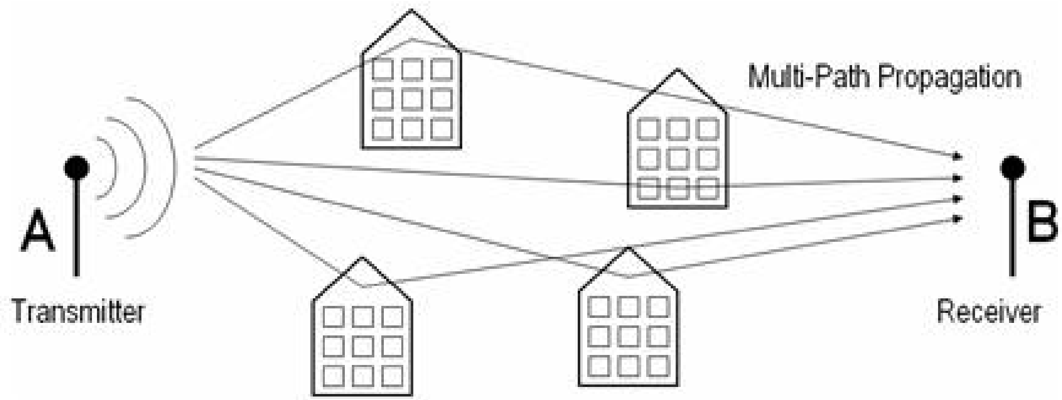
Introduction to Wireless Signal Propagation



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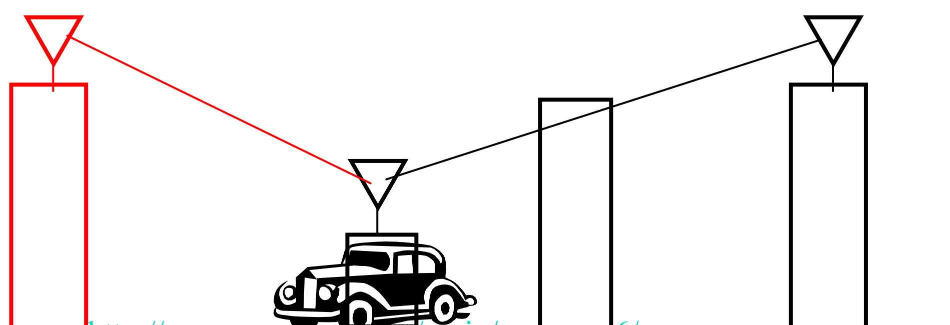
Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-16/

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.

Wireless Radio Channel

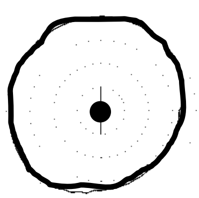
- Path loss: Depends upon distance and frequency
- Noise
- Shadowing: Obstructions
- Frequency Dispersion (Doppler Spread) due to motion
- Interference
- Multipath: Multiple reflected waves
- Inter-symbol interference (ISI) due to dispersion



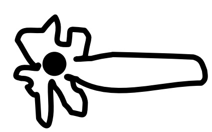
Antenna

- 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

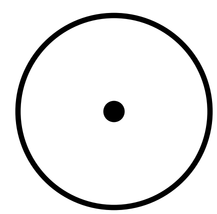
$$P_r = P_t\, G_t\, G_r\, (\lambda/4\pi d)^2$$



Omni-Directional

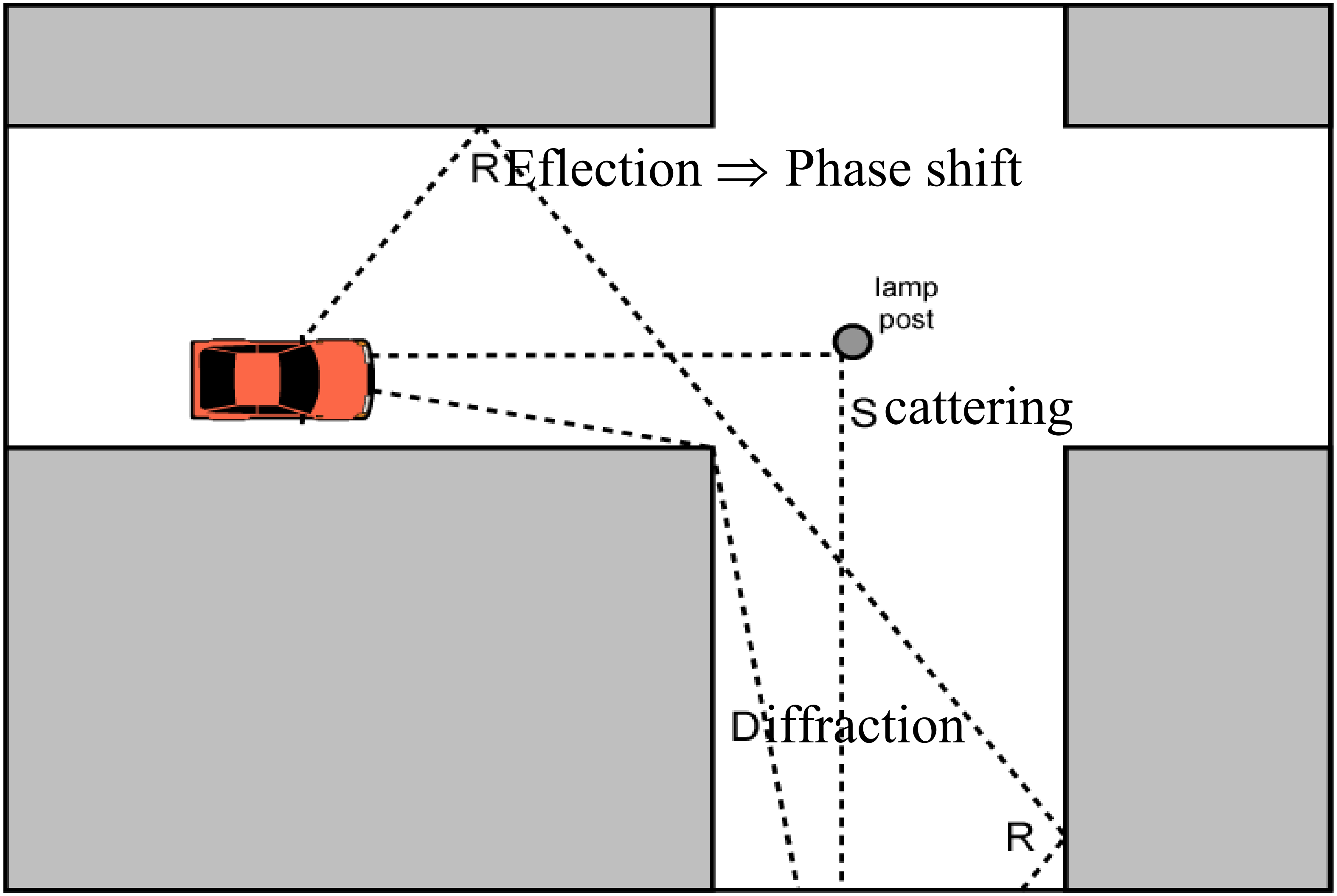


Directional



Isotropic

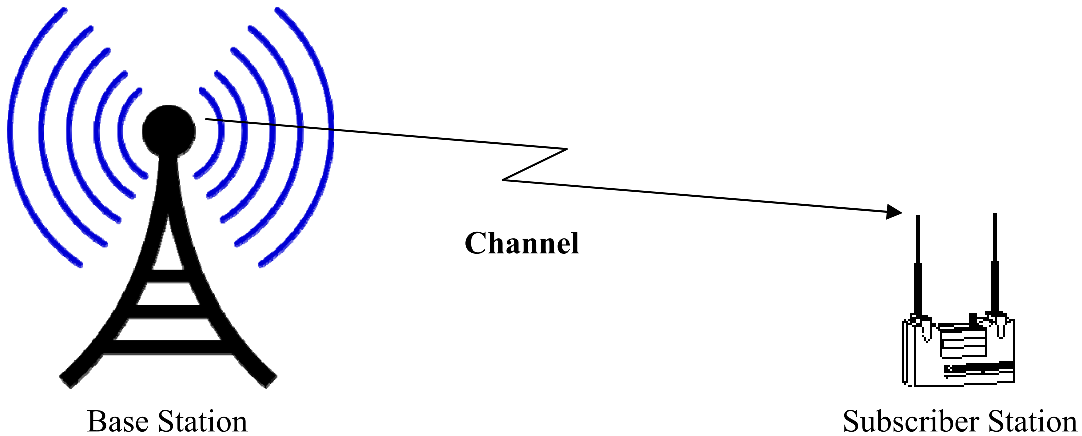
Reflection, Diffraction, Scattering



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

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:

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

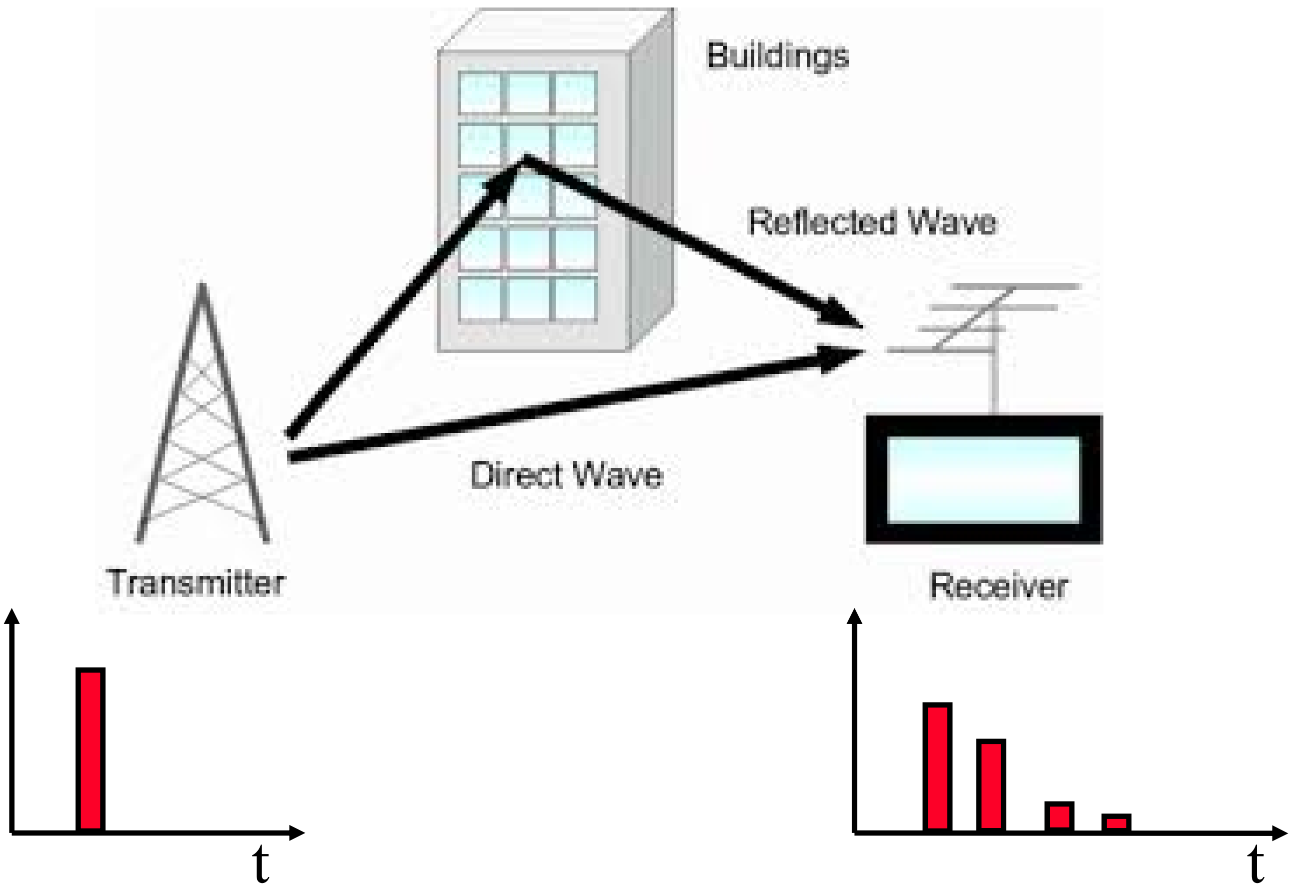
- Receiving Antenna Gain

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

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

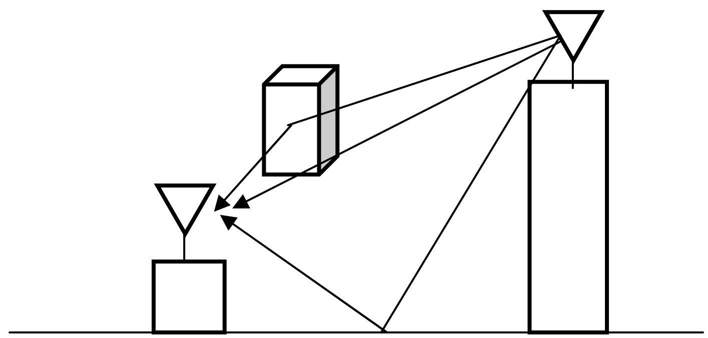
- This is known as **Frii's Law**.
  Attenuation in free space increases with frequency.

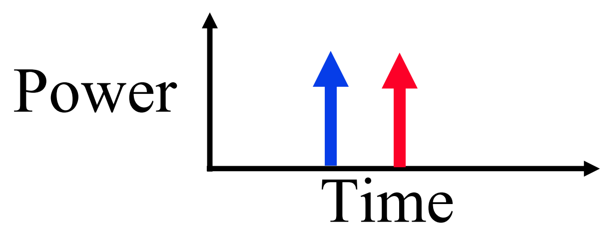
Multipath

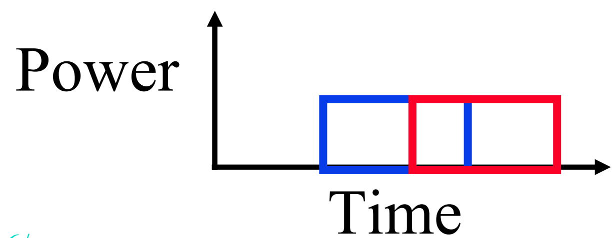


- Multiple reflected copies of the signal are received

Inter-Symbol Interference

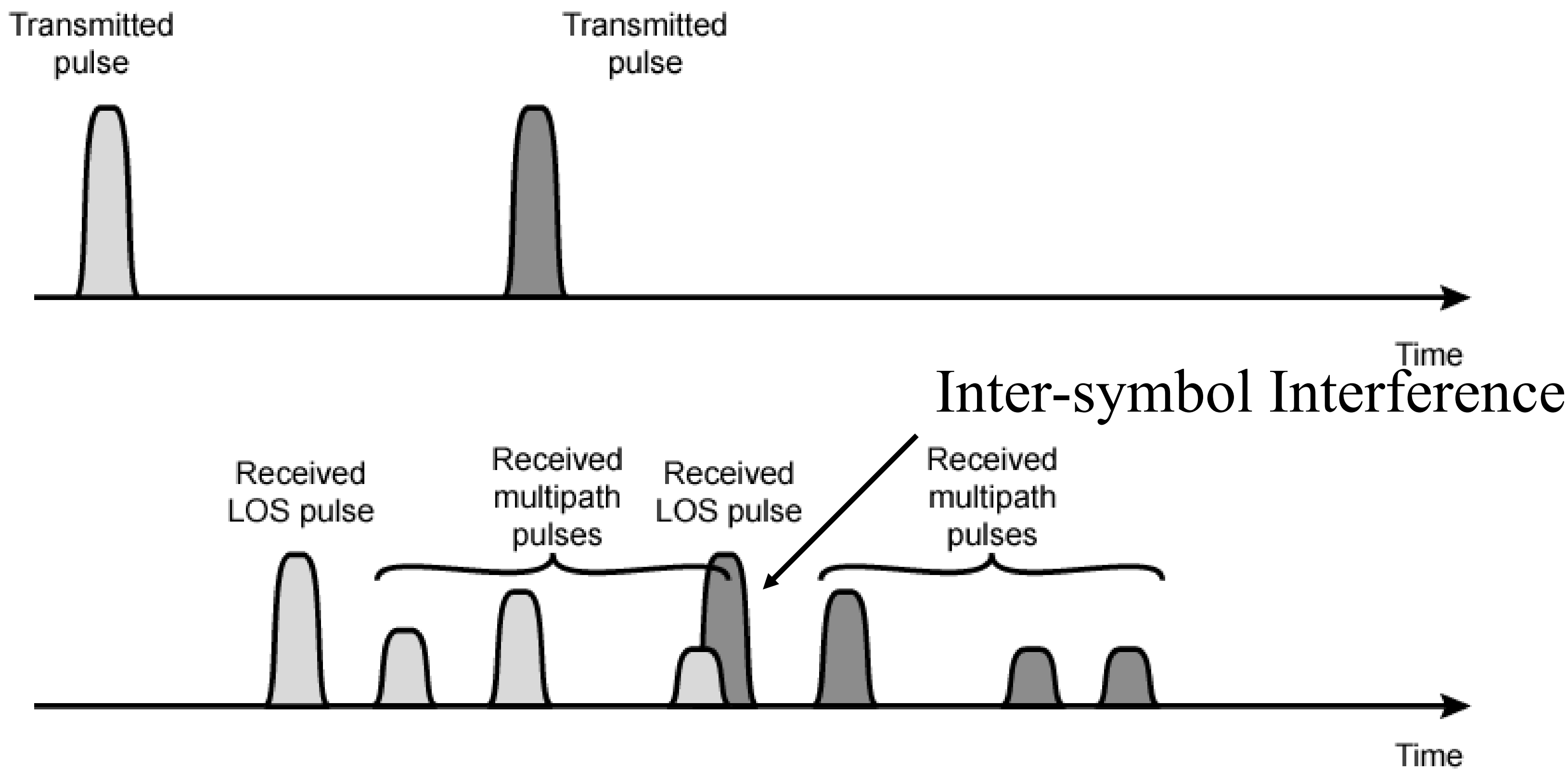






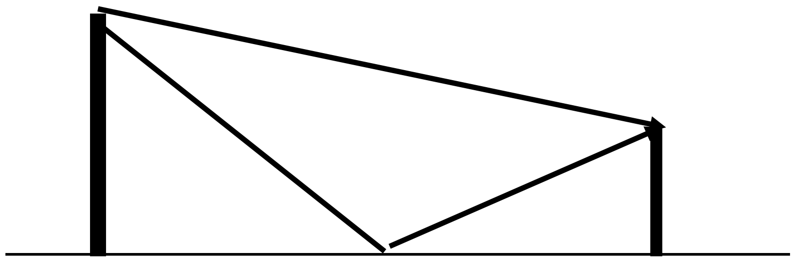
- Symbols become wider
  ⇒ Limits the number of bits/s

Multipath Propagation



- 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

d^{-4} Power Law



- Using a two-ray model

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

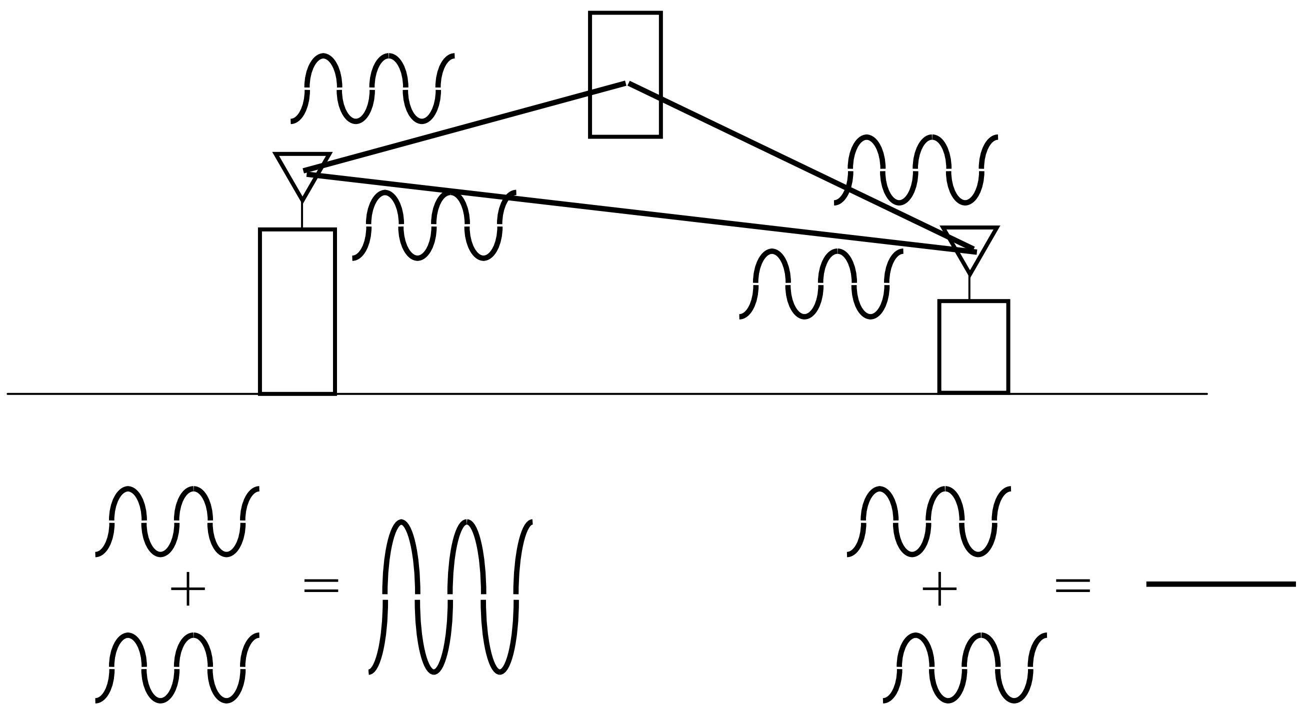
- Here, h_T and h_R are heights of transmit and receive antennas
- It is valid for distances larger than

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

- Note that the received power becomes independent of the frequency.
- Measured results show n=1.5 to 5.5. Typically 4.

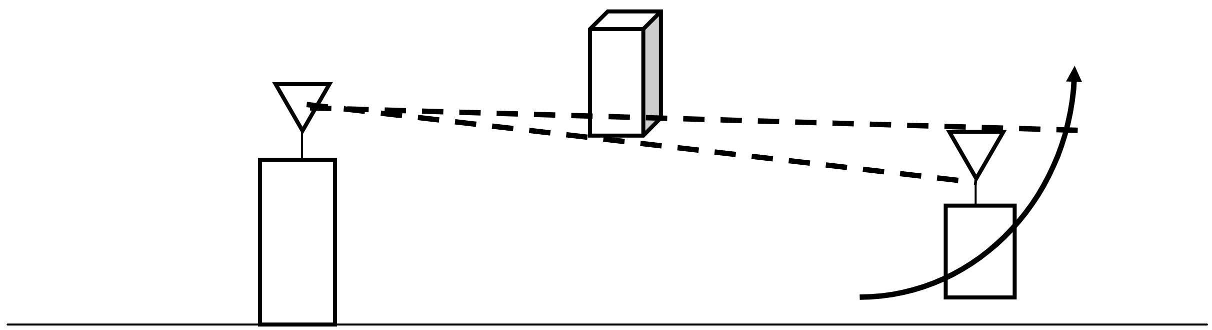
Small Scale Fading

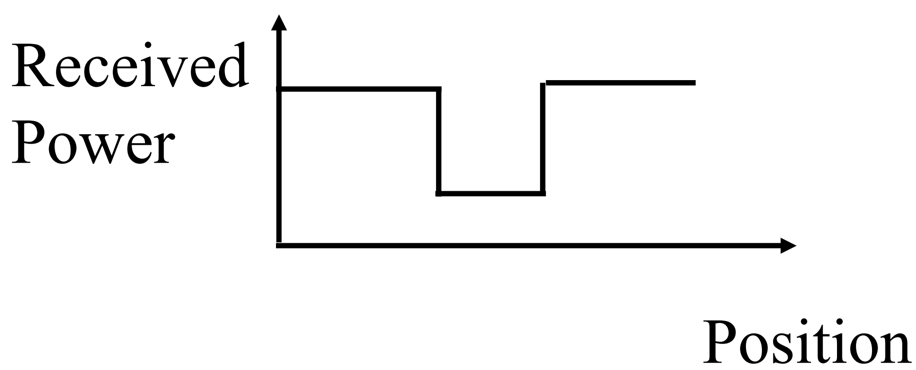
- The signal amplitude can change by moving a few inches ⇒ Small scale fading



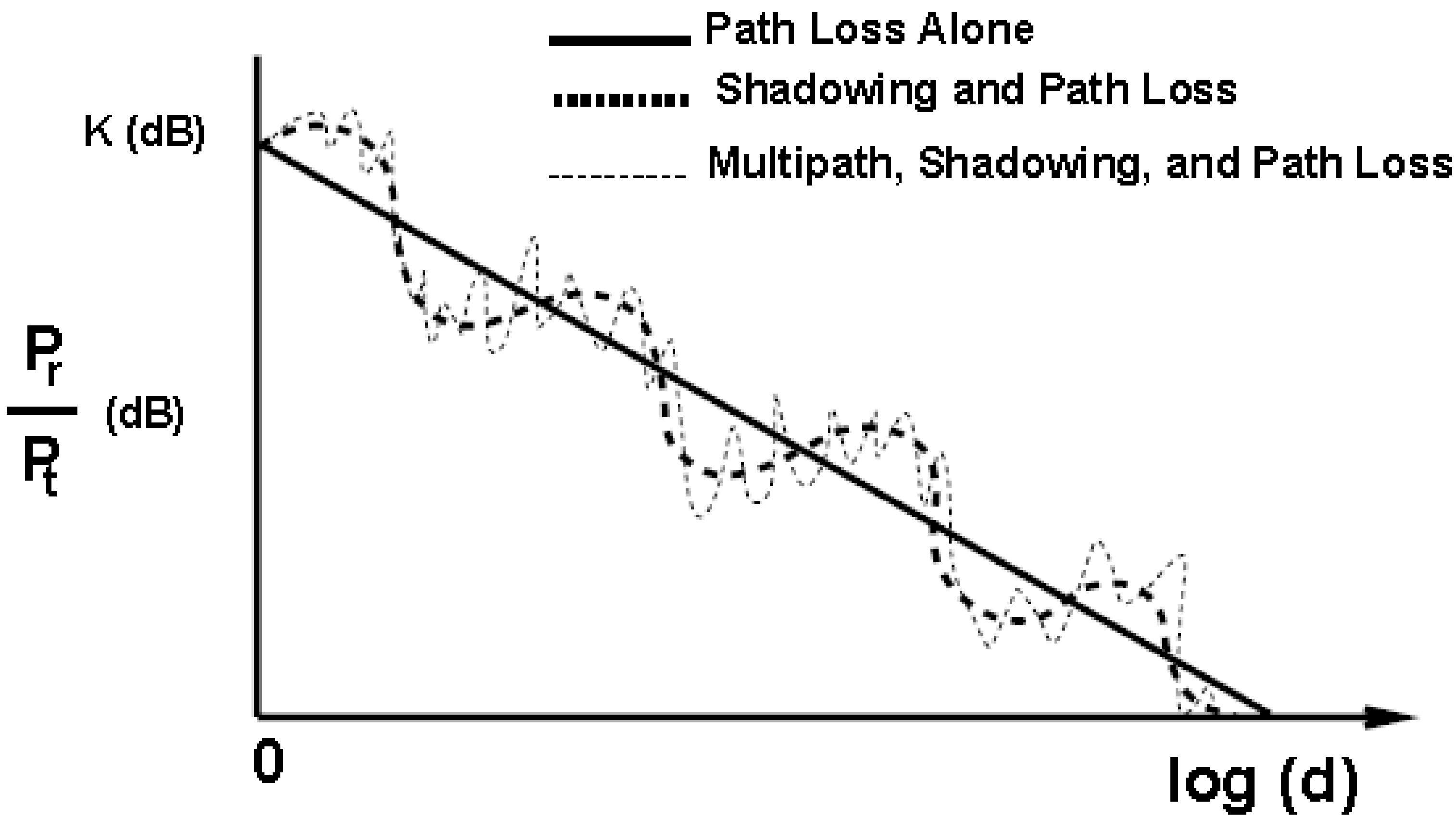
Shadowing

- Shadowing gives rise to large scale fading

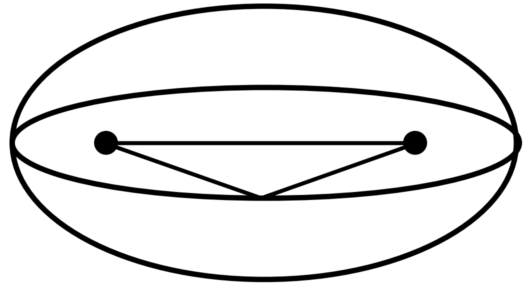




Total Path Loss



Fresnel Zones

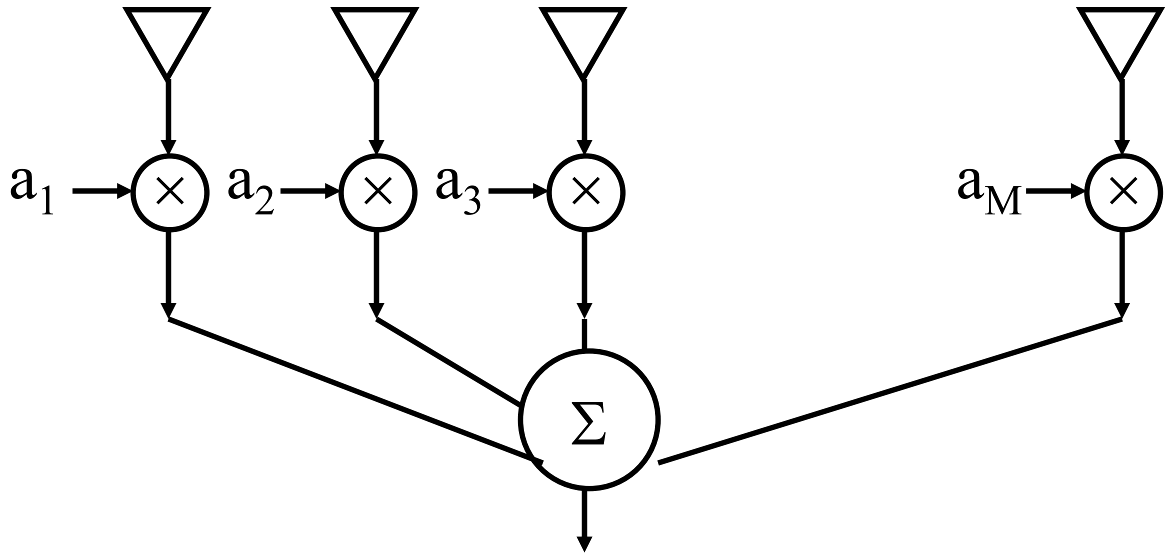


- Draw an ellipsoid with BS and MS as Foci
- All points on ellipsoid have the same BS-MS run length
- Fresnel ellipsoids = Ellipsoids for which run length = LoS + iλ/2
- At the Fresnel ellipsoids results in a phase shift of i\pi
- Radius of the i^{th} ellipsoid at distance d_T from the transmitter and 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

Multi-Antenna Systems

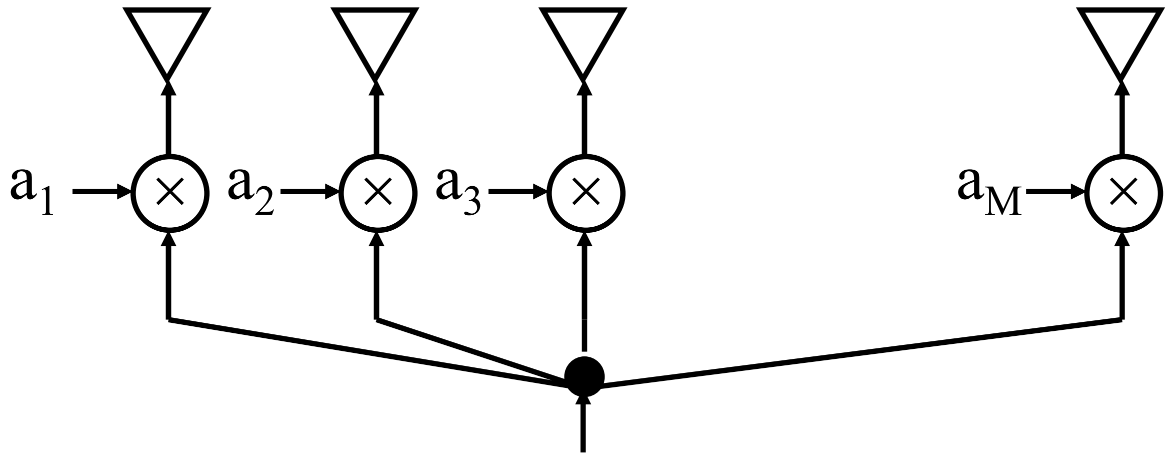
- Receiver Diversity
- Transmitter Diversity
- Beam forming
- MIMO

Receiver Diversity



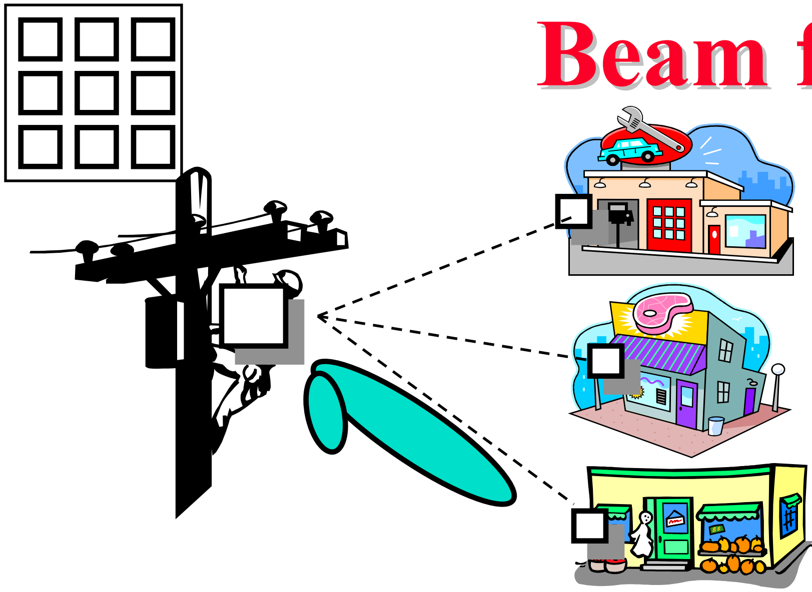
- User multiple receive antenna
- Selection combining: Select antenna with highest SNR
- Threshold combining: Select the first antenna with SNR above a threshold
- Maximal Ratio Combining: Phase is adjusted so that all signals have the same phase. Then weighted sum is used to maximize SNR

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

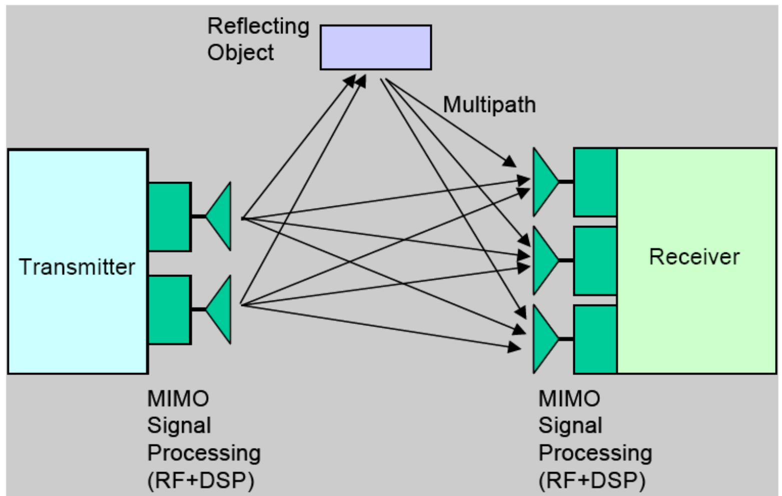
Beam forming



- Phased Antenna Arrays:
  Receive the same signal using multiple antennas
- By phase-shifting various received signals and then summing ⇒ Focus on a narrow directional beam
- Digital Signal Processing (DSP) is used for signal processing ⇒ Self-aligning

MIMO

- Multiple Input Multiple Output
- RF chain for each antenna
  ⇒ Simultaneous reception or transmission of multiple streams

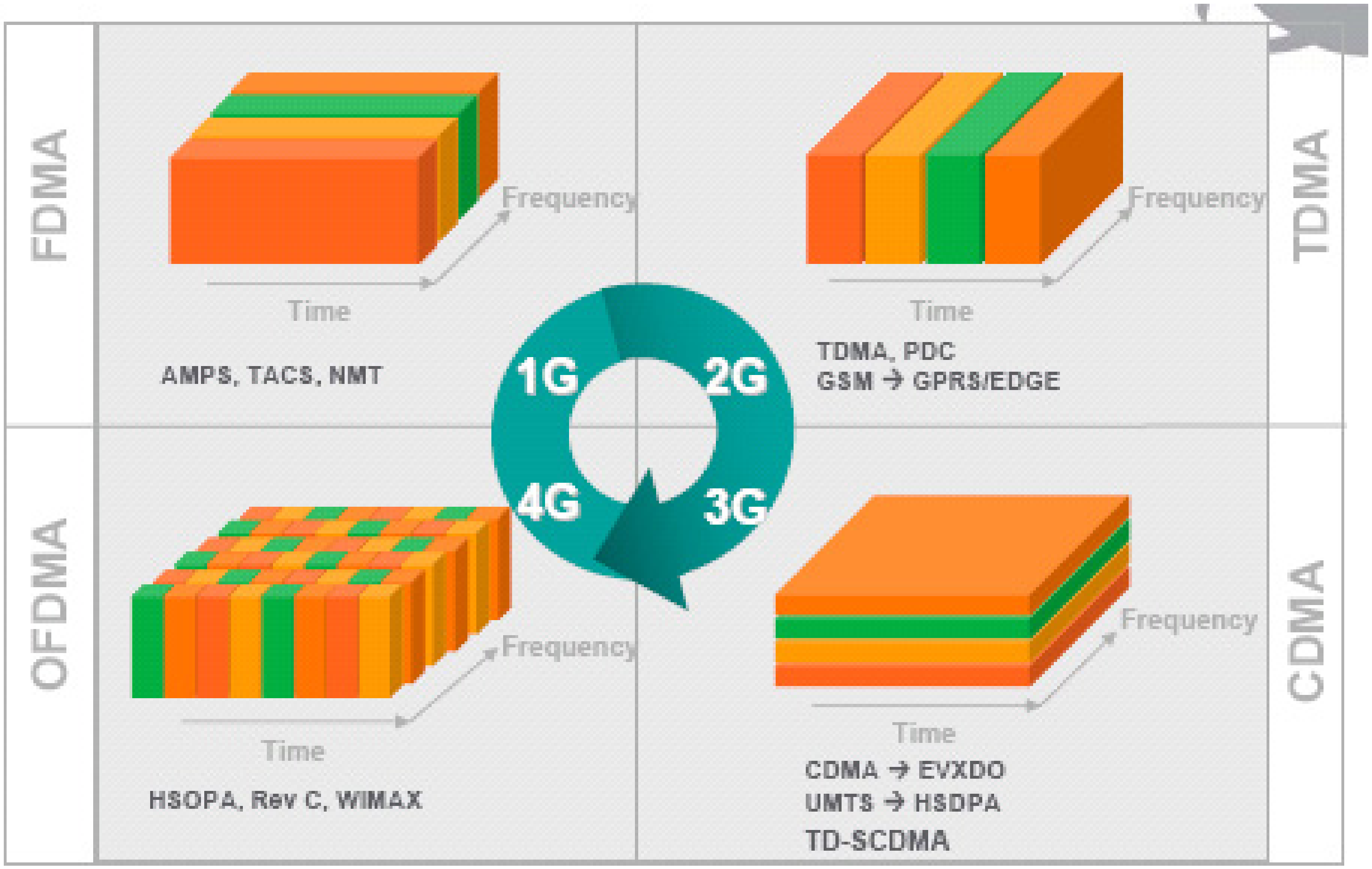


2x3

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

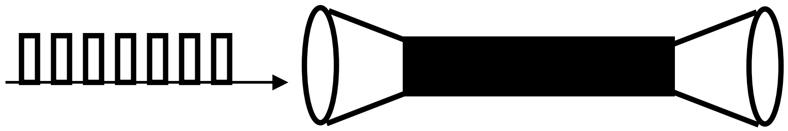
Multiple Access Methods

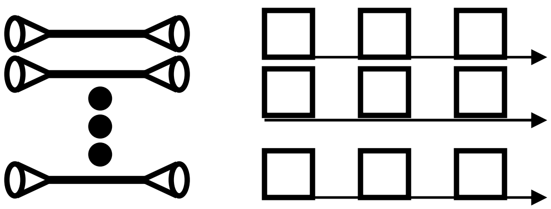


Source: Nortel

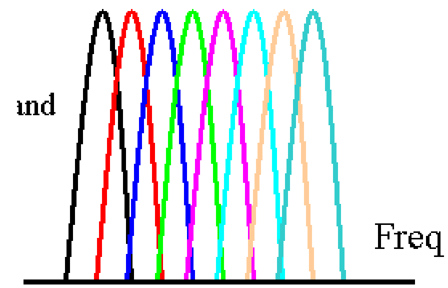
OFDM

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

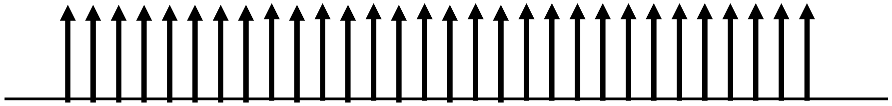




- Frequency band is divided into 256 or more sub-bands.
  Orthogonal ⇒ Peak of one at null of others
- Each carrier is modulated with a BPSK, QPSK, 16-QAM, 64-QAM etc depending on the noise (Frequency selective fading)
- Used in 802.11a/g, 802.16,
  Digital Video Broadcast handheld (DVB-H)

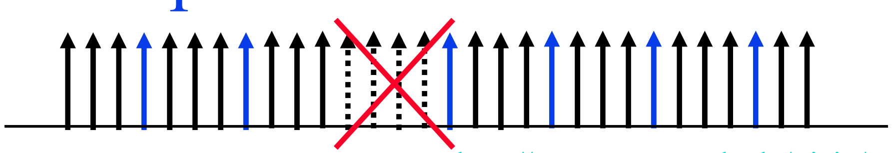


- Easy to implement using FFT/IFFT



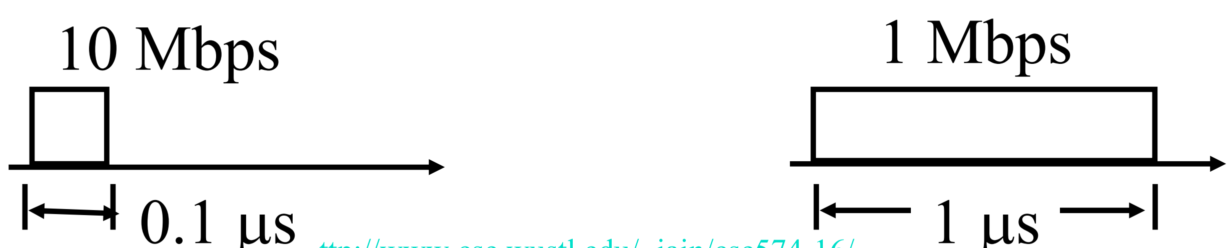
Advantages of OFDM

- Easy to implement using FFT/IFFT
- Computational complexity = O(B log BT) compared to previous $O(B^2T)$ 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



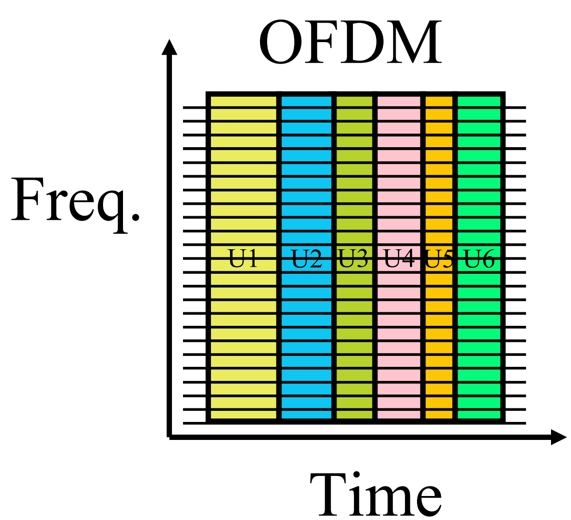
OFDM: Design considerations

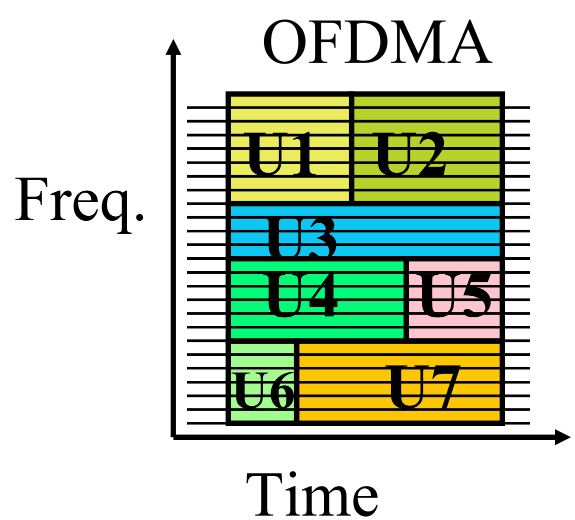
- Large number of carriers ⇒ Smaller data rate per carrier ⇒ Larger symbol duration ⇒ Less inter-symbol interference
- Reduced subcarrier spacing ⇒ Increased inter-carrier interference due to Doppler spread in mobile applications
- Easily implemented as Inverse Discrete Fourier Transform (IDFT) of data symbol block
- Fast Fourier Transform (FFT) is a computationally efficient way of computing DFT



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

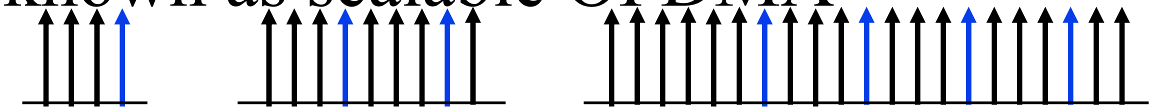




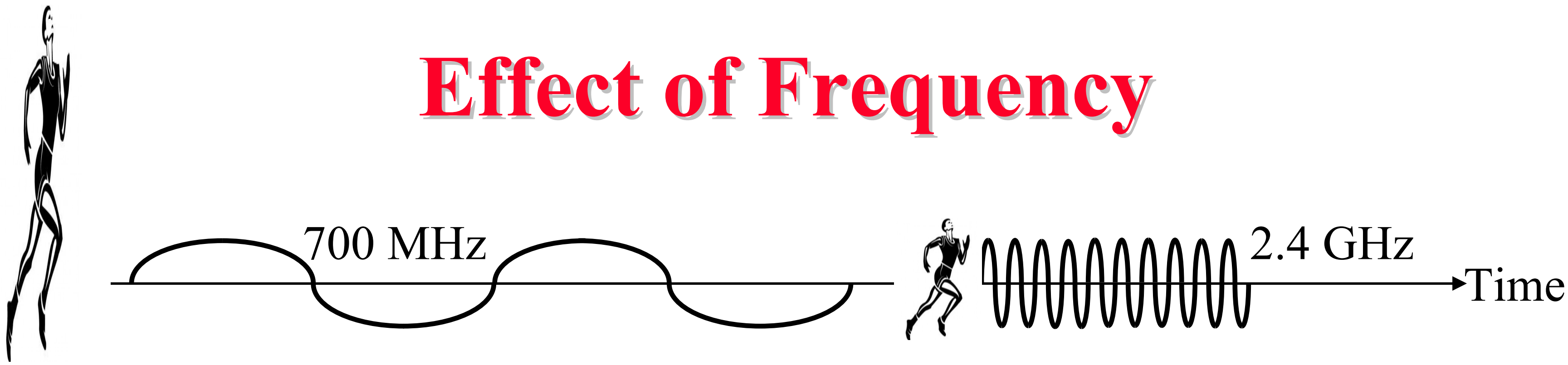
Scalable OFDMA (SOFDMA)

- 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



Effect of Frequency

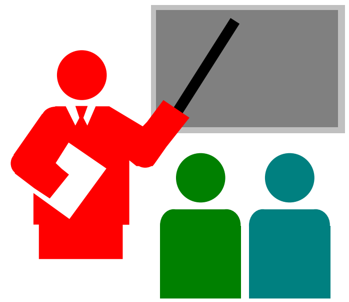


- Higher Frequencies have higher attenuation, e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- Higher frequencies need smaller antenna Antenna $\geq$ Wavelength/2, 800 MHz $\Rightarrow$ 6”
- Higher frequencies are affected more by weather Higher than 10 GHz affected by rainfall 60 GHz affected by absorption 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.

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 $\times$Frequency/(speed of light)
  $\Rightarrow$ Lower Doppler spread at lower frequencies
- Mobility $\Rightarrow$ Below 10 GHz

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+iλ/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

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.

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.

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

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

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

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
STBC	Space Time Block Codes
TDMA	Time Division Multiple Access

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Related Modules

Introduction to 5G,
http://www.cse.wustl.edu/~jain/cse574-16/j_195g.htm

Low Power WAN Protocols for IoT,
http://www.cse.wustl.edu/~jain/cse574-16/j_14ahl.htm

Introduction to Vehicular Wireless Networks,
http://www.cse.wustl.edu/~jain/cse574-16/j_08vwn.htm

Internet of Things,
http://www.cse.wustl.edu/~jain/cse574-16/j_10iot.htm

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