

PHY FUNDAMENTALS II

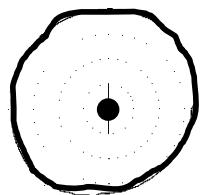
Wireless Signal Propagation

Overview

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

Antenna

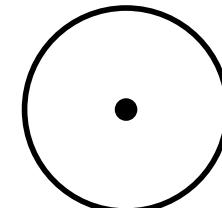
- Transmitter converts electrical energy to electromagnetic waves
- Receiver converts electromagnetic waves to electrical energy
- Same antenna is used for transmission and reception
- Omni-Directional: Power radiated in all directions
- Directional: Most power in the desired direction
- Isotropic antenna: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

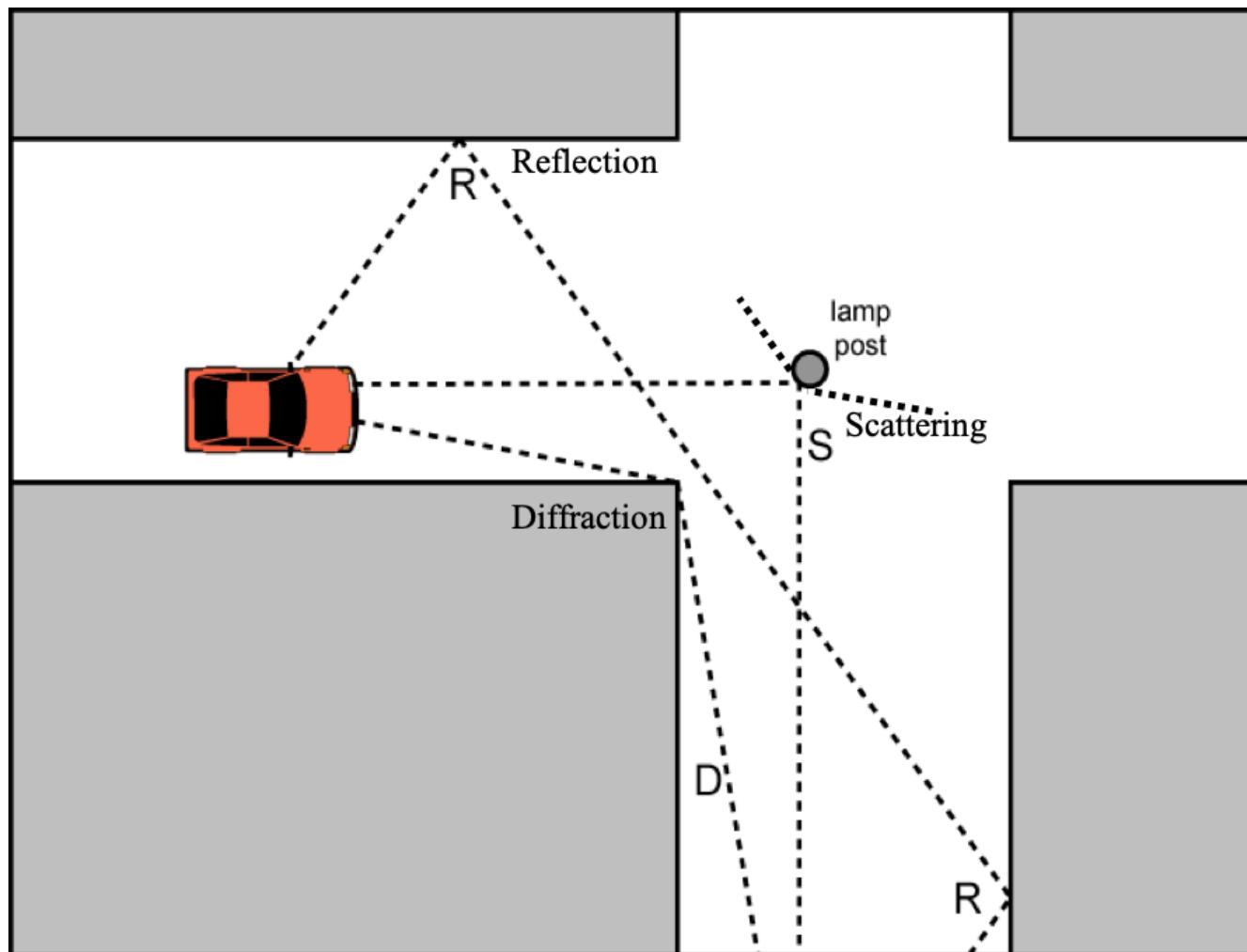
$$17 = 10\log_{10}(P/P_{iso})$$

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?)
- 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



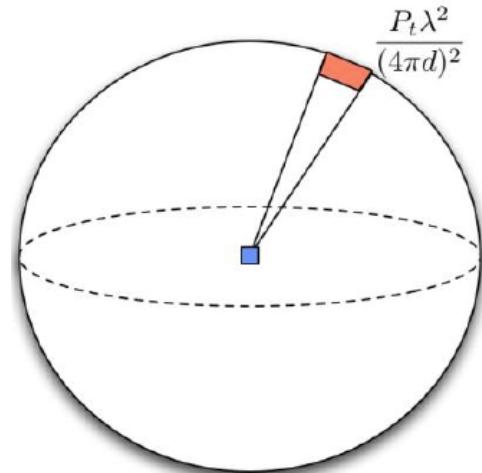
Reflection, Diffraction and Scattering (Cont)

- **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, 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 path loss?
- ❑ 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)*

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

- 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 i)
- For isotropic antennas: $P_R = P_T \left(\frac{c}{4\pi df} \right)^2$

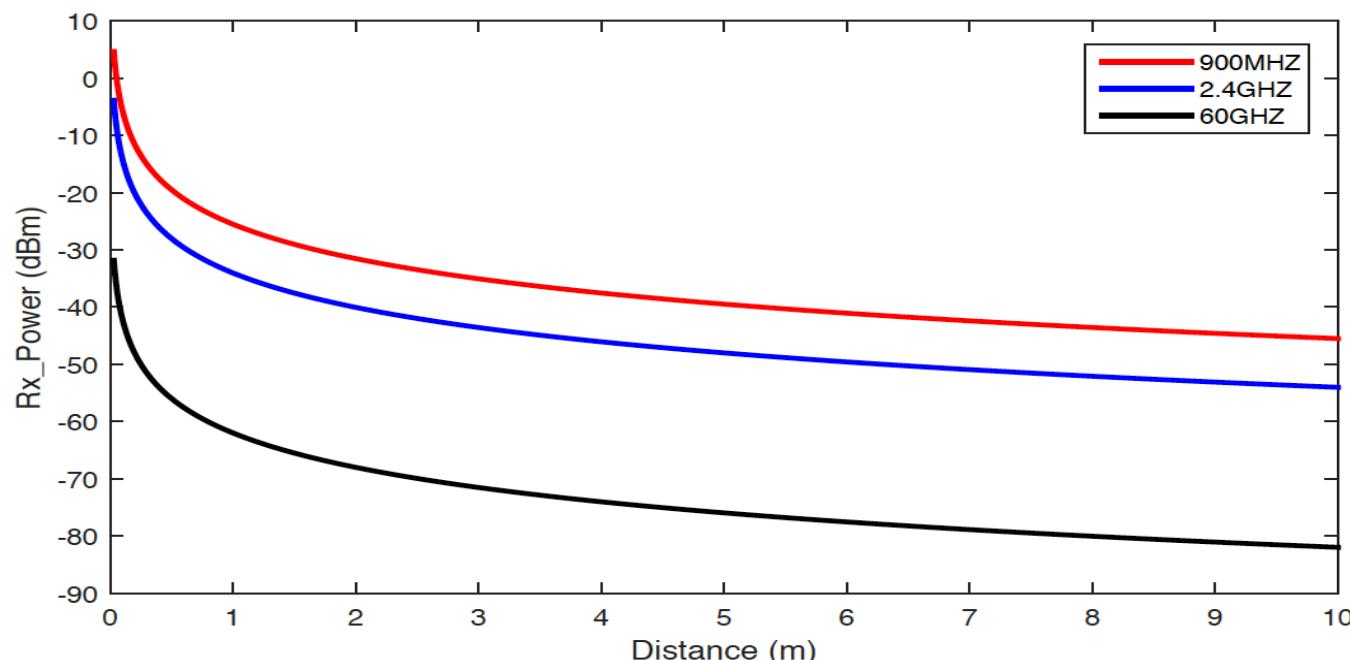
Surface area of sphere $A_{sphere} = 4\pi d^2$ (d=radius); surface area of antenna $A_{ant} = \lambda^2/4\pi$

Power density at sphere surface = $P_T/4\pi d^2$

P_R = 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

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

Unit antenna gain means: $G_T = G_R = 1$.

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:

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

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

$$\text{Pathloss} = 20 \log_{10} \left(\frac{4\pi f d}{c} \right) \text{ dB} = 60 \text{ dB} \text{ (approx.)}$$

$$P_R = P_T - \text{pathloss} = 20 - 60 = -40 \text{ dBm} \text{ (approx.)}$$

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]

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.

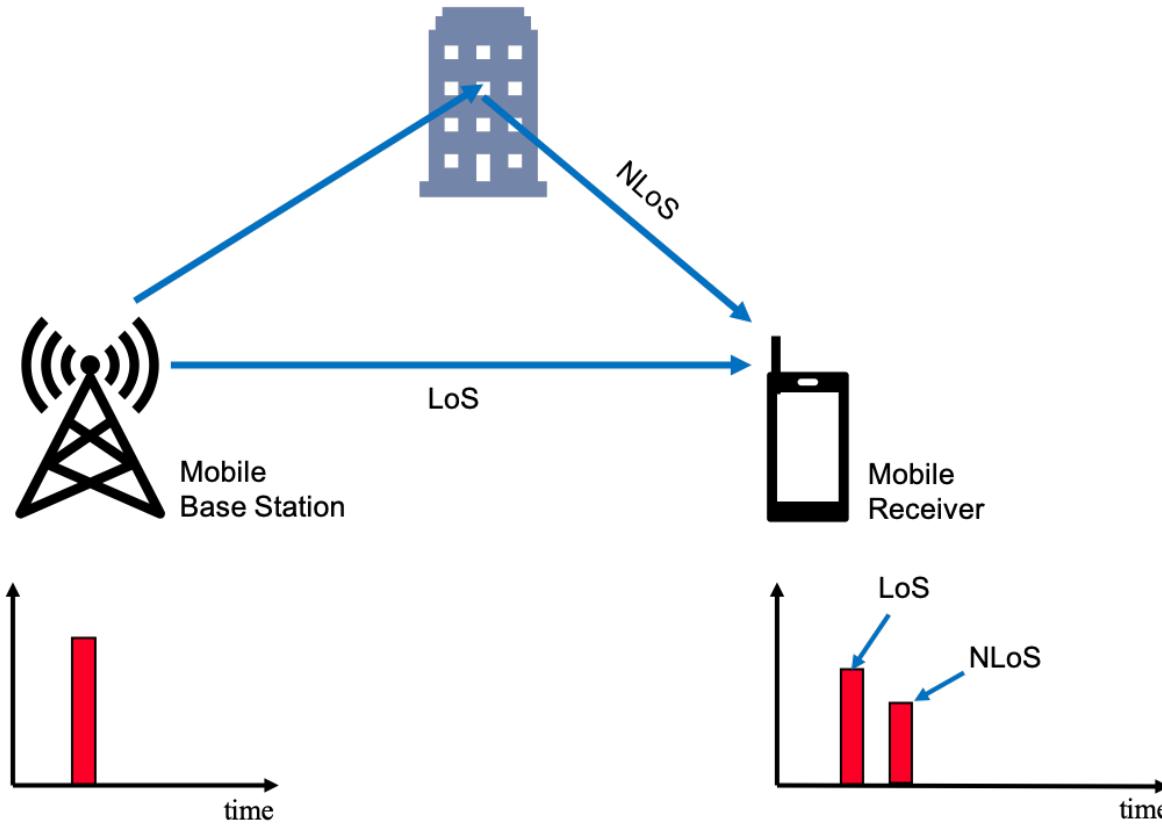
Bluetooth frequency $f = 2.4 \text{ GHz}$, $P_T = 1 \text{ mW}$, $P_R = -80 \text{ dBm} = 10^{-8} \text{ mW}$

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

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

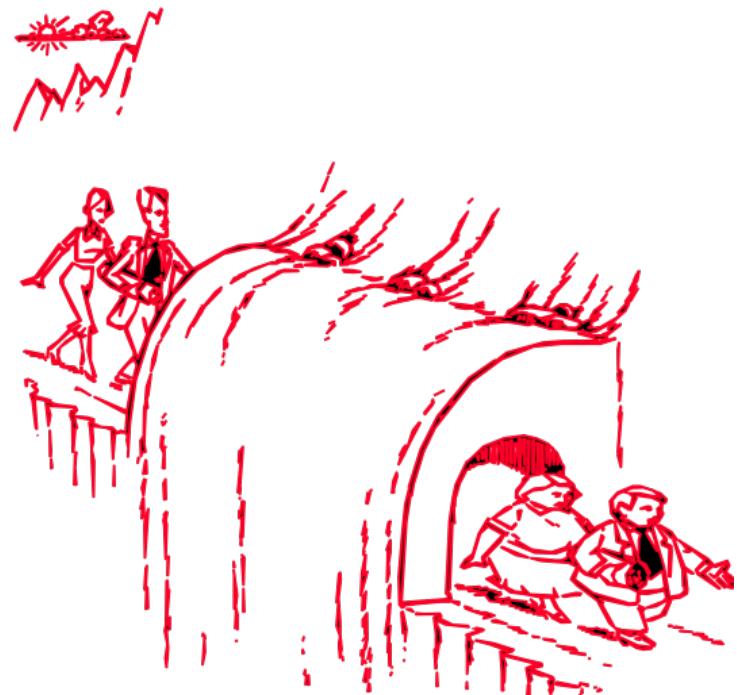
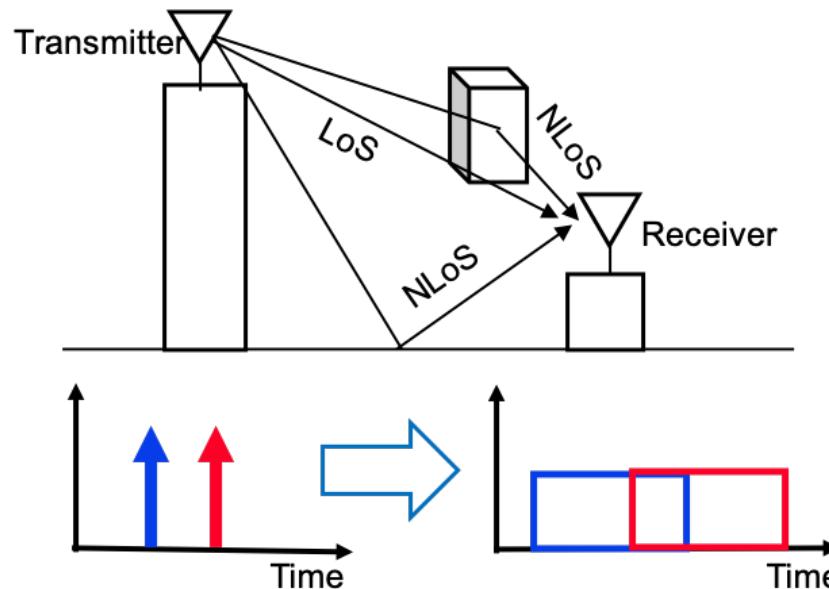
= 99.5 meter

Multipath



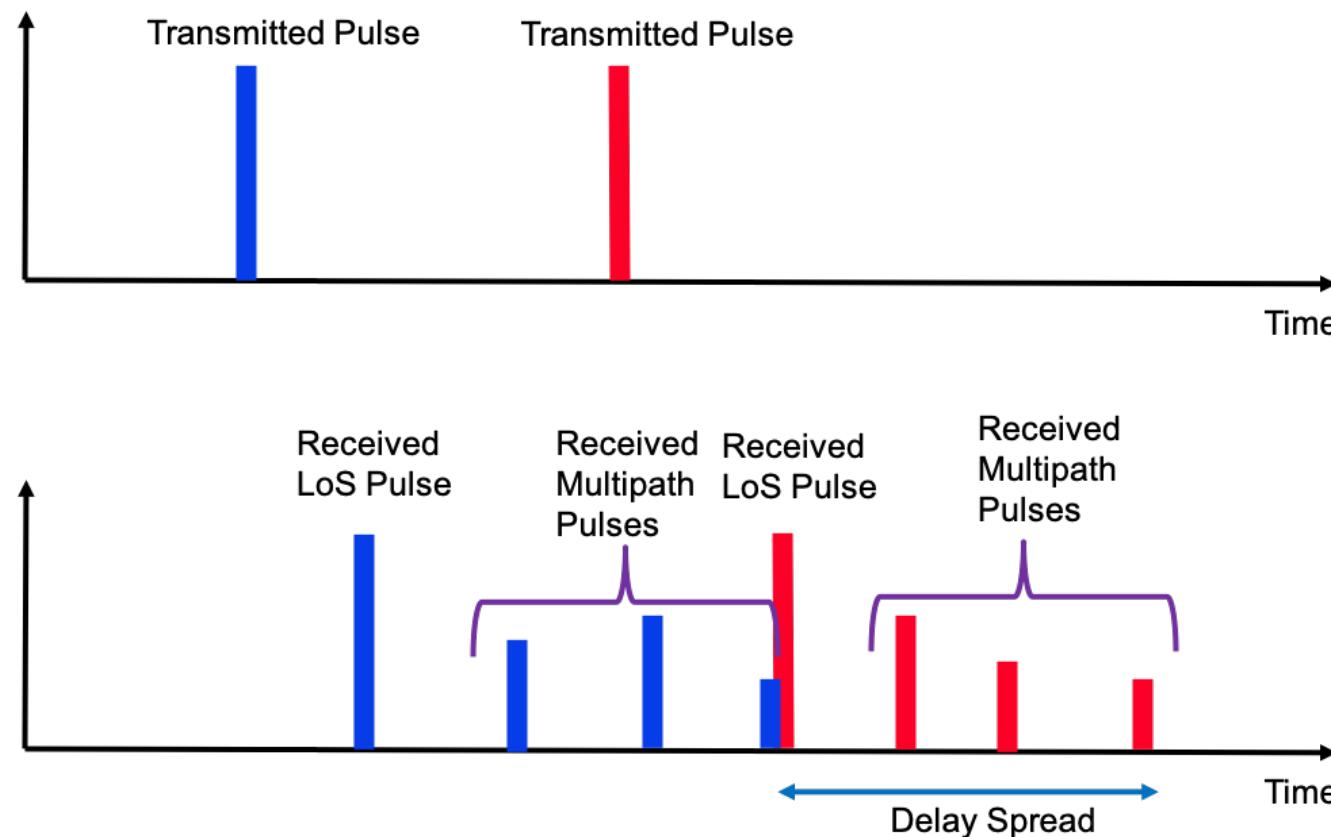
- Multiple copies of the signal received (LoS+reflected NLoS)
- The LoS signal reaches the receiver first followed by the NLoS copy (NLoS has longer path length compared to the LoS path)
- $\text{RSS}(\text{LoS}) > \text{RSS}(\text{NLoS})$. NLoS signal travels further and hence attenuates more compared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

Inter-Symbol Interference



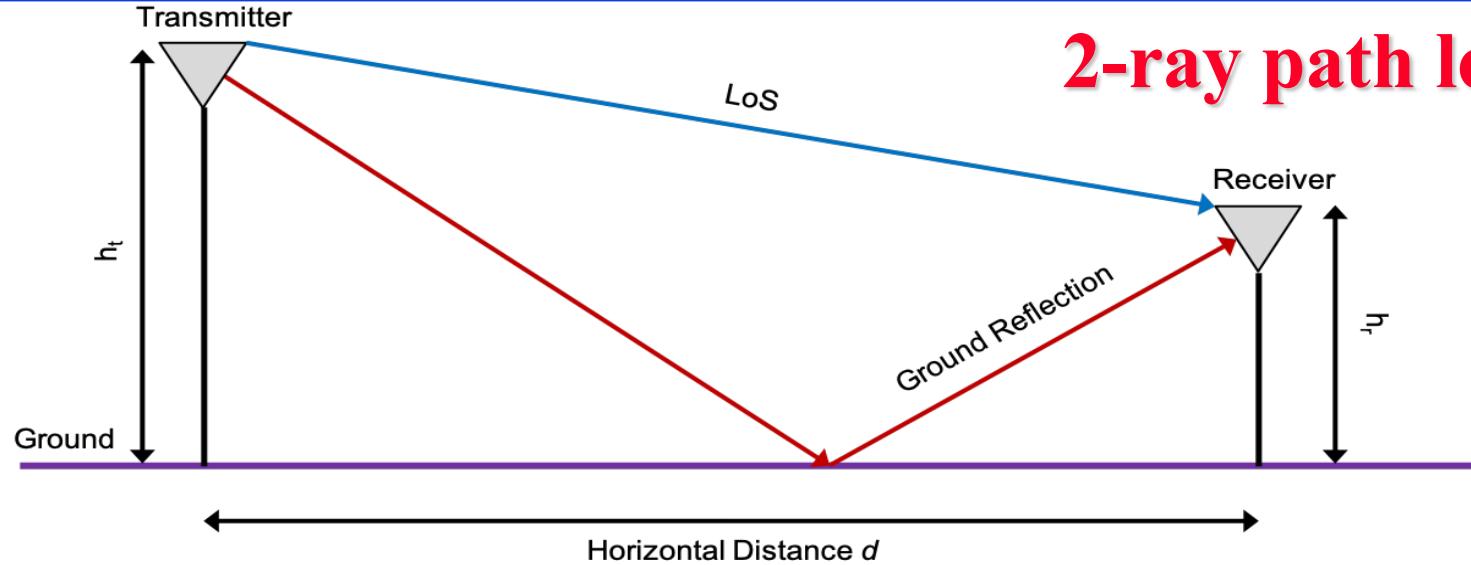
- Multipath effect: receiver continues to receive the signal (its reflections) even after the transmitter completes symbol transmission
- As a result, symbols become wider; two consecutively transmitted symbols overlap and interfere with each other
- Longer bit intervals or symbol lengths are required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

Delay Spread



- ❑ 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



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

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

Solution:

We have $h_t = 10\text{m}$, $h_r = 1\text{m}$, $d = 500\text{m}$, $f = 1.8 \times 10^9 \text{ Hz}$, $P_T = 30\text{dBm}$, $c = 3 \times 10^8 \text{ m/sec}$

$$d_{break} = 4 \left(\frac{h_t h_r f}{c} \right) = 240\text{m}$$

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

$$\text{pathloss} = 20 \log_{10} \left(\frac{d^2}{h_t h_r} \right) = 87.96\text{dB}$$

The received power = $30 - 87.96 = -57.96\text{dBm}$

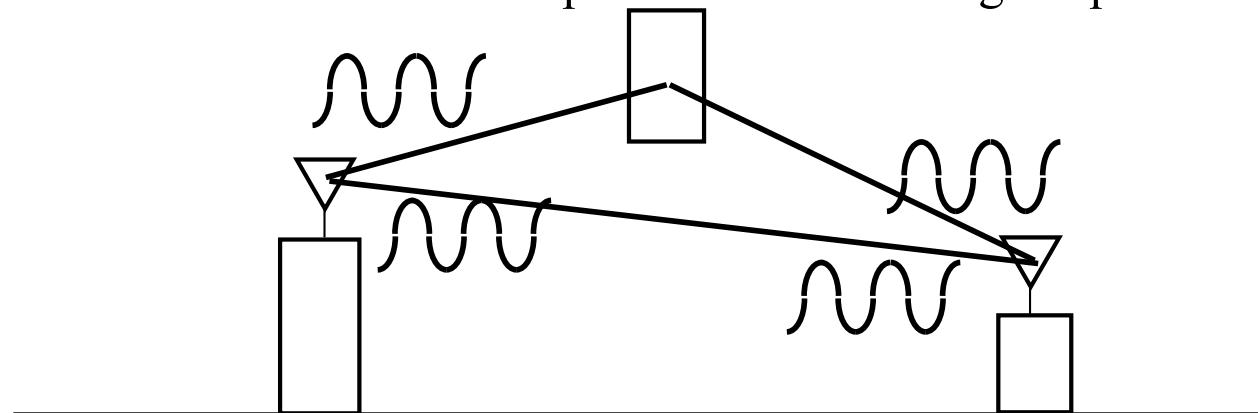
Path loss exponent

- 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)
 - $PL(dB) = 10\log_{10}(d^n) + C = 10n \log_{10}(d) + C$ (a 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



$$\begin{array}{c} \text{wavy line} \\ + \\ \text{wavy line} \end{array} = \begin{array}{c} \text{wavy line} \\ \text{wavy line} \\ \text{wavy line} \end{array}$$

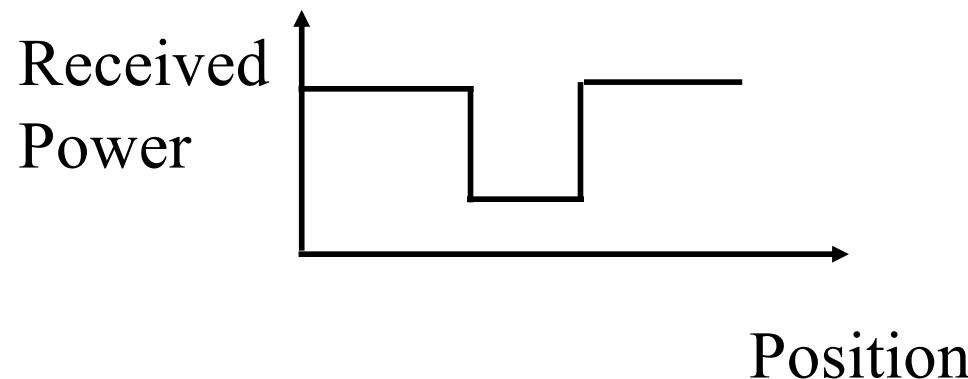
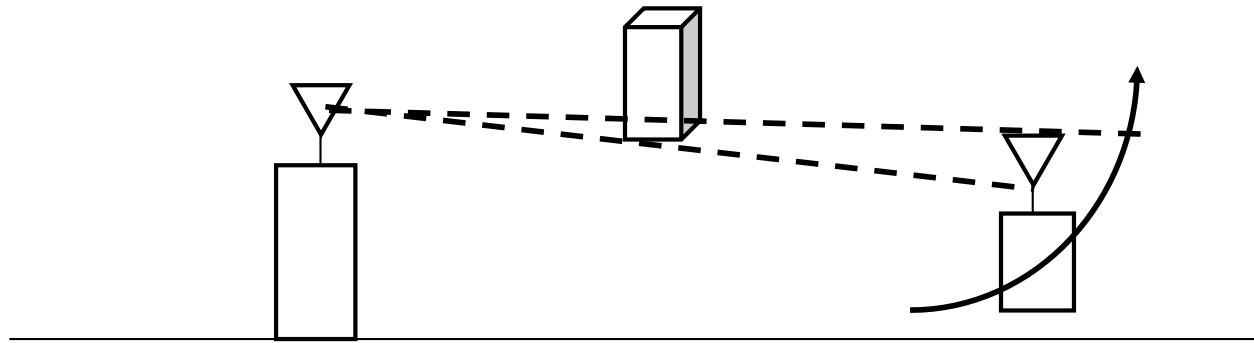
Constructive

$$\begin{array}{c} \text{wavy line} \\ + \\ \text{wavy line} \end{array} = \underline{\quad}$$

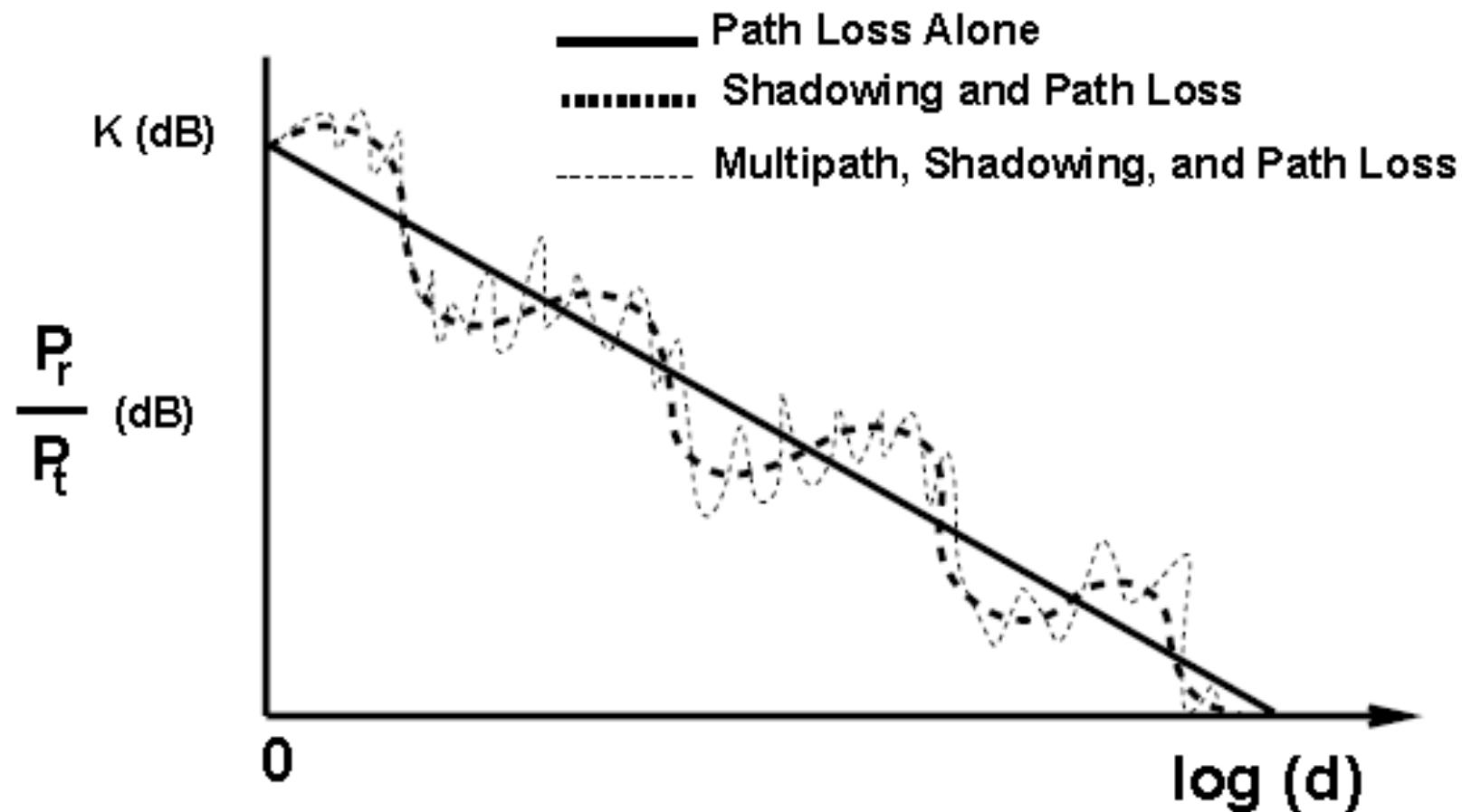
Destructive

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 (multiple antennas at the *receiver*)
- MIMO – multiple input multiple output

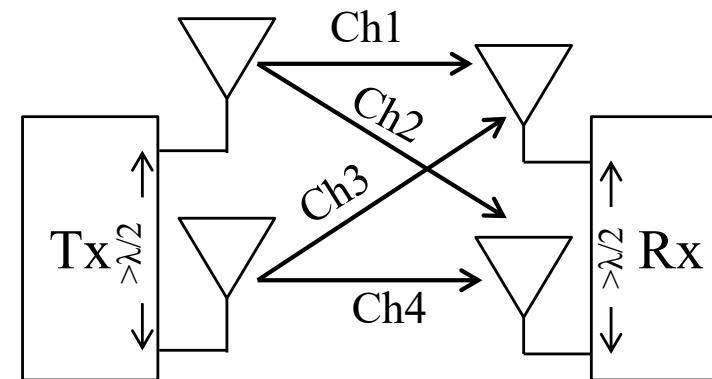
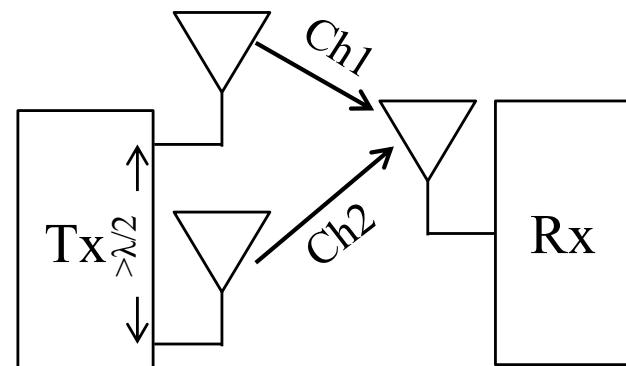
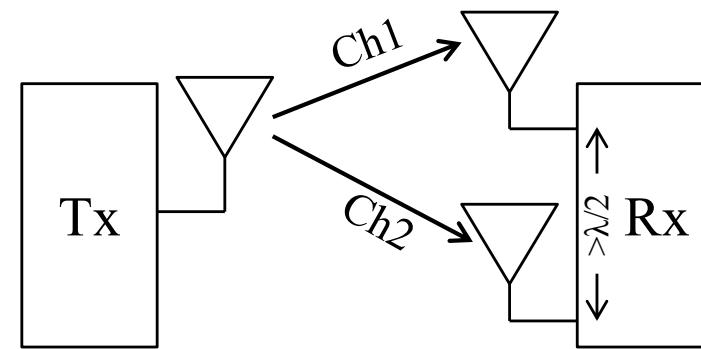
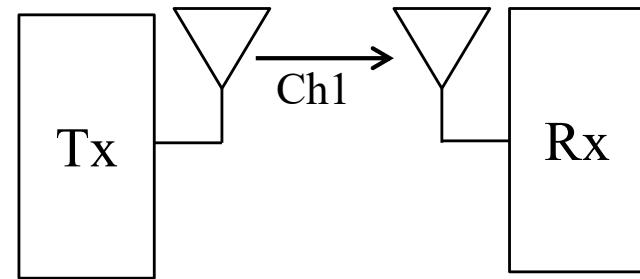
MIMO Antenna Configurations

- 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)

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 (LOS) scenario: multiple antennas at the transmitter can be used to realize *virtual directional 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 *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*)

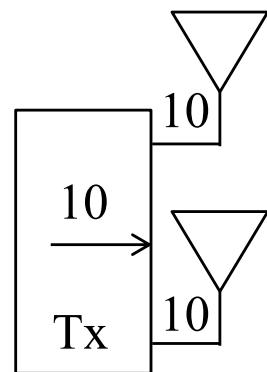
Example

- 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?

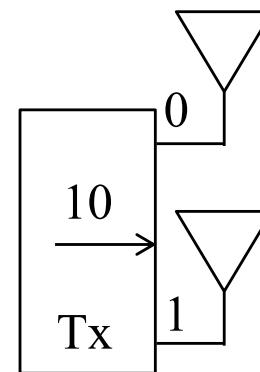
Answer: It is a 100×1 MIMO. 100 spatial channels are possible.

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



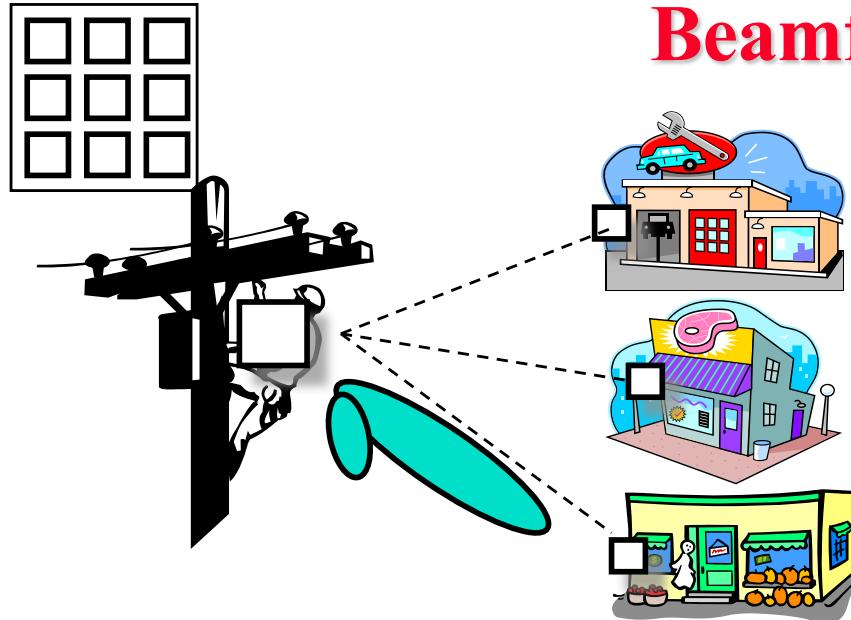
Multiplexing

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

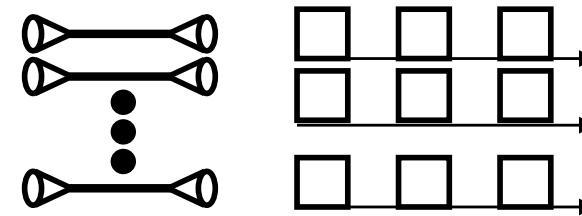
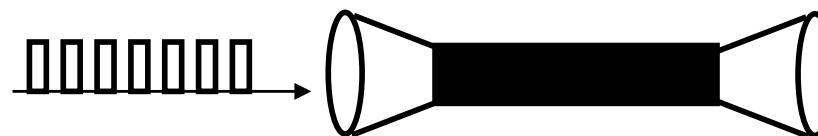
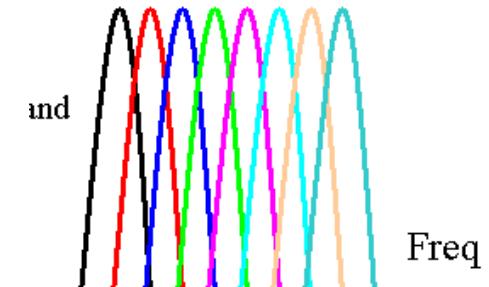
Beamforming



- ❑ Phased Antenna Arrays:
Transmit the same signal using multiple antennas
- ❑ 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

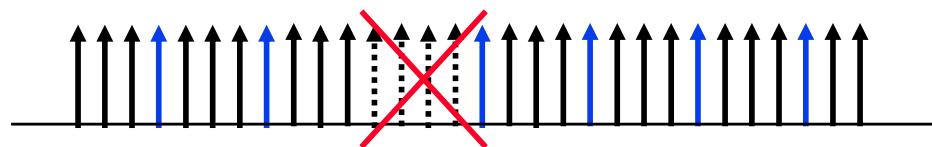
- Orthogonal Frequency Division Multiplexing
- Ten 100 kHz channels are better than one 1 MHz Channel



- 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

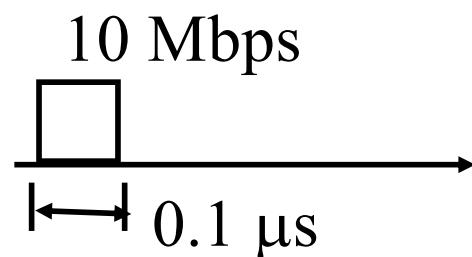
Advantages of OFDM

- 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

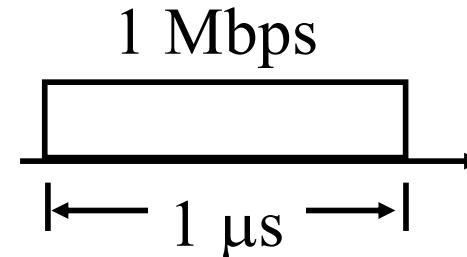


OFDM: Design considerations

- 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



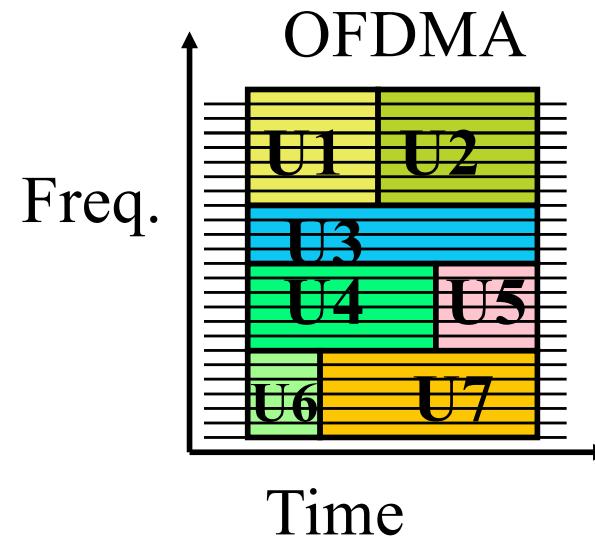
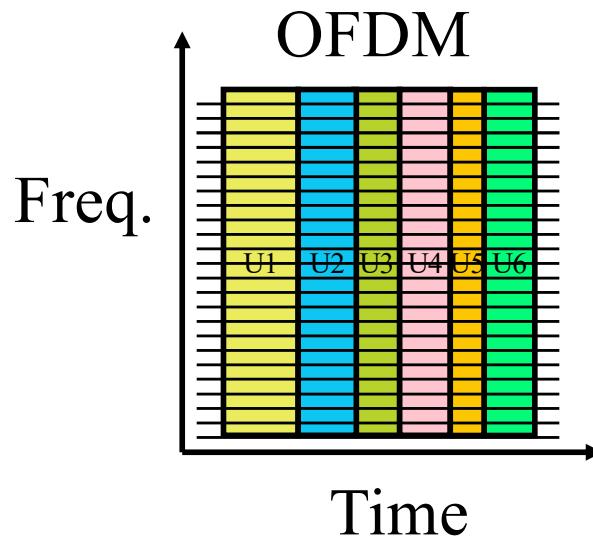
Small # of carriers
Shorter symbol durations
Higher data rates per carrier



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



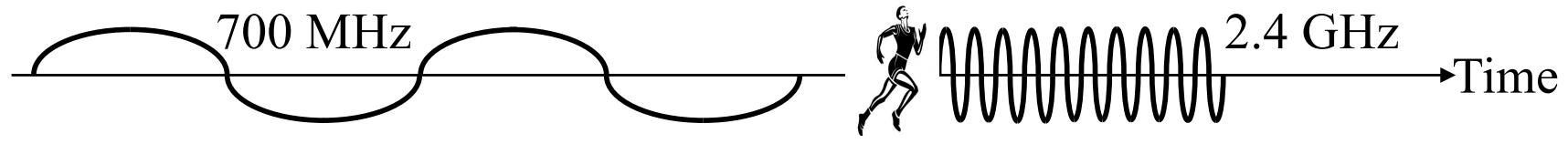
Example

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

*Number of subcarriers = channel bandwidth/subcarrier spacing
= $20 \times 10^6 / 10 \times 10^3 = 2000$*



Effect of Frequency

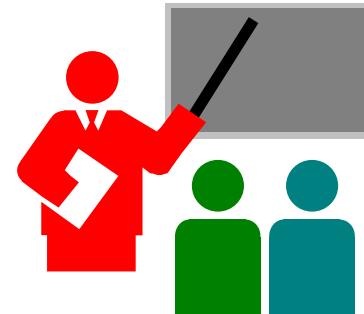


- Higher Frequencies have higher attenuation,
e.g., 18 GHz has 20 dB/m more than 1.8 GHz
- Higher frequencies need smaller antenna
 $\text{Antenna} \geq \text{Wavelength}/2$, 800 MHz $\Rightarrow 6''$
- Higher frequencies are affected more by weather
Higher than 10 GHz affected by rainfall
60 GHz affected 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
3. Multiple Antennas: Receive diversity, transmit 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 Memory Access
❑ DSP	Digital Signal Processing
❑ DVB-H	Digital Video Broadcast handheld
❑ FDMA	Frequency Division Multiple Access
❑ FFT	Fast Fourier Transform
❑ IDFT	Inverse Discrete Fourier Transform
❑ IFFT	Inverse Fast Fourier Transform
❑ ISI	Inter-symbol interference
❑ kHz	Kilo Hertz
❑ LoS	Line of Sight

Acronyms (Cont)

❑ MHz	Mega Hertz
❑ MIMO	Multiple Input Multiple Output
❑ MS	Mobile Station
❑ OFDM	Orthogonal Frequency Division Multiplexing
❑ OFDMA	Orthogonal Frequency Division Multiple Access
❑ QAM	Quadrature Amplitude Modulation
❑ QPSK	Quadrature Phase-Shift Keying
❑ RF	Radio Frequency
❑ SNR	Signal to Noise Ratio
❑ SS	Subscriber Station
❑ STBC	Space Time Block Codes
❑ TDMA	Time Division Multiple Access