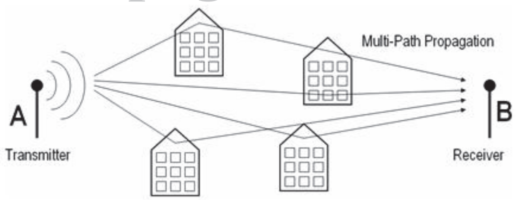
Introduction to Wireless Signal Propagation



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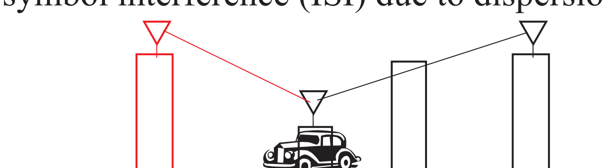
Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-16/

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

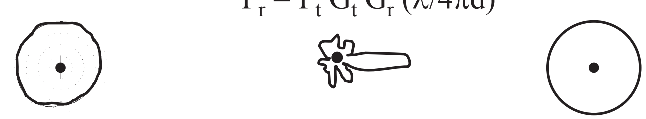
- Path loss: Depends upon distance and frequency
- Noise
- Shadowing: Obstructions
- Frequency Dispersion (Doppler Spread) due to motion
- Interference
- Multipath: Multiple reflected waves
- Inter-symbol interference (ISI) due to dispersion



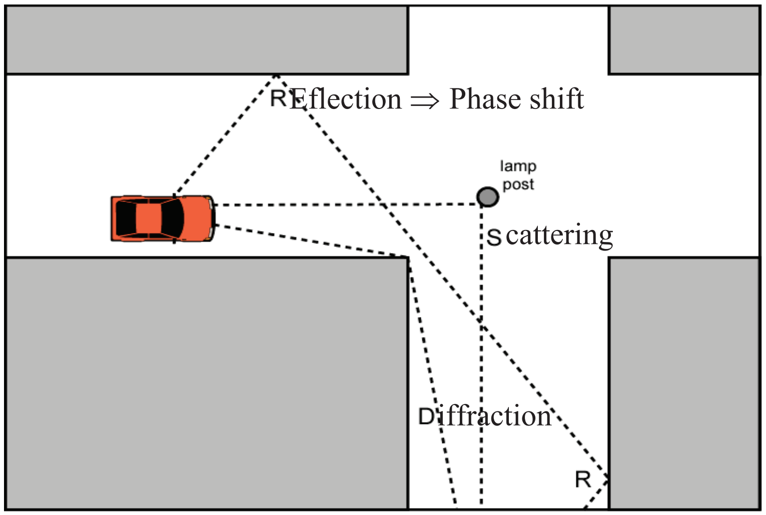
Antenna

- 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

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



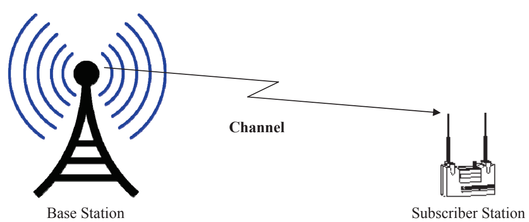
Reflection, Diffraction, Scattering



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:

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

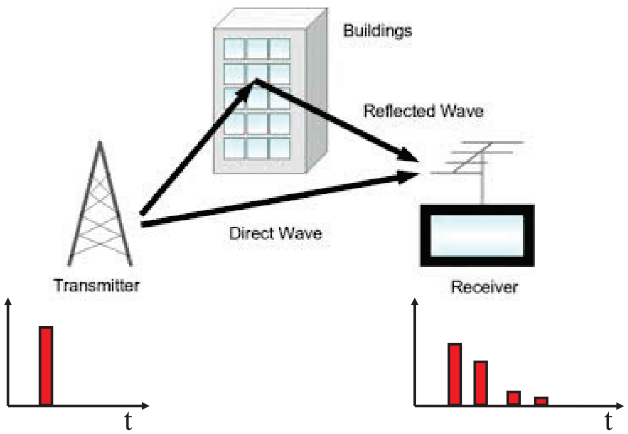
- Receiving Antenna Gain

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

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

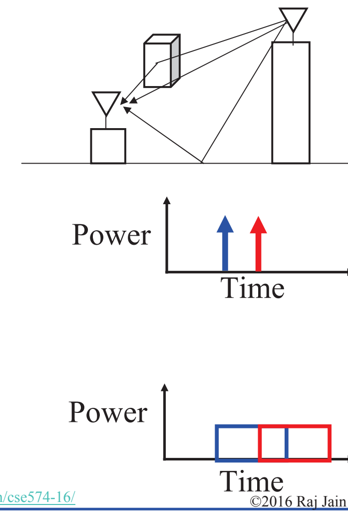
- This is known as **Frii's Law**.
  Attenuation in free space increases with frequency.

Multipath



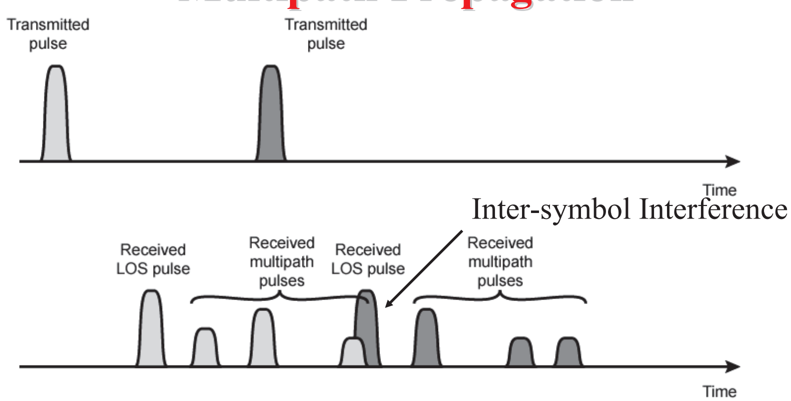
- Multiple reflected copies of the signal are received

Inter-Symbol Interference



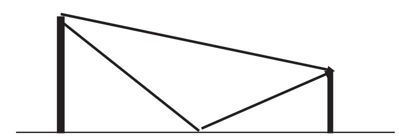
- Symbols become wider
  ⇒ Limits the number of bits/s

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

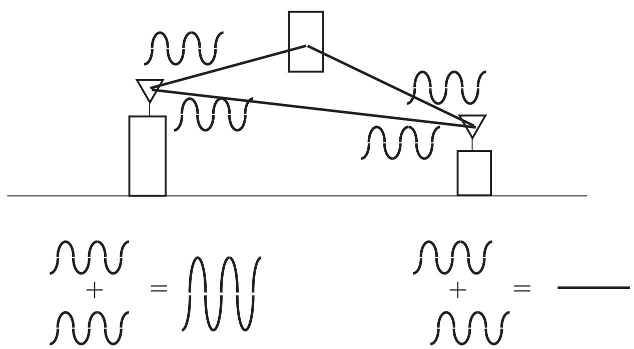
d^{-4} Power Law



- 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
$$d_{\text{break}} = 4h_T h_R/\lambda$$
- Note that the received power becomes independent of the frequency.
- Measured results show n=1.5 to 5.5. Typically 4.

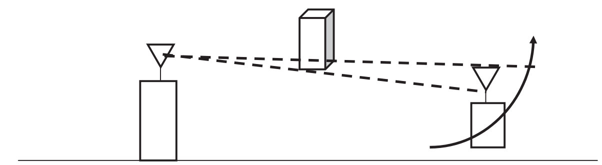
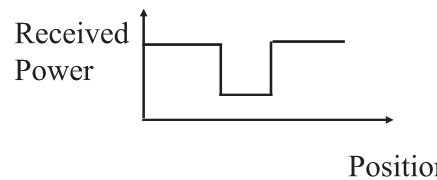
Small Scale Fading

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

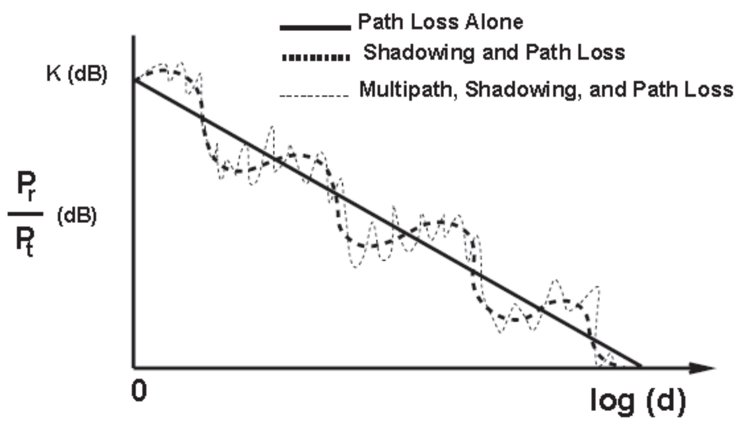


Shadowing

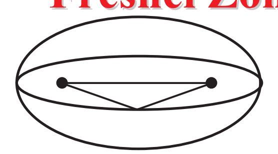
- Shadowing gives rise to large scale fading

Total Path Loss



Fresnel Zones

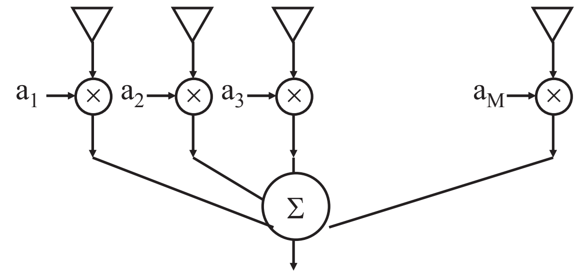


- Draw an ellipsoid with BS and MS as Foci
- All points on ellipsoid have the same BS-MS run length
- Fresnel ellipsoids = Ellipsoids for which run length = LoS + iλ/2
- At the Fresnel ellipsoids results in a phase shift of i\pi
- Radius of the i^{th} ellipsoid at distance d_T from the transmitter and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

Multi-Antenna Systems

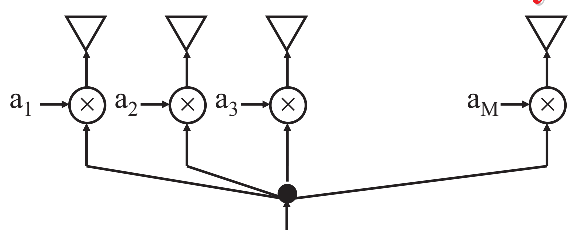
- Receiver Diversity
- Transmitter Diversity
- Beam forming
- MIMO

Receiver Diversity



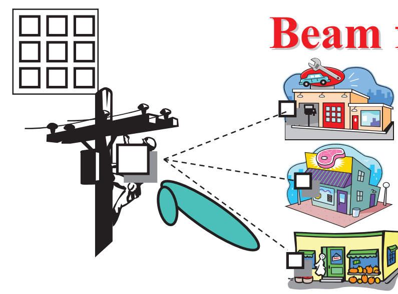
- User multiple receive antenna
- Selection combining: Select antenna with highest SNR
- Threshold combining: Select the first antenna with SNR above a threshold
- Maximal Ratio Combining: Phase is adjusted so that all signals have the same phase. Then weighted sum is used to maximize SNR

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

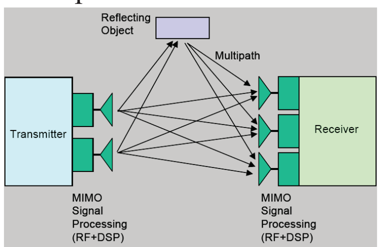
Beam forming



- 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

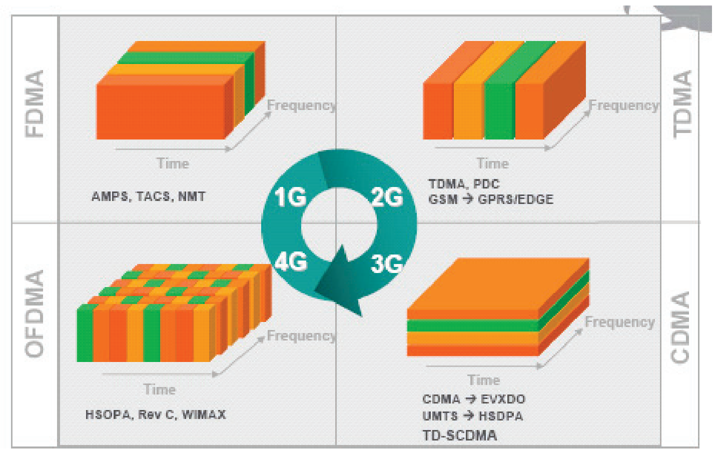


2x3

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

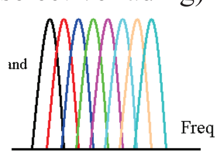


Source: Nortel

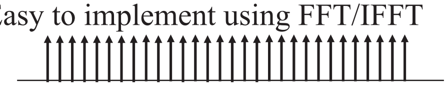
OFDM

- 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)

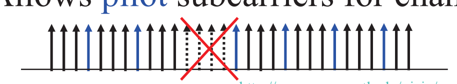


- Easy to implement using FFT/IFFT



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

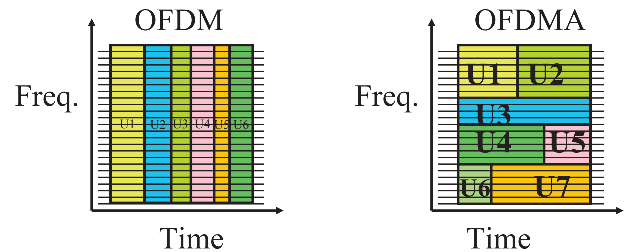


OFDM: Design considerations

- 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

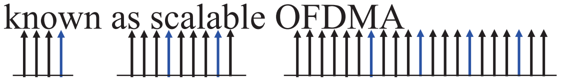
OFDMA

- 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

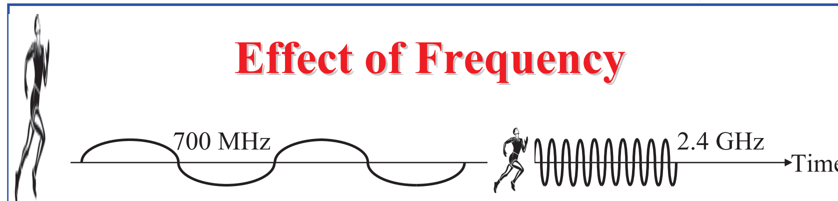


Scalable OFDMA (SOFDMA)

- 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 ≥ Wavelength/2, 800 MHz ⇒ 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
  ⇒ Longer Cell Radius
  ⇒ Good for rural areas
  ⇒ Smaller number of towers
  ⇒ Longer battery life
- Lower frequencies require larger antenna and antenna spacing
  ⇒ MIMO difficult particularly on mobile devices
- Lower frequencies ⇒ Smaller channel width
  ⇒ Need aggressive MCS, e.g., 256-QAM
- Doppler shift = vf/c = Velocity ×Frequency/(speed of light)
  ⇒ Lower Doppler spread at lower frequencies
- Mobility ⇒ 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

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http://www.cse.wustl.edu/~jain/cse574-16/j_195g.htm

Low Power WAN Protocols for IoT,
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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