PHY FUNDAMENTALS II

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 (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

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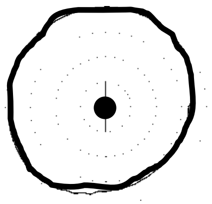
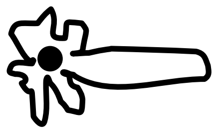
Antenna

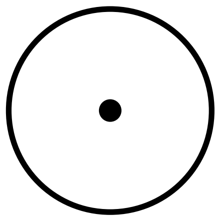
- Transmitter converts electrical energy to electromagnetic waves
- Receiver converts electromagnetic waves to electrical energy
- Same antenna is used for transmission and reception
- Omni-Directional: Power radiated in all directions
- Directional: Most power in the desired direction
- Isotropic antenna: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



Omni-Directional



Directional



Isotropic

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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.

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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 = ½ wavelength
  - So that electrons can travel back and forth the antenna in one cycle
- If dipole (two rods), each rod is ¼ wavelength

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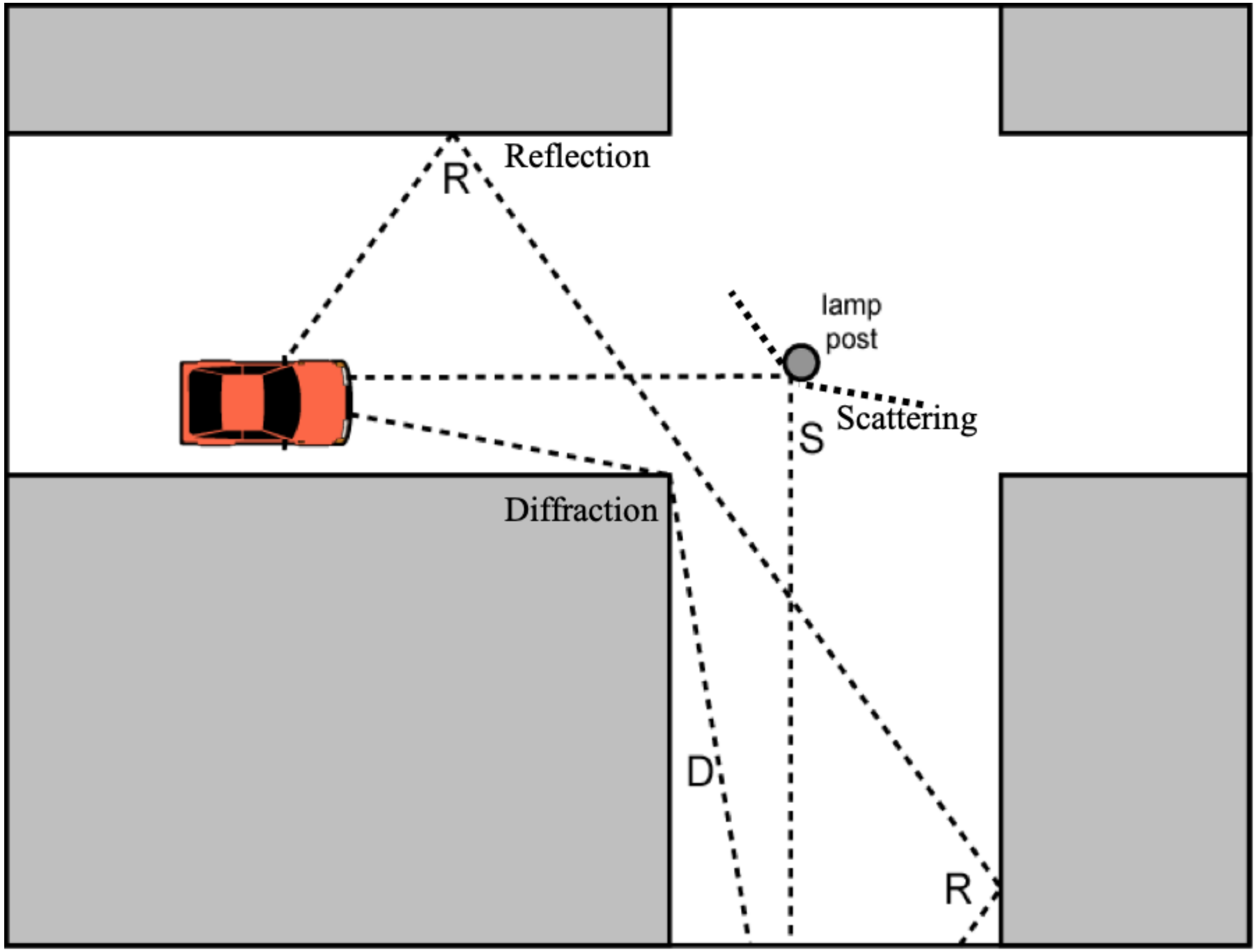
Reflection, Diffraction, Scattering



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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 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

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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)

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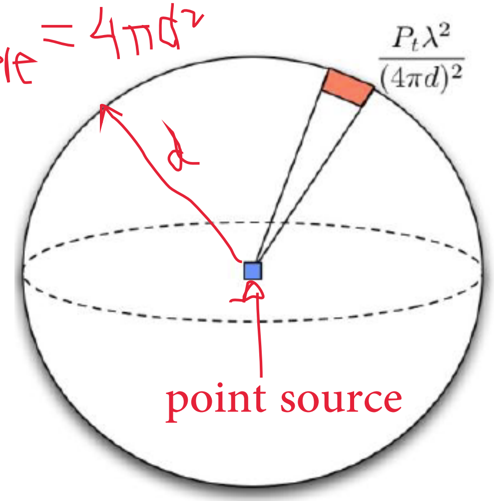
Free Space Path Loss (Frii's Law)

$A_{sphere} = 4\pi d^2$



- Power density at shpere surface = $\frac{P_T}{4\pi d^2}$

$A_{ant} = \frac{\lambda^2}{4\pi}$

- 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 dBi)*

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

P_R = Power density x A_{ant}

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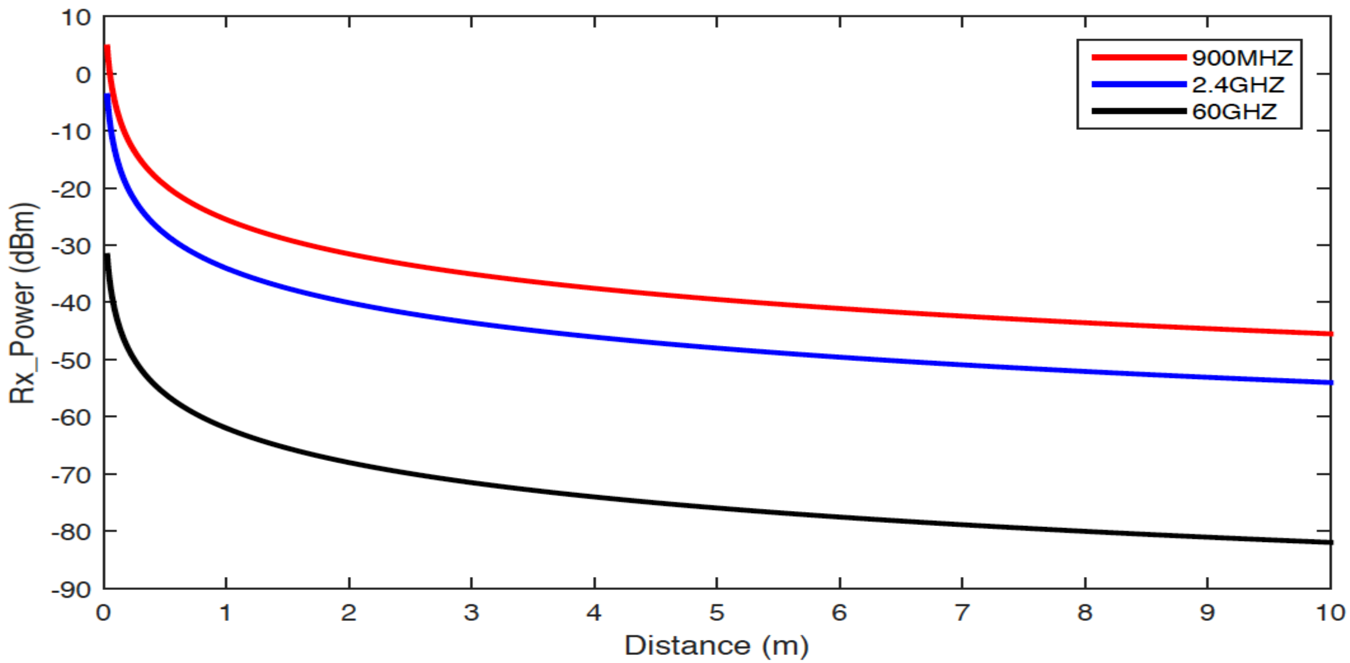
Free-space path loss (cont)

- 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

20dB diff



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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).

huge power loss !!

Solution

Unit antenna gain means: G_T=G_R=1.

We have d=100m, f=900x10^6 Hz, P_T=50W, c=3x10^8 m/sec, and $\pi = 3.14$

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

linear formula

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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=0dBm.

We have d=10m, f=2.4x10^9 Hz, P_T=100mW=20dBm, c=3x10^8 m/sec, and $\pi = 3.14$

log formula

from π & c

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

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

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

100 mW = 20 dBm

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

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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/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

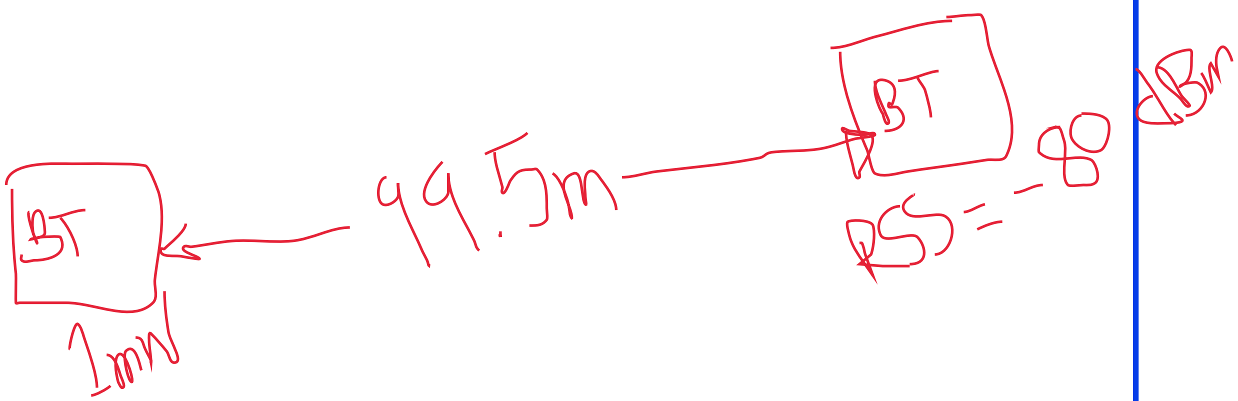
- To increase the coverage with low transmit power, a manufacturer produced Bluetooth chipsets with a receiver sensitivity of -80 dBm. What is the maximum communication range that could be achieved for this chipset for a transmit power of 1 mW? Assume Free Space Path Loss with unit antenna gains.

Bluetooth frequency $f = 2.4$ GHz, $P_T = 1$ mW, $P_R = -80$ 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



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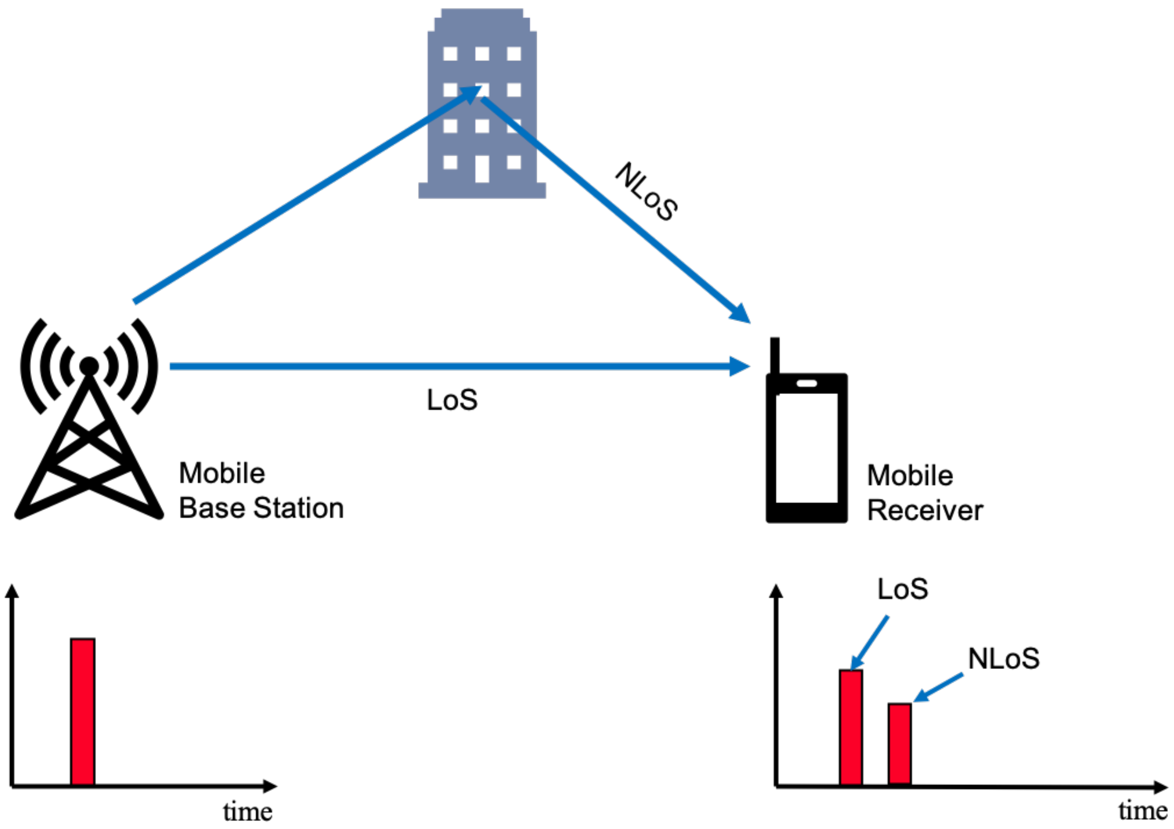
Multipath



- 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.

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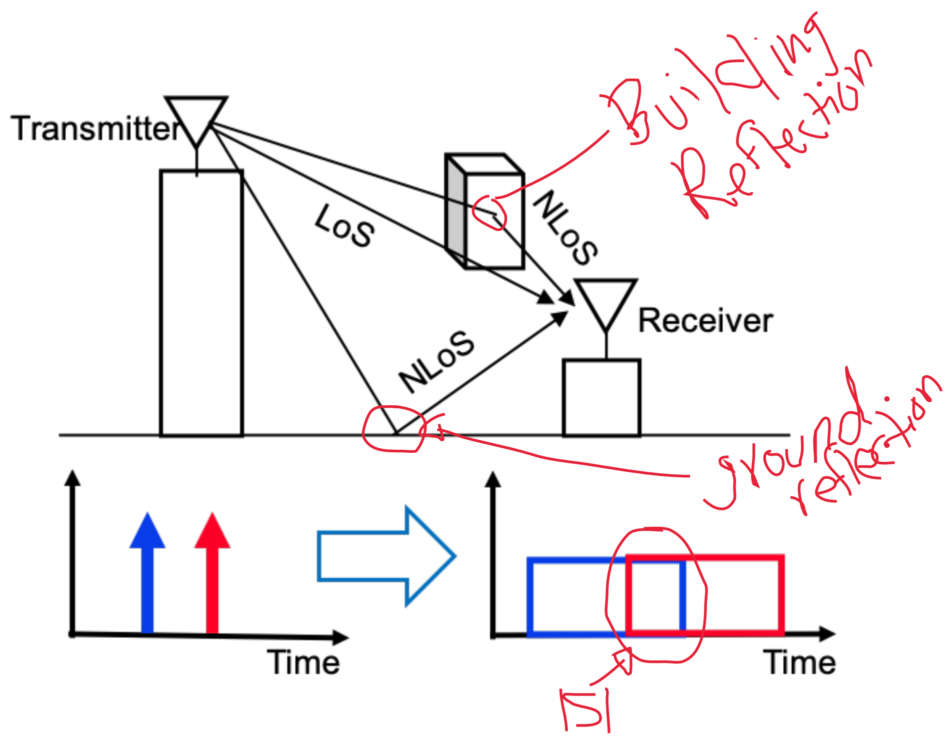
Inter-Symbol Interference



- 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)

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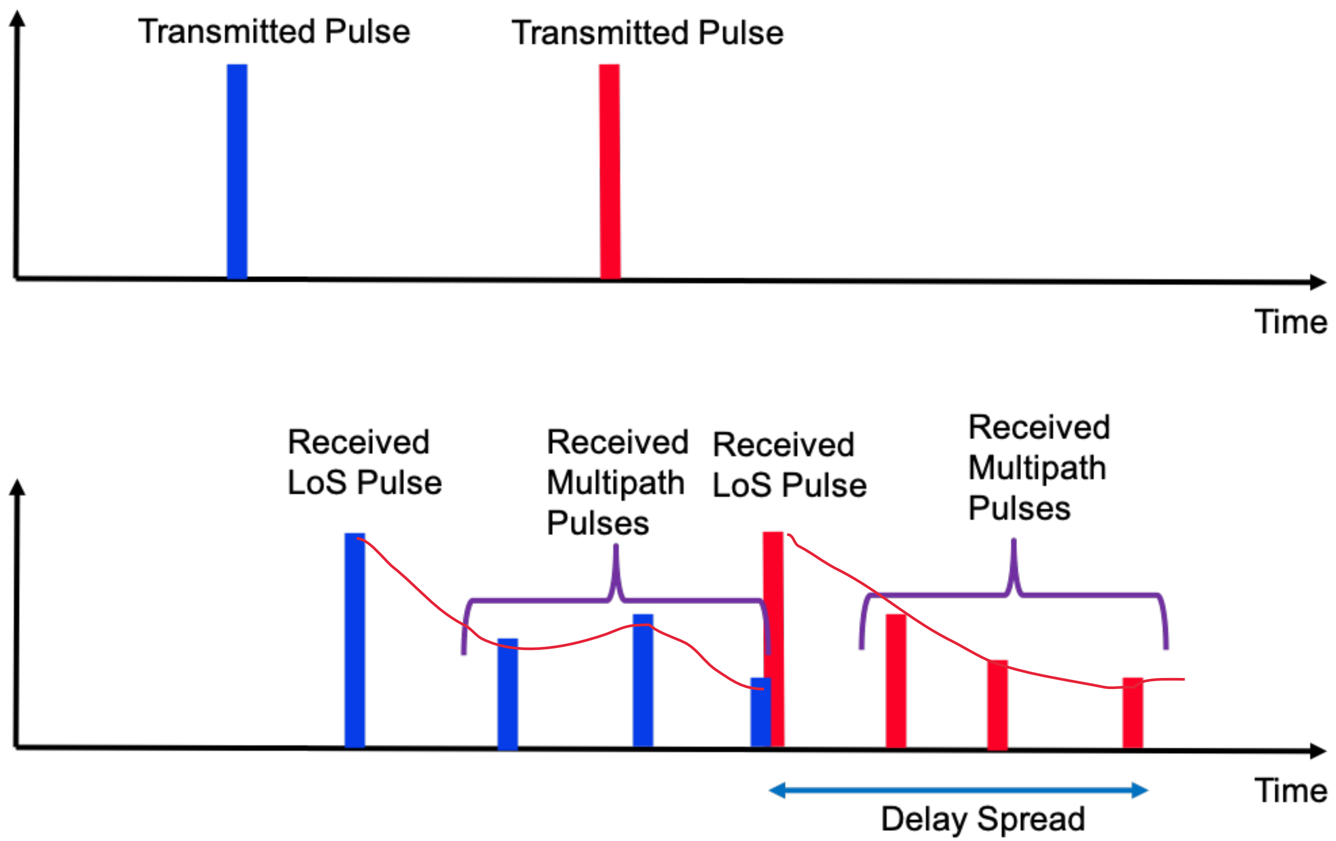
Delay Spread



- 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)

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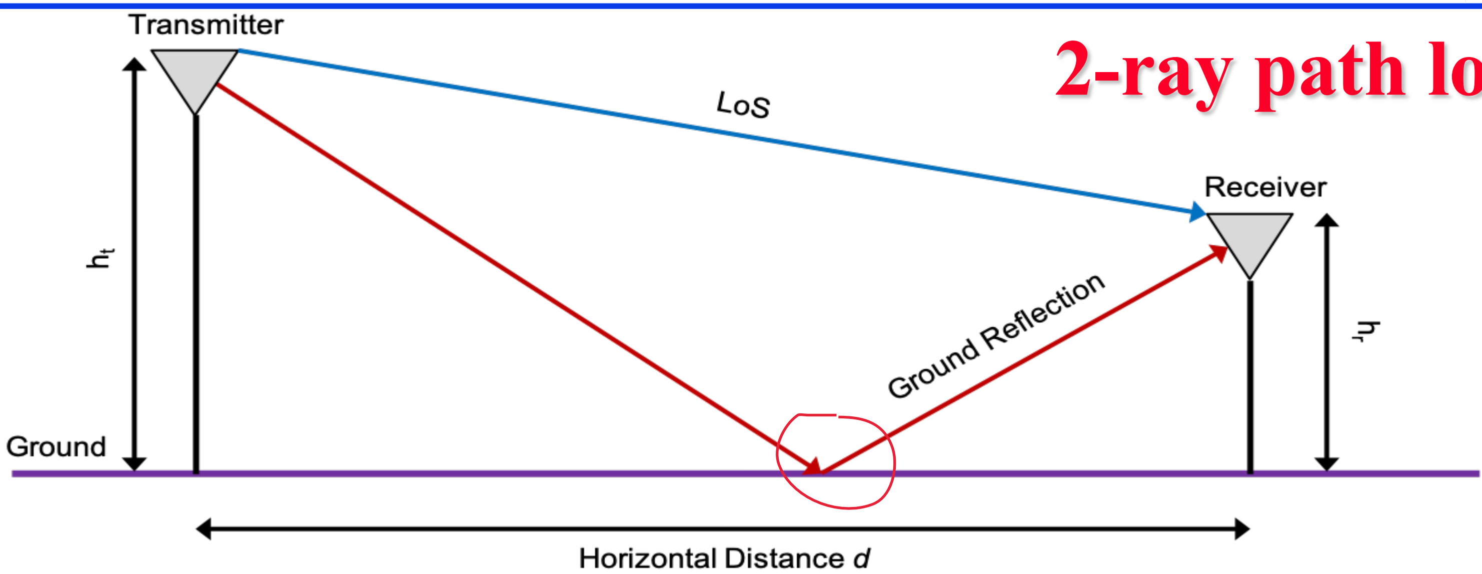
2-ray path loss model



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

- pathloss (dB) $= 40log_{10}(d) - 20log_{10}(h_t h_r)$ [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 $d_{\text{break}} = 4h_T h_R/\lambda$ far field
- 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)

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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.

We have h_t = 10m, h_r=2m, d=500m, f=1.8x10^9 Hz, P_T=30dBm, c=3x10^8 m/sec

$$d_{break} = 4\left(\frac{h_t h_r f}{c}\right) = 480m$$

far field

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

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

The received power = 30 – 81.94 = -78.94dBm

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

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

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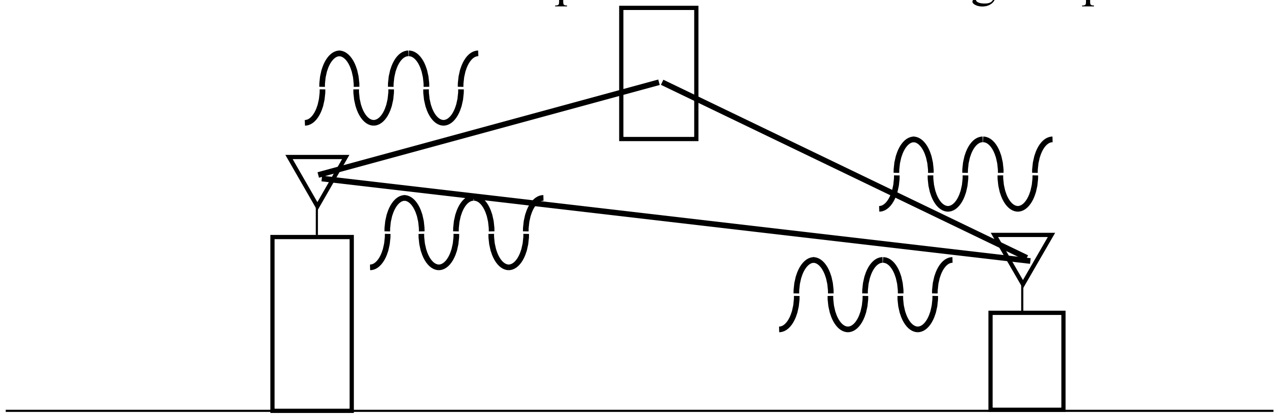
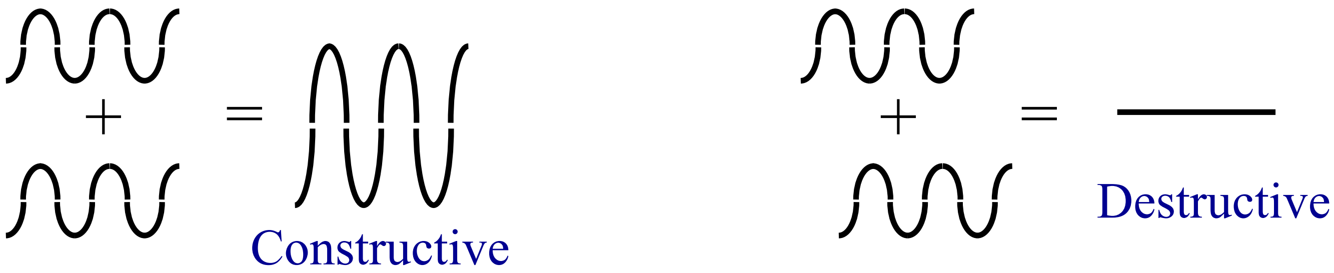
Small Scale Fading

- 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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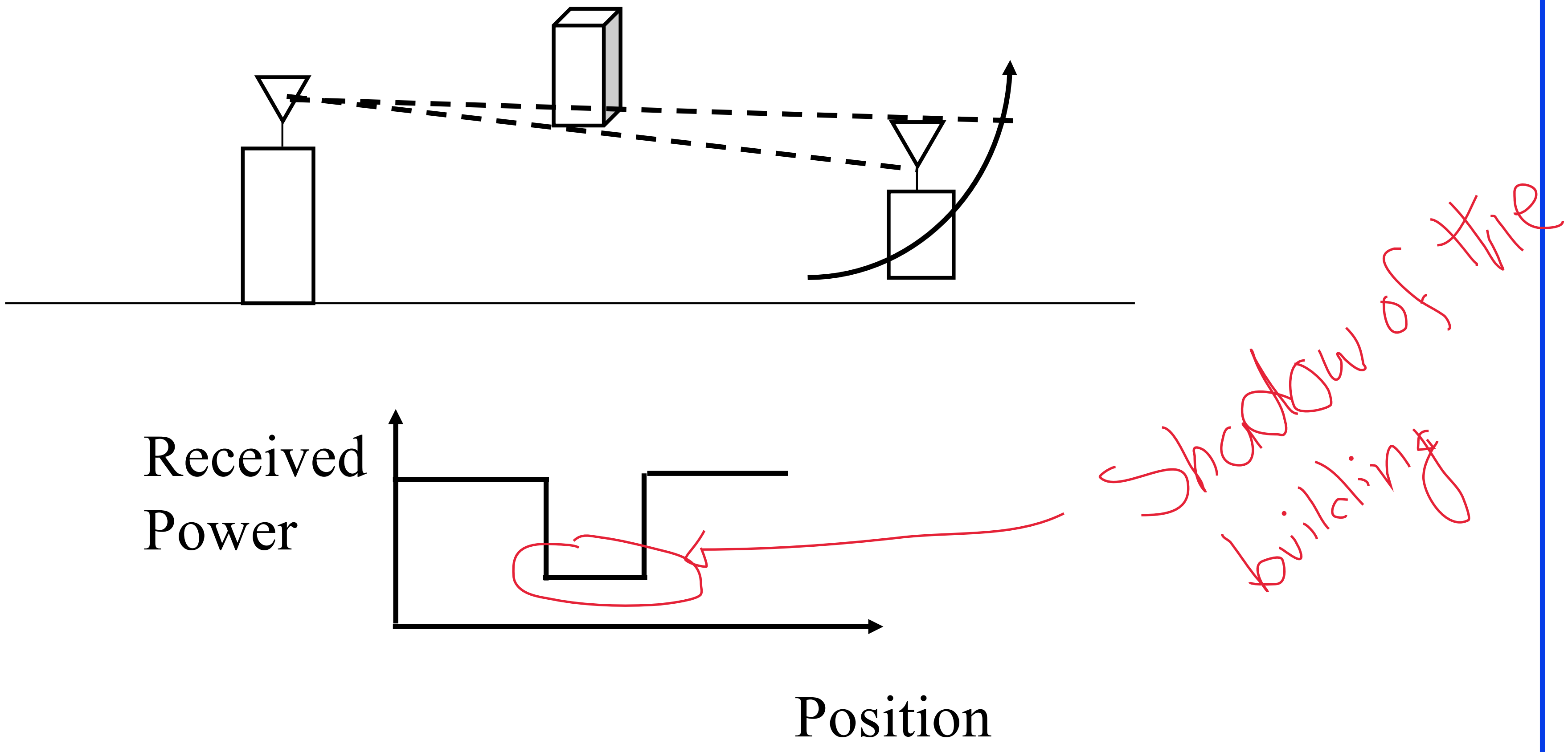
Shadowing (large scale fading)

- 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



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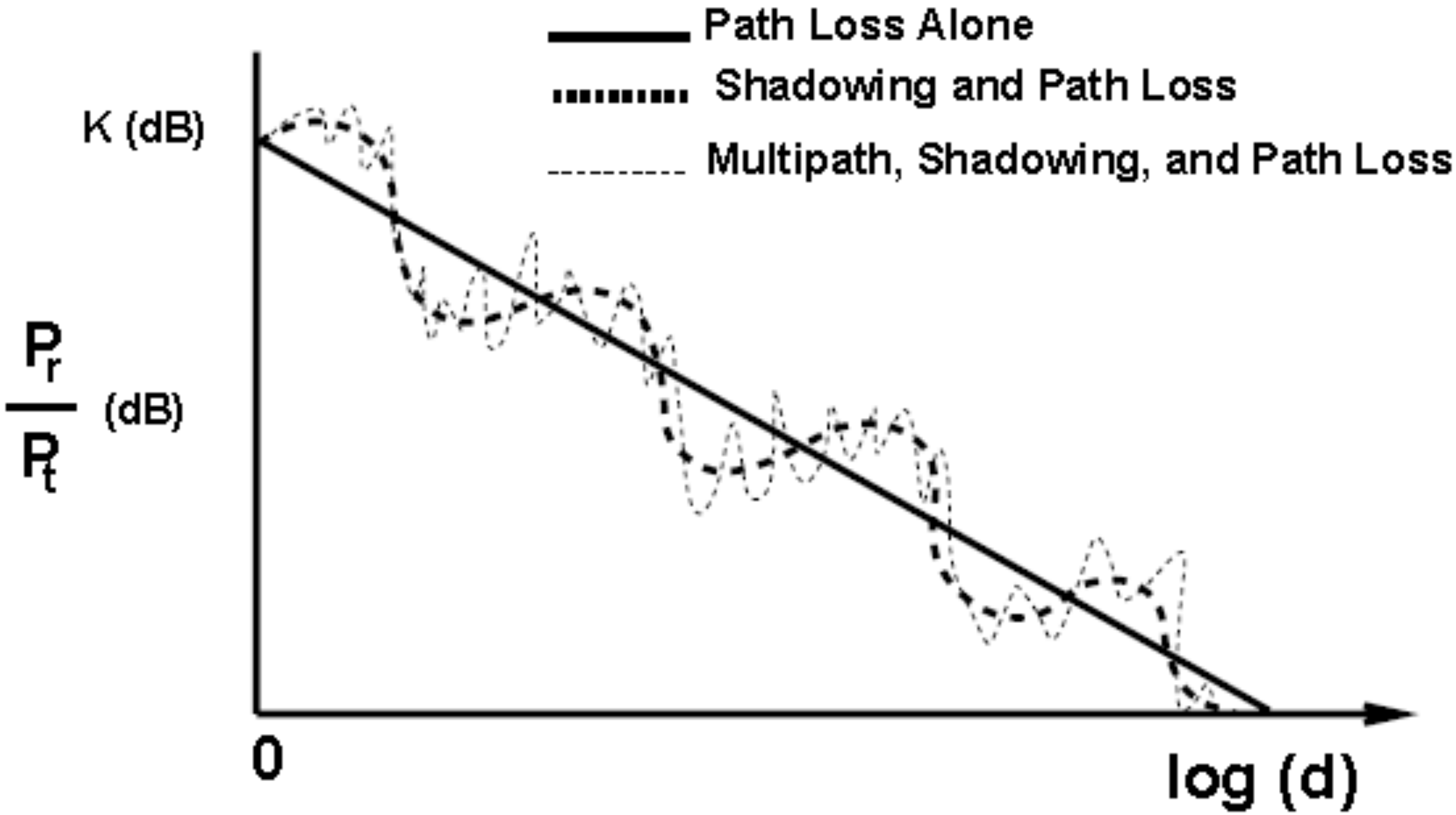
Total Path Loss



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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 WiFi routers have multiple antennas
- Multiple input (multiple antennas at the *transmitter*)
- Multiple output (multiple antennas at the *receiver*)
- MIMO – multiple input multiple output

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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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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

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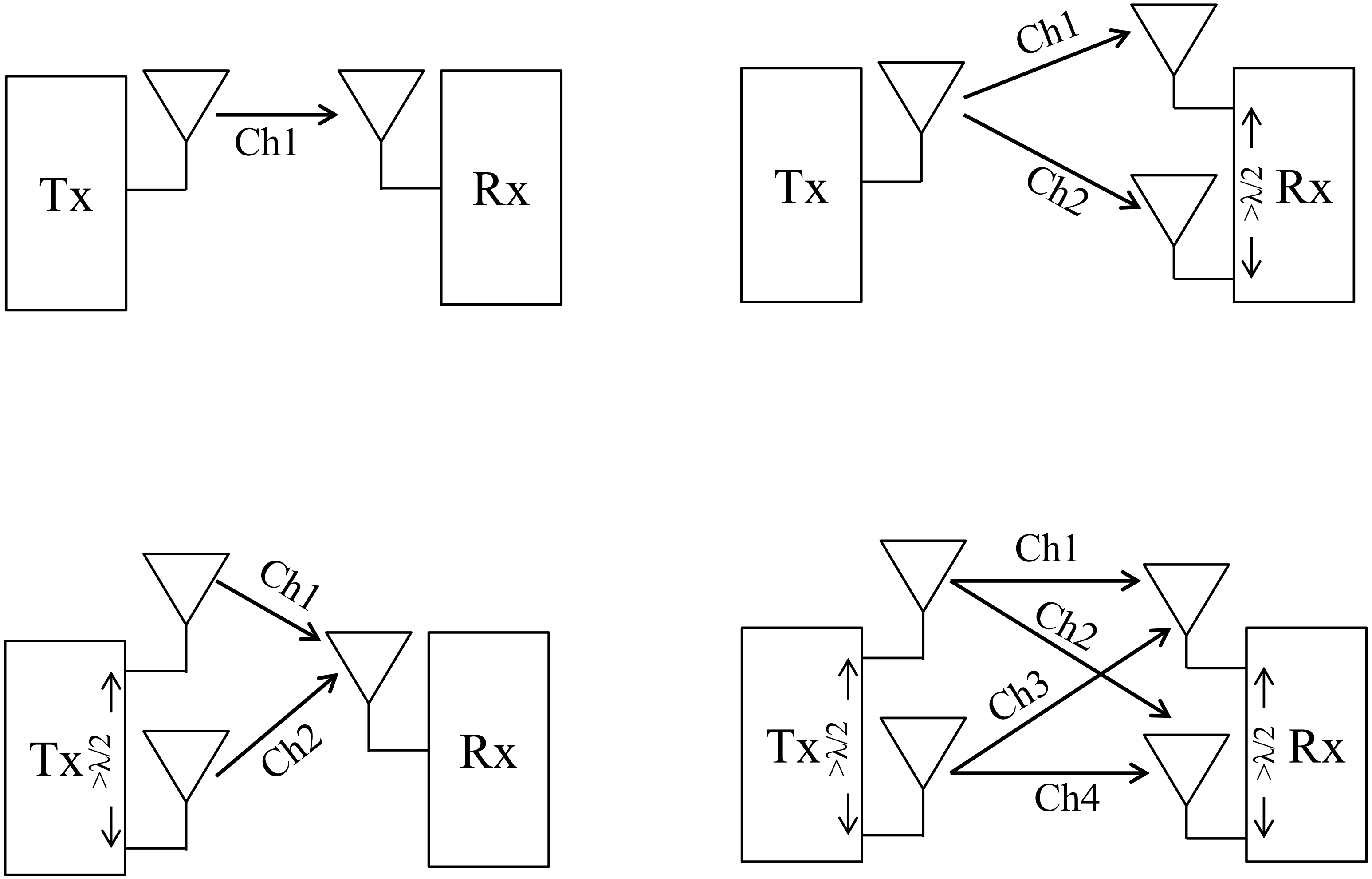
Spatial Channels



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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 *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

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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 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?

Answer: It is a 100x1 MIMO. 100 spatial channels are possible.

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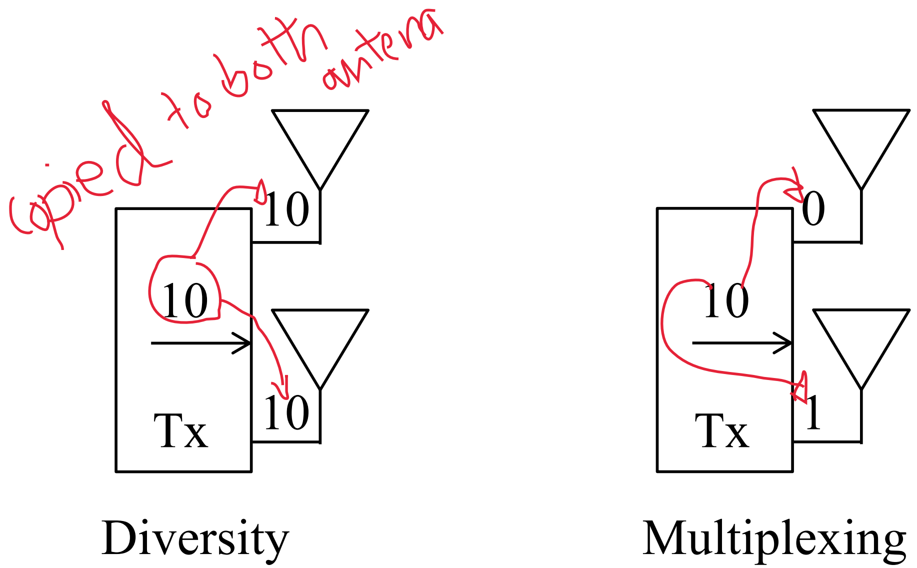
Multiplexing

- 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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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

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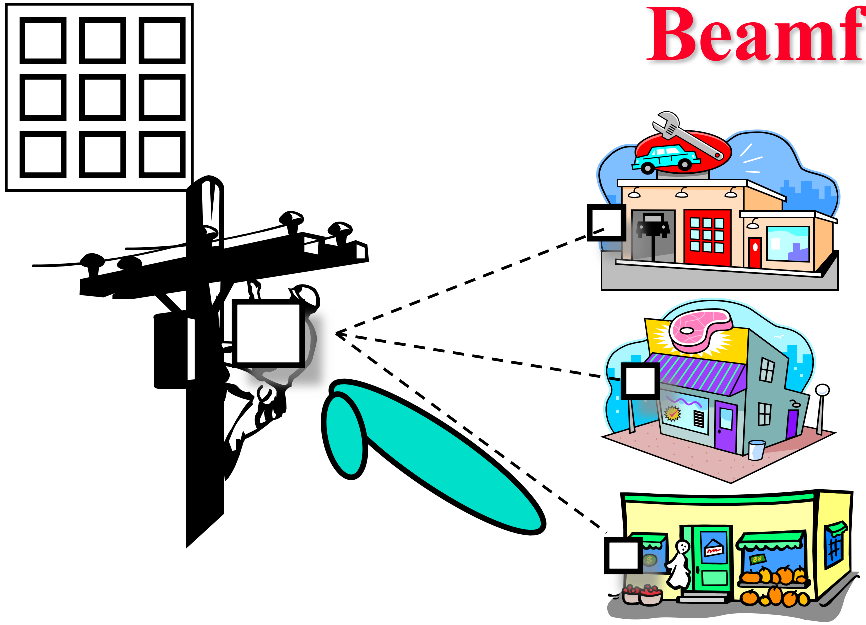
Beamforming



- Phased Antenna Arrays:
  Transmit the same signal using multiple antennas
- By phase-shifting various signals ⇒ 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

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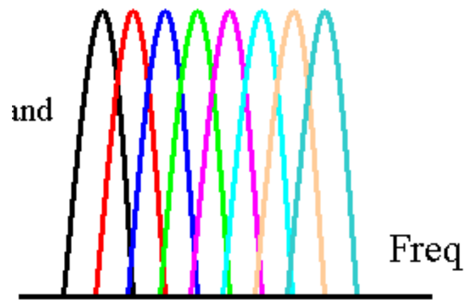
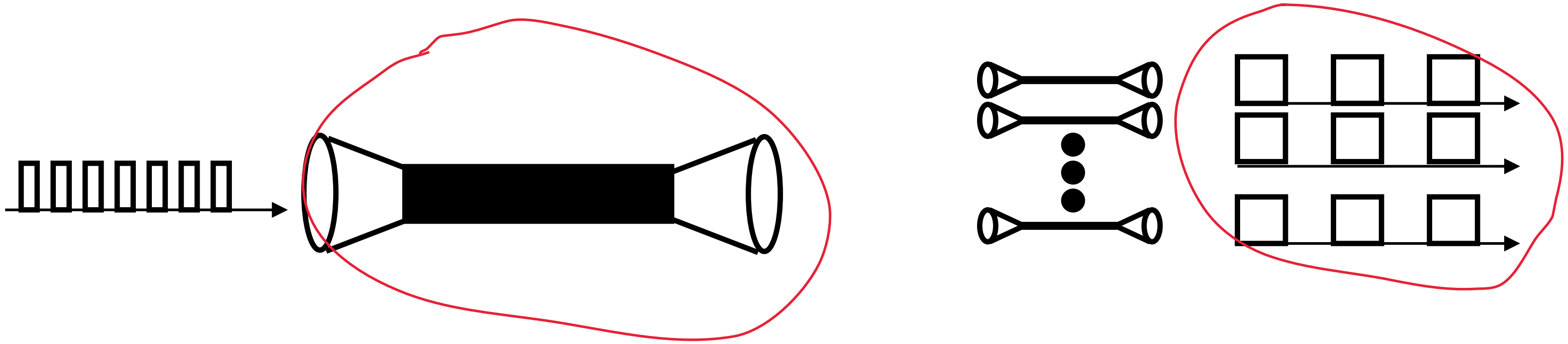
OFDM



- **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 indecently 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

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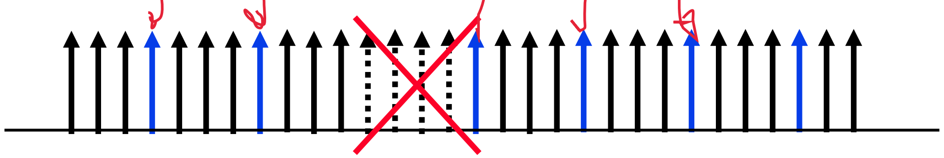
Advantages of OFDM

- 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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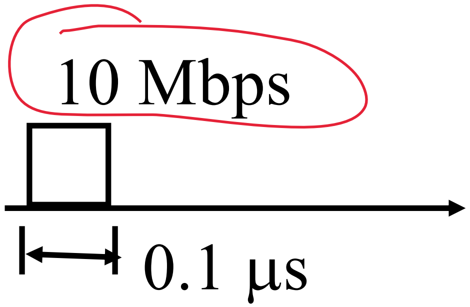
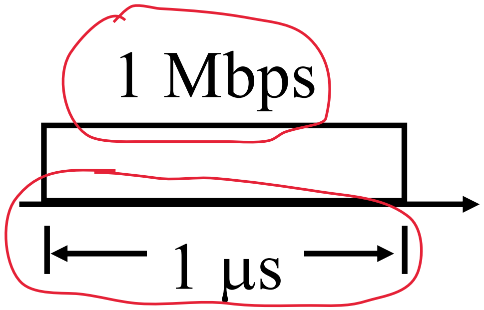
OFDM: Design considerations

- Subcarrier spacing = Frequency bandwidth/Number of subcarriers
- Large number of carriers ⇒ 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



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



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

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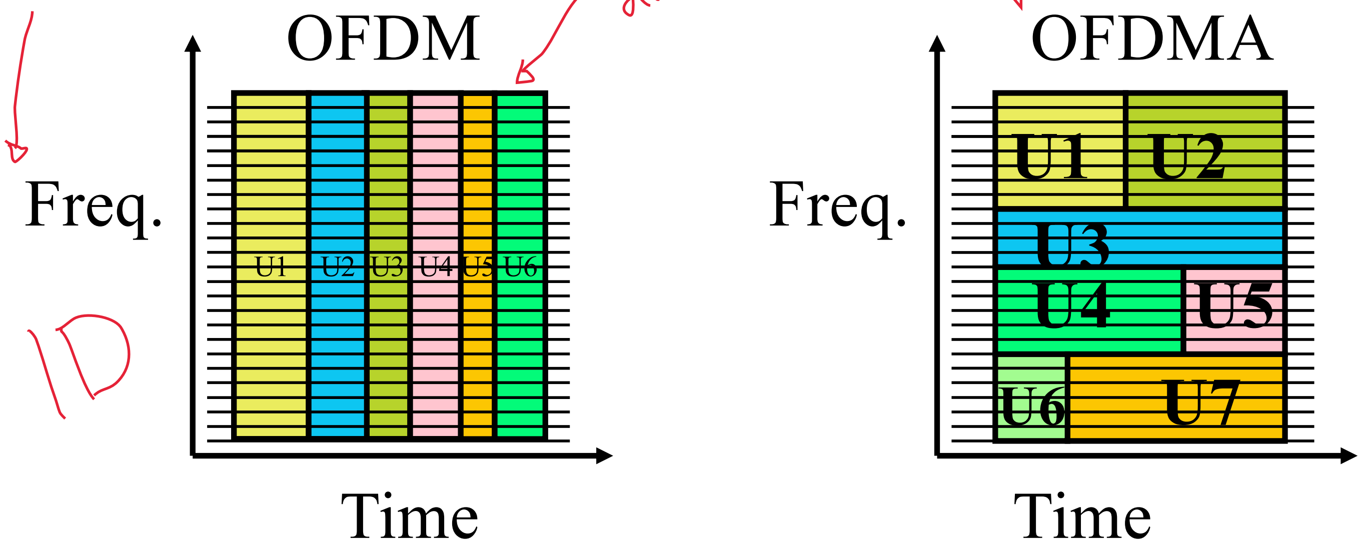
OFDMA

- 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

OFDM subcarriers

all subcarriers are used



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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?*

Number of subcarriers = channel bandwidth/subcarrier spacing
$= 20x10^6/10x10^3 = 2000$

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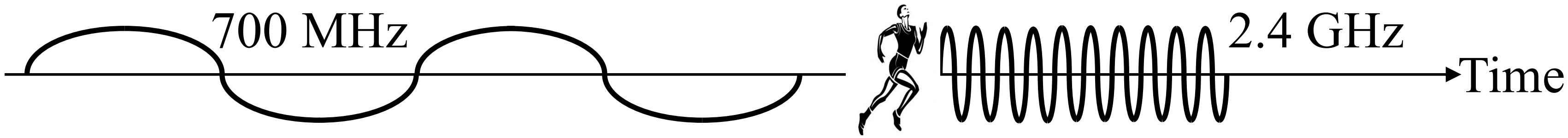
Effect of Frequency



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

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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 × Frequency/(speed of light)
  ⇒ Lower Doppler spread at lower frequencies
- Mobility ⇒ Below 10 GHz

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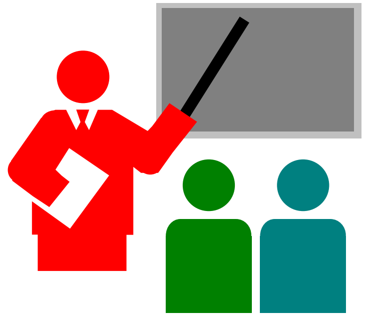
Summary



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

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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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