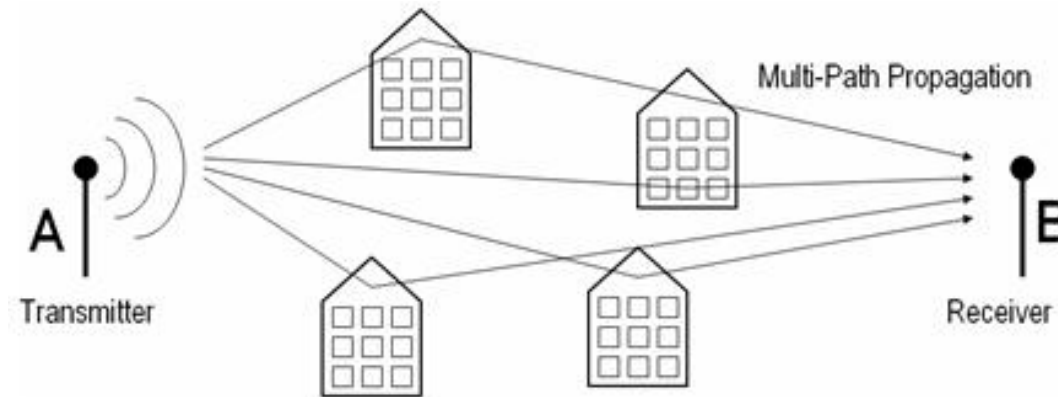# Introduction to Wireless Signal Propagation

**Raj Jain**

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Jain@cse.wustl.edu

Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-22/

**Student Questions**

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# Overview

1. Reflection, Diffraction, Scattering
2. Fading, Shadowing, multipath
3. Fresnel Zones
4. Multi-Antenna Systems, Beam forming, MIMO
5. OFDM

Note: This is the 2nd in a series of 2 lectures on wireless physical layer. Modulation, coding, Shannon's theorem, etc were discussed in the other lecture.

**Student Questions**

# 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

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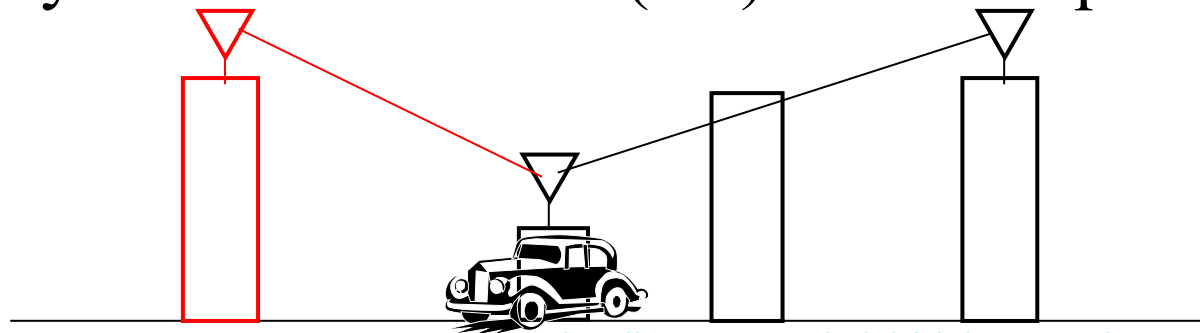
# Antenna

- Transmitter converts electrical energy to electromagnetic waves
- Receiver converts electromagnetic waves to electrical energy
- Same antenna is used for transmission and reception
- Omni-Directional: Power radiated in all directions
- Directional: Most power in the desired direction
- Isotropic antenna: Radiates in all directions equally
- Antenna Gain = Power at particular point/Power with Isotropic Expressed in dBi

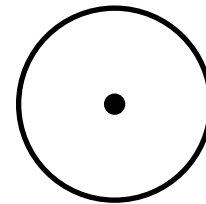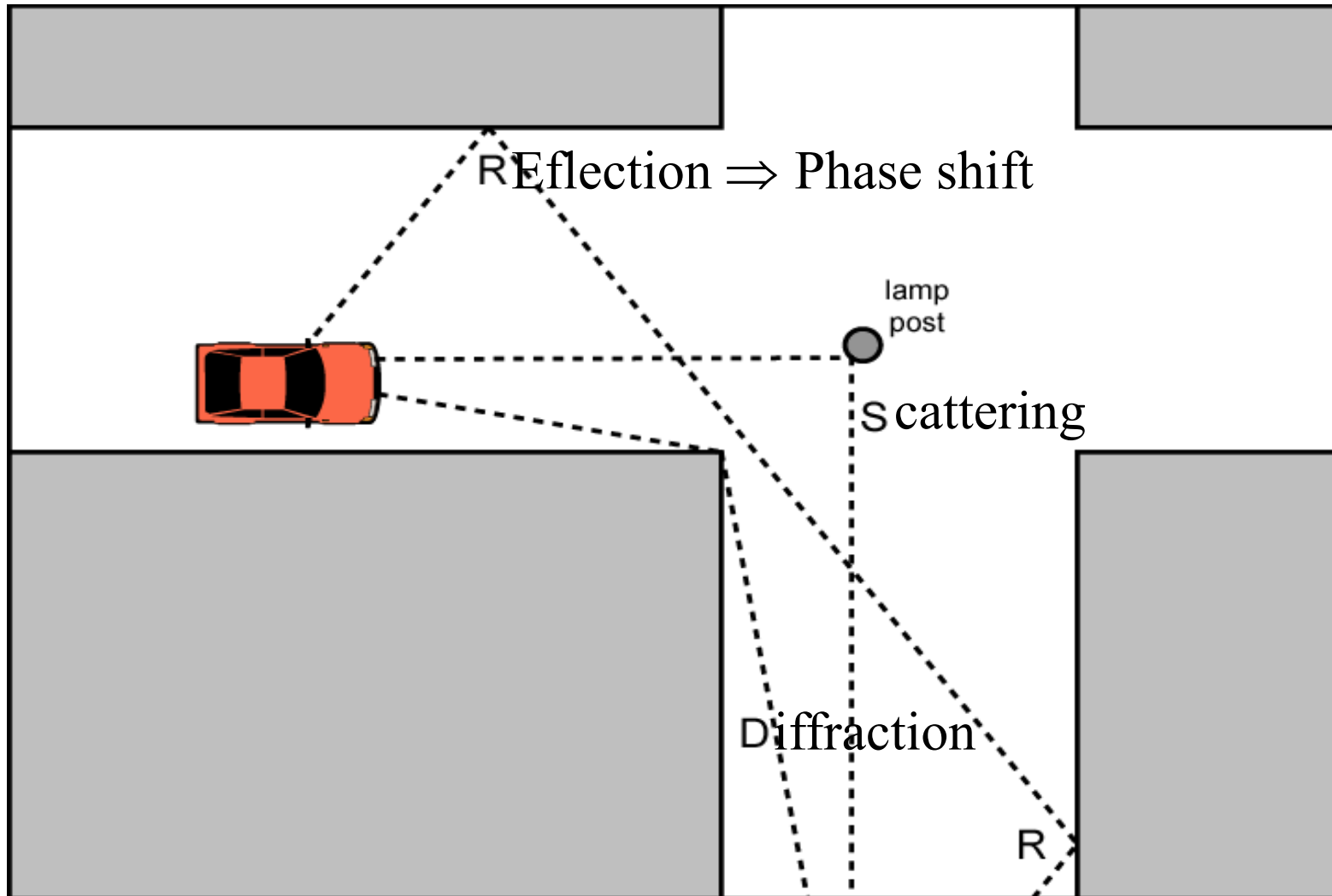$$P_r = P_t\, G_t\, G_r\, (\lambda/4\pi d)^2$$
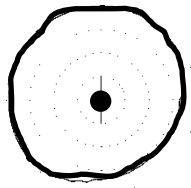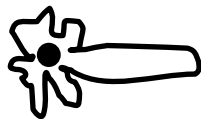
Omni-Directional      Directional      Isotropic

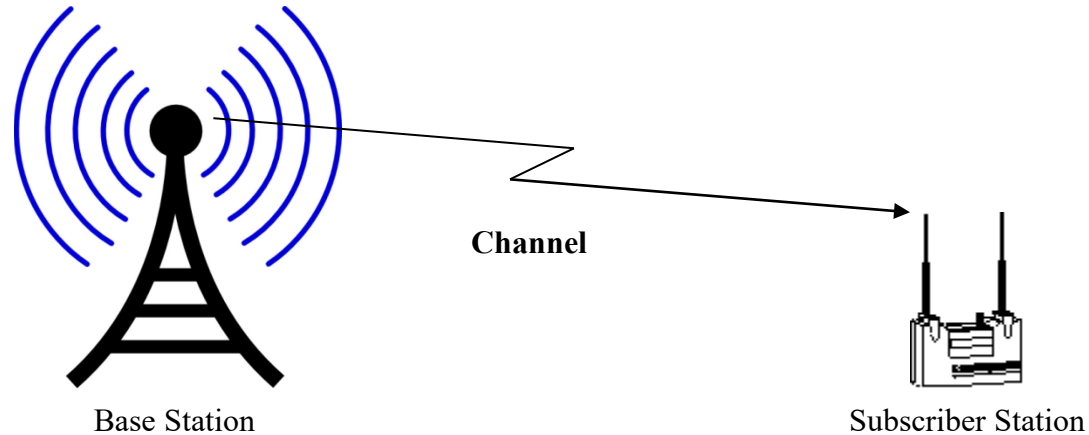**Student Questions**

# Reflection, Diffraction, Scattering



Reflection ⇒ Phase shift

Scattering

Diffraction

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# Reflection, Diffraction and Scattering (Cont)

- **Reflection**: Surface large relative to wavelength of signal
  - ➢ May have phase shift from original
  - ➢ May cancel out original or increase it
- **Diffraction**: Edge of impenetrable body that is large relative to λ
  - ➢ May receive signal even if no line of sight (LOS) to transmitter
- **Scattering**
  - ➢ Obstacle size on order of wavelength.  Lamp posts etc.
- If LOS, diffracted and scattered signals not significant
  - ➢ Reflected signals may be
- If no LOS, diffraction and scattering are primary means of reception

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# Channel Model

Base Station

Channel

Subscriber Station

❑ 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 $A_R$:

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

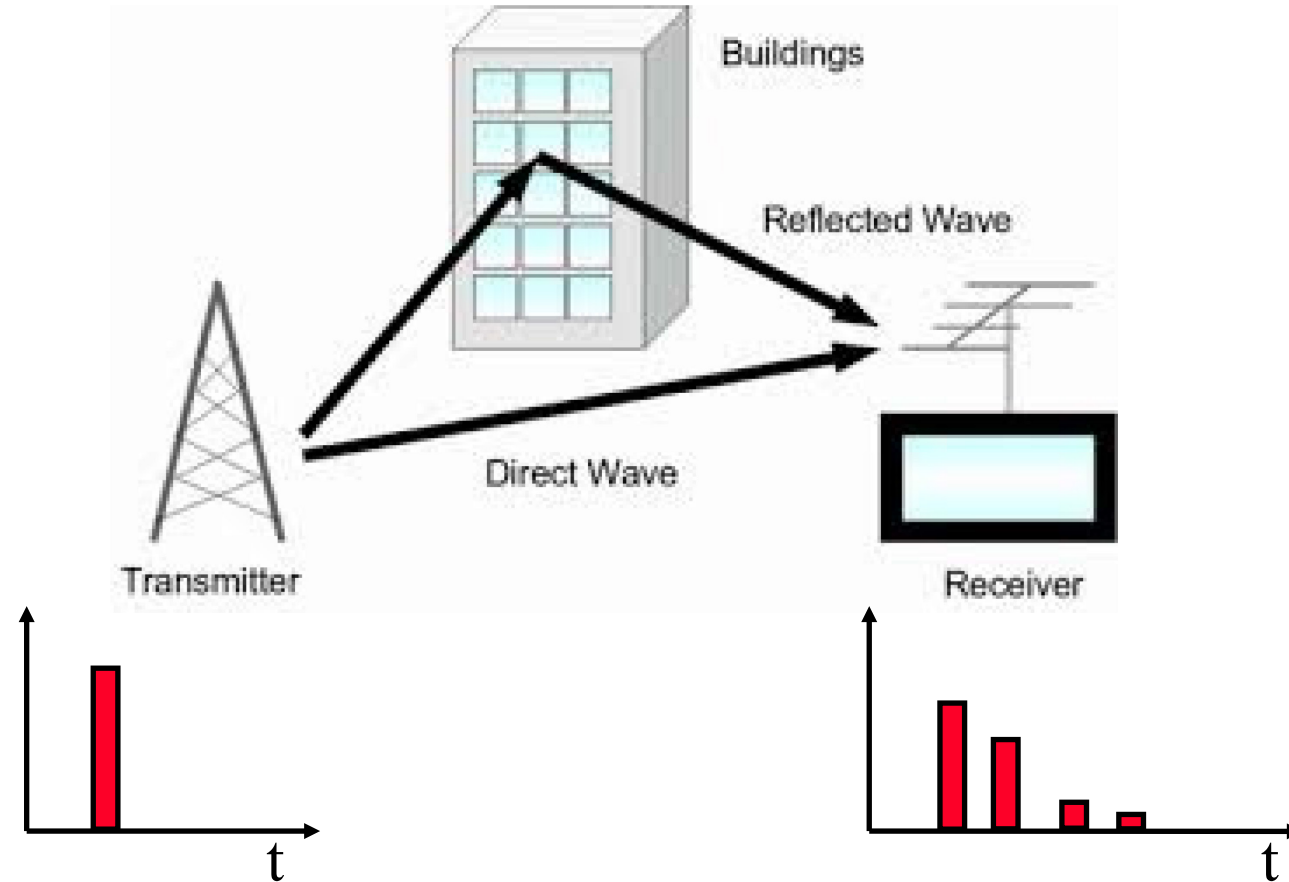❑ Receiving Antenna Gain

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

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

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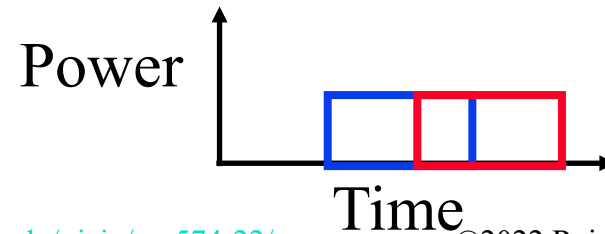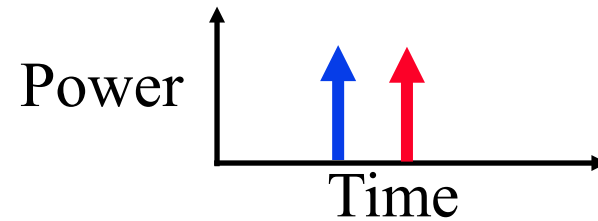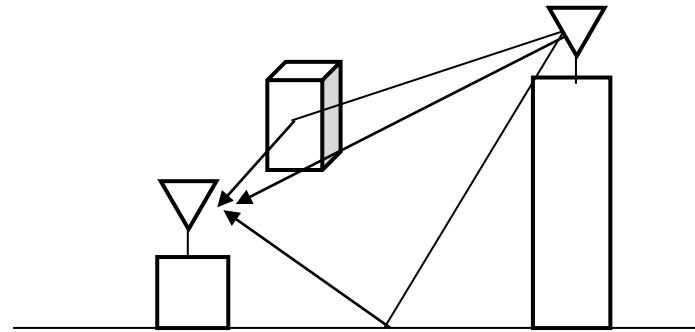Attenuation in free space increases with frequency.

**Student Questions**

# Multipath



Buildings

Reflected Wave

Direct Wave

Transmitter

Receiver

t

t

**Student Questions**

# Inter-Symbol Interference

Power

Time

Power

Time

❑ Symbols become wider
  ⇒ Limits the number of bits/s

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# **Multipath Propagation**



Transmitted pulse     Transmitted pulse

Time

Inter-symbol Interference

Received LOS pulse     Received multipath pulses     Received LOS pulse     Received multipath pulses
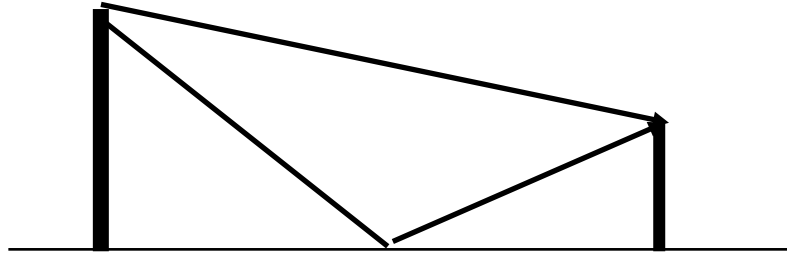
Time

- ❑ Delay Spread = Time between first and last versions of signal
- ❑ Fading: Fluctuation in amplitude, phase or delay spread
- ❑ Multipath may add constructively or destructively
  ⇒ Fast fading

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# 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
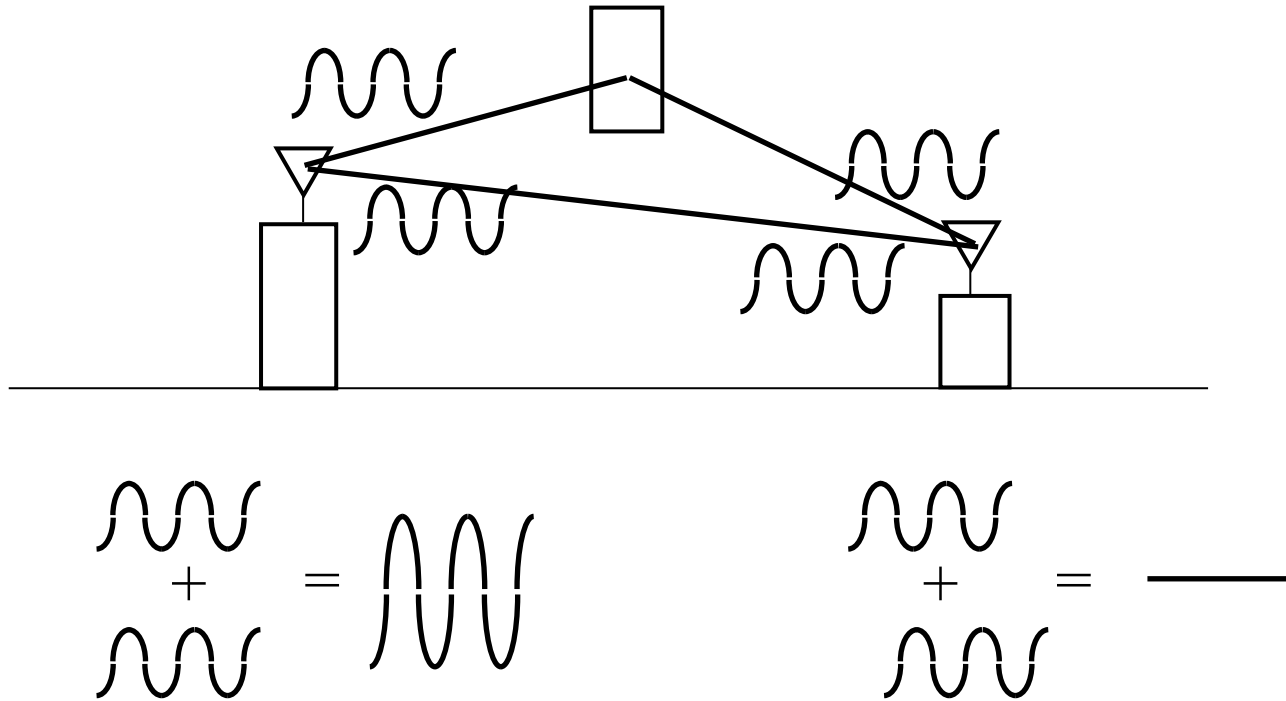
- It is valid for distances larger than

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

- Note that the received power becomes independent of the frequency.

- Measured results show n=1.5 to 5.5. Typically 4.

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# Small Scale Fading
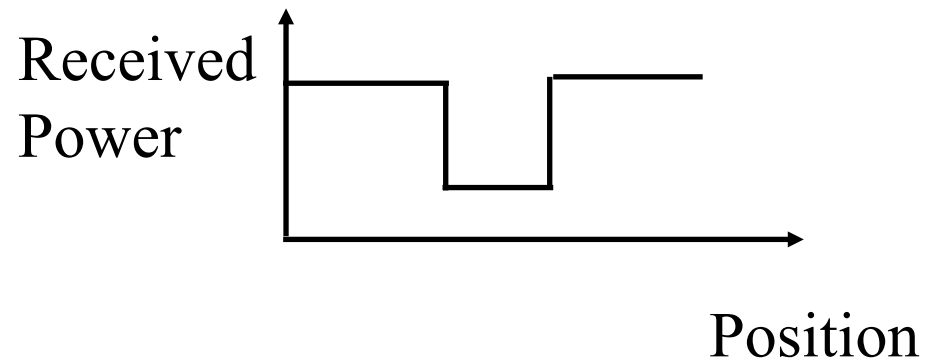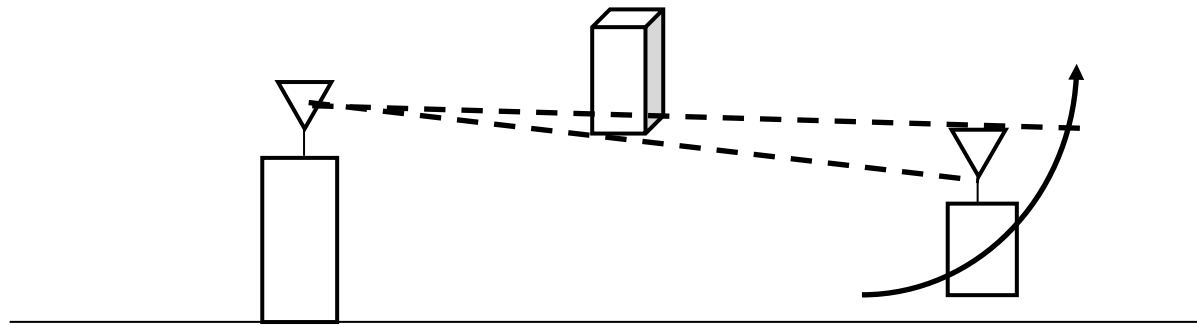
❑ The signal amplitude can change by moving a few inches ⇒ Small scale fading

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# Shadowing

❑ Shadowing gives rise to large scale fading

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**Student Questions**

# Total Path Loss



Legend:
- —— Path Loss Alone
- ▪▪▪▪▪▪ Shadowing and Path Loss
- --------- Multipath, Shadowing, and Path Loss

Axes: $K$ (dB), $\dfrac{P_r}{P_t}$ (dB) versus $\log(d)$

4-15
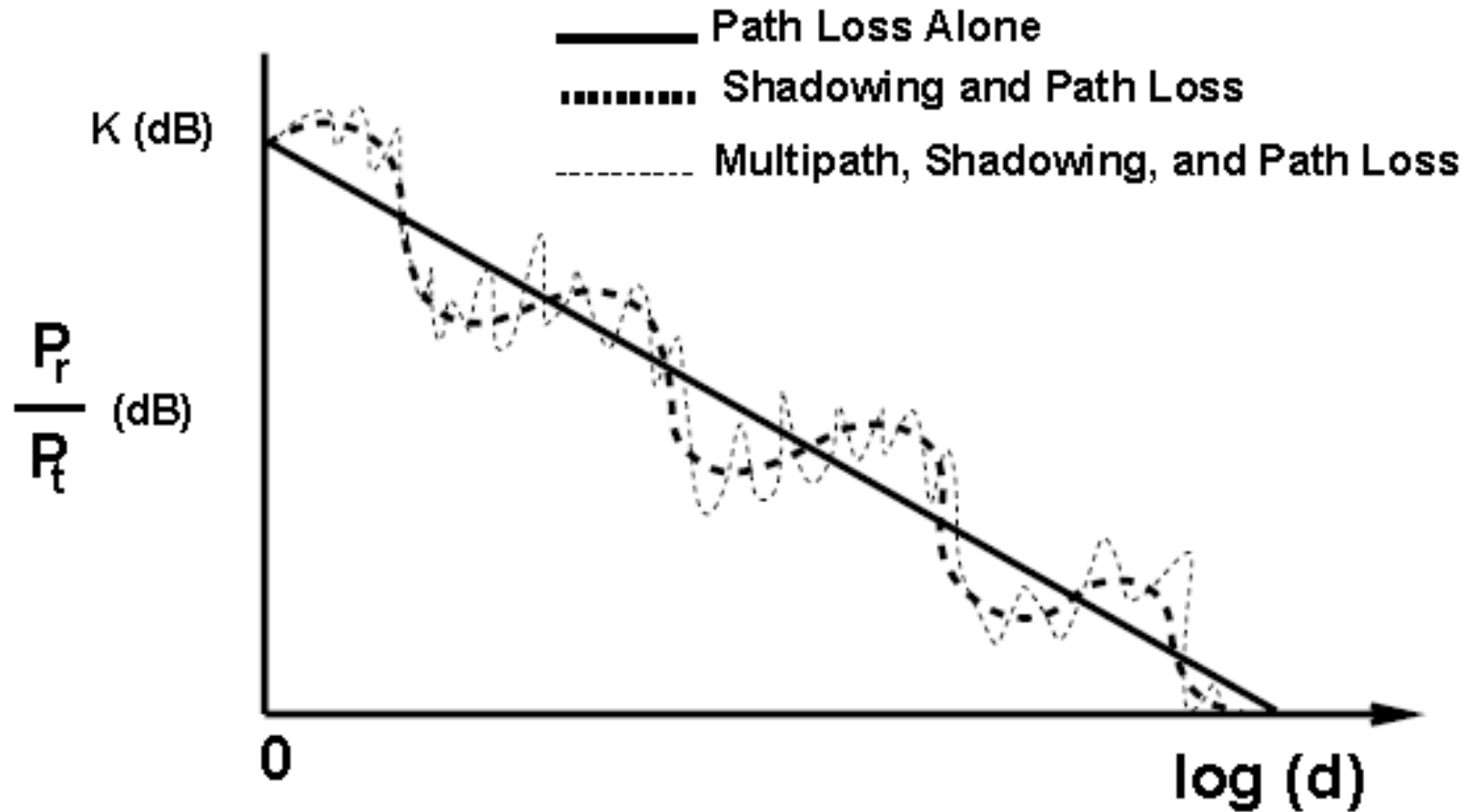
# Fresnel Zones
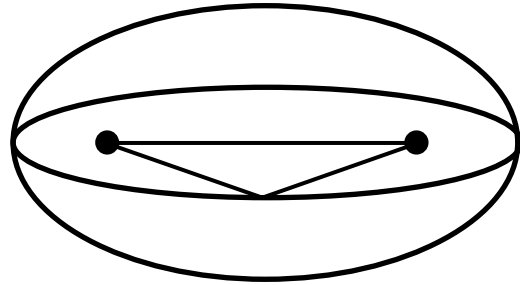


- ❑ Draw an ellipsoid with BS and MS as Foci
- ❑ All points on ellipsoid have the same BS-MS run length
- ❑ Fresnel ellipsoids = Ellipsoids for which run length
  = LoS + i$\lambda$/2
- ❑ At the Fresnel ellipsoids results in a phase shift of i\pi
- ❑ Radius of the $i^{\text{th}}$ ellipsoid at distance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

**Student Questions**
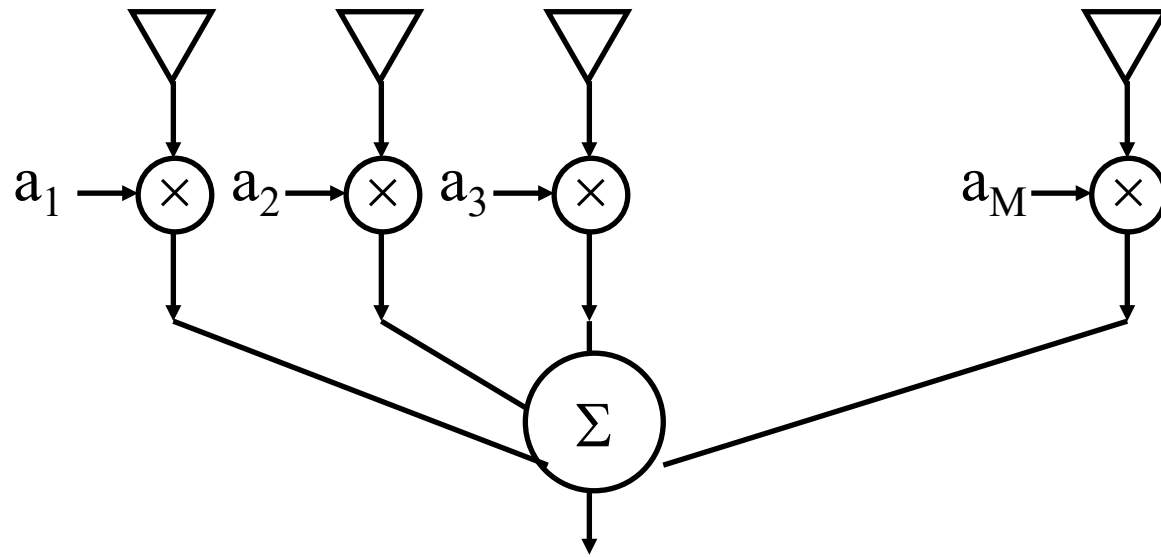
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# Multi-Antenna Systems

❑ Receiver Diversity

❑ Transmitter Diversity

❑ Beam forming

❑ MIMO

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# Receiver Diversity



- User multiple receive antenna
- Selection combining: Select antenna with highest SNR
- Threshold combining: Select the first antenna with SNR above a threshold
- Maximal Ratio Combining: Phase is adjusted so that all signals have the same phase. Then weighted sum is used to maximize SNR

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# Transmitter Diversity
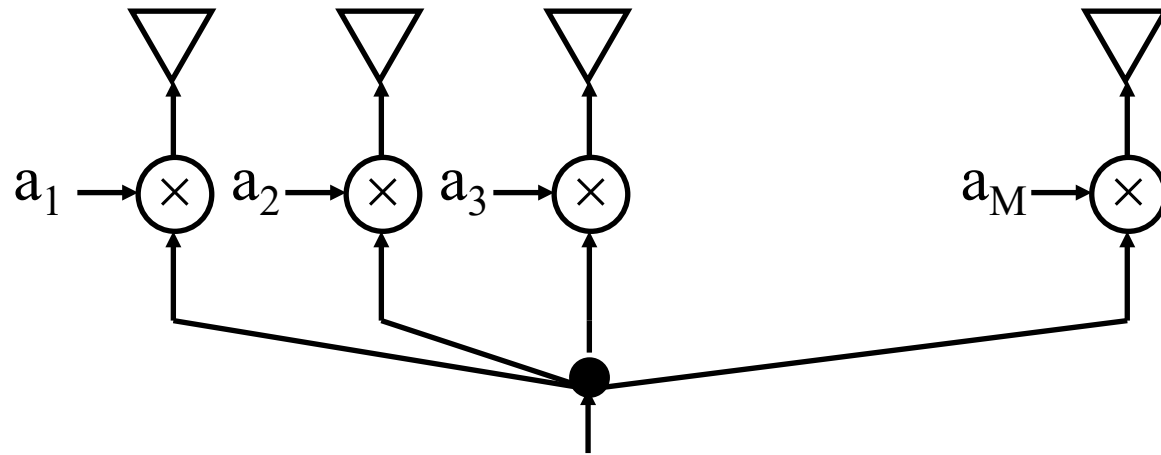


❑ Use multiple antennas to transmit the signal
ample space, power, and processing capacity at the transmitter
(but not at the receiver).

❑ If the channel is known, phase each component and weight it
before transmission so that they arrive in phase at the receiver
and maximize SNR

❑ If the channel is not known, use space time block codes

**Student Questions**

# Beam forming
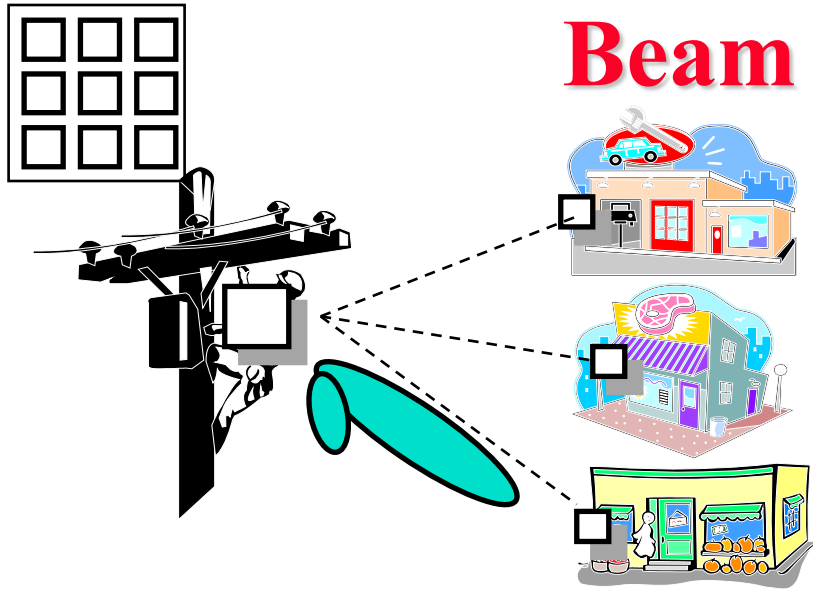
❑ Phased Antenna Arrays:
Receive the same signal using multiple antennas

❑ By phase-shifting various received signals and then summing $\Rightarrow$ Focus on a narrow directional beam

❑ Digital Signal Processing (DSP) is used for signal processing $\Rightarrow$ Self-aligning

# MIMO

❑ Multiple Input Multiple Output

❑ RF chain for each antenna

$\Rightarrow$ Simultaneous reception or transmission of multiple streams



2x3
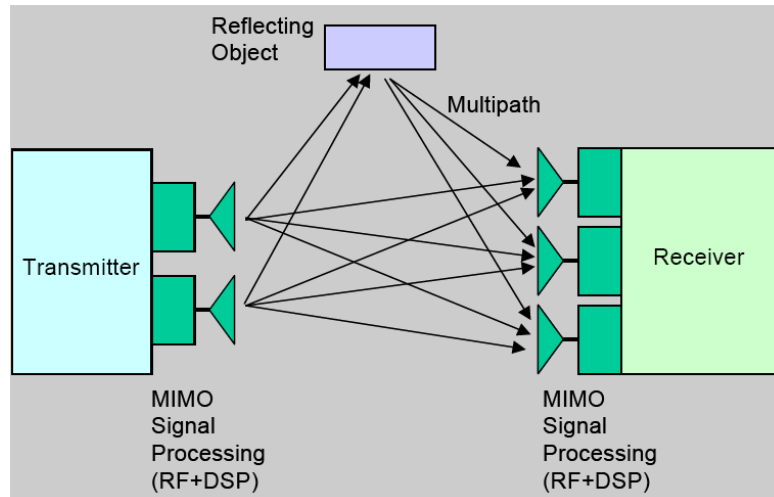
802.16e at 2.5 GHz, 10 MHz TDD, D:U=2:1

| T:R | 1x1 | 1x2 | 2x2 | 2x4 | 4x2 | 4x4 |
|-----|-----|-----|-----|-----|-----|-----|
| b/Hz | 1.2 | 1.8 | 2.8 | 4.4 | 3.7 | 5.1 |

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# Multiple Access Methods
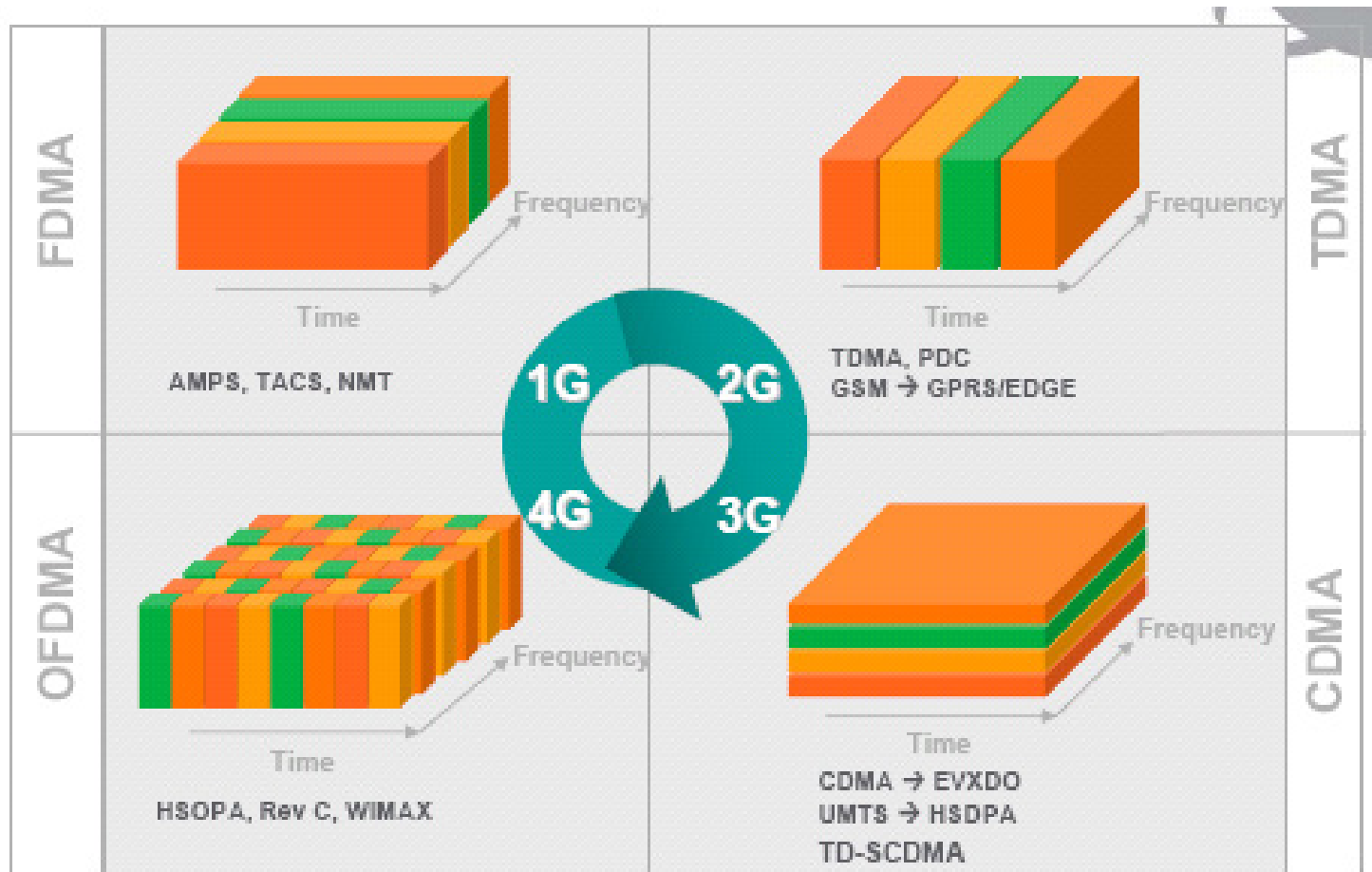


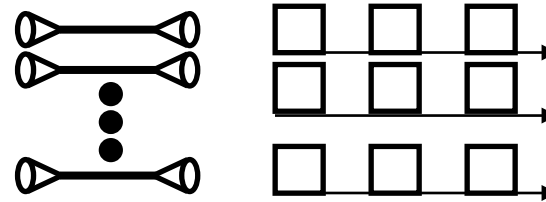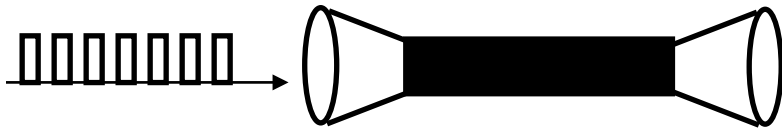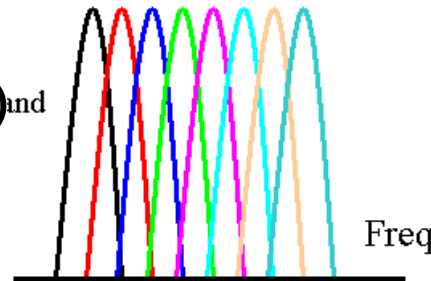**Student Questions**

Source: Nortel

# OFDM

- Orthogonal Frequency Division Multiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel
  $\Rightarrow$ Multi-carrier modulation

- Frequency band is divided into 256 or more sub-bands.
  Orthogonal $\Rightarrow$ Peak of one at null of others
- Each carrier is modulated with a BPSK, QPSK, 16-QAM, 64-QAM etc depending on the noise (Frequency selective fading)
- Used in 802.11a/g, 802.16, Digital Video Broadcast handheld (DVB-H)
- Easy to implement using FFT/IFFT

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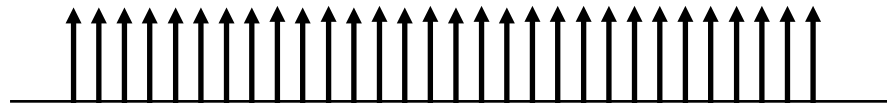
# Advantages of OFDM

❑ Easy to implement using FFT/IFFT.
FFT/IFFT are implemented only as powers of 2 (256, 1024, …)

❑ Computational complexity = O(B log BT) compared to previous O(B$^2$T) for Equalization. Here B is the bandwidth and T is the delay spread.

❑ Graceful degradation if excess delay

❑ Robustness against frequency selective burst errors

❑ Allows adaptive modulation and coding of subcarriers

❑ Robust against narrowband interference (affecting only some subcarriers)

❑ Allows pilot subcarriers for channel estimation



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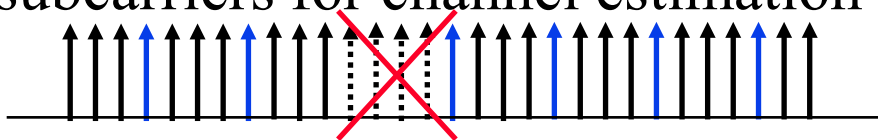
# OFDM: Design considerations

- Large number of carriers $\Rightarrow$ Smaller data rate per carrier $\Rightarrow$ Larger symbol duration $\Rightarrow$ Less inter-symbol interference

- Reduced subcarrier spacing $\Rightarrow$ Increased inter-carrier interference due to Doppler spread in mobile applications

- Easily implemented as Inverse Discrete Fourier Transform (IDFT) of data symbol block

- Fast Fourier Transform (FFT) is a computationally efficient way of computing DFT

10 Mbps

0.1 μs

1 Mbps
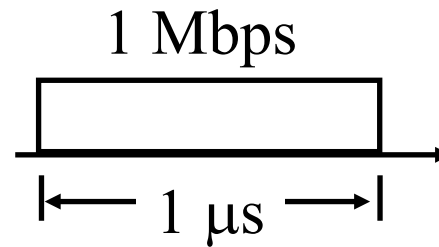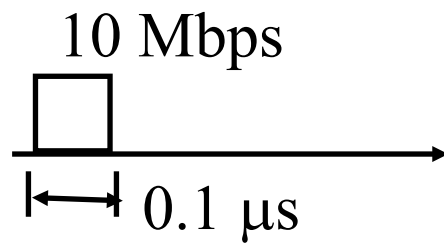
1 μs

# OFDMA

❑ Orthogonal Frequency Division Multiple Access

❑ Each user has a subset of subcarriers for a few slots

❑ OFDM systems use TDMA

❑ OFDMA allows Time+Freq DMA ⇒ 2D Scheduling

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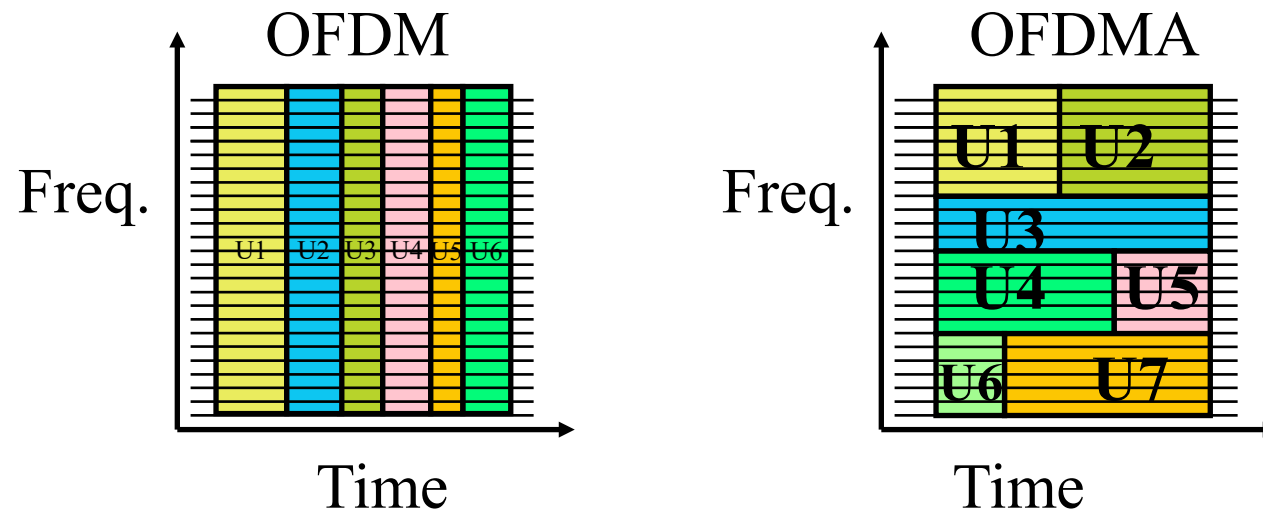
# Scalable OFDMA (SOFDMA)

❑ OFDM symbol duration = f(subcarrier spacing)

❑ Subcarrier spacing = Frequency bandwidth/Number of subcarriers

❑ Frequency bandwidth=1.25 MHz, 3.5 MHz, 5 MHz, 10 MHz, 20 MHz, etc.

❑ Symbol duration affects higher layer operation
   ⇒ Keep symbol duration constant at 102.9 us
   ⇒ Keep subcarrier spacing 10.94 kHz
   ⇒ Number of subcarriers ∝ Frequency bandwidth
   This is known as scalable OFDMA
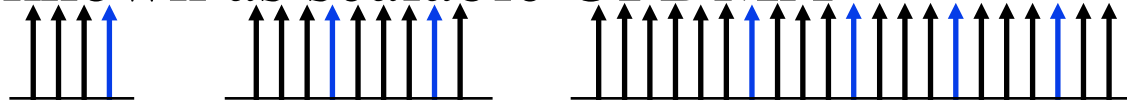
**Student Questions**

# Effect of Frequency

700 MHz · · · · 2.4 GHz → Time
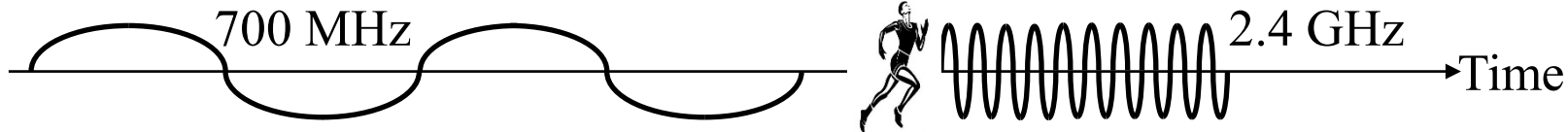
- ❑ Higher Frequencies have higher attenuation,
  e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- ❑ Higher frequencies need smaller antenna
  Antenna $\geq$ Wavelength/2, 800 MHz $\Rightarrow$ 6"
- ❑ Higher frequencies are affected more by weather
  Higher than 10 GHz affected by rainfall
  60 GHz affected by absorption of oxygen molecules
- ❑ Higher frequencies have more bandwidth and higher data rate
- ❑ Higher frequencies allow more frequency reuse
  They attenuate close to cell boundaries. Low frequencies
  propagate far.

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# Effect of Frequency (Cont)

❑ Lower frequencies have longer reach
  $\Rightarrow$ Longer Cell Radius
  $\Rightarrow$ Good for rural areas
  $\Rightarrow$ Smaller number of towers
  $\Rightarrow$ Longer battery life

❑ Lower frequencies require larger antenna and antenna spacing
  $\Rightarrow$ MIMO difficult particularly on mobile devices

❑ Lower frequencies $\Rightarrow$ Smaller channel width
  $\Rightarrow$ Need aggressive MCS, e.g., 256-QAM

❑ Doppler shift = vf/c = Velocity ×Frequency/(speed of light)
  $\Rightarrow$ Lower Doppler spread at lower frequencies

❑ Mobility $\Rightarrow$ Below 10 GHz

**Student Questions**

# Summary
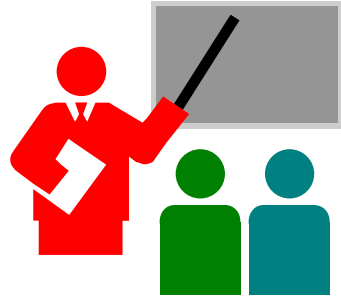
1. Path loss increase at a power of 2 to 5.5 with distance.

2. Fading = Changes in power changes in position

3. Fresnel zones = Ellipsoid with distance of LoS+i$\lambda$/2
   Any obstruction of the first zone will increase path loss

4. Multiple Antennas: Receive diversity, transmit diversity, Smart Antenna, MIMO

5. OFDM splits a band in to many orthogonal subcarriers.
   OFDMA = FDMA + TDMA

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# Homework 4

A. 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 Receiver antenna gains are 10dB and 5 dB respectively. Use a power exponent of 4. Transmitted power is 30 dBm. Do All calculations using dB.

B. With a subcarrier spacing of 10 kHz, how many subcarriers will be used in a system with 8 MHz channel bandwidth and what size FFT will be used?

C. In a scalable OFDMA system, the number of carriers for 10 MHz channel is 1024. How many carriers will be used if the channel was 1.25 MHz, 5 MHz, or 8.75 MHz.

**Student Questions**

# Reading List

- Jim Geier, "Radio Wave Fundamentals," Chapter 2 in his book "Designing and Deploying 802.11 Wireless Networks: A Practical Guide to Implementing 802.11n and 802.11ac Wireless Networks, Second Edition," Cisco Press, May 2015, 600 pp., ISBN:1-58714-430-1 (Safari Book), Chapter 2.

- Raj Jain, "Channel Models: A Tutorial," WiMAX Forum AATG, February 2007, first 7 of 21 pages, http://www.cse.wustl.edu/~jain/wimax/channel_model_tutorial.htm

- Jim Geier, "Wireless Networks first-step," Cisco Press, August 2004, 264 pp., ISBN:1-58720-111-9 (Safari Book), Chapter 3.

- Steve Rackley, "Wireless Networking Technology," Newnes, March 2007, 416 pp., ISBN:0-7506-6788-5 (Safari Book), Chapter 4.

- Stephan Jones; Ronald J. Kovac; Frank M. Groom, "Introduction to Communications Technologies, 3rd Edition," CRC Press, July 2015, 364 pp., ISBN:978-1-4987-0295-9 (Safari Book), Chapters 3 and 4.

**Student Questions**

# Wikipedia Links

- https://en.wikipedia.org/wiki/Omnidirectional_antenna
- https://en.wikipedia.org/wiki/Antenna_gain
- https://en.wikipedia.org/wiki/Equivalent_isotropically_radiated_power
- https://en.wikipedia.org/wiki/High-gain_antenna
- https://en.wikipedia.org/wiki/Signal_reflection
- https://en.wikipedia.org/wiki/Scattering
- https://en.wikipedia.org/wiki/Path_loss
- https://en.wikipedia.org/wiki/Free-space_path_loss
- https://en.wikipedia.org/wiki/Log-distance_path_loss_model
- https://en.wikipedia.org/wiki/Multipath_propagation
- https://en.wikipedia.org/wiki/Multipath_interference
- https://en.wikipedia.org/wiki/Intersymbol_interference
- https://en.wikipedia.org/wiki/Fading
- https://en.wikipedia.org/wiki/Shadow_fading
- https://en.wikipedia.org/wiki/Fresnel_zone

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# Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Antenna_diversity
- https://en.wikipedia.org/wiki/Beamforming
- https://en.wikipedia.org/wiki/Antenna_array_(electromagnetic)
- https://en.wikipedia.org/wiki/Phased_array
- https://en.wikipedia.org/wiki/Smart_antenna
- https://en.wikipedia.org/wiki/Multiple-input_multiple-output_communications
- https://en.wikipedia.org/wiki/Diversity_combining
- https://en.wikipedia.org/wiki/Maximal-ratio_combining
- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing
- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access

**Student Questions**

# Acronyms

- BPSK      Binary Phase-Shift Keying
- BS      Base Station
- dB      DeciBels
- dBi      DeciBels Intrinsic
- dBm      DeciBels milliwatt
- DFT      Discrete Fourier Transform
- DMA      Direct Memory Access
- DSP      Digital Signal Processing
- DVB-H      Digital Video Broadcast handheld
- FDMA      Frequency Division Multiple Access
- FFT      Fast Fourier Transform
- IDFT      Inverse Discrete Fourier Transform
- IFFT      Inverse Fast Fourier Transform
- ISI      Inter-symbol interference
- kHz      Kilo Hertz
- LoS      Line of Sight

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# Acronyms (Cont)

- MHz        Mega Hertz
- MIMO      Multiple Input Multiple Output
- MS          Mobile Station
- OFDM      Orthogonal Frequency Division Multiplexing
- OFDMA     Orthogonal Frequency Division Multiple Access
- QAM       Quadrature Amplitude Modulation
- QPSK      Quadrature Phase-Shift Keying
- RF           Radio Frequency
- SNR        Signal to Noise Ratio
- SS          Subscriber Station
- TDMA      Time Division Multiple Access

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http://www.cse.wustl.edu/~jain/cse574-22/j_04wsp.htm

http://www.cse.wustl.edu/~jain/cse574-22/

# Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),

https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

**Student Questions**

http://www.cse.wustl.edu/~jain/cse574-22/