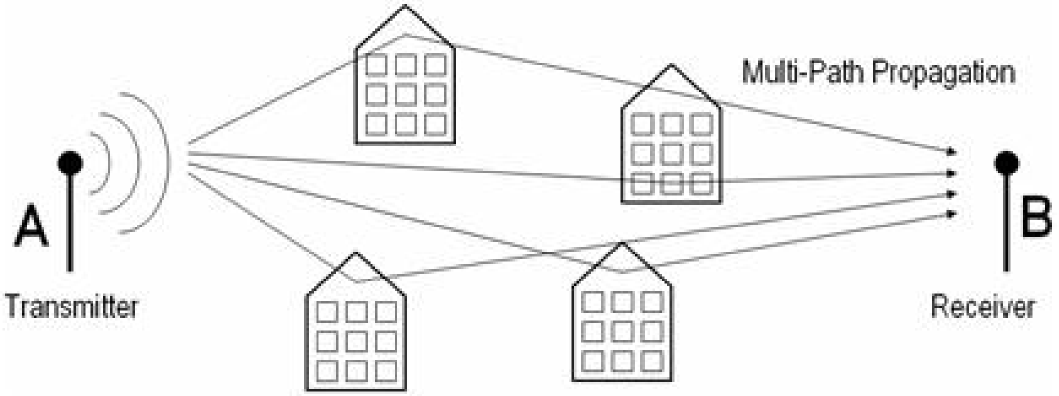
# Introduction to Wireless Signal Propagation

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

## Student Questions





Q on 10b, 12,26, 27, 29,31a,31b


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

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

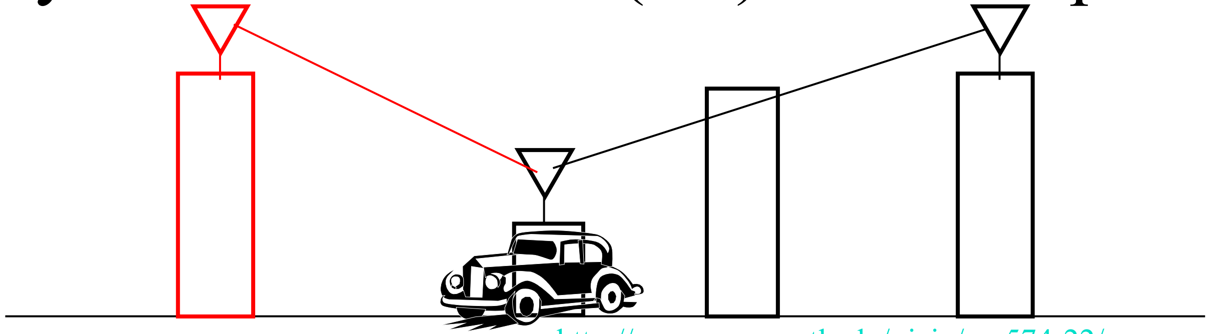




**Student Questions**

# 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







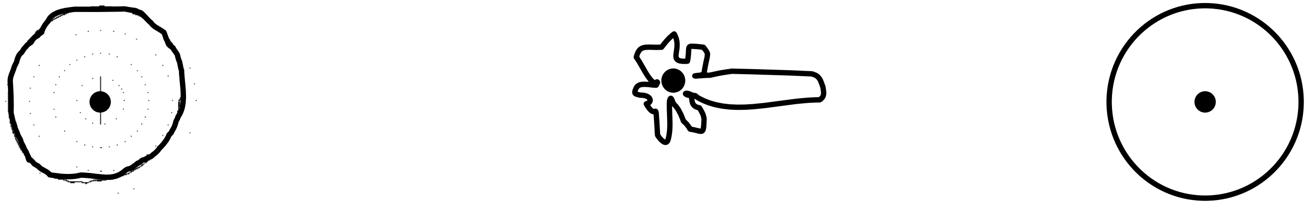
## Student Questions

- Could we go over how this figure relates to the terms above? *Shows different path loss in red and black paths*
- So both Multipath and ISI are interference of the transmitted waves themselves but multipath is due to the existence of reflector(s) and ISI is due to moving waves? *Multipath is due to interference of waves. ISI can happen even in a single wave it travels too far. See Slide 4-10.*

# Antenna

- Transmitter converts electrical energy to electromagnetic waves
- Receiver converts electromagnetic waves to electrical energy
- The 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 is expressed in dBi.

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



Omni-Directional　　Directional　　Isotropic





## Student Questions

- Can you explain the difference between Omni-Directional, Directional, and Isotropic? *Isotropic is the ideal omni-directional antenna (used for reference).*
- Omni-directional is radiated in all directions, but not equally? *Almost equally but not a perfect circle. Isotropic is theoretical, while omni-directional, as shown, is what you get in practice.*

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- What is the unit dBi, and how would you work with it in the equation given?

*dBi = Deci-Bel isotropic = Power compared to isotropic antenna*
*The formula gives power in Watts.*
*$10\log_{10}P$ changes it to dB.*

# Antenna

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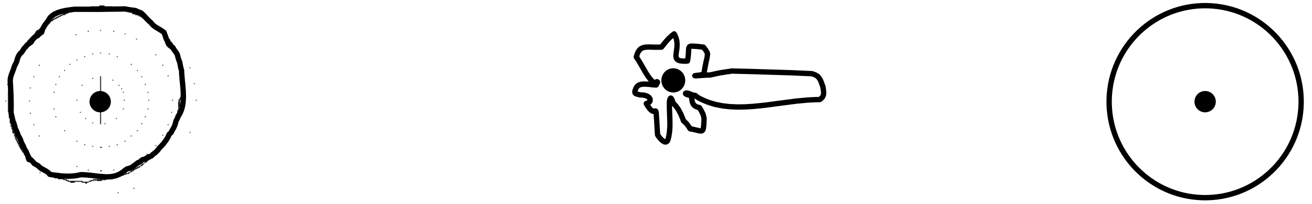

Omni-Directional Directional Isotropic

## Student Questions

- Isn't the difference between isotropic and Omni that iso transmits the power in a circle shape and Omni in a sphere shape?

*Isotropic = equal in 3D*

*Omni = Equal in 2D*

- I wonder why the azimuth pattern of Omni-directional (left figure) is not a circle.

*Isotropic is theoretical. Omni shown here is realistic.*

# Antenna

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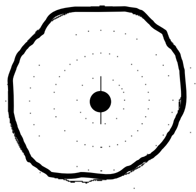
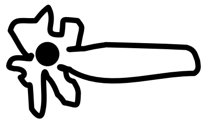
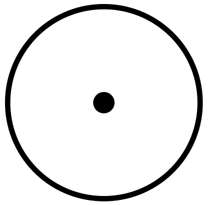


Omni-Directional



Directional



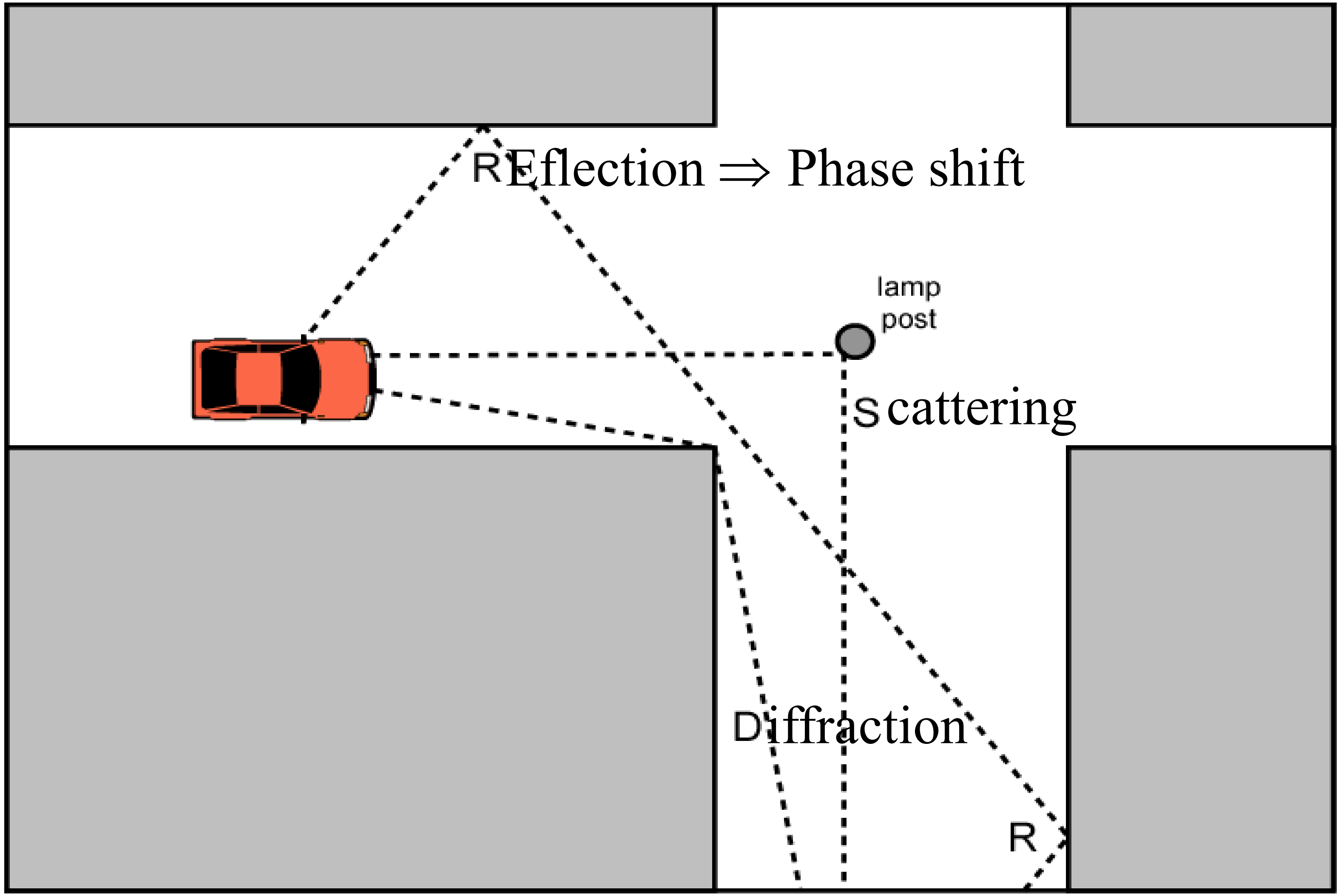
Isotropic

## Student Questions

- Does the 'd' variable mean the distance between the antennas? And is there a reason we consider the area formula instead of the volume, as the transmissions will be spherical?

*The formula is for the power received at an antenna.*

# Reflection, Diffraction, Scattering




## Student Questions

# Reflection, Diffraction and Scattering (Cont)

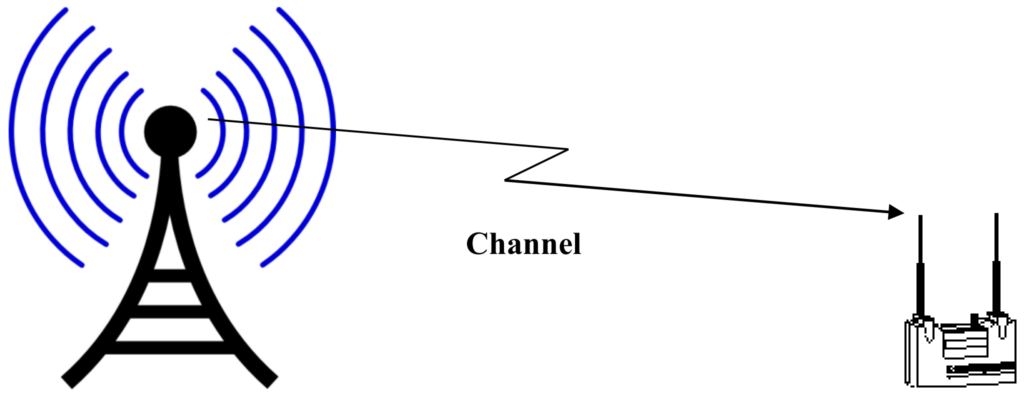
- **Reflection**: Surface large relative to the wavelength of the signal
  - May have phase shift from the original
  - May cancel out original or increase it
- **Diffraction**: Edge of the impenetrable body that is large relative to λ
  - May receive signal even if no line of sight (LOS) to the transmitter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

## Student Questions

- Why is scattering a primary means of reception if there is no LOS?

*Power received = LOS + Reflection, diffraction, and scattering*
*If one or more are missing, others become the means for a 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 the frequency domain
- 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 $f$.





## Student Questions

- What is the power profile of the transmitted signal?

*Power profile = power as a function of frequency*

# Path Loss

- Power is distributed equally to spherical area $4\pi\ d^2$
  d = distance = radius
- 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

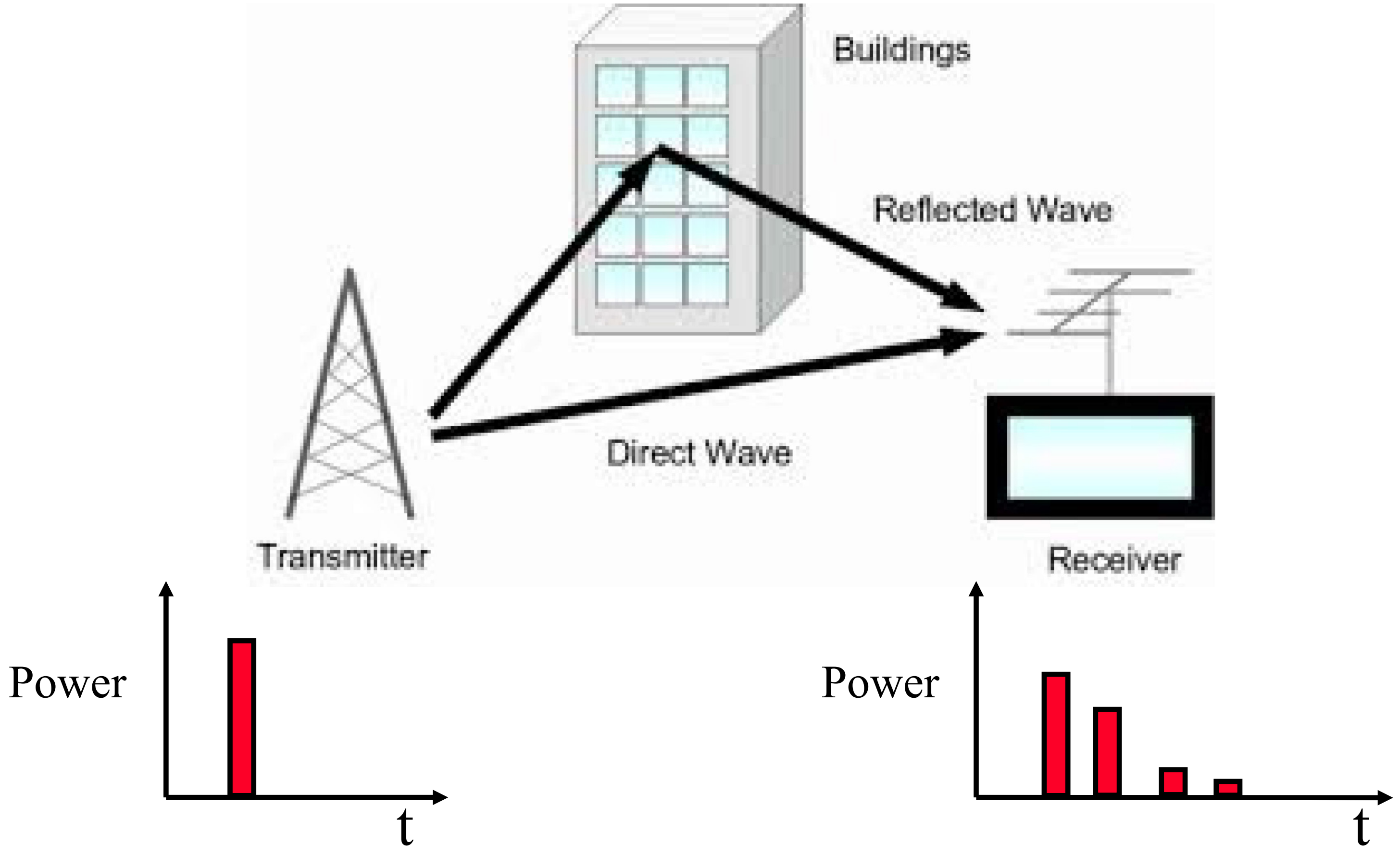
- I am confused, does the formula give us the power in Watts or dB?

*Any time you see a multiplication or division, you know it is Watts. dBs can't be multiplied.*

- Where does the formula here for $G_R$ come from?
  *See the reading list.*
- Is d diameter or radius?

*d is distance = radius*

# Multipath




❑ Multiple reflected copies of the signal are received




## Student Questions

❑ What is the point of this? Is the reflected wave compared to the direct wave to verify integrity?

*What you receive is very different from what was transmitted. So you have to find real signal from this kind of "noisy" signal.*

---

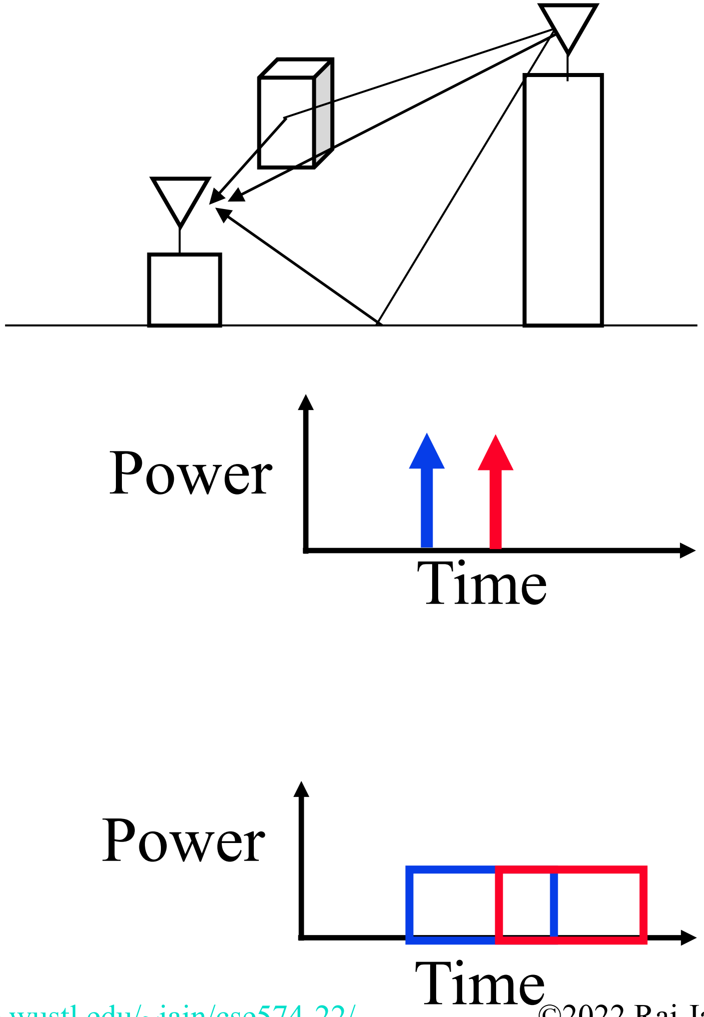
❑ What is the Y axis in the figure?

*Power*

❑ How does the receiver decide whether what it receives is waves from a different source or a single wave with its multipath?

*Receivers get a mixture and generally do not distinguish the source. Different sources should ideally use different frequencies.*

# Inter-Symbol Interference




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



## Student Questions

- Is inter symbol interference due only to having multiple signals in a space, or could it be due to differing mediums?

*This is how waves propagate. The pulses become wider and run in to each other. In some media, it happens faster (higher dispersion index).*

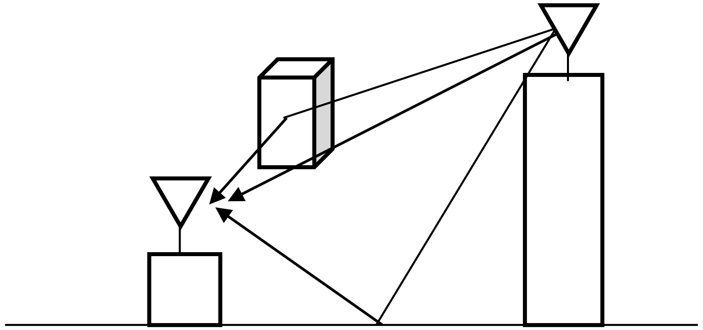
- The people are analogous to the symbols; what is analogous to the tunnel?

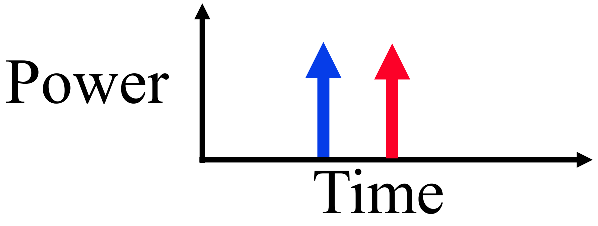
*Medium. This applies to the wire, fiber, and wireless.*

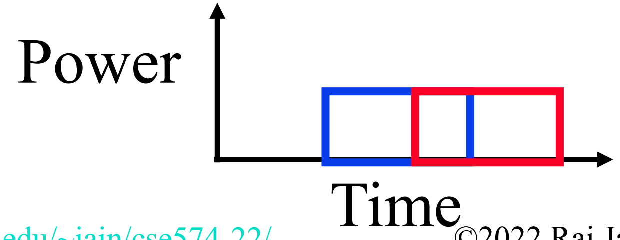
- Is the dispersion of symbols also present in the frequency domain? The Doppler effect is not just due to relative motion but the change of frequency due to multi-path reflections.

*If there is no motion, multi-path does not change frequency.*
*Time domain dispersion does affect the frequency profile.*

# Inter-Symbol Interference





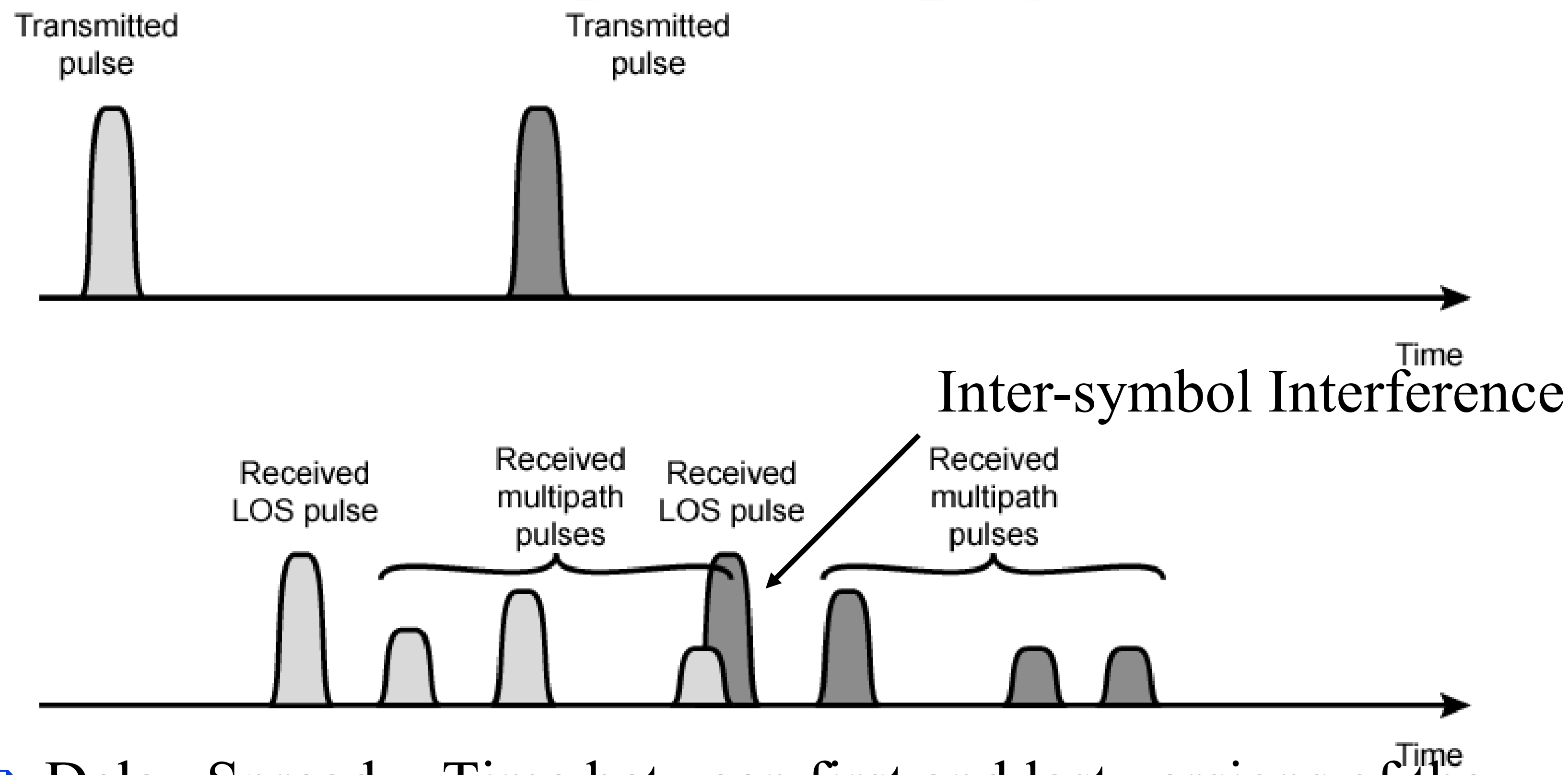

- Symbols become wider
  ⇒ Limits the number of bits/s

## Student Questions

- ❖ Why having a large symbol duration means having less ISI?

*Fatter symbols need more inter-symbol gaps to avoid interference.*

# Multipath Propagation




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





## Student Questions

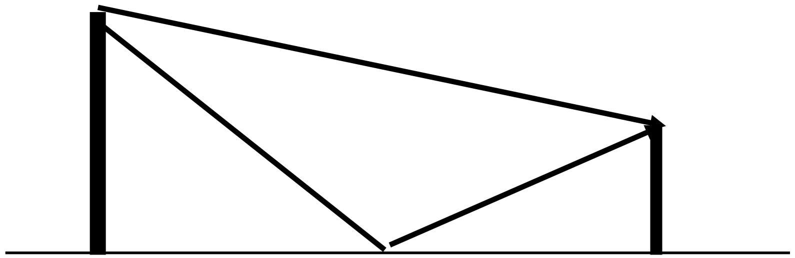
- What are fast fading and slow fading?

*Fast=high frequency*
*Slow = low frequency*
*See Slide 4-15*

- How do we usually solve ISI?

*By design and computation.*

# $d^{-4}$ 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: $P \propto d^{-n}$
- Measured results show n=1.5 to 5.5. Typically, 4.





## Student Questions

- How can the received power is independent of frequency? I thought they were always correlated.

*You are right up to $d_{break}$. And assuming antennas in free space.*

- Can you please explain what n is in this slide?

*Negative Power of d*

- When do we use this law?

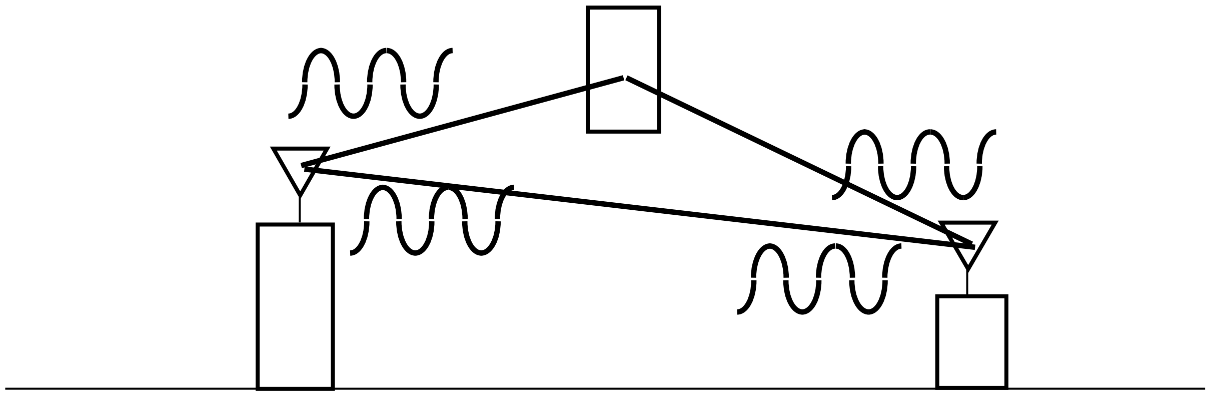
*When planning for tower placement.*

- *How to correctly use the $d^{-4}$ law?*

*Whenever you want to determine the height of the tower and its reach, you use this $P_R$ formula. See homework 4*

# Small Scale Fading

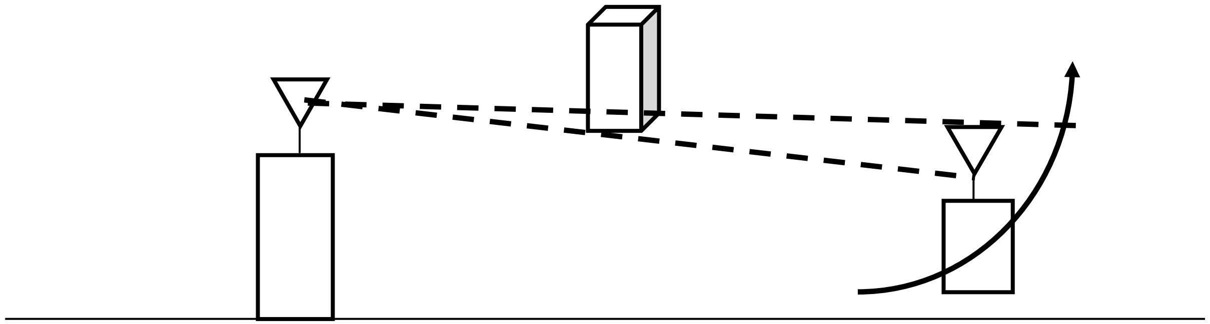
- The signal amplitude can change by moving a few inches ⇒ Small scale fading

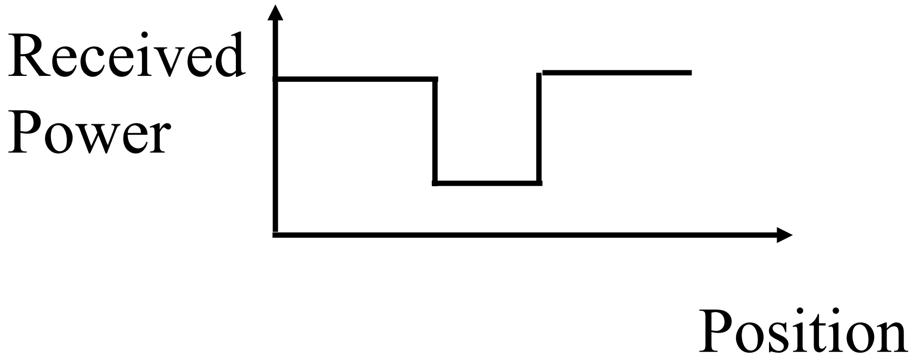


# Student Questions

# Shadowing

- Shadowing gives rise to large scale fading







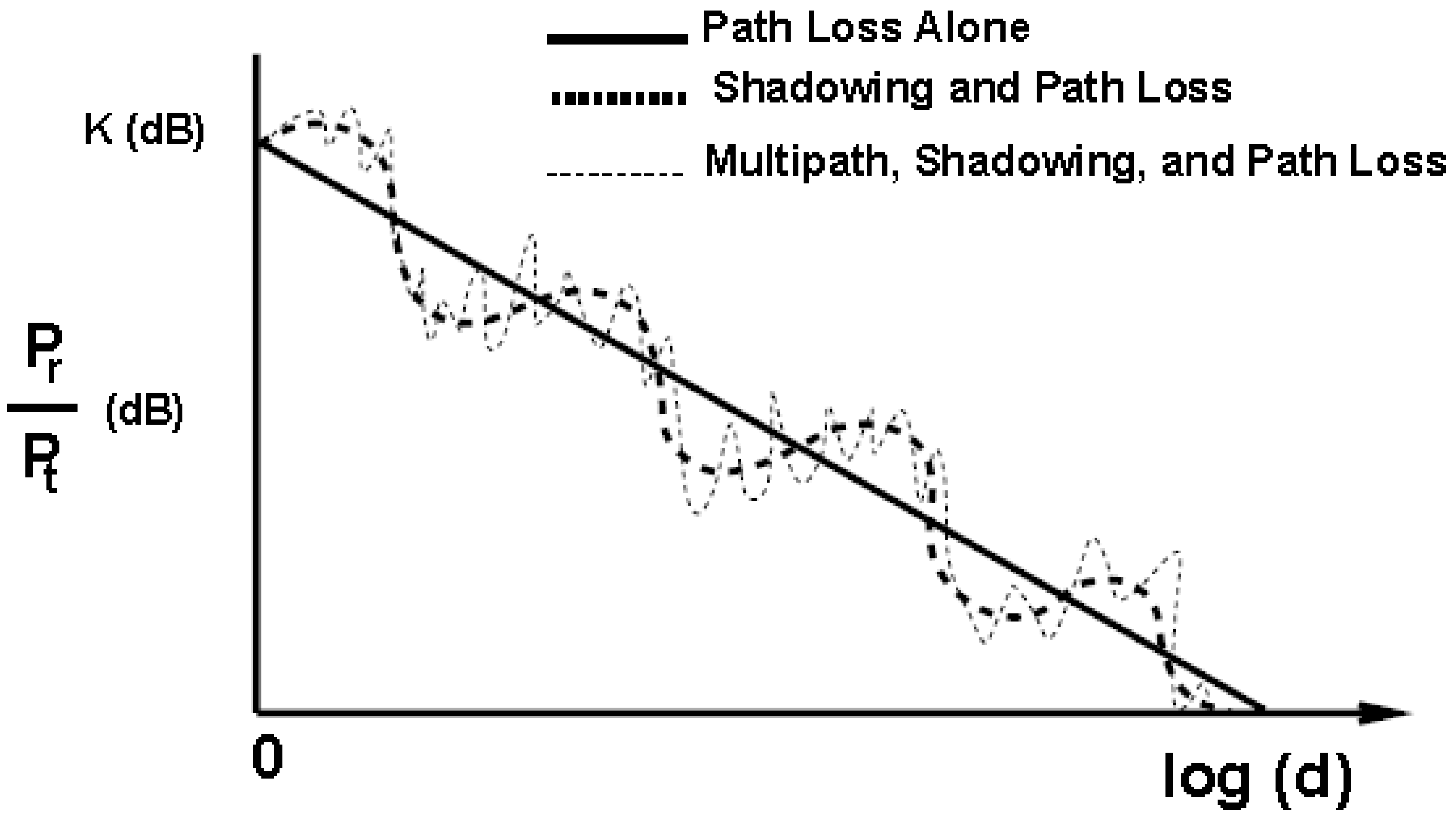



## Student Questions

- Could you clarify the difference between shadowing and fading?

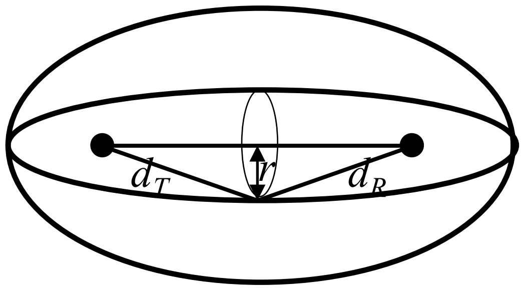
*See slide 4-15*

# Total Path Loss




## Student Questions

# Fresnel Zones




- Draw an ellipsoid with BS and MS as Foci
- All points on the 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 a distance $d_T$ from the transmitter and $d_R$ from the receiver is

$$r_i \approx \sqrt{\frac{i\lambda d_T d_R}{d_T + d_R}}$$

- Free space ($d^2$) law is followed up to the distance at which the first Fresnel Ellipsoid touches the ground

## Student Questions

- Can you repeat how the ellipsoid relates to the positions of the transmitters?

*A circle has one center. An ellipse has two "foci." Ellipse is in 2D. Ellipsoid is in 3D. Fresnel zone is an ellipsoid with foci at the transmitter and receiver antenna.*

- Can you go over what the purpose of a Fresnel Zone is? I get the formula, but what is the theoretical purpose of it?

*Any objects in the zone, will reduce the signal even if they are not in the straightline joining the two antenna.*

- What is the radius that the 5th bullet point refers to? Would that formula be used to solve for *i*?

*See the updated figure.*

- What is the '1' in the equation of point #5?

*See the updated formula.*

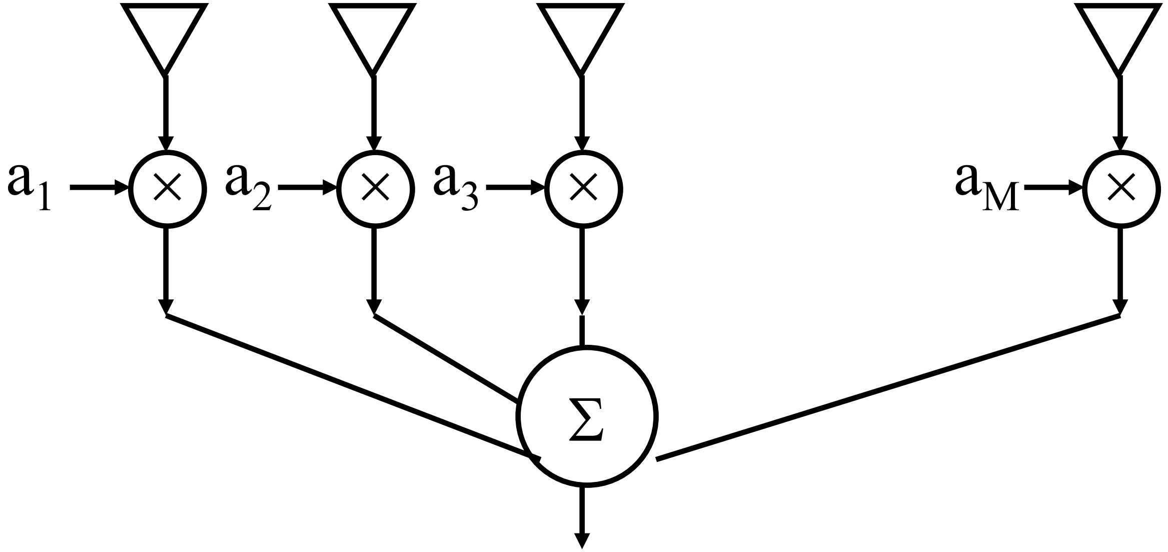
- Slide 16 was vague. Could you please explain it again?

# Multi-Antenna Systems

- Receiver Diversity
- Transmitter Diversity
- Beam forming
- MIMO

**Student Questions**

# Receiver Diversity



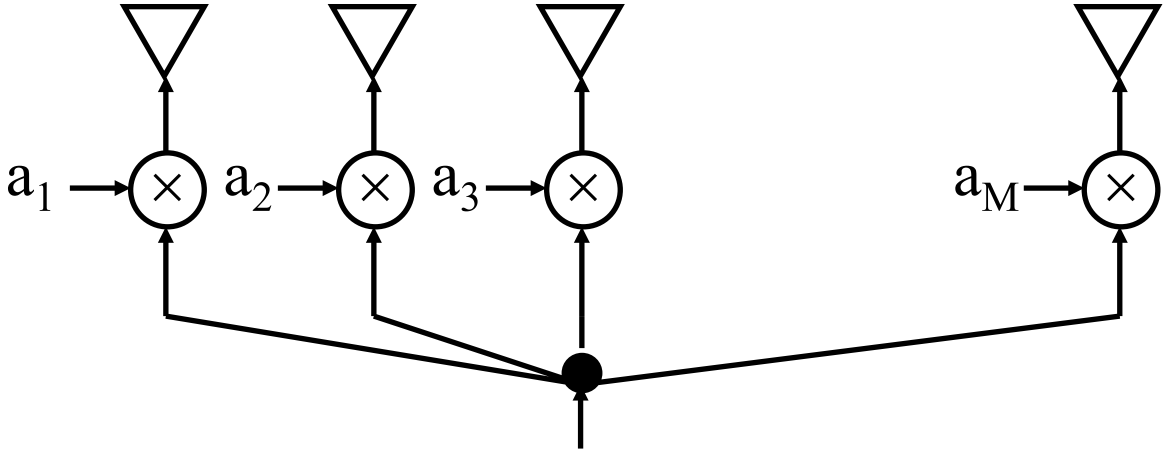

- User multiple receive antenna
- Selection combining: Select the antenna with the highest SNR
- Threshold combining: Select the first antenna with SNR above a threshold
- Maximal Ratio Combining: Phase is adjusted so that all signals have the same phase. Then the weighted sum is used to maximize SNR

## Student Questions

- Is Maximal Ratio Combining a better way than Select and Threshold combining? Or are they used in different situations?

*Each has a different cost. So these are used based on cost/performance tradeoff.*

# Transmitter Diversity




- Use multiple antennas to transmit the signal.
  Ample space, power, and processing capacity at the transmitter (but not 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

- What is Ample space?

*ample = sufficient, a lot*

- Is receiver and transceiver diversity similar to how a load balancer works for handling network traffic?

*Load balancers are used for wired traffic. Diversity shown here is used to increase the data rate. Most current routers use multiple antenna.*

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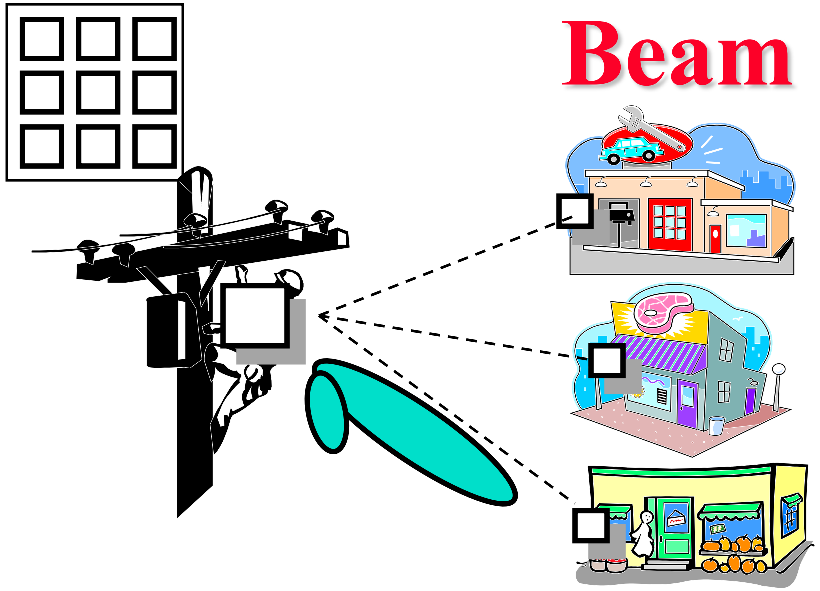
- How is the rotation angle of the user's antenna array calculated with respect to the moving direction?

*Rotation is another complexity. Too complex for this course.*

# 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

## Student Questions

- Why are there 9 antennas? 3 for each receiver?

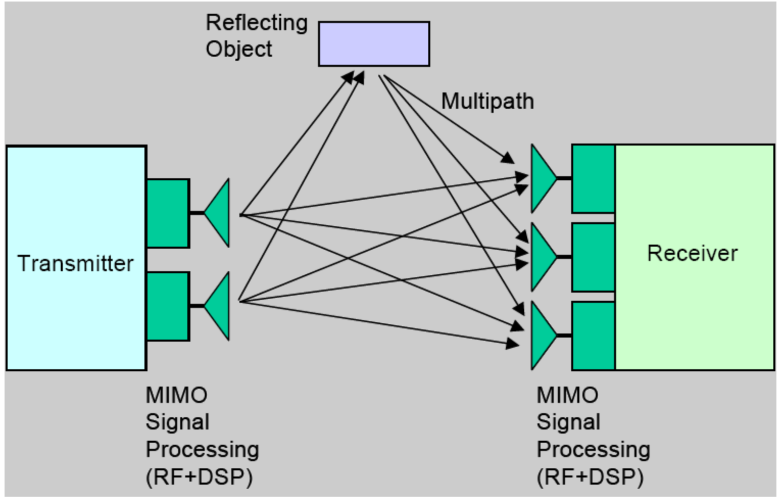
*The 9 dots on the top house are window panes. Not antenna.*

- Is beam forming done only at the receiver?

*At the transmitter*

# 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 |

## Student Questions

- ❑ I noticed the router on the slide. Are the multiple antennae on this kind of router strictly for MIMO? If it is the transmitter, then "T" in "T:R" is always 3.?

*Yes, multiple antennas are for MIMO. No, it is not always 3. It can be any number.*

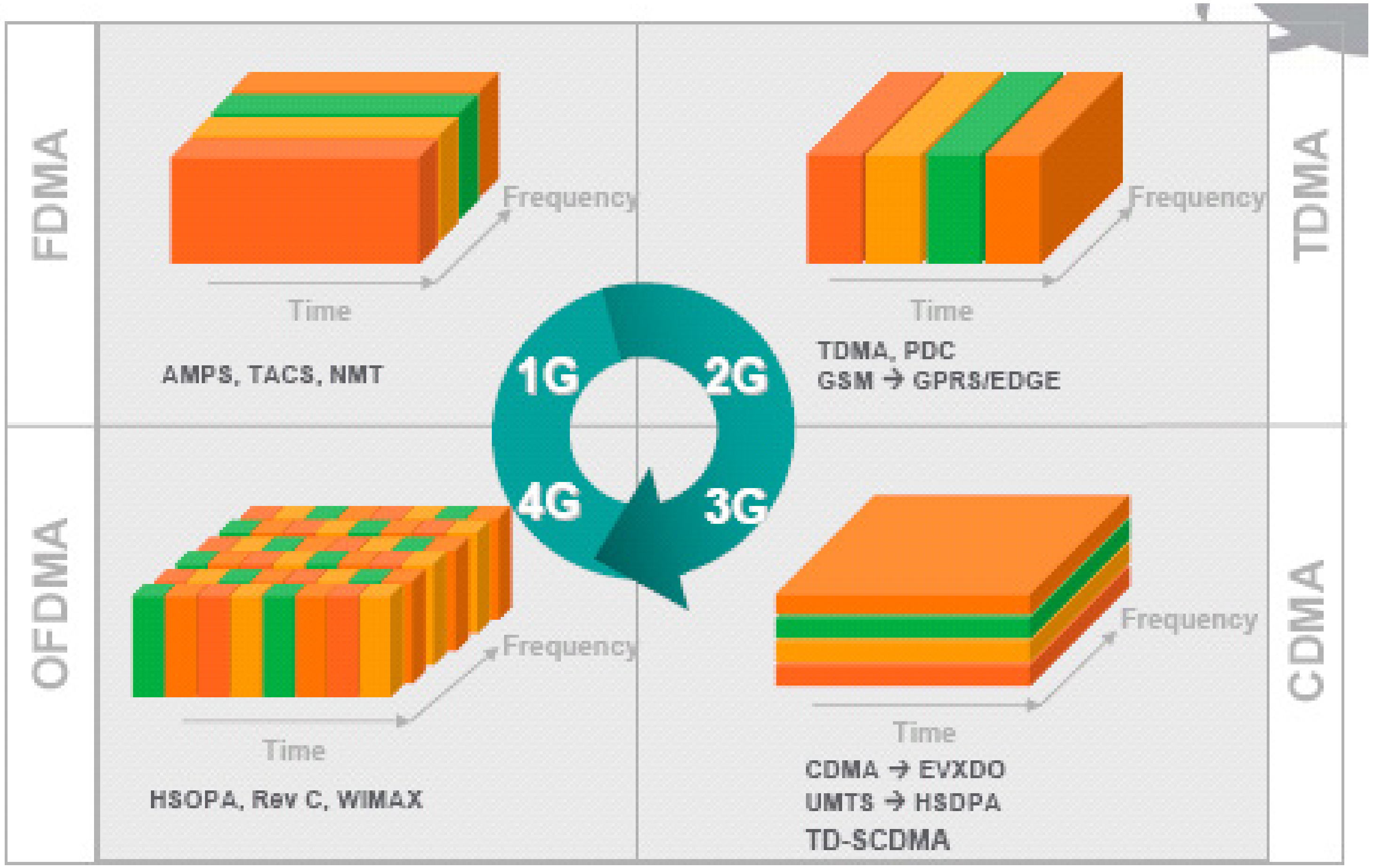
- ❑ From my understanding, MIMO is a form of transmitter diversity, so what is the difference?

*MIMO = Transmitter diversity + receiver diversity*

- ❑ What is D:U, and how does it affect the b/Hz?

*D=Down power*
*U=Up power*

# Multiple Access Methods




Source: Nortel





## Student Questions

- How does 5G compare?

*It is similar to 4G (OFDMA) but significantly improved. Wait for the last module of this course.*

- What's the speed difference among these generations?

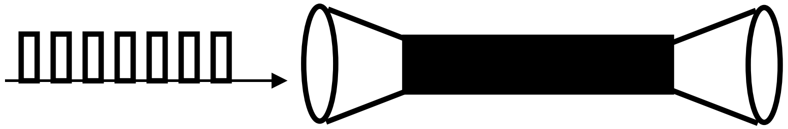
*Generally, a factor of 10.*

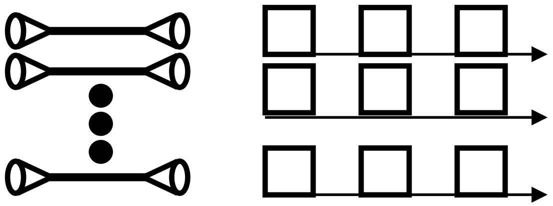
- Does 5G also do OFDMA?

*Yes.*

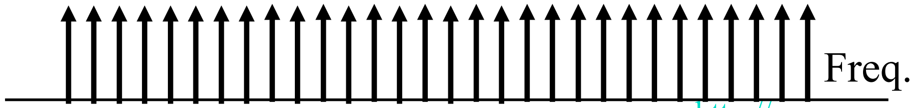
# OFDM

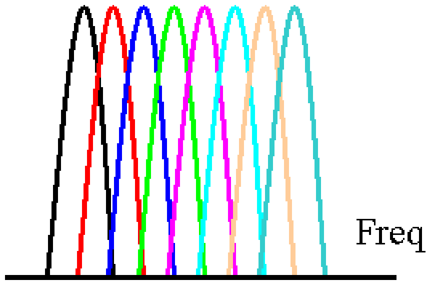
- Orthogonal Frequency Division Multiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel
  $\Rightarrow$ Multi-carrier modulation





- 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




## Student Questions

- What is multi-carrier modulation?

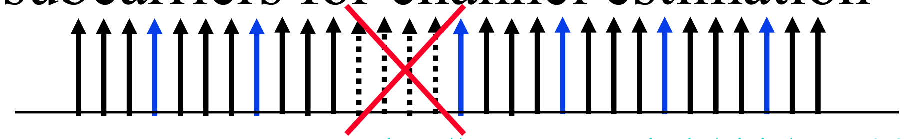
*Multicarrier = multiple frequency signals.*

- What is the input to FFT, and what is the output of it?

*FFT: Time domain to Frequency domain*
*IFFT: Frequency domain to time domain*

# 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 $O(B^2T)$ for Equalization. Here B is the bandwidth, and T is the delay spread.
- Graceful degradation if an 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



## Student Questions

- Why does OFDM have graceful degradation?
  *Because there are multiple carriers. Not all carrier get damaged or equally damaged.*

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- What is Equalization?
  *Frequency-specific amplification.*

# OFDM: Design considerations

- A 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 the data symbol block
- Fast Fourier Transform (FFT) is a computationally efficient way of computing DFT






## Student Questions

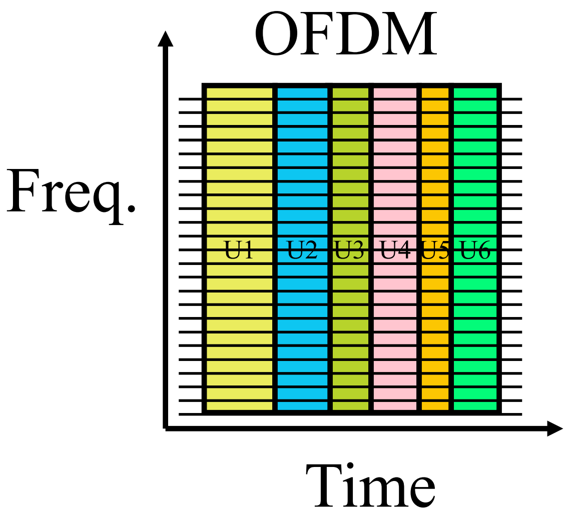
- So, do we have an increase in inter-carrier interference and a decrease in inter-symbol interference at the same time? Is there a trade-off here?

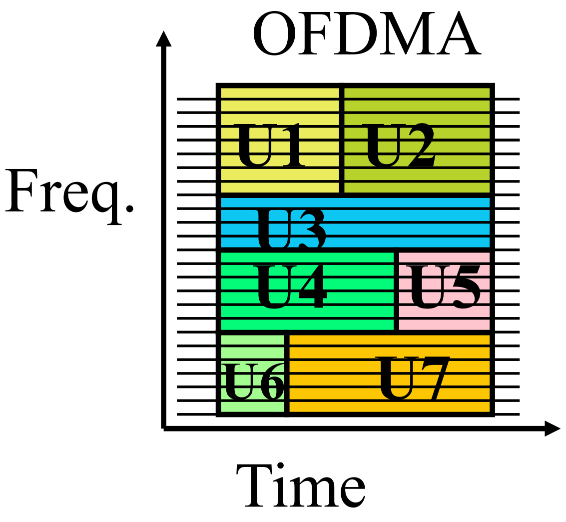
*If carriers are close, there is inter-carrier interference, and the symbols are larger, ⇒ Less Inter-symbol interference. These affect the design.*

*A 0.5μs spreading of 0.1μs will result in the total obliteration of the data. A 0.5 μs spreading of a 1 μs symbol will result in a 50% loss of efficiency.*

# 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









## Student Questions

- What do you mean by 'Each user has a subset of subcarriers for a few slots"?

*As shown by colored rectangles in the right diagram.*

---

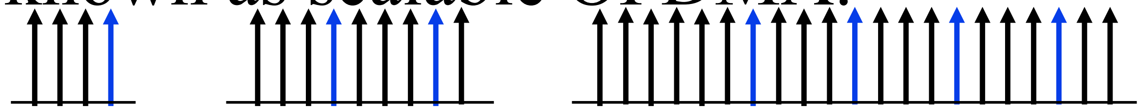
- Can we say OFDM uses TDMA whereas TDMA uses FDMA + TDMA

*OFDM=Orthogonal subcarriers with TDMA*
*OFDMA= Orthogonal subcarriers with FDMA+TDMA*
*FD=Frequency Division of the band into subcarriers*

# 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 μs
  - ⇒ Keep subcarrier spacing 10.94 kHz
  - ⇒ Number of subcarriers ∝ Frequency bandwidth

  This is known as scalable OFDMA.



## Student Questions

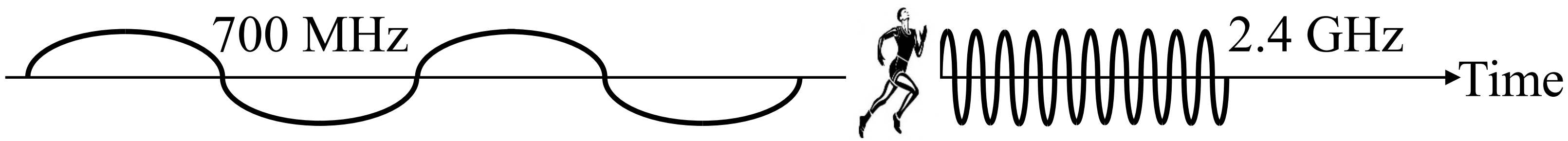
- What is the advantage of SOFDMA over OFDMA? Why does 102.9 us correspond to 10.94KHz?

*This is an example. 10.94 kHz with 128 FFT was used in Mobile WiMAX for 1.25 MHz.*

- 10.94 kHz with 128 FFT was used in Mobile WiMAX for 1.25 MHz. How is this possible?

*1.25 MHz/10.94 kHz = 114.26*
*⇒ 114 subcarriers ⇒ 128 FFT*

# Effect of Frequency




- Higher Frequencies have a higher attenuation, e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- Higher frequencies need a 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.




## Student Questions

- Another course taught that antenna size should be wavelength/4. I wonder which one is correct, a factor of 2 or 4?

*$\lambda$/2 is correct.*

# Effect of Frequency (Cont)

- Lower frequencies have a 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 is difficult, particularly on mobile devices
- Lower frequencies ⇒ Smaller channel width
  ⇒ Need aggressive modulation coding scheme (MCS), e.g., 256-QAM
- Doppler shift = vf/c = Velocity ×Frequency/(speed of light)
  ⇒ Lower Doppler spread at lower frequencies
- Mobility ⇒ Below 10 GHz

## Student Questions

- Why does a low frequency mean low channel width? Suppose we use 10 MHz to 100 MHz. Isn't it possible theoretically?

*Each frequency band has different behavior. You do not cross bands. So it is impossible to give 1000 MHz in a 700 MHz band.*

- what is MCS?

*Modulation coding scheme*

- Why do lower frequencies have longer battery life? Is this related to the power required to reach a certain distance?

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

*More power received at large* $\lambda$

# Effect of Frequency (Cont)

- Lower frequencies have a more extended 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 is difficult, particularly on mobile devices
- Lower frequencies $\Rightarrow$ Smaller channel width
  $\Rightarrow$ Need aggressive modulation coding scheme (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



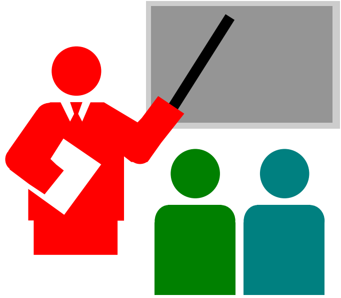


## Student Questions

- Why does mobility require below 10 GHz?

*Doppler spread*

# Summary



1. Path loss increases at a power of 2 to 5.5 with distance.
2. Fading = Changes in power changes in position
3. Fresnel zones = Ellipsoid with a 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 into many orthogonal subcarriers.
   OFDMA = FDMA + TDMA





## Student Questions

# Homework 4

A. Determine the mean received power at a subscriber station (SS). The channel between a base station at 14 m and the subscriber stations at 4 m at a distance of 500 m. The Transmitter and Receiver antenna gains are 10 dB and 5 dB respectively. Use a power exponent of 4. The transmitted power is 30 dBm. Do All calculations using dB and dBm.

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 a 10 MHz channel is 1024. How many carriers will be used if the channel is 1.25 MHz, 5 MHz, or 8.75 MHz?

## Student Questions

- ❑ Part A. Does SS refer to the subscriber station?

*Yes.*

- ❑ Part A. In the exam, will you mention which power exponent to use explicitly?

*Use four if not given.*

- ❖ Can you please go over the solution to Homework 4?

*Sure.*

# Homework 4

A. Determine the mean received power at a subscriber station (SS). The channel between a base station at 14 m and the subscriber stations at 4 m at a distance of 500 m. The Transmitter and Receiver antenna gains are 10 dB and 5 dB respectively. Use a power exponent of 4. The transmitted power is 30 dBm. Do All calculations using dB and dBm.

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 a 10 MHz channel is 1024. How many carriers will be used if the channel is 1.25 MHz, 5 MHz, or 8.75 MHz?

## Student Questions

- *Part A: What does it mean to do all calculations in DB?*

*Use a log scale only. Add. Do not multiply.*

- I googled it, and it said dB and dBm could not be converted to each other, dB is just a ratio, and only dBm can be converted to watts and refer to power. Is it correct? If so, how can the dB be used in the calculation of S/N? How can the dB be directly used to calculate the solution?

*The difference between two dBm is dB. A subtraction in a log scale results in a ratio.*

# 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

**Student Questions**

# 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





## Student Questions

# 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

**Student Questions**

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Raj Jain
http://rajjain.com

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





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# 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