

Assignment Project Exam Help
PHYFUNDAMENTALS II
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Wireless Signal Propagation

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Overview

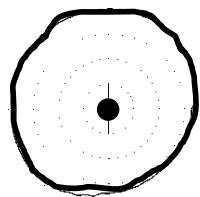
1. Antenna
2. Reflection, Diffraction, Scattering
3. Fading, Shadowing, Multipath
4. Inter-symbol Interference
5. Path loss model (Friis, 2-ray)
6. MIMO (Diversity, Multiplexing, Beamforming)
7. Orthogonal Frequency Division Multiplexing (OFDM)
8. Orthogonal Frequency Division Multiple Access (OFDMA)
9. Effect of Frequency

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Antenna

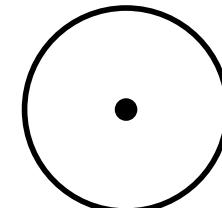
- Transmitter converts electrical energy to electromagnetic waves
- Receiver converts electromagnetic waves to electrical energy
- Same antenna is used for transmission and reception
- Omni-Directional: Power radiated in all directions
- Directional: Most power in the desired direction
- Isotropic antenna: Radiates in all directions *equally*
- Antenna Gain = $\frac{\text{Power at particular point}}{\text{Power with Isotropic}}$ 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 = P_{iso}

Power of 17 dBi antenna = P

We have

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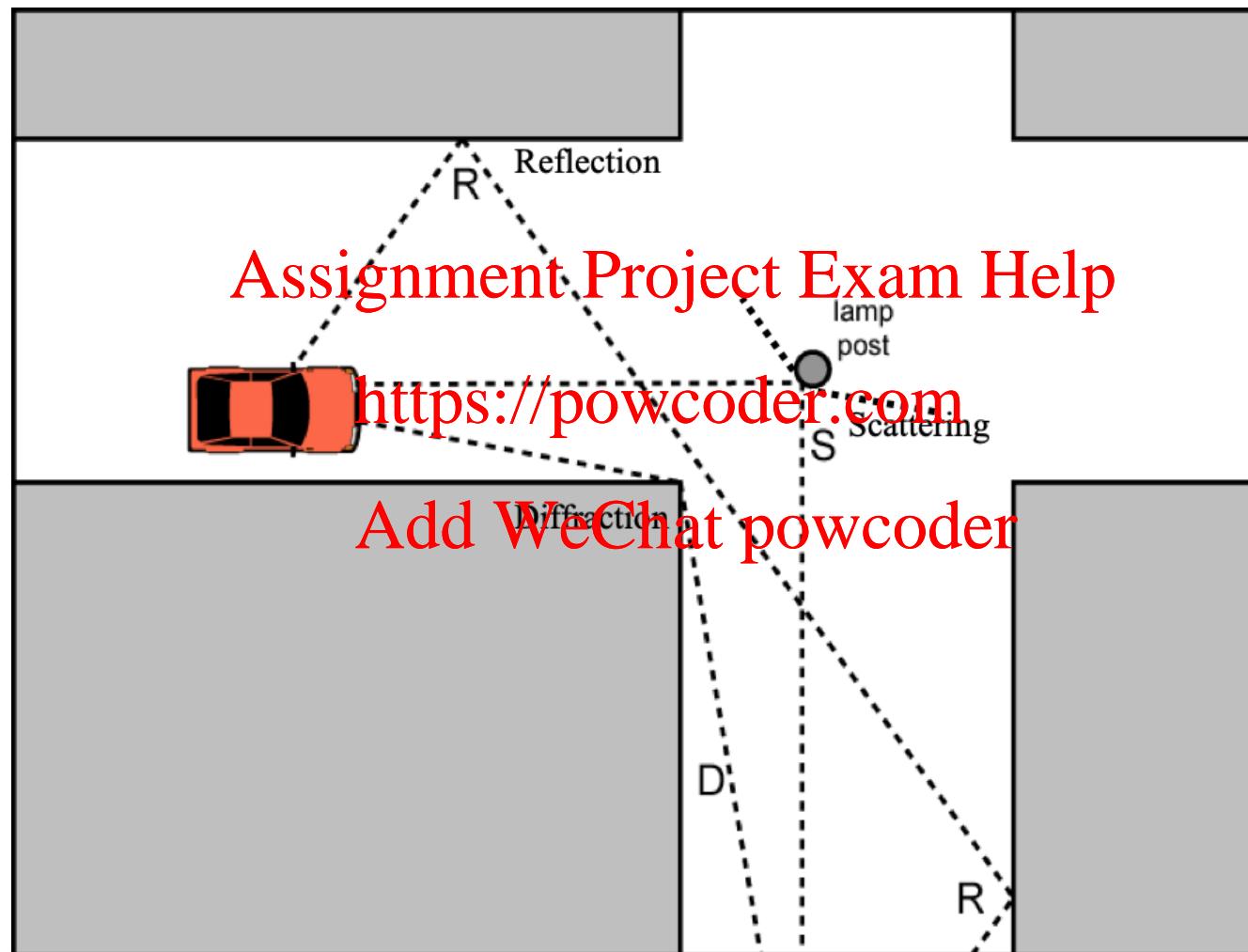
$$17 = 10\log_{10}(P/P_{iso})$$

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 a TV antenna for wireless router, or vice-versa (why?) <https://powcoder.com>
- End-to-end antenna length = $\frac{1}{2}$ wavelength
 - So that electrons can travel back and forth the antenna in one cycle
- If dipole (two rods), each rod is $\frac{1}{4}$ wavelength

Reflection, Diffraction, Scattering



Reflection, Diffraction and Scattering (Cont)

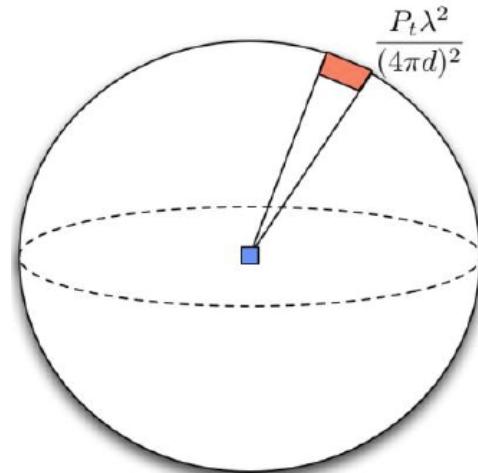
- **Reflection**: Surface large relative to wavelength (λ) of signal
 - May have phase shift from original
 - May cancel out original signal or increase/strengthen it at receiver
- **Diffraction**: Edge of impenetrable body; large relative to λ
 - Receiver may receive signal even if no line-of-sight (LOS) to transmitter
- **Scattering**
 - Obstacle size on order of wavelength. Lamp posts etc.
 - Reflection/diffraction are more directional; scattering in 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://powcoder.com>
- ❑ There are well-known path loss models
 - Frii's model: designed for free-space (no reflections); frequency dependent
 - 2-Ray model: reflections considered, but frequency-independent (antenna heights are important)

Free Space Path Loss (Frii's Law)

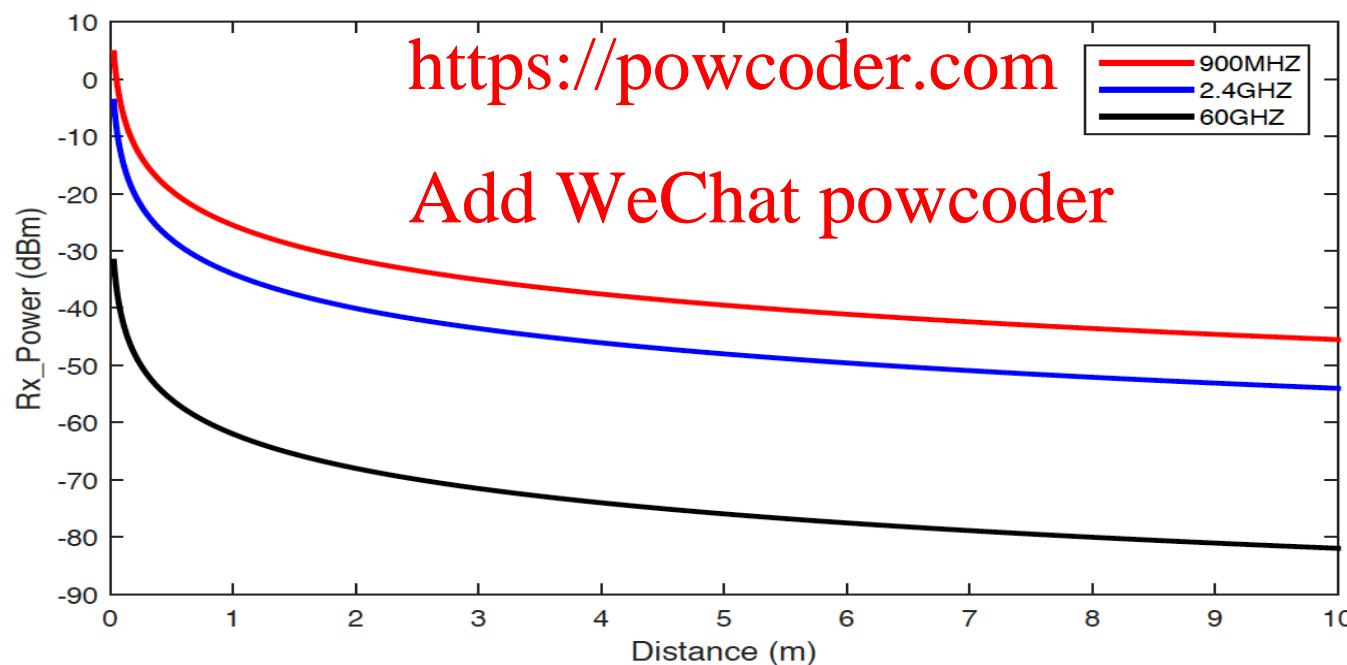
- - Tx and Rx placed in *empty space*
 - No absorbing/reflecting obstacles
 - Received power (P_R) decreases as *inverse square of distance (d⁻² law)*
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- Where G_T = Tx antenna gain, G_R = Rx antenna gain
- For isotropic antennas, $G_T = G_R = 1$ ("unit gain antennas" or 0 dB)
- For isotropic antennas: $P_R = P_T \left(\frac{c}{4\pi d f} \right)^2$



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 means: $G_T = G_R = 1$.

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We have $d = 100\text{m}$, $f = 900 \times 10^6 \text{ Hz}$, $P_T = 50\text{W}$, $c = 3 \times 10^8 \text{ m/sec}$, and $\pi = 3.14$

$$P_R = P_T \left(\frac{c}{4\pi f d} \right)^2 = 3.5 \mu\text{W}$$

Example

Question: What is the received power in dBm at 10 meter from a 2.4GHz WiFi router transmitting with 100mW of power (assume free space path loss and isotropic antennas).

Solution

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For isotropic antennas: $G_T = G_R = 0 \text{ dBm}$.

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We have $d = 10 \text{ m}$, $f = 2.4 \times 10^9 \text{ Hz}$, $P_T = 100 \text{ mW} = 20 \text{ dBm}$, $c = 3 \times 10^8 \text{ m/sec}$, and $\pi = 3.14$

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$$\text{Pathloss(dB)} = 20 \log_{10} \left(\frac{4\pi f d}{c} \right) \text{dB} = 40 \text{ dB} \text{ (approx.)}$$

Or, we can use the other path loss expression as follows:

$$\text{PL}_{\text{dB}} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.55 = 40 \text{ dB} \text{ (approx.)}$$

$$P_R = P_T - \text{pathloss} = 20 - 40 = -20 \text{ dBm} \text{ (approx.)}$$

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/standard/equipment specify different values
 - Depends on channel bandwidth and receiver noise figure (and temperature)
 - Larger bandwidth → larger minimum power (and vice versa)
 - Larger receiver noise → larger minimum power (and vice versa)
- Examples (for room temperature)
 - LTE: -52 dBm [roughly]
 - Bluetooth: -70 dBm [roughly]

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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 $f = 2.4 \text{ GHz}$, $P_T = 1 \text{ mW}$, $P_R = -80 \text{ dBm} = 10^{-8} \text{ mW}$

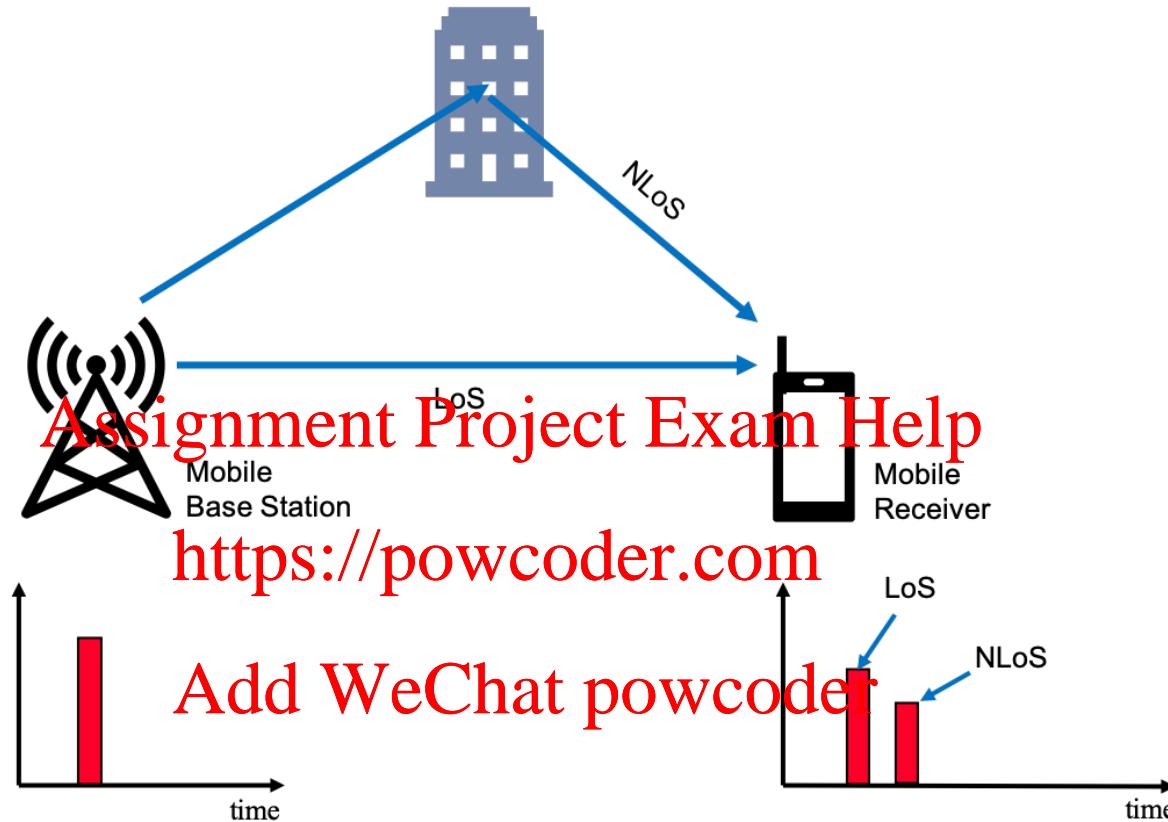
We have $P_R = P_T \left(\frac{c}{4\pi d f} \right)^2$ Add WeChat powcoder

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

Or,

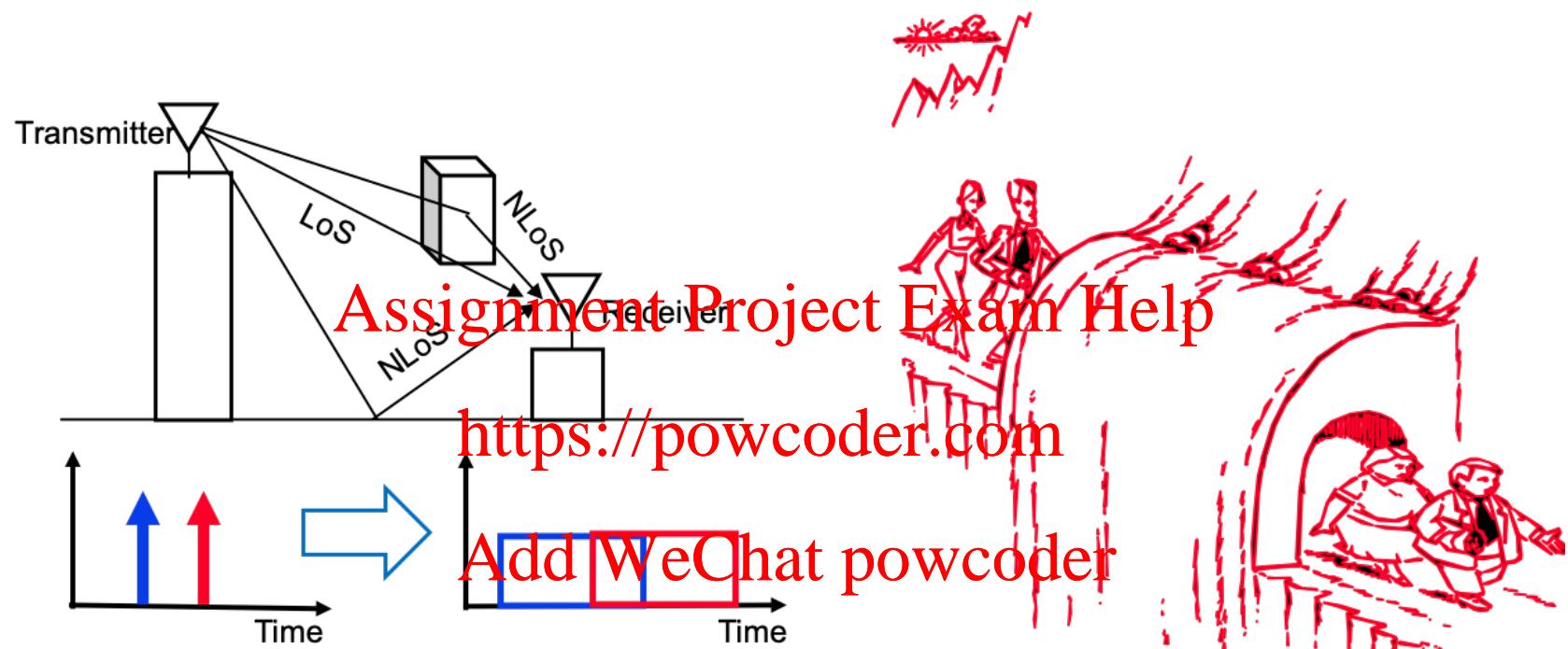
$$= 99.5 \text{ meter}$$

Multipath



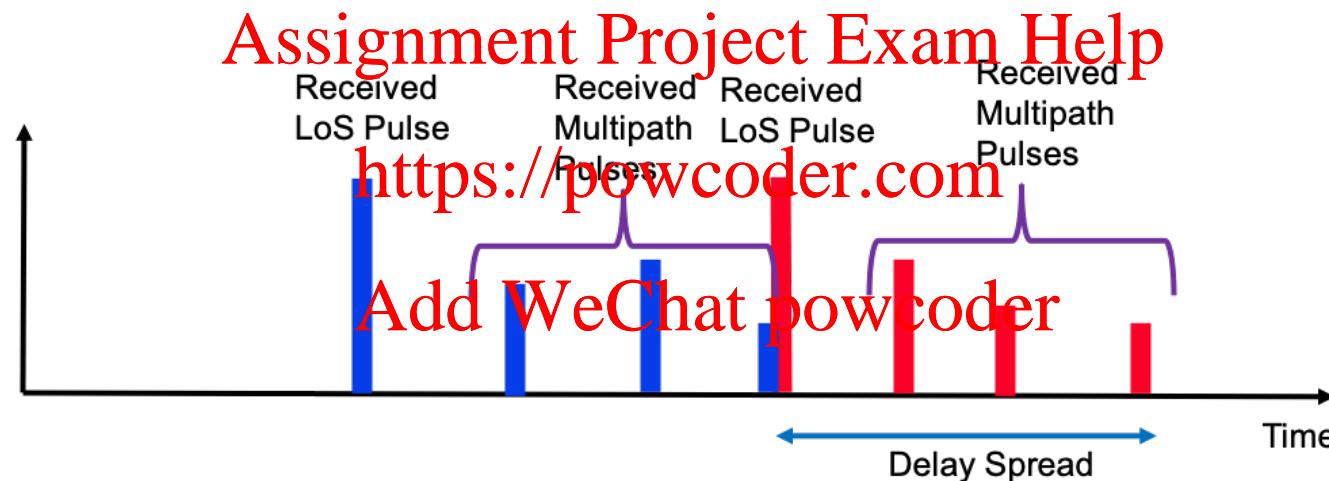
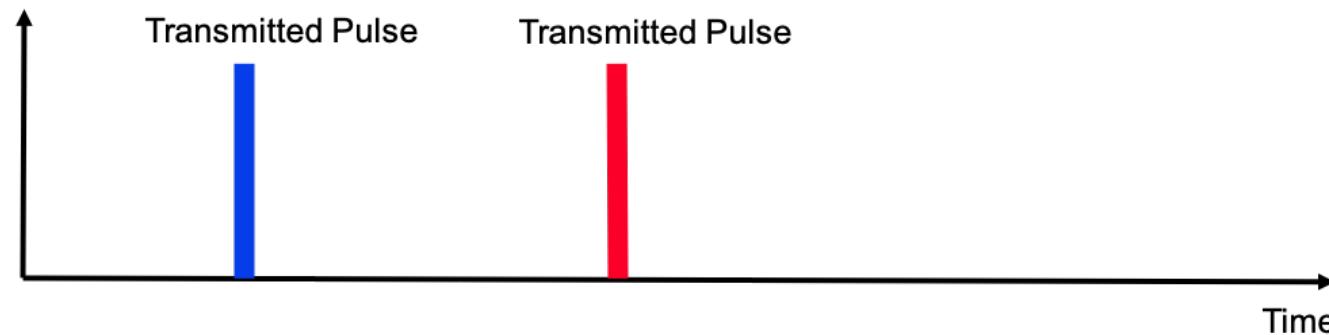
- Multiple copies of the signal received (LoS+reflected NLoS)
- The LoS signal reaches the receiver first followed by the NLoS copy (NLoS has longer path length compared to the LoS path)
- $\text{RSS}(\text{LoS}) > \text{RSS}(\text{NLoS})$. NLoS signal travels further and hence attenuates more compared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

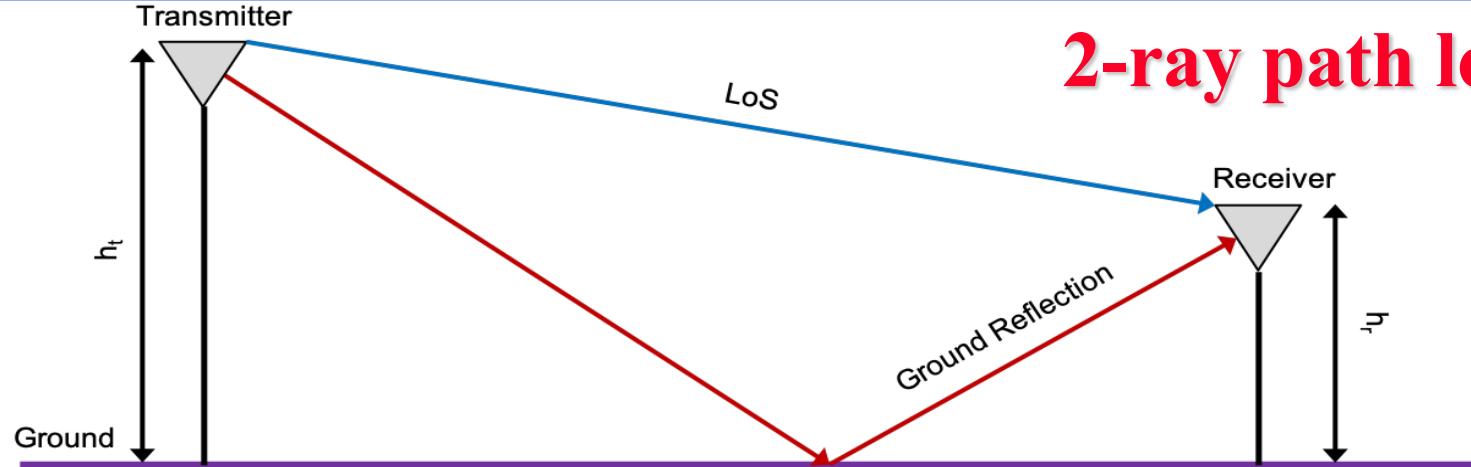


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- ❑ How long to wait to avoid ISI?
- ❑ RSS of late arrivals fluctuate, but consistently diminish on average
- ❑ **Delay Spread** = Time between the first (LoS) and the last copy of NLoS
 - ❑ $\text{RSS}(\text{last copy of NLoS}) < \text{RSS}_{\text{threshold}}$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



2-ray path loss model

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

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- pathloss (dB) = $40 \log_{10}(d) - 20 \log_{10}(h_T h_R)$ [unit gain antenna]
 - Where, h_T and h_R are heights of transmit and receive antennas
 - 1 LoS ray and 1 reflected from the ground
- 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*.
- Higher the transmit antenna, better the signal at receiver (explains why BSs are installed at a higher location than the ground)

Example

Question: A 2m tall user is holding his smartphone at half of his height while standing 500m from a 10m high base station. The base station is transmitting a 1.8GHz signal using a transmission power of 30dBm. What is the received power (in dBm) at the smartphone? Assume *unit gain* antennas.

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We have $h_t = 10\text{m}$, $h_r = 2\text{m}$, $d = 500\text{m}$, $f = 1.8 \times 10^9 \text{ Hz}$, $P_T = 30\text{dBm}$, $c = 3 \times 10^8 \text{ m/sec}$

$$d_{break} = 4 \left(\frac{h_t h_r}{c} \right)^{1/2} = 480\text{m}$$

This means that the 2-ray model can be applied to estimate the pathloss at 500m.

$$pathloss = 20 \log_{10} \left(\frac{d^2}{h_t h_r} \right) = 81.94\text{dB}$$

The received power = $30 - 81.94 = -78.94\text{dBm}$

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)
 - $PL(dB) = 10\log_{10}(d^n) + C = 10 \log_{10}(d) + C$ (a 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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$$\begin{array}{c} \text{Sine Wave 1} \\ + \\ \text{Sine Wave 2} \end{array} = \begin{array}{c} \text{Resultant Sine Wave} \end{array}$$

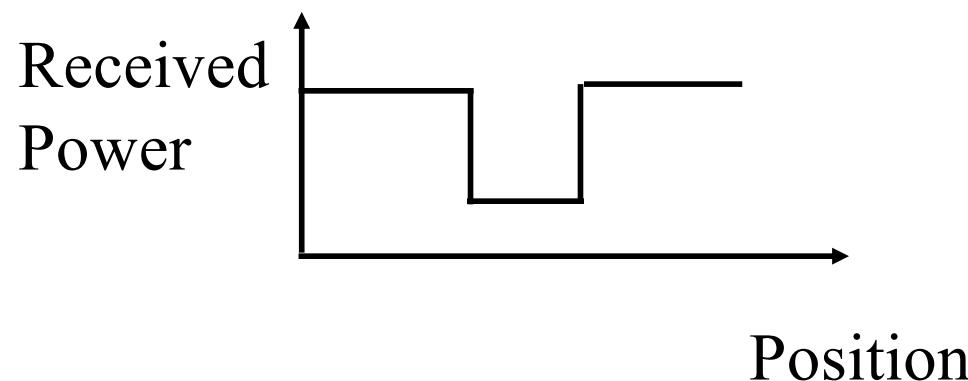
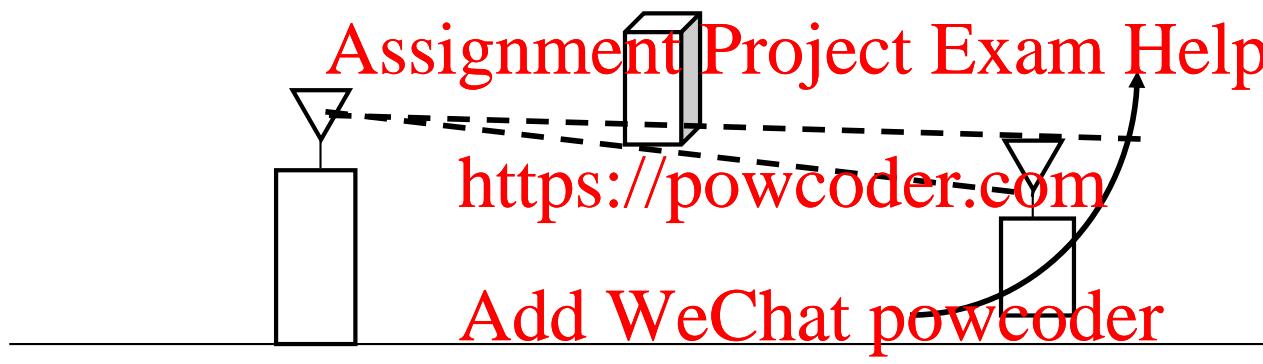
Constructive

$$\begin{array}{c} \text{Sine Wave 1} \\ + \\ \text{Sine Wave 2} \end{array} = \begin{array}{c} \text{Zero Line} \end{array}$$

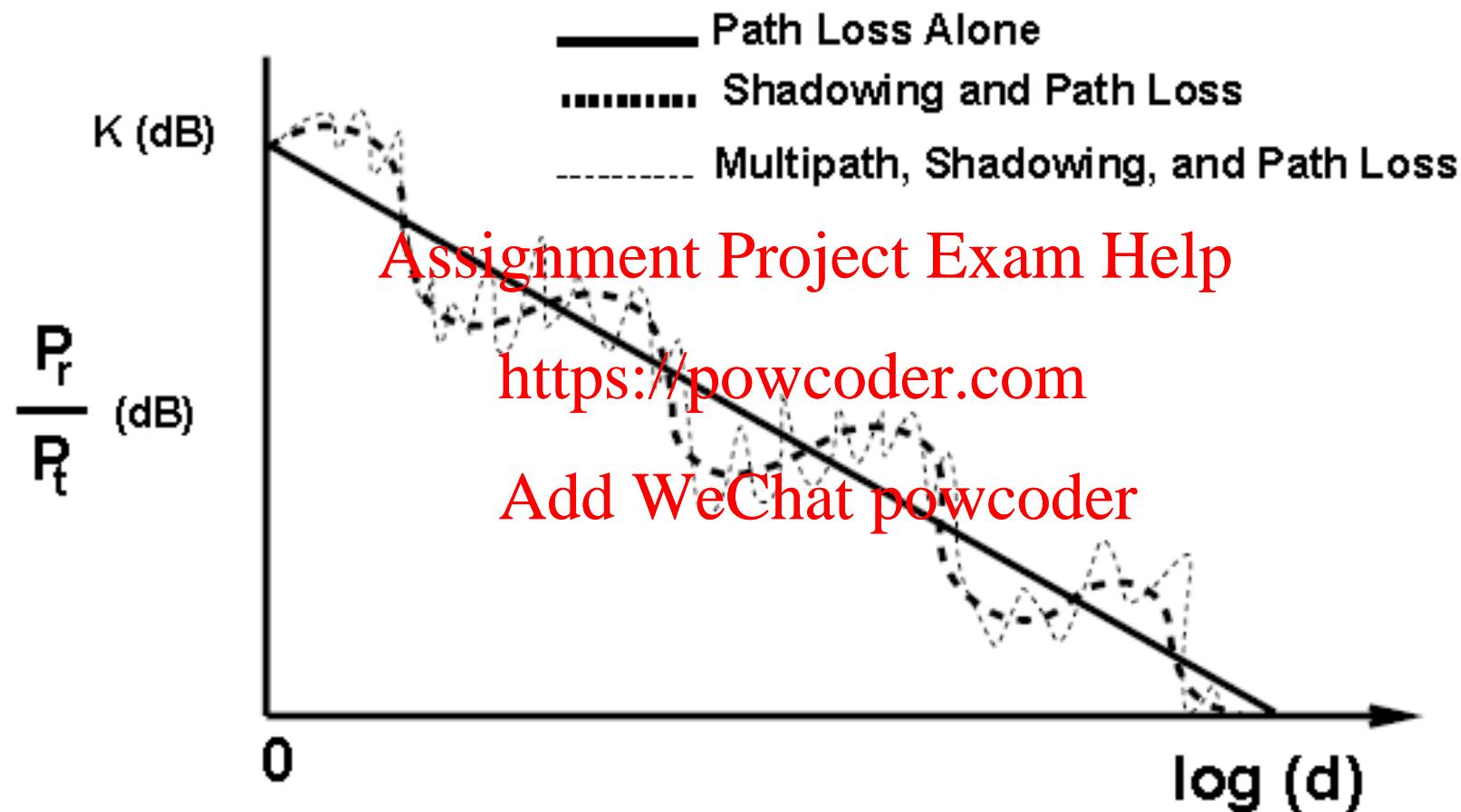
Destructive

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



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 WiFi routers have multiple antennas
- Multiple input (multiple antennas at the *transmitter*)
- Multiple output (~~Add WeChat~~ ~~powcoder~~ *receiver*)
- 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 input & 2 output (2 Tx antennas & 2 Rx antennas)
 - 4x2 MIMO – 4 input & 2 output (4 Tx antennas & 2 Rx antennas)
 - 1000x2 MIMO – 1000 input & 2 output (1000 Tx antennas & 2 Rx antennas)

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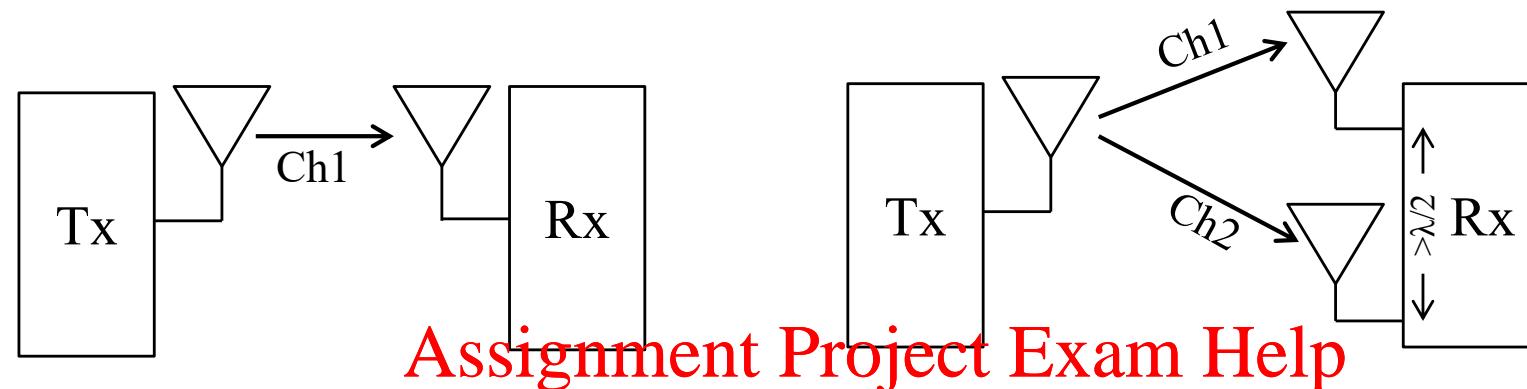
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Why Multiple Antennas Can Improve Performance?

- 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*
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- Line-of-Sight (LOS) scenario: multiple antennas at the transmitter can be used to realize *beamforming* (beamforming)
 - Increase *coverage* and *signal strength* at a particular direction of choice

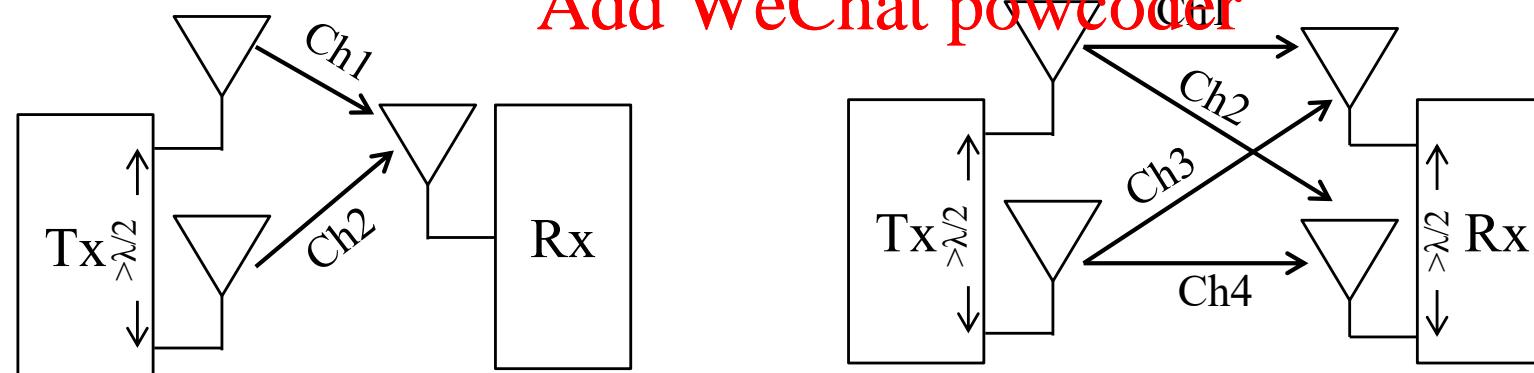
Spatial Channels



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MIMO Techniques

- Spatial Diversity (a.k.a. Diversity)
 - Improve *reliability* by exploiting spatial channels
- Spatial Multiplexing (a.k.a. Multiplexing)
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 - Improve *data rate* by exploiting spatial channels
- Beamforming
 - Increase *coverage* and *signal strength* 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 same time is low
 - SNR at receiver can be improved (*diversity gain*)
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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 100x1 MIMO. 100 spatial channels are possible.

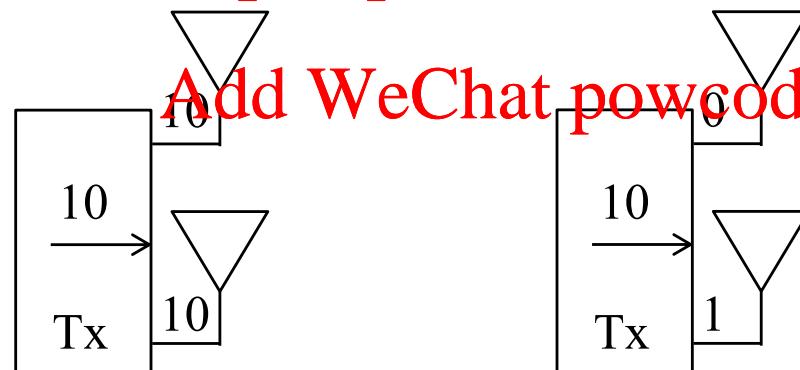
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Multiplexing

- 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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Diversity

Multiplexing

Example

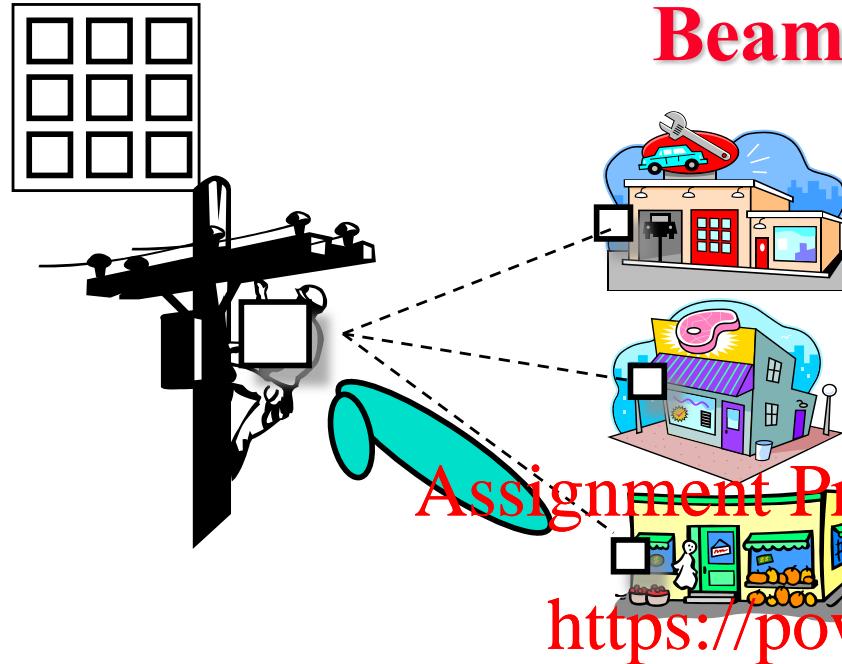
- What is the *degrees of freedom* for an 802.11ac WiFi system with the access point having 8 antennas and communicating to a laptop equipped with 2 antennas?

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- Answer: degrees of freedom = $\min(8,2) = 2$

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Beamforming



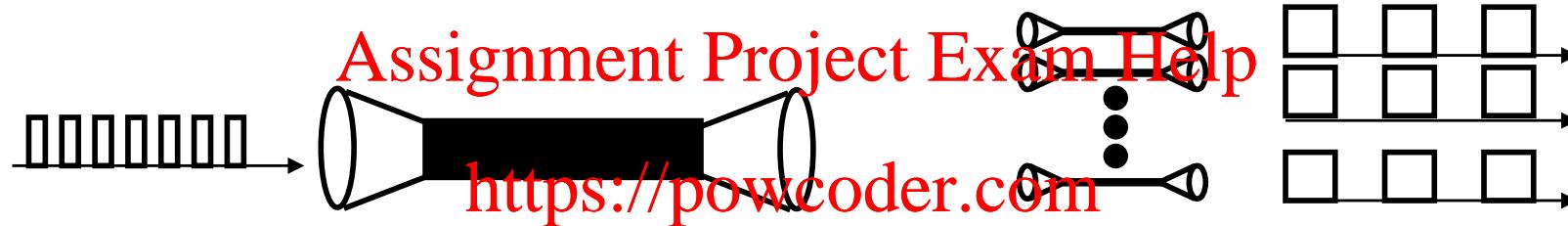
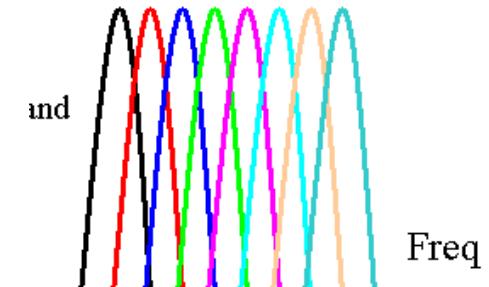
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- Phased Antenna Arrays:
Transmit the same signal using multiple antennas **Add WeChat powcoder**
- By phase-shifting various signals \Rightarrow Focus on a narrow directional beam (increased SNR and long-distance coverage)
- Receiver does the same, i.e., focus its reception from a particular BS
- Used when LOS



OFDM

- ❑ 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

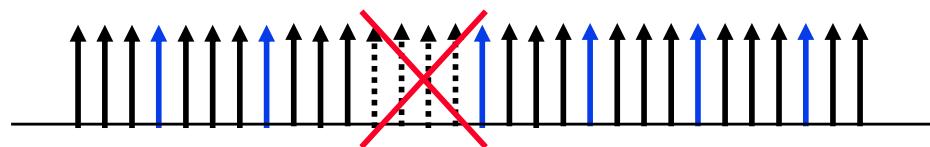
Advantages of OFDM

- 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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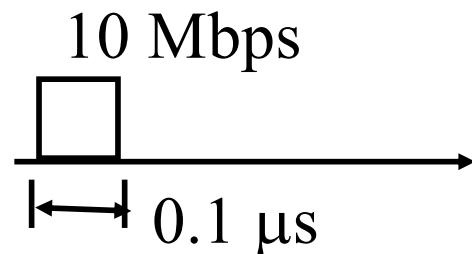
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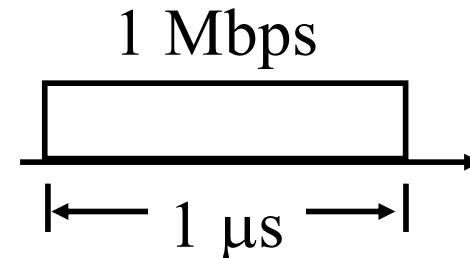
OFDM: Design considerations

- 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 spacing \Rightarrow Increased inter-carrier interference due to Doppler spread in mobile applications

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



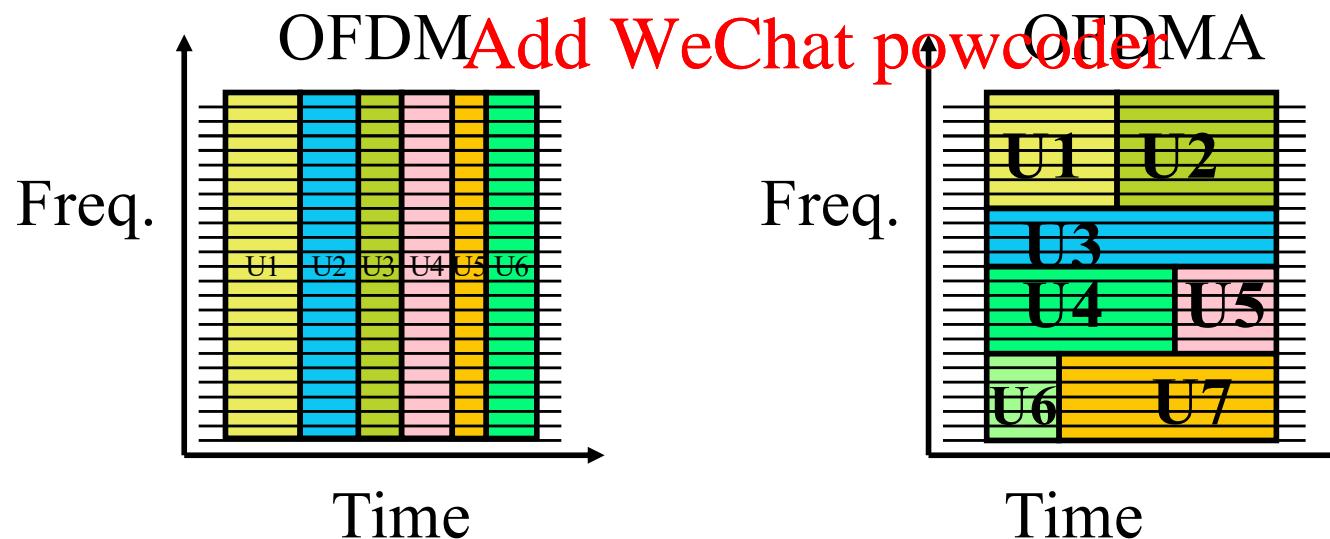
Large # of carriers
Longer symbol durations
Lower data rates per carrier

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

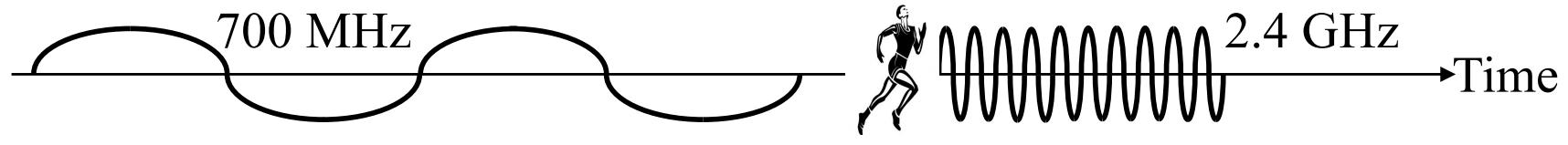
- *With a subcarrier spacing of 10 kHz, how many subcarriers will be used in an OFDM system with 20 MHz channel bandwidth?*

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Number of subcarriers = $\frac{\text{channel bandwidth}}{\text{subcarrier spacing}}$
= $20 \times 10^6 / 10 \times 10^3 = 2000$ Add WeChat powcoder



Effect of Frequency



- Higher Frequencies have higher attenuation,
e.g., 18 GHz has 20 dB/m more than 1.8 GHz
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- 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
 - ⇒ 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 \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 = Changes in power with changes in position
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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 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

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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 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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