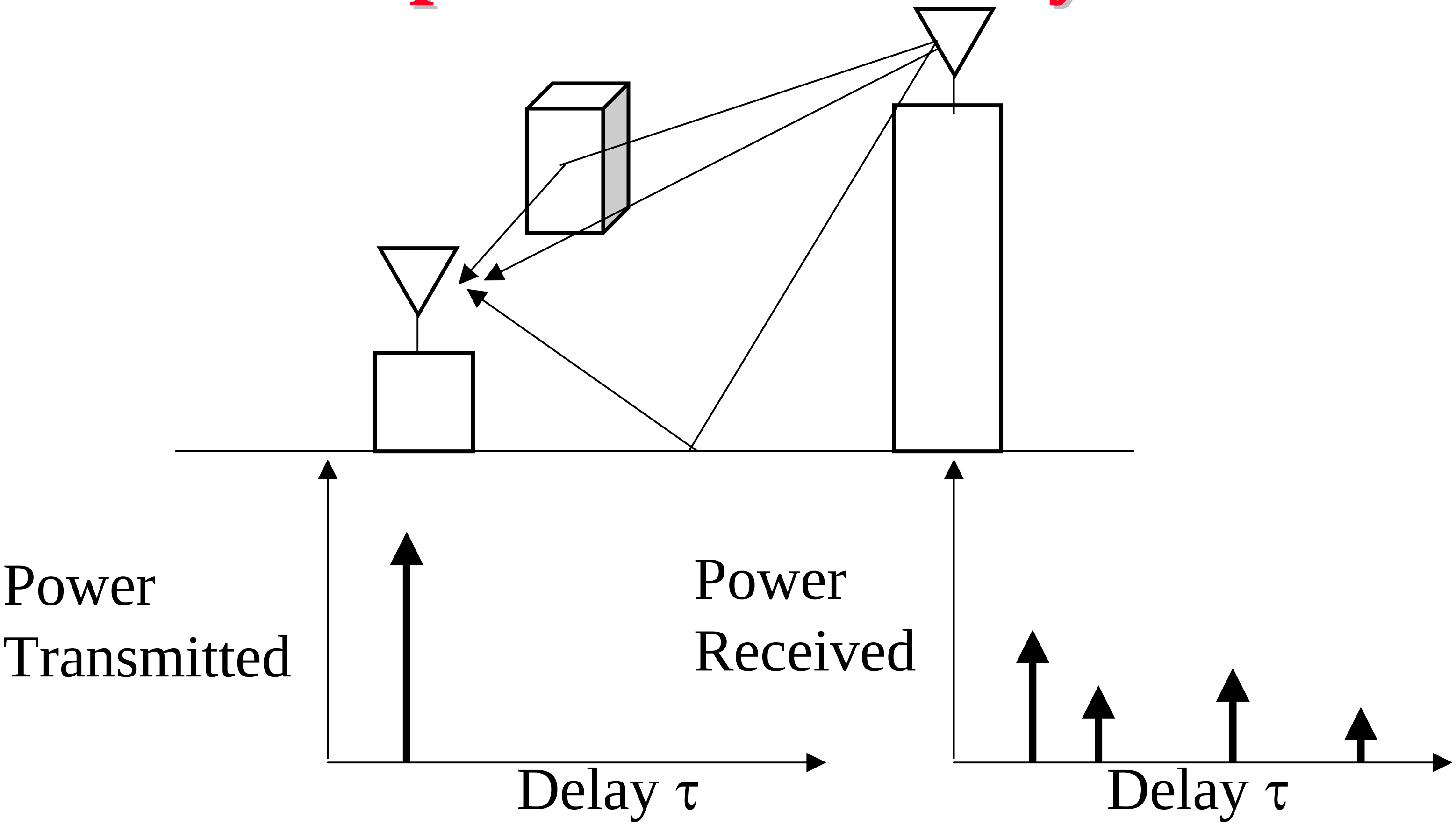
Link Budget

Transmitted Power $P_T = 30\text{W}$	$=$ 45 dBm
Cable Loss	$=$ -5 dB
Antenna Gain G_T	10 dB
EIRP (Equivalent Isotropically Radiated Power)	50 dBm

Receiver Sensitivity	-102 dBm
Fade Margin	12 dB
Minimum Received Power	-90 dBm

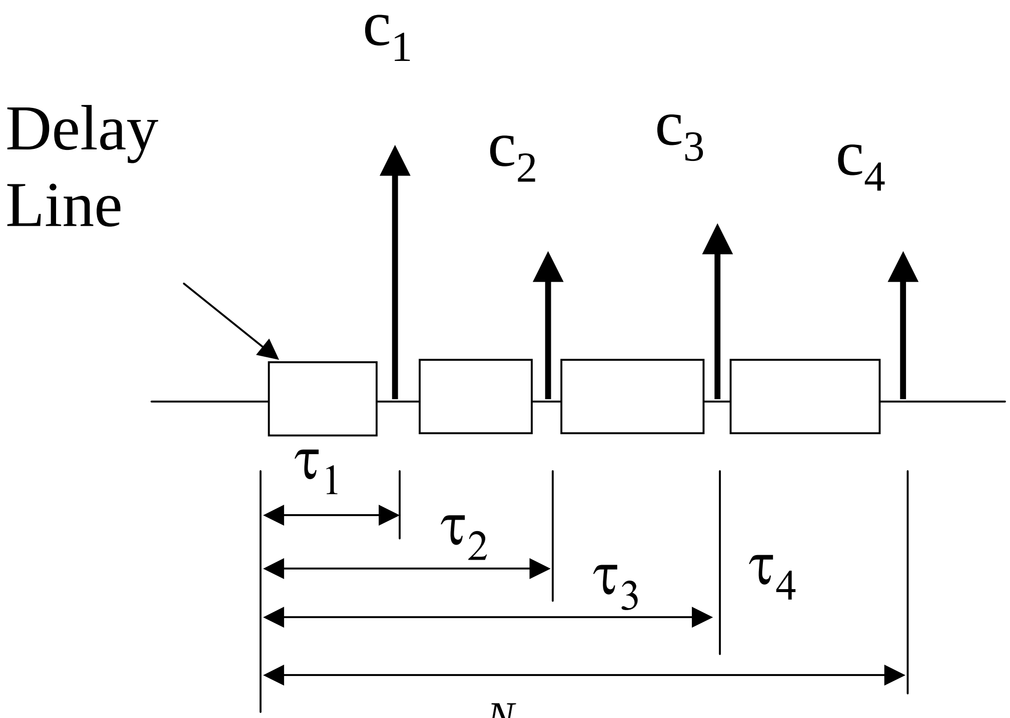
Allowable Path Loss	140 dB
Path loss at d_{break}=100m $\frac{\lambda}{4\pi d)^2}$	72 dB
Path loss beyond breakpoint $(d/100)^{-n}$	68 dB
Coverage distance $100 \times 10^{6.8/n}$	8.8 km if n=3.5

Multipath Power Delay Profile



- A single impulse results in multiple impulses at different times
- Delay Spread = Maximum delay after which the received signal becomes negligible = τ_{max}.

Tapped Delay Line Model



$$h(t,\tau) = \sum_{i=1}^{N} c_i(t)\delta(\tau - \tau_i)$$

- Coherence Time = Time for which channel remains same
- Coherence Bandwidth = Bandwidth for which channel remains same

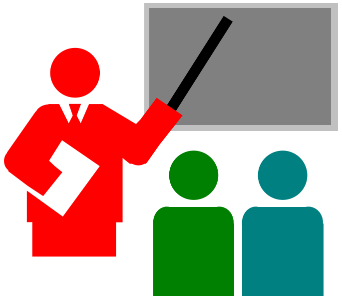
Doppler Spread

- ☐ Power Delay Profile of Channel = Power distribution over time for an impulse signal
- ☐ Doppler Power Spectrum = Power Distribution over frequency for a signal transmitted at one frequency
- ☐ Non-zero for ($f-f_D$ to $f+f_D$)
- ☐ Doppler spread = f_D
- ☐ Coherence Time = 1/Doppler Spread
- ☐ If the transmitter, receiver, or intermediate objects move very fast, the doppler spread is larege and coherence time is small

Typical Doppler Spread

Carrier Freq	Speed	Max Doppler Spread	Coherence Time
2.5 GHz	2 km/hr	4.6 Hz	200 ms
2.5 GHz	45 km/hr	104.2 Hz	10 ms
2.5 GHz	100 km/hr	231.5 Hz	4 ms
5.8 GHz	2 km/hr	10.7 Hz	93 ms
5.8 GHz	45 km/hr	241.7 Hz	4 ms
5.8 GHz	100 km/hr	537 Hz	2 ms

Summary



- Path loss increase at a power of 2 to 5.5 with distance.
- Fading = Changes in power changes in position
- Fresnel zones = Ellipsoid with distance of LoS+iλ/2
  Any obstruction of the first zone will increase path loss
- Coherence time = Time for which channel remains same
- Doppler Spread = Frequency Band over which channel remains same

Homework 4

- Determine the mean received power at a SS. The channel between a base station at 14 m and the subscriber stations at 4m at a distance of 500m. The Transmitter and Reciver antenna gains are 10dB and 5 dB respectively. Use a power exponent of 4. Transmitted power is 30 dBm.

References

- R. Jain, “**Channel Models Tutorial**,” http://www.cse.wustl.edu/~jain/cse574-08/ftp/channel_model_tutorial.pdf