PHY FUNDAMENTALS II

Wireles pagation

Overview

1. Antenna
2. Reflection, Diffraction, Scattering
3. Fading, Shadowing, Multipath
4. Inter-symbol In
5. Path loss model
6. MIMO (Diversity, Multiplexi rming)
7. Orthogonal Frequency Divisio xing (OFDM)
8. Orthogonal Frequency Division Multiple Access (OFDMA)
9. Effect of Frequency

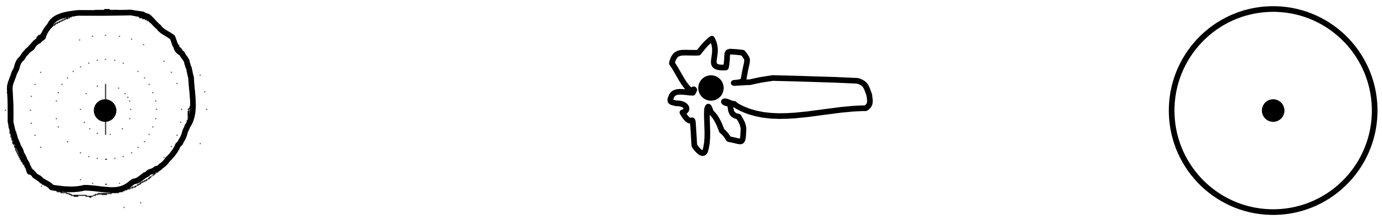
Antenna

- 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: Mos rection

- Isotropic antenna: s *equally*
- Antenna Gain = Power at partic ower with Isotropic

  Expressed in dBi ("decibel relati ic")



Omni-Directional Directional Isotropic

Example

Question: How much stronger a 17 dBi antenna effectively receives (transmits) the signal compared to the isotropic antenna?

Solution

Let

Power of isotropic anten

Power of 17 dBi antenna

We have

$17 = 10\log_{10}(P/P_{iso})$

Thus $P/P_{iso} = 10^{1.7} = 50.12$, i.e., the 17 dBi antenna will *effectively* receive (transmit) the signal 50.12 times stronger than the isotropic antenna albeit using the same *actual* transmit power.

Relationship between antenna size and frequency

- Antennas are designed to transmit or receive a specific frequency band

  - Cannot use ss router, or vice-versa (why?)

- End-to-end antenna length = h

  - So that electrons can trave orth the antenna in one cycle
- If dipole (two rods), each rod is ¼ wavelength

Reflection, Diffraction, Scattering

Reflection, Diffraction and Scattering (Cont)

- **Reflection**: Surface large relative to wavelength (λ) of signal
  - May have phase shift from original
  - May cancel out original signal or increase/strengthen it at receiver

- **Diffraction**: Edge of impenetrable body; large relative to λ
  - Receiver may recei (LOS) to transmitter

- **Scattering**
  - Obstacle size on order of wavelength.

  - Reflection/diffraction are more directio n many directions
- If LOS, diffracted and scattered signals not significant (LOS dominates)
  - Reflected signals may be significant
- If no LOS, reflection/diffraction/scattering are primary means of reception

Path Loss

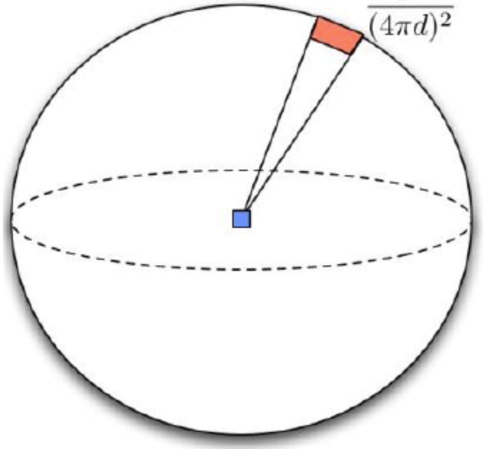
- Received power (P_R) at a particular location is only a fraction of the total power used by the transmitter to transmit the signal (P_T)
- Path loss = $P_T - P_R$
  - Depends on distance/separation between Tx-Rx

- Need to estimate path loss to design wireless links
- How to estimate pat

- There are well-know
  - Frii's model: designed for free-spac ns); frequency dependent

  - 2-Ray model: reflections considered, but frequency-independent (antenna heights are important)

Free Space Path Loss (Frii's Law)



$$P_R = P_T\left(\frac{c}{4\pi df}\right)^2$$

Surface area of sphere $A_{sphere} = 4\pi d^2$ (d=radius); surface area of antenna $A_{ant} = \lambda^2/4\pi$
Power density at sphere surface = $P_T/4\pi d^2$
PR = power density x surface area of antenna

Free-space path loss (cont)

- A factor of 10 increase in distance → 20dB more path loss (20dB/decade)
  - 2.4 GHz path loss at 1 meter = 40.04dB, 10 meter = 60.04dB
- The higher the frequency, the greater the path loss at fixed distance
  - At 10 meter, 2.4GHz = 60.04dB, 5GHz = 67.25dB

Example

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Example

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Receiver Sensitivity

- The received power (received signal strength or RSS) has to be greater than a threshold for the receiver to decode information correctly (with low error probability)
  - To achieve a minimum signal-to-noise ratio (SNR)

- Different hardware/s ifferent values
  - Depends on channel b nd temperature)
  - Larger bandwidth → larger minimum powe)
  - Larger receiver noise → larger minimum po rsa)

- Examples (for room temperature)
  - LTE: -52 dBm [roughly]
  - Bluetooth: -70 dBm [roughly]

Example

- To increase the coverage with low transmit power, a manufacturer produced Bluetooth chipsets with a receiver sensitivity of -80 dBm. What is the maximum communication range that could be achieved for this chipset for a transmit power of 1 mW? Assume Free Space Path Loss with unit antenna gains.

Bluetooth frequency f = dBm=10^{-8} mW

We have $$P_R = P_T\left(\frac{c}{4\pi d f}\right)^2$$

Or, $$d = \frac{c}{4\pi f}\sqrt{P_T / P_R}$$

= 99.5 meter

Multipath

- Multiple copies of the signal received (LoS+reflected NLoS)
- The LoS signal reaches the receiver first followed by the NLoS copy (NLoS has longer path length compared to the LoS path)
- RSS(LoS) > RSS(NLoS). NLoS signal travels further and hence attenuates more compared to the LoS.

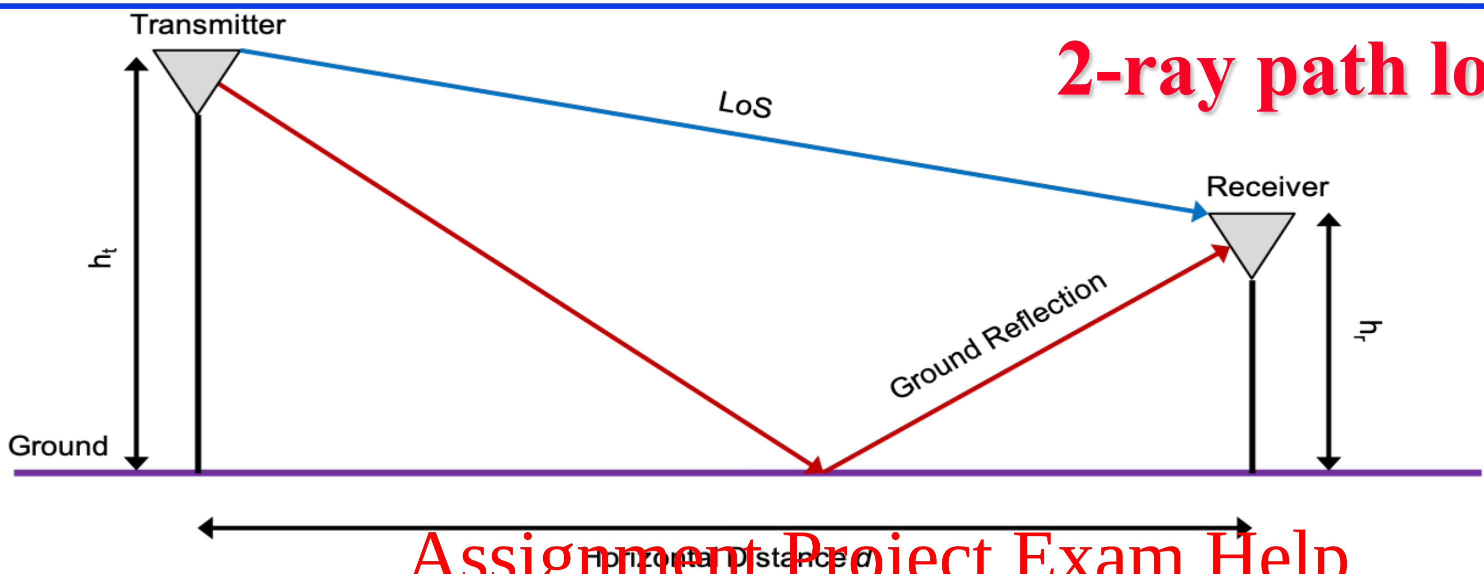
Inter-Symbol Interference

- Multipath effect: receiver continues to receive the signal (its reflections) even after the transmitter completes symbol transmission
- As a result, symbols become wider; two consecutively transmitted symbols overlap and interfere with each other
- Longer bit intervals or symbol lengths are required to avoid ISI
  - Limits the number of bits/s (data rate *inverse* of symbol length)

Delay Spread

- How long to wait to avoid ISI?
- RSS of late arrivals fluctuate, but consistently diminish on average
- Delay Spread = Time between the first (LoS) and the last copy of NLoS
  - RSS(last copy of NLoS) < $RSS_{threshold}$ (so next symbol can still be decoded)

2-ray path loss model



$$d_{break} = 4\left(\frac{h_t h_r}{\lambda}\right) = 4\left(\frac{h_t h_r f}{c}\right)$$

Example

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Path loss exponent

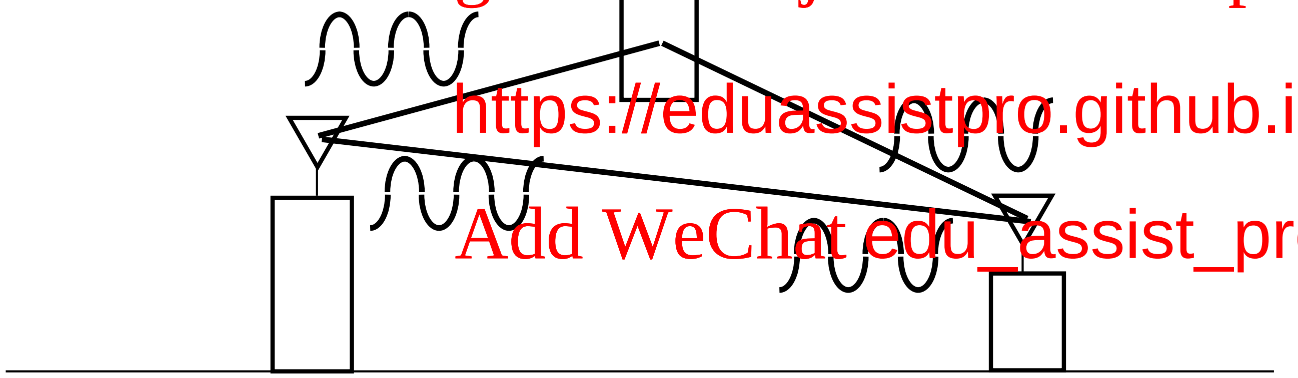
- Empty/free space (no reflector) → d^{-2} law (Frii's)
  - $PL(dB) = 10\log_{10}(d^2) + C = 10 \times 2 \times \log_{10}(d) + C$ (a straight line with slope = 2)
- 2-ray model → d^{-4} law
  - $PL(dB) = 10\log_{10}(d^4) + C = 10 \times 4 \times \log_{10}(d) + C$ (a straight line with slope = 4)

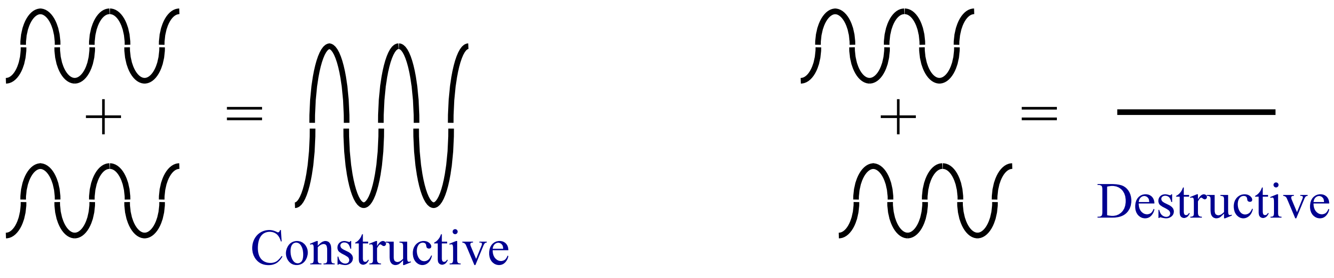
- Measurements in real environments → d^{-n} (n = 1.5 to 5.5, typically 4)
  - $PL(dB) = 10\log_{10}$ straight line with slope = n)

C is a constant; frequency related (Free-space) or antenna height related (2-ray)

Small Scale Fading

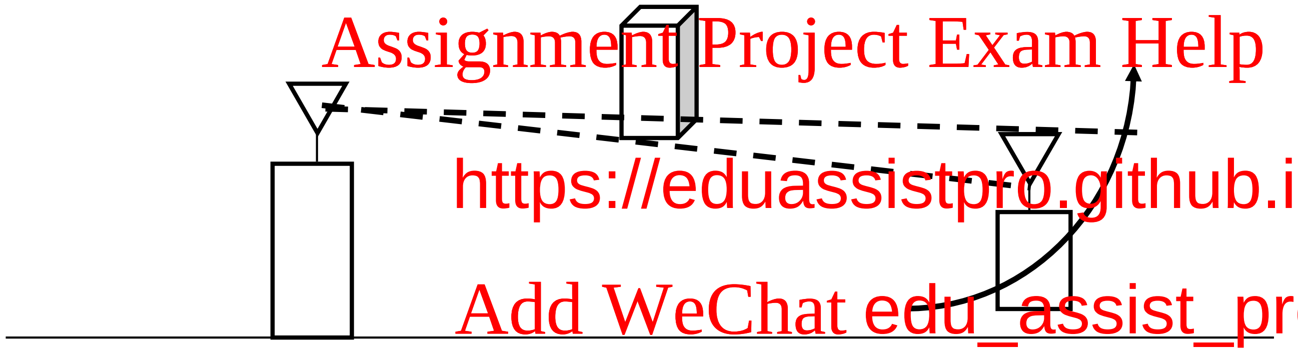
- Multipath has phase change (due to reflection and different path to travel)
- Fading: the signal amplitude can change significantly by moving a *few centimeters* (called *small scale fading*: fluctuates in small time scale): *half-wavelength path distance can cause 180 degree phase shift!*
  - **Constructive:** increased amplitude due to alignment of phase
  - **Destructive:** reduced amplitude due to misaligned phase

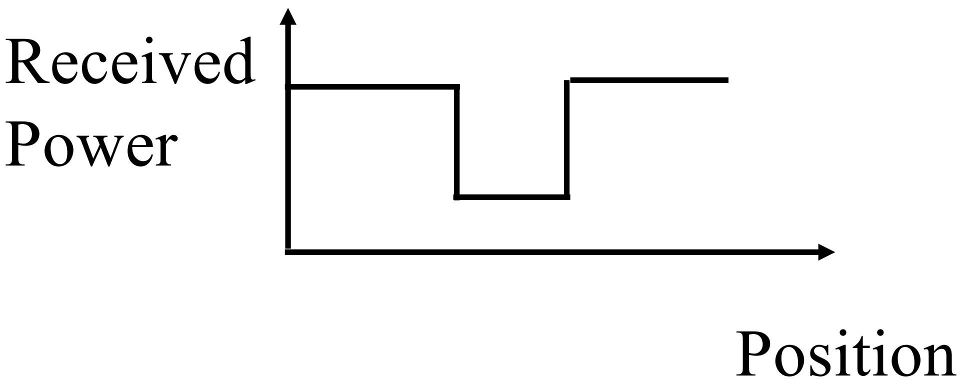




Shadowing (large scale fading)

- Shadowing gives rise to *large scale* fading
  - Mobile may be in the *shadow* of a building (fading) for *several meters*
  - RSS drops when in shadow





Total Path Loss

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MIMO

- Traditionally, single antennas were used
- Multiple antennas are increasingly being used to boost quality/reliability and capacity of wireless communications
  - E.g., most rec ultiple antennas
- Multiple input (*ansmitter*)
- Multiple output (multiple anten *eiver*)
- MIMO – multiple input multiple output

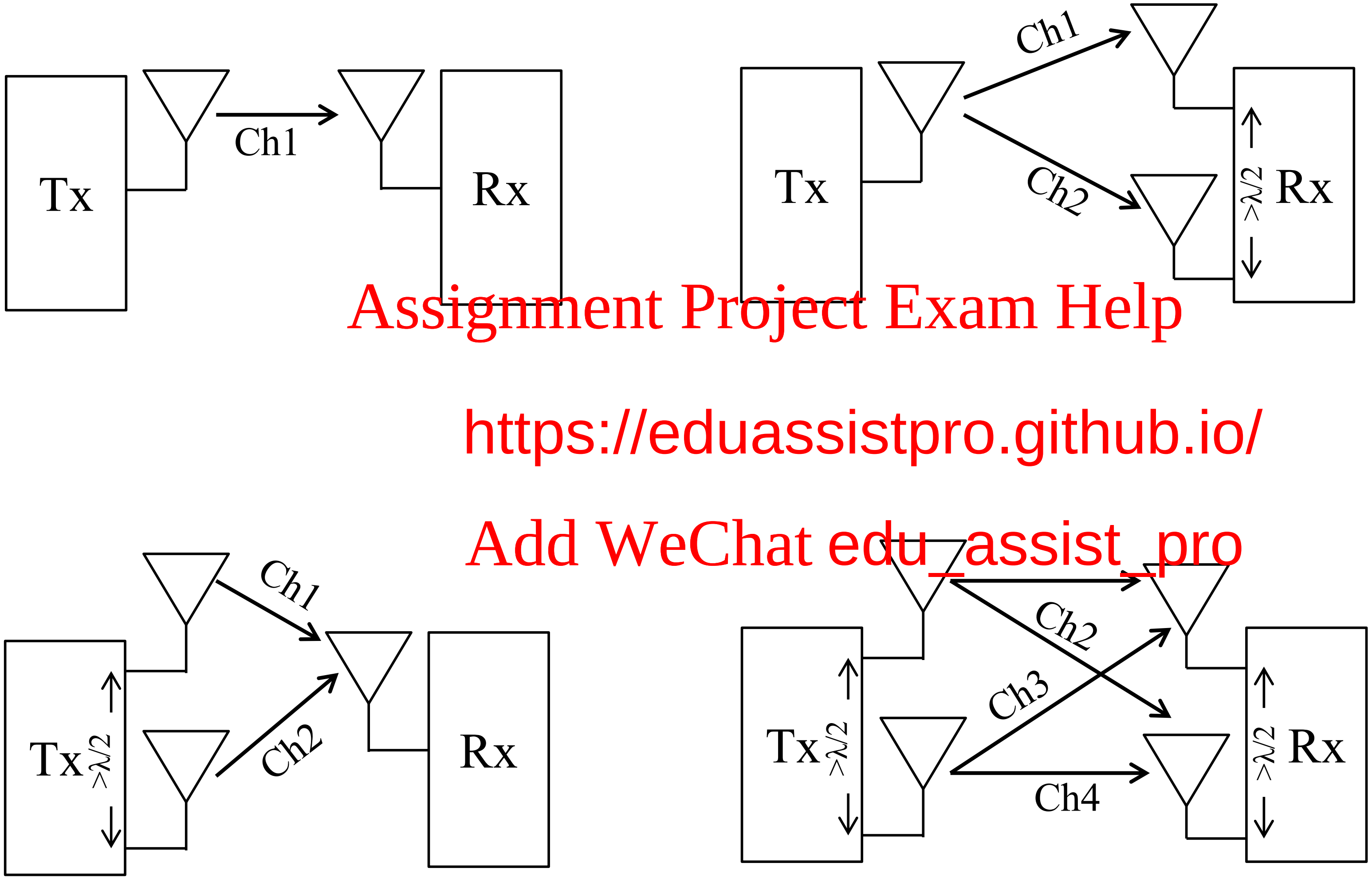
MIMO Antenna Configurations

- SISO – single input (1 Tx antenna) single output (1 Rx antenna)
- SIMO – single input (1 Tx antenna) multiple output (>1 Rx antenna)
- MISO – multiple input (>1 Tx antenna) single output (1 Rx antenna)
- MIMO – multiple input (>1 Tx antenna) multiple output (>1 Rx antenna)
  - 2x2 MIMO – 2 in s & 2 Rx antennas)
  - 4x2 MIMO – 4 in s & 2 Rx antennas)
  - 1000x2 MIMO – 1000 input & 2 o antennas & 2 Rx antennas)

Why Multiple Antennas Can Improve Performance?

- Multi-path scenario: if antennas are spaced >λ/2 apart, multipath signals for different antennas can be uncorrelated
  - multiple (*spatial*) channels using the same frequency!
  - More channels means opportunity to improve *signal quality* and *data rate*
- Line-of-Sight (L tennas at the transmitter can be used to realize ctional antennas* (beamforming)
  - Increase *coverage* and *signal strength* at a particular direction of choice

Spatial Channels



MIMO Techniques

- Spatial Diversity (a.k.a. Diversity)
  - Improve *reliability* by exploiting spatial channels
- Spatial Multiplexing (a.k.a. Multiplexing)

  - Improve *dat* patial channels

- Beamforming

  - Increase *coverage* and *si* *th* by exploiting multiple Tx antennas to focus the beam at a narrow angle

Diversity

- Total # of *independent* paths = N_T x N_R
  - N_T = # of transmit antenna, N_R = # of receive antenna
- Send same data (copied) over N_T x N_R redundant paths
- Increases reliability – probability that all paths will suffer bad fading at the sam
  - SNR at receiv)

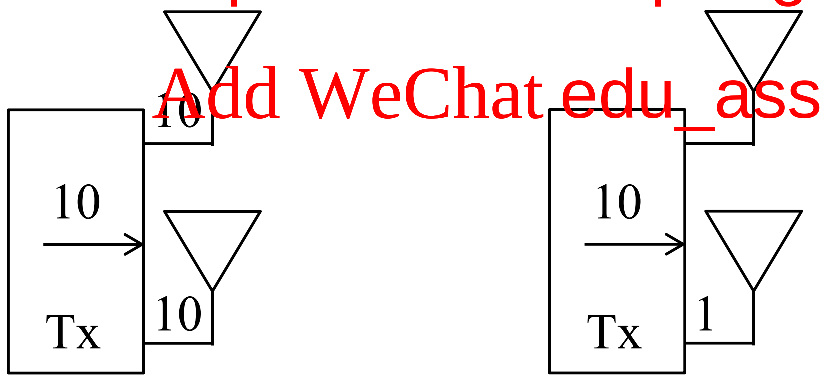
Example

- A base station is equipped with an *antenna array* consisting of 100 elements. What is the maximum number of spatial channels that could be created from this base station to an ordinary mobile device equipped with a *single* antenna?

Answer: It is a 100x annels are possible.

Multiplexing

- Send different bits of the data on different channels
- The combined data rate is increased due to multiplexing
- Overall multiplexing gain is limited by *degrees of freedom*
- Degrees of freedom = min(N_T, N_R)



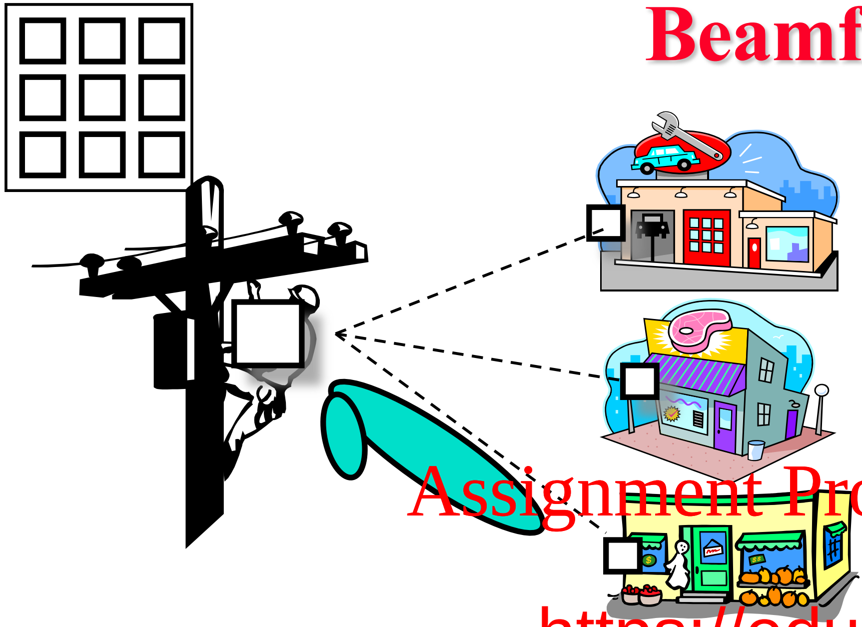
Diversity Multiplexing

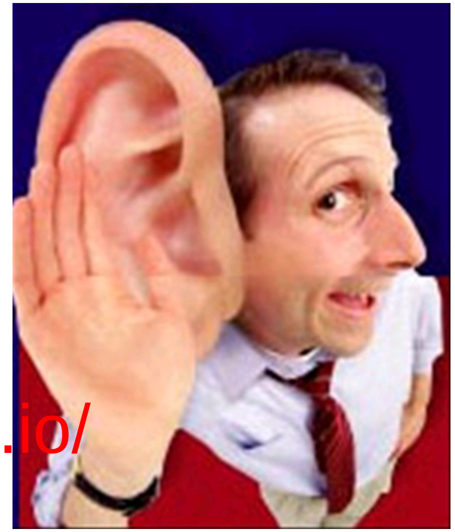
Example

- What is the *degrees of freedom* for an 802.11ac WiFi system with the access point having 8 antennas and communicating to a laptop equipped with 2 antennas?

- Answer: degre ,2) = 2

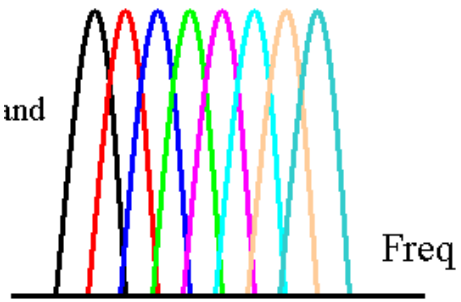
Beamforming



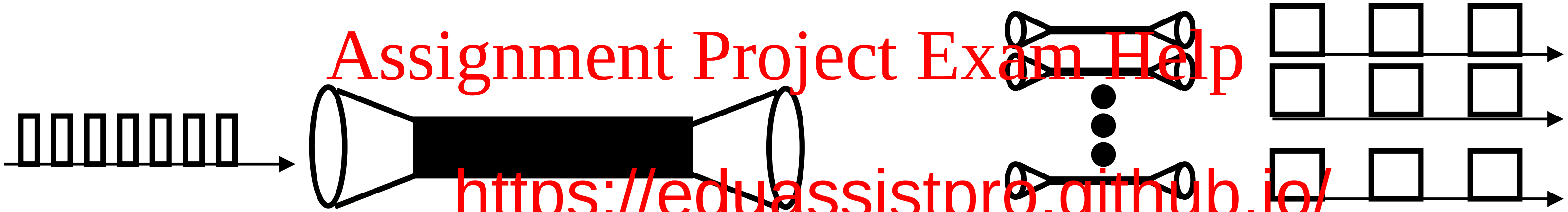


- Phased Antenna Arra
  Transmit the same signal using multipl
- By phase-shifting various signals ⇒ Fo w directional beam (increased SNR and long-distance coverage)
- Receiver does the same, i.e., focus its reception from a particular BS
- Used when LOS

OFDM



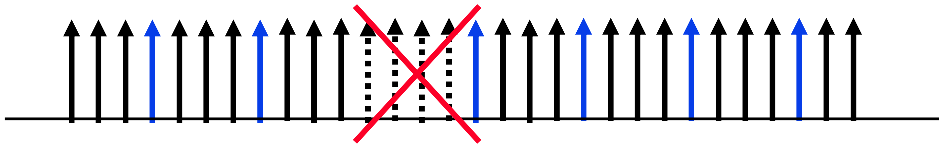
- **O**rthogonal **F**requency **D**ivision **M**ultiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel



- Frequency band is divided into 256 or more sub-bands.
  - Orthogonal: Peak of one at null of others
- Each carrier is modulated independtly with a BPSK, QPSK, 16-QAM, 64-QAM etc. depending on the fading in the channel (frequency selective fading means different channel has different fading and requires different modulation and coding)
- Used in newer generation of WiFi and 4G/5G

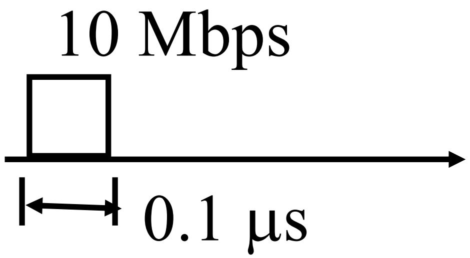
Advantages of OFDM

- 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

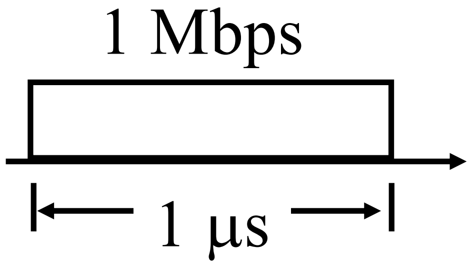


OFDM: Design considerations

- Subcarrier spacing = Frequency bandwidth/Number of subcarriers
- Large number of carriers ⇒ Smaller data rate per carrier ⇒ Larger symbol duration ⇒ Less inter-symbol interference
- Reduced subcarri nter-carrier interference due t le applications



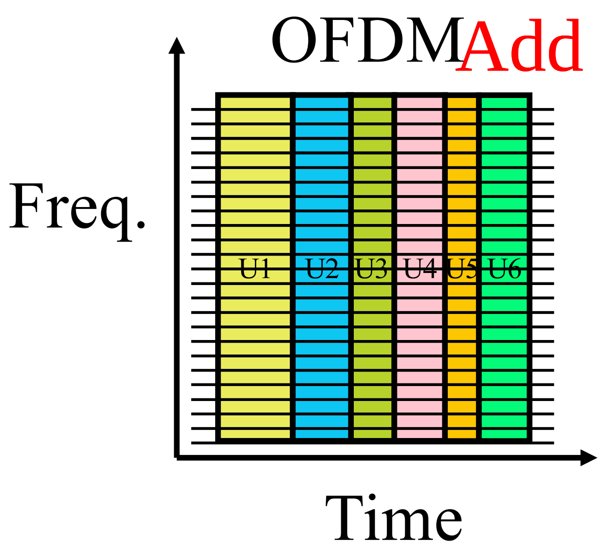
Small # of carriers
Shorter symbol durations
Higher data rates per carrier

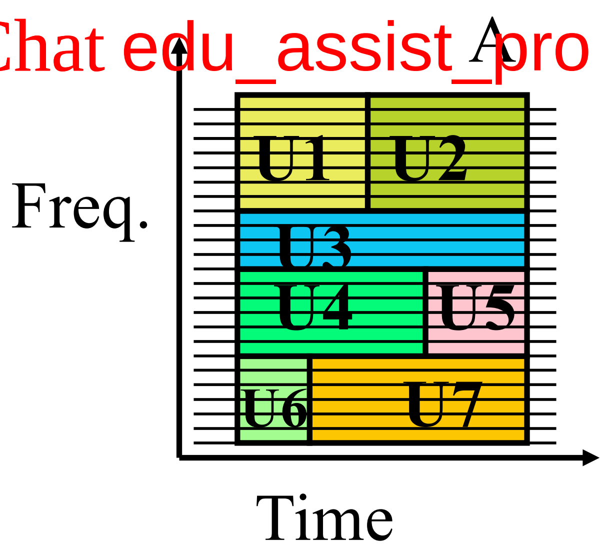


Large # of carriers
Longer symbol durations
Lower data rates per carrier

OFDMA

- Orthogonal Frequency Division Multiple Access
- Each user has a subset of subcarriers for a few time slots
- OFDM systems use TDMA (e.g., in WiFi)
- OFDMA allows Time+Freq DMA ⇒ 2D Scheduling





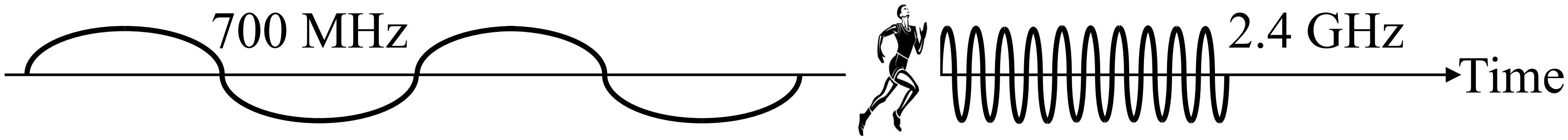
Example

- *With a subcarrier spacing of 10 kHz, how many subcarriers will be used in an OFDM system with 20 MHz channel bandwidth?*

Number of subcarri[illegible]*h/subcarrier spacing*

$= 20x10^6/10x10^3 = 2000$

Effect of Frequency



- Higher Frequencies have higher attenuation,
  e.g., 18 GHz has Hz

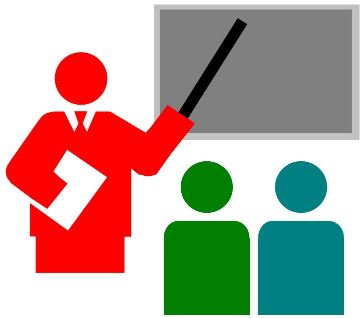
- Higher frequenci
  Antenna $\geq$ Wavelength/2, 800

- Higher frequencies are affected eather
  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
- Lower frequencie and antenna spacing
  ⇒ MIMO difficult particularly evices
- Lower frequencies ⇒ Smaller ch
  ⇒ 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 increases at a power of 2 to 5.5 with distance.
2. Fading = Chang

s in position

3. Multiple Antennas: Receive d

nsmit diversity,

multiplexing, and beamforming

4. OFDM splits a band into many orthogonal subcarriers. OFDMA = FDMA + TDMA

Acronyms

- BPSK Binary Phase-Shift Keying
- BS Base Station
- dB DeciBels
- dBi DeciBels Intrinsic
- dBm DeciBels milliwatt

- DFT Discrete Fourier Transform
- DMA Direct

- DSP Digital
- DVB-H Digital Video Broadcast

- FDMA Frequency Division Mul
- 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	Quadr
RF	Radio
SNR	Signal to Noise Ratio
SS	Subscriber Station
STBC	Space Time Block Codes
TDMA	Time Division Multiple Access