

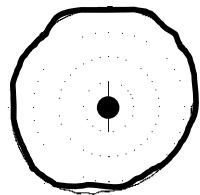
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PHYFUNDAMENTALS II
Wireless <https://eduassistpro.gitbook.io/>
pagation
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Overview

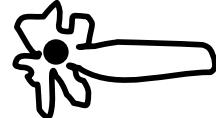
1. Antenna
2. Reflection, Diffraction, Scattering
3. Fading, Shadowing, Multipath
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4. Inter-symbol In
5. Path loss model <https://eduassistpro.github.io/>
6. MIMO (Diversity, Multiplexing)
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7. Orthogonal Frequency Division Multiplexing (OFDM)
8. Orthogonal Frequency Division Multiple Access (OFDMA)
9. Effect of Frequency

Antenna

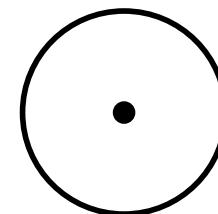
- Transmitter converts electrical energy to electromagnetic waves
- Receiver converts electromagnetic waves to electrical energy
- Same antenna is used for transmission and reception
- Omni-Directional: Power radiated in all directions
- Directional: Most power in one direction
- Isotropic antenna: Power distributed equally in all directions
- Antenna Gain = Power at particular angle / Power with Isotropic
Expressed in dBi (“decibel relative to isotropic”)



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 antenna <https://eduassistpro.github.io/>

Power of 17 dBi antenna

We have

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

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 **Assignment Project Exam Help** ss router, or vice-versa (why?) <https://eduassistpro.github.io/>
- End-to-end antenna length = **Add WeChat edu_assist_pro**
 - So that electrons can travel the length of the antenna in one cycle
- If dipole (two rods), each rod is $\frac{1}{4}$ wavelength

Reflection, Diffraction, Scattering

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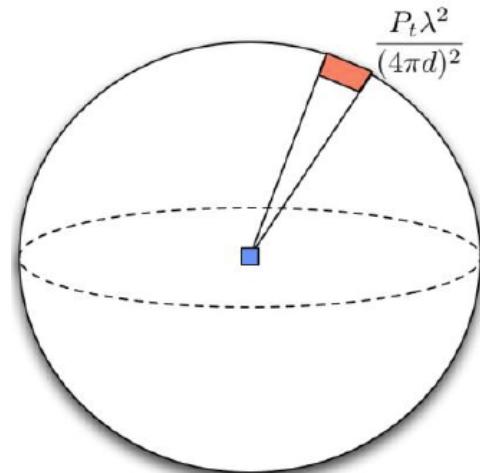
Reflection, Diffraction and Scattering (Cont)

- **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 receive (LOS) to transmitter
- **Scattering**
 - Obstacle size on order of wavelength
 - Reflection/diffraction are more directional than many directions
- If LOS, diffracted and scattered signals not significant (LOS dominates)
 - Reflected signals may be significant
- If no LOS, diffraction and 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 path loss <https://eduassistpro.github.io/>
- ❑ There are well-known
 - Frii's model: designed for free-space (no obstacles), frequency dependent
 - 2-Ray model: reflections considered, but frequency-independent (antenna heights are important)

Free Space Path Loss (Frii's Law)



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

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

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Example

Question: If 50W power is applied to a 900 MHz frequency at a transmitter, find the receive power at a distance of 100 meter from the transmitter (assume free space path loss with unit antenna gains).

Solution

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Unit antenna gain mean

We have $d=100\text{m}$, $f=900$ P_T and $\pi = 3.14$

$$P_R = P_T \left(\frac{1}{4\pi f d} \right)$$

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
 - Depends on channel bandwidth (different values)
 - Larger bandwidth → larger minimum power requirement (higher SNR required at room temperature)
 - Larger receiver noise → larger minimum power requirement (higher SNR required at room temperature)
- 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.

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Bluetooth frequency $f = \frac{c}{4\pi d^2}$ dBm = -80 mW

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

$$d = \sqrt{\frac{c}{4\pi f} \cdot \frac{P_T}{P_R}}$$

Or,

= 99.5 meter

Multipath

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- 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)
- $\text{RSS(LoS)} > \text{RSS(NLoS)}$. NLoS signal travels further and hence attenuates more compared to the LoS.

Inter-Symbol Interference

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- 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)

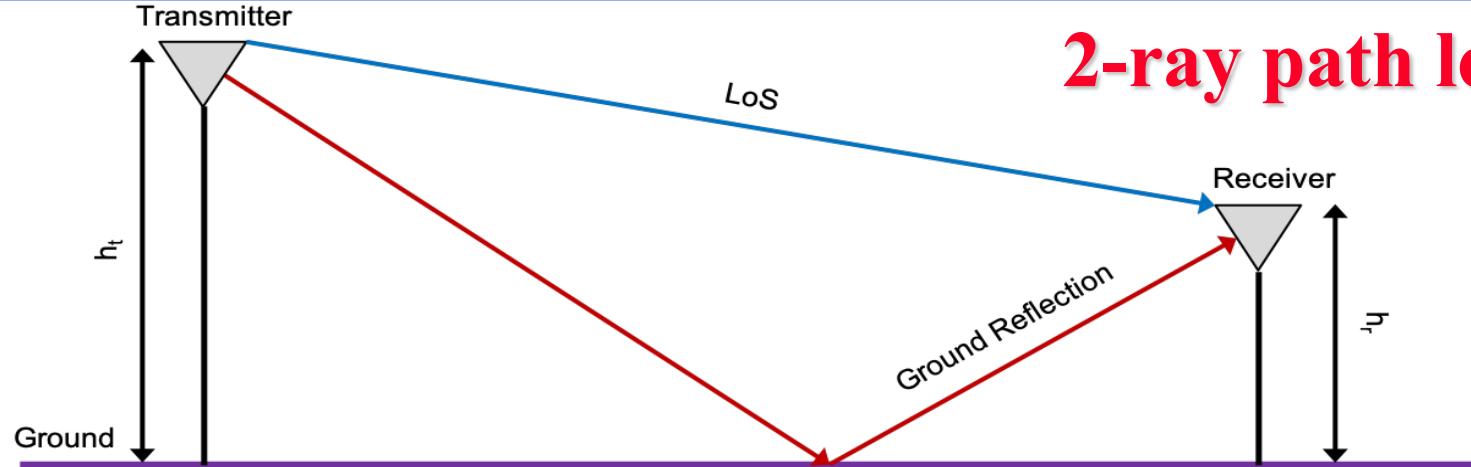
Delay Spread

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- ❑ 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
 - ❑ $\text{RSS}(\text{last copy of NLoS}) < \text{RSS}_{\text{threshold}}$ (so next symbol can still be decoded)



2-ray path loss model

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

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)
 - $PL(dB) = 10\log_{10} \frac{https://eduassistpro.github.io/}{d^n} + C$ (straight line with slope = n)

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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

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$$\begin{array}{c} \text{Sine Wave} \\ + \\ \text{Sine Wave} \end{array} = \begin{array}{c} \text{Sine Wave} \\ \text{Sine Wave} \\ \text{Sine Wave} \end{array}$$

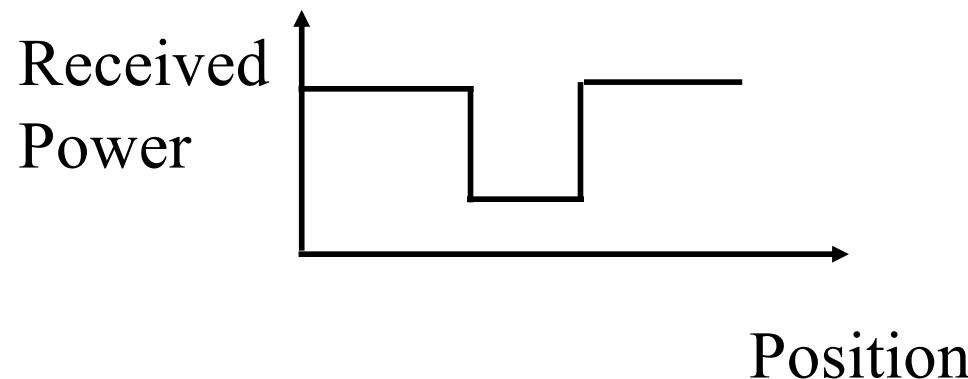
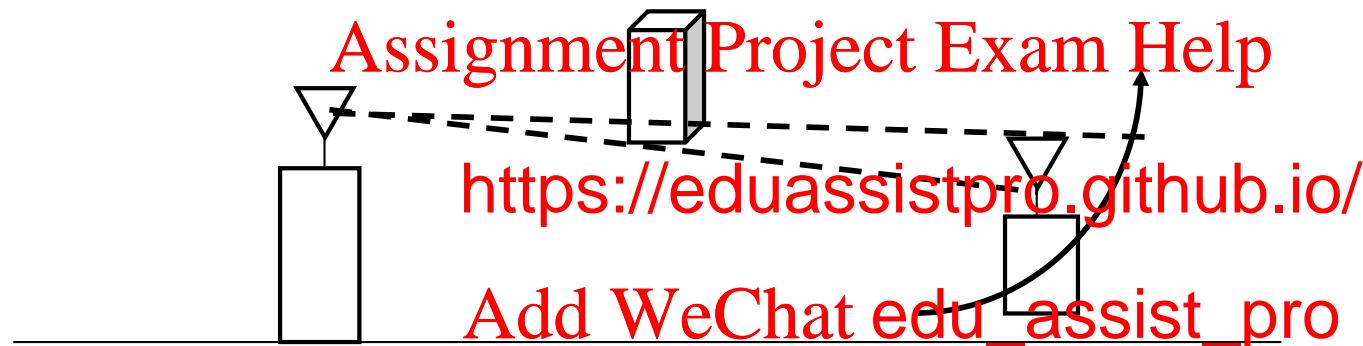
Constructive

$$\begin{array}{c} \text{Sine Wave} \\ + \\ \text{Sine Wave} \end{array} = \begin{array}{c} \text{Sine Wave} \\ \text{Sine Wave} \end{array}$$

Destructive

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 recent transmitter uses multiple antennas
- Multiple input (multiple antenna transmitter) <https://eduassistpro.github.io/>
- Multiple output (multiple antenna receiver) [Add WeChat edu_assist_pro](https://edu_assist_pro)
- MIMO – multiple input multiple output

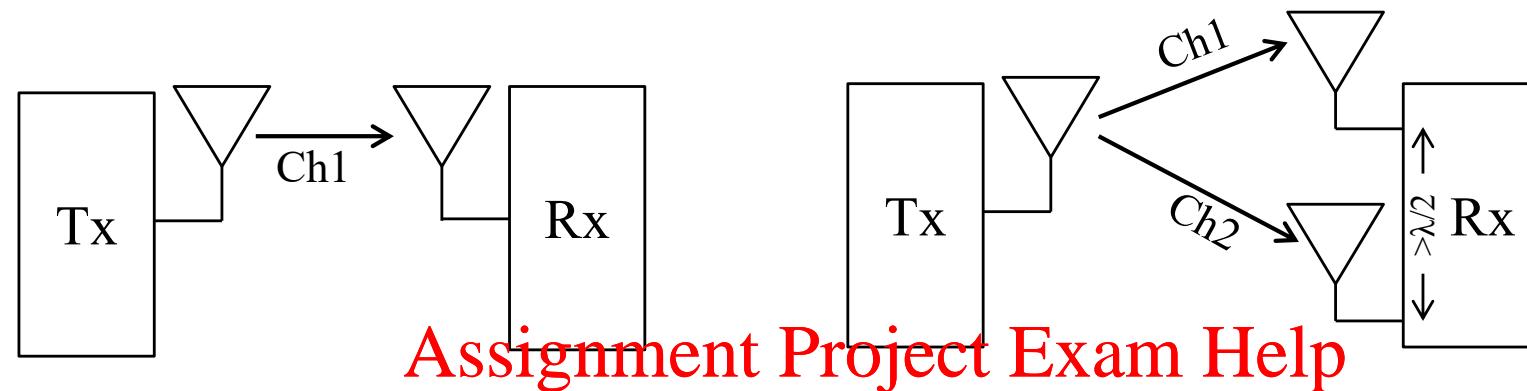
MIMO Antenna Configurations

- 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 & 2 Rx antennas
 - 4x2 MIMO – 4 in & 2 Rx antennas
 - 1000x2 MIMO – 1000 input & 2 Rx antennas

Why Multiple Antennas Can Improve Performance?

- Multi-path scenario: if antennas are spaced $>\lambda/2$ 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) <https://eduassistpro.github.io/> tennas at the transmitter can be used to realize optional antennas (beamforming)
 - Increase *coverage* and *signal strength* at a particular direction of choice

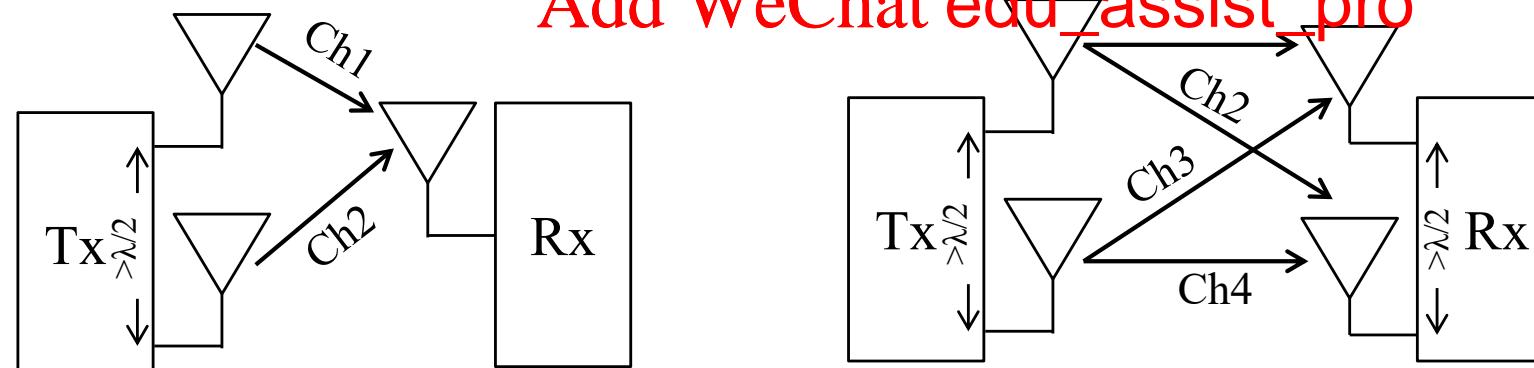
Spatial Channels



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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 = $N_T \times N_R$
 - N_T = # of transmit antenna, N_R = # of receive antenna
 - Send same data (copied) over $N_T \times N_R$ redundant paths
 - Increases reliability – probability that all paths will suffer bad fading at the sam <https://eduassistpro.github.io/>
 - SNR at receiv)
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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?

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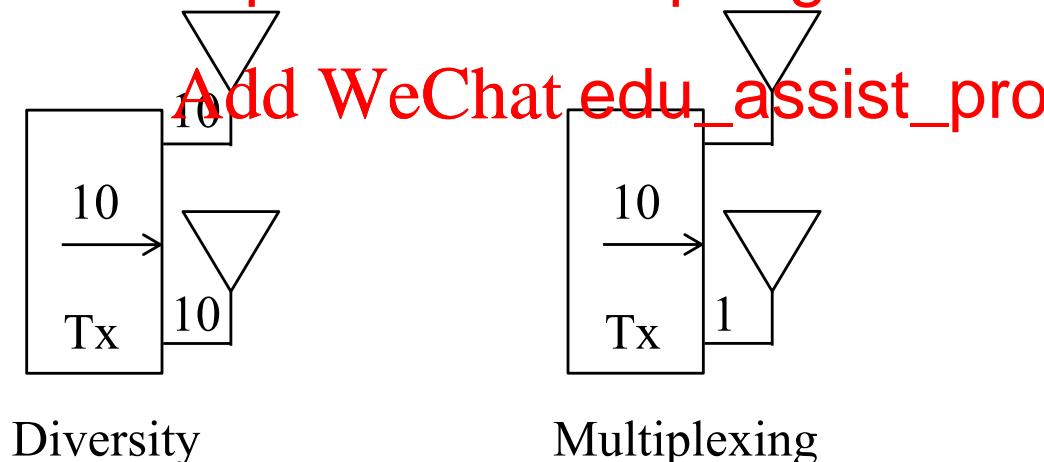
Answer: It is a 100x <https://eduassistpro.github.io/> channels are possible.

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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 = $\min(N_T, N_R)$

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Example

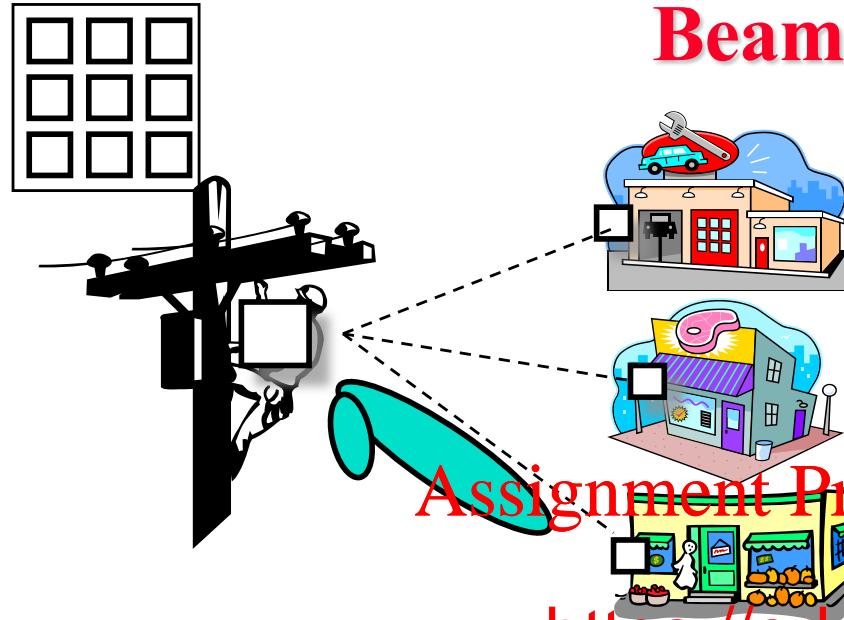
- What is the *degrees of freedom* for an 802.11ac WiFi system with the access point having 8 antennas and communicating to a laptop equipped with 2 antennas?

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- Answer: degree <https://eduassistpro.github.io/>

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Beamforming



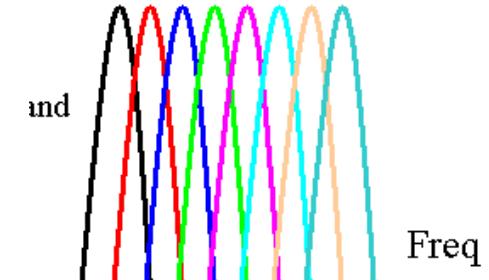
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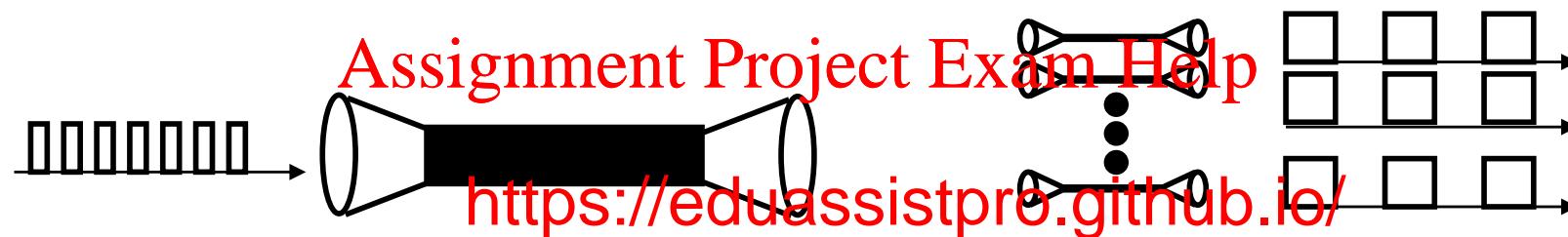
- Phased Antenna Arra
Transmit the same signal using multipl
- By phase-shifting various signals \Rightarrow Fo
(increased SNR and long-distance coverage)
- Receiver does the same, i.e., focus its reception from a particular BS
- Used when LOS



OFDM



- ❑ Orthogonal Frequency Division Multiplexing
- ❑ Ten 100 kHz channels are better than one 1 MHz Channel



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- ❑ Frequency band is divided into 256 or more sub-bands.
 - ❑ Orthogonal: Peak of one at null of others
- ❑ Each carrier is modulated independently 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

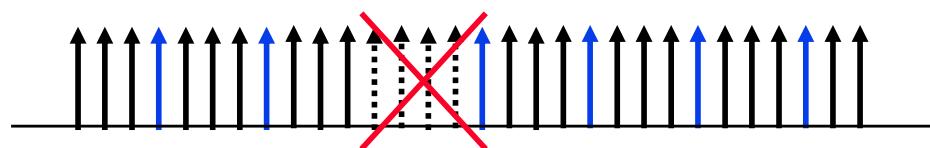
Advantages of OFDM

- 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

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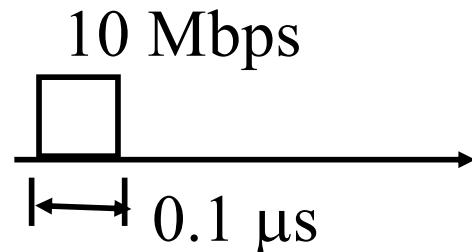


OFDM: Design considerations

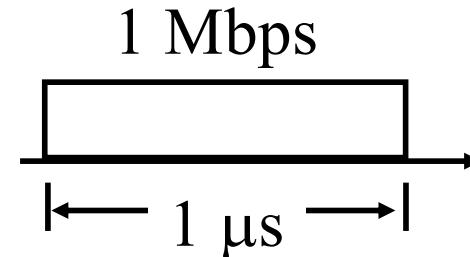
- Subcarrier spacing = Frequency bandwidth/Number of subcarriers
- Large number of carriers \Rightarrow Smaller data rate per carrier
 \Rightarrow Larger symbol duration \Rightarrow Less inter-symbol interference
- Reduced subcarrier interference due to inter-carrier interference

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tele applications

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



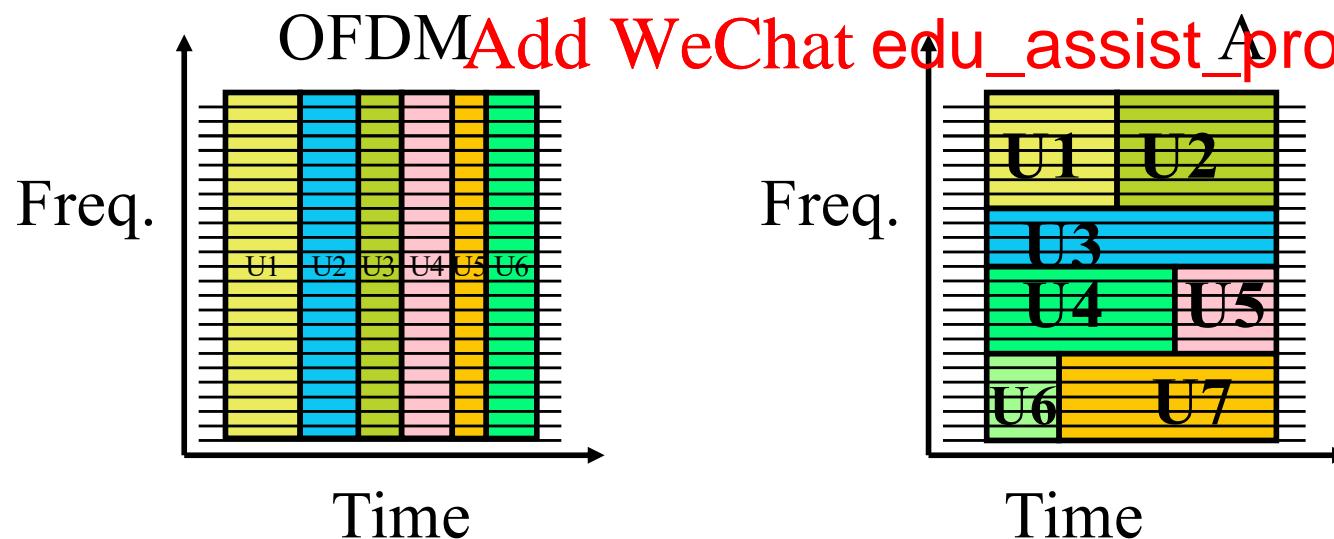
Large # of carriers
Longer symbol durations
Lower data rates per carrier

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 \Rightarrow 2D Scheduling

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Example

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

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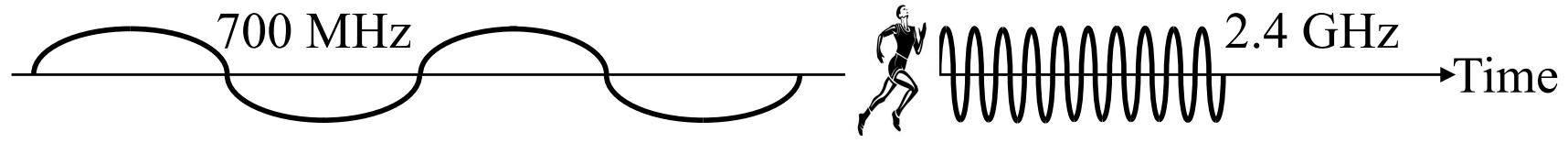
Number of subcarriers = $\frac{20 \times 10^6}{10 \times 10^3} = 2000$

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Effect of Frequency

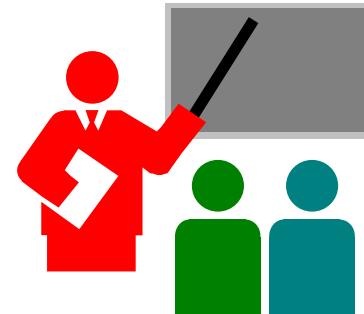


- Higher Frequencies have higher attenuation,
e.g., 18 GHz has $\frac{1}{f}$ Hz
- Higher frequency Antenna \geq Wavelength/2, 800
- Higher frequencies are affected by eather
Higher than 10 GHz affected by rainfall
60 GHz affected by absorption of oxygen molecules
- Higher frequencies have more bandwidth 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 frequencies <https://eduassistpro.github.io/> and antenna spacing
 - ⇒ MIMO difficult particularly at lower frequencies
- Lower frequencies ⇒ Smaller channels
 - ⇒ Need aggressive MCS, e.g., 256-QAM
- Doppler shift = vf/c = Velocity \times 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 = Change <https://eduassistpro.github.io/> S in position
3. Multiple Antennas: Receive diversity, transmit diversity, multiplexing, and beamforming
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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 <https://eduassistpro.github.io/>
- ❑ 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

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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 Quadr <https://eduassistpro.github.io/>
- ❑ RF Radio
- ❑ SNR Signal to Noise Ratio
- ❑ SS Subscriber Station
- ❑ STBC Space Time Block Codes
- ❑ TDMA Time Division Multiple Access

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