

CS/ECE 439: Wireless Networking

Physical Layer – Antennas and Propagation

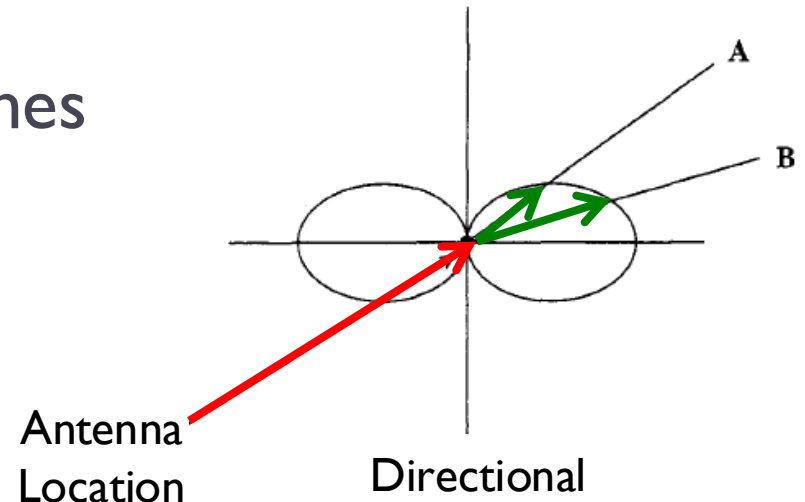
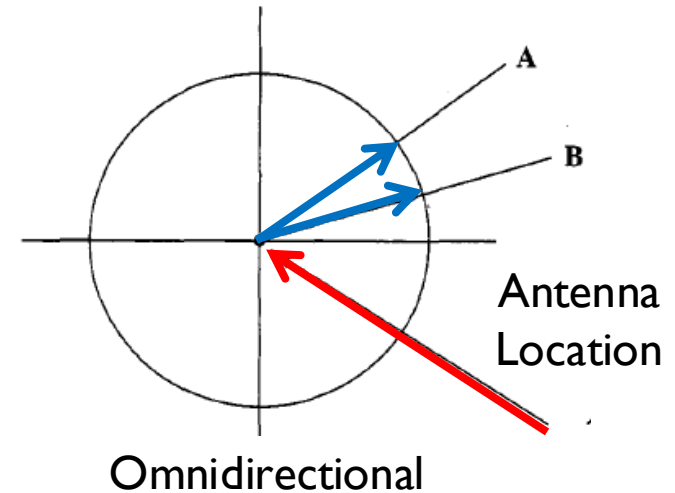
What is an Antenna?

- ▶ **Conductor that carries an electrical signal**
 - ▶ **Transmission**
 - ▶ Radiates RF signal (electromagnetic energy) into space
 - ▶ **Reception**
 - ▶ Collects electromagnetic energy from space
 - ▶ The RF signal “is a copy of” the electrical signal in the conductor
- ▶ **Two-way communication**
 - ▶ Same antenna used for transmission and reception
- ▶ **Efficiency of the antenna depends on its size, relative to the wavelength of the signal**
 - ▶ e.g. quarter a wavelength



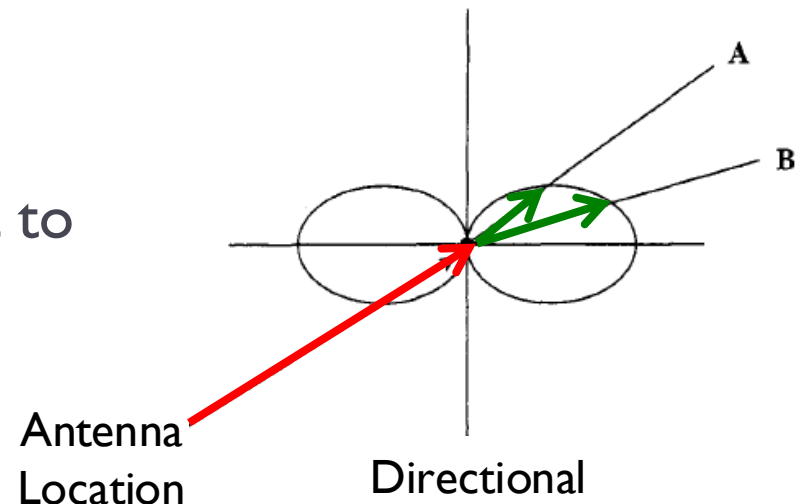
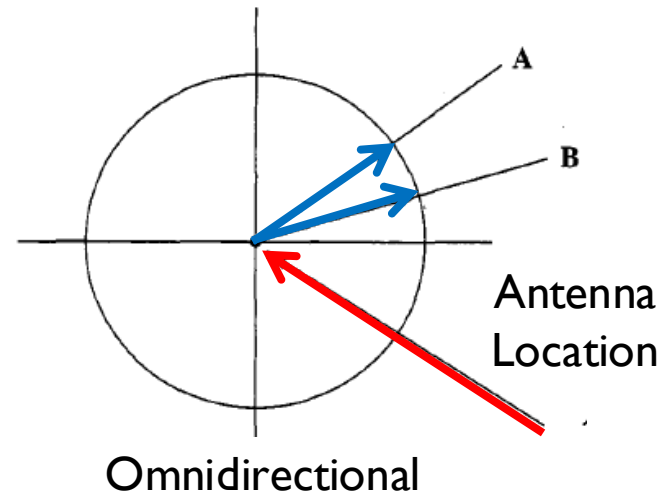
Radiation Patterns

- ▶ **Radiation pattern**
 - ▶ Graphical representation of radiation properties of an antenna
 - ▶ Depicted as two-dimensional cross section
 - ▶ Relative distance determines relative power



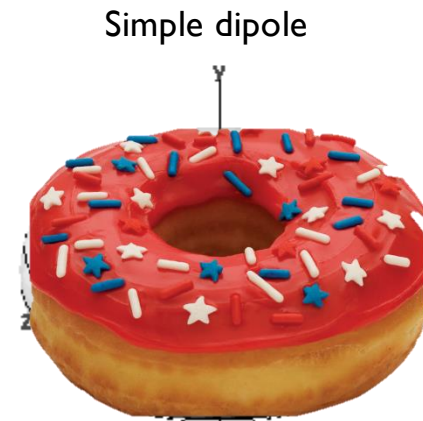
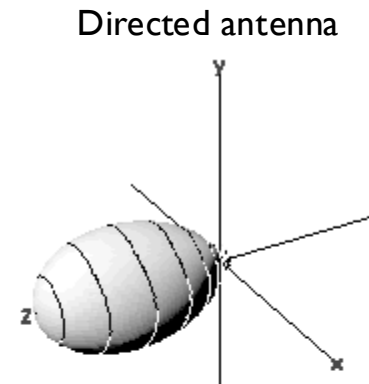
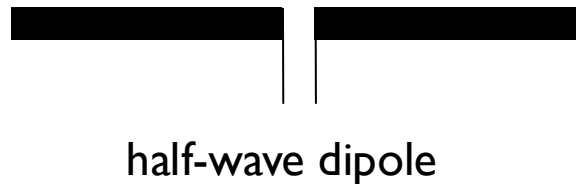
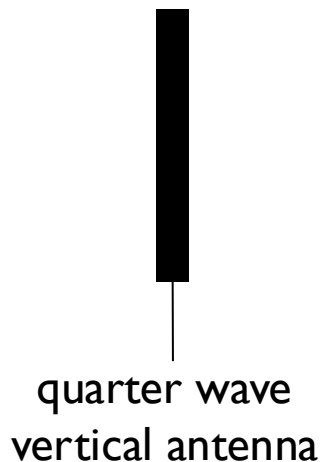
Radiation Patterns

- ▶ Beam width (or half-power beam width)
 - ▶ Measure of directivity of antenna
 - ▶ Angle at which the power radiated by the antenna is at least half of the power at the preferred direction
- ▶ Reception pattern
 - ▶ Receiving antenna's equivalent to radiation pattern



Antenna Types: Dipoles

- ▶ Simplest
 - ▶ Quarter wave vertical (Marconi)
 - ▶ Automobile and portable radios
 - ▶ Half-wave dipole (Hertz)
 - ▶ Very simple and very common
 - ▶ Elements are quarter wavelength of frequency that is transmitted most efficiently
- ▶ Donut shape
- ▶ Many other designs

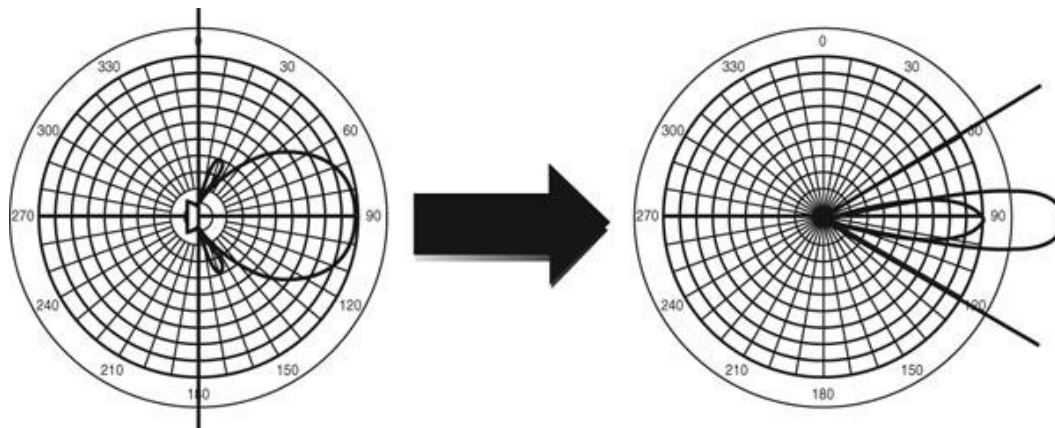


Antenna Gain

▶ Antenna gain

▶ Measure of directionality

- ▶ Definition: Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna
- ▶ ex. Antenna with a gain of 3dB
 - Improves on an omnidirectional antenna in that direction by 3dB (or a factor of 2)
- ▶ Reduced power in other directions!



Antenna Gain

- ▶ **Antenna gain**

- ▶ **Measure of directionality**

- ▶ Definition: Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna
 - ▶ ex. Antenna with a gain of 3dB
 - Improves on an omnidirectional antenna in that direction by 3dB (or a factor of 2)
 - ▶ Reduced power in other directions!

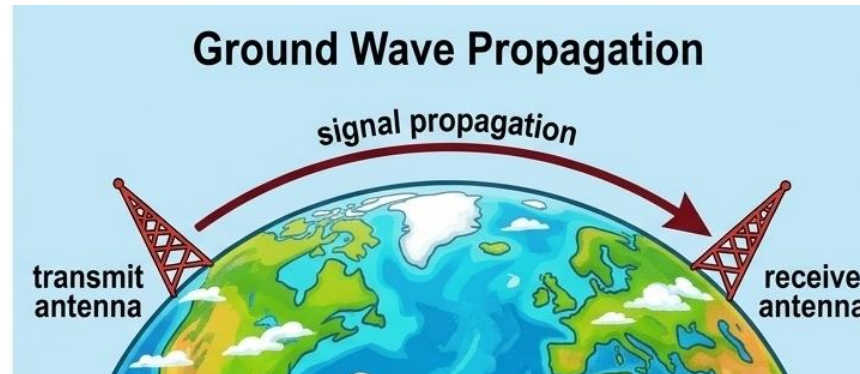
- ▶ **Effective area**

- ▶ Related to physical size and shape of antenna



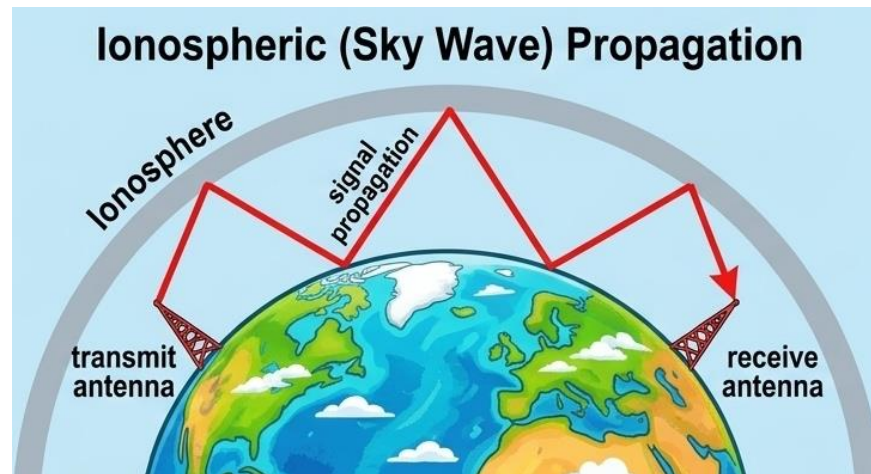
Propagation Modes

- ▶ **Ground-wave propagation**
 - ▶ More or less follows the contour of the earth
 - ▶ Past the visual horizon!
 - ▶ Electromagnetic wave induces a current in the earth's surface
 - Slows the wavefront near the earth and causes the wavefront to tilt down
 - ▶ For frequencies up to about 2 MHz, e.g. AM radio



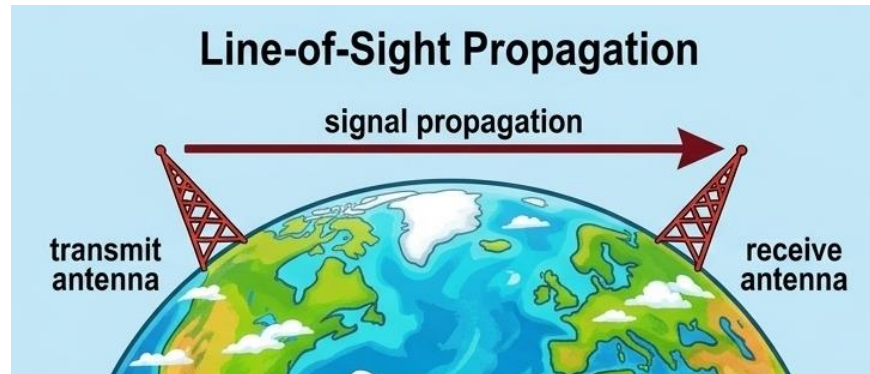
Propagation Modes

- ▶ Sky wave propagation
 - ▶ Signal “bounces” off the ionosphere back to earth
 - ▶ Can go multiple hops and 1000s of km
 - ▶ Used for amateur radio and international broadcasts



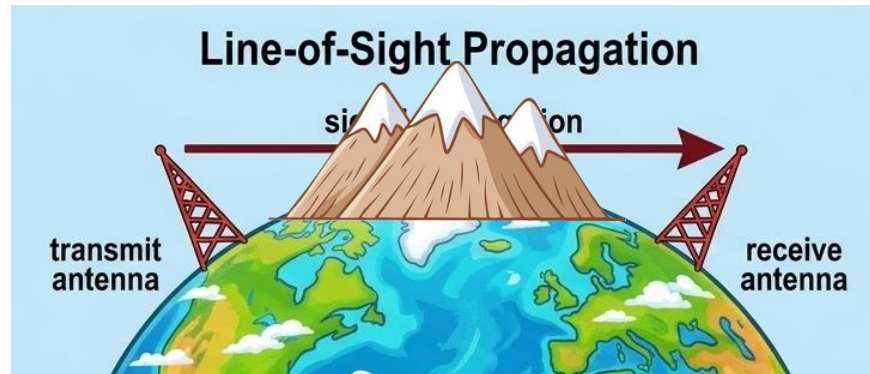
Propagation Modes

- ▶ **Line-of-sight (LOS) propagation**
 - ▶ Most common form of propagation
 - ▶ Happens above ~ 30 MHz
 - ▶ Subject to many forms of degradation!



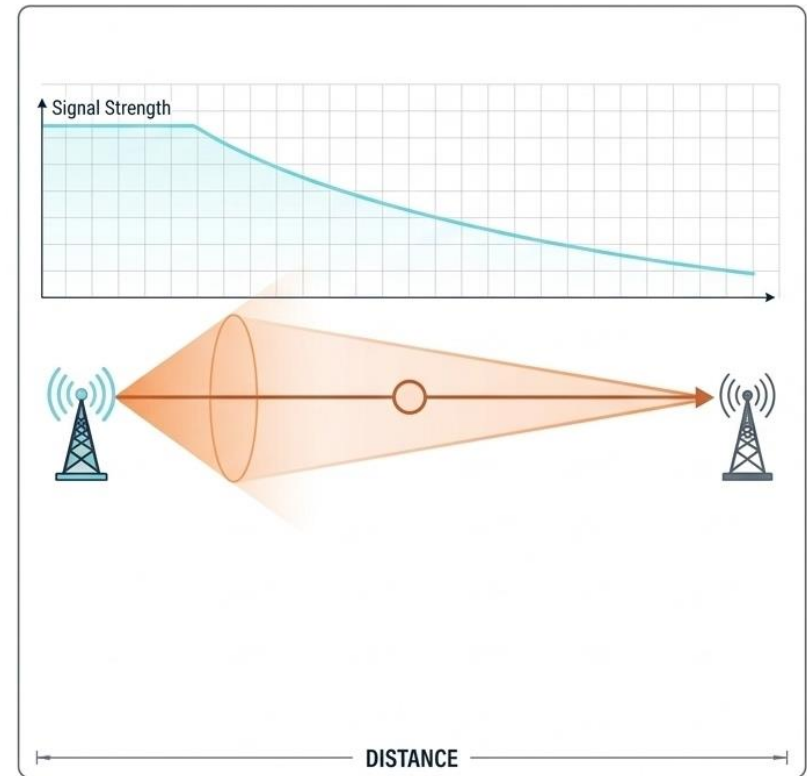
Propagation Modes

- ▶ **Line-of-sight (LOS) propagation**
 - ▶ Most common form of propagation
 - ▶ Happens above ~ 30 MHz
 - ▶ Subject to many forms of degradation!



Propagation Degrades RF Signals

- ▶ **Attenuation in free space**
 - ▶ Signal gets weaker as it travels over longer distances
 - ▶ Radio signal spreads out – free space loss
 - ▶ Refraction and absorption in the atmosphere



Free Space Loss

- ▶ Loss increases quickly with distance (d^2)
- ▶ Ideal:

$$\begin{aligned}\text{Loss} &= P_t / P_r \\ &= (4\pi d)^2 / (G_r G_t \lambda^2) \\ &= (4\pi f d)^2 / (G_r G_t c^2)\end{aligned}$$

Free Space Loss

- ▶ Loss increases quickly with distance (d^2)

- ▶ Ideal:

$$\begin{aligned}\text{Loss} &= P_t / P_r \\ &= (4\pi d)^2 / (G_r G_t \lambda^2) \\ &= (4\pi f d)^2 / (G_r G_t c^2)\end{aligned}$$


- ▶ Loss depends on frequency
 - ▶ Higher loss with higher frequency
 - ▶ Adjust gain of the antennas at transmitter and receiver



Log Distance Path Loss Model

- ▶ **Log-distance path loss model**

- ▶ Captures free space attenuation plus additional absorption by of energy by obstacles:

$$\text{Loss}_{db} = L_0 + 10 n \log_{10}(d/d_0)$$

- ▶ L_0 is the loss at distance d_0
 - ▶ n is the path loss distance component

- ▶ **Value of n depends on the environment**

- ▶ 2 free space model
 - ▶ 2.2 office with soft partitions
 - ▶ 3 office with hard partitions
 - ▶ Higher if more and thicker obstacles

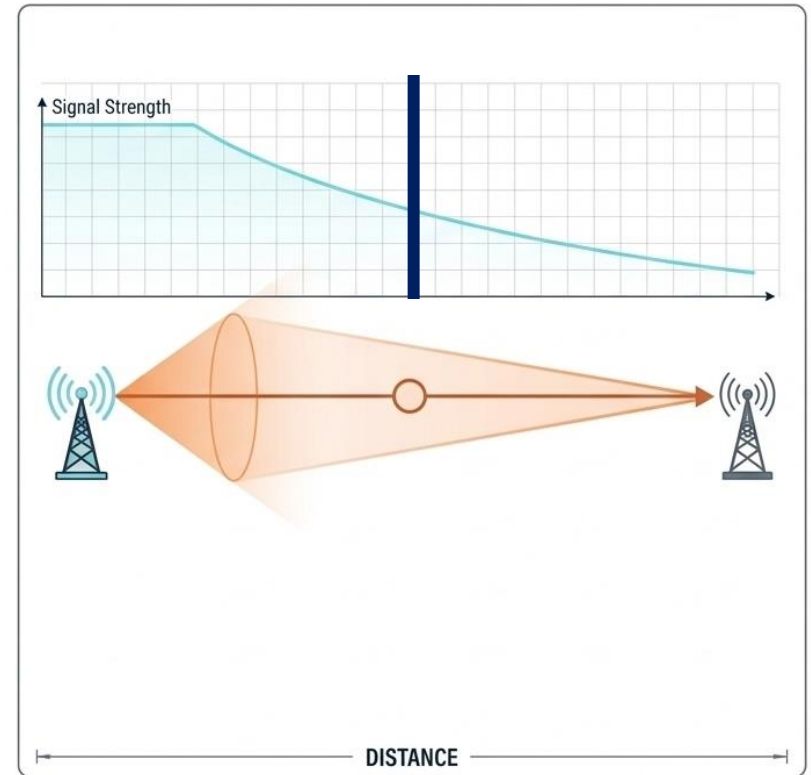
Attenuation

► Attenuation factors

- Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
- Signal must maintain a level sufficiently higher than noise to be received without error

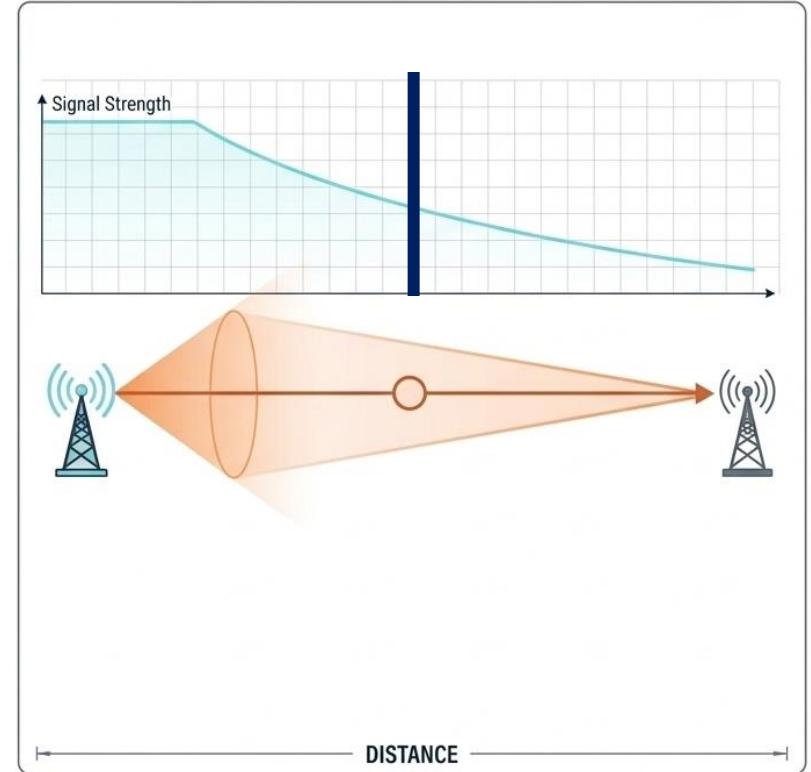
⇒ Power control, amplifiers

- Signal must not be too strong, overwhelming the circuitry of the receiver!



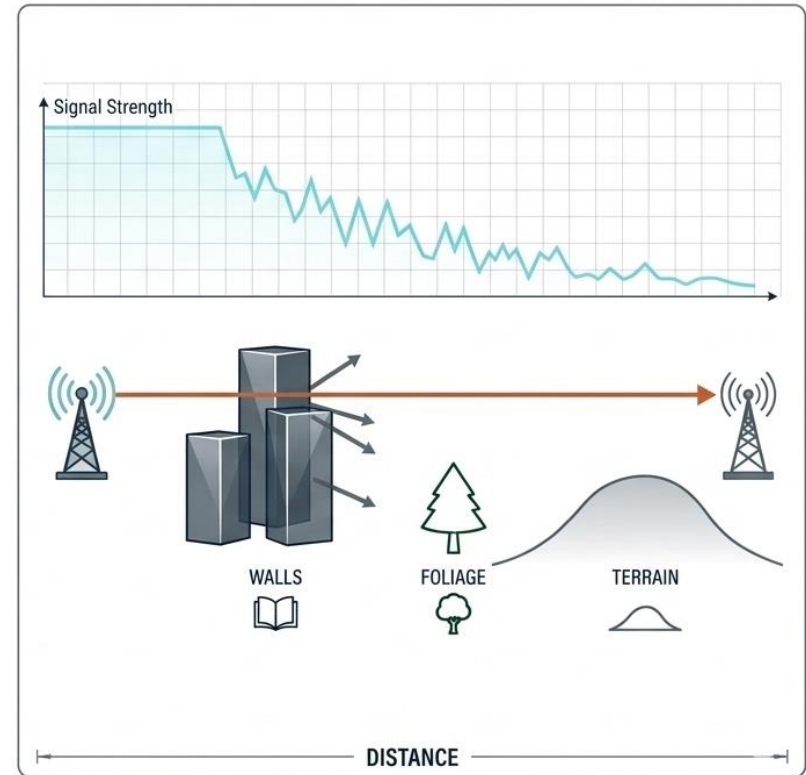
Attenuation

- ▶ Attenuation factors
 - ▶ Attenuation is greater at higher frequencies, causing distortion
 - ▶ Attenuation distortion
- ⇒ Equalize attenuation
 - ▶ Amplify high frequencies more



Propagation Degrades RF Signals

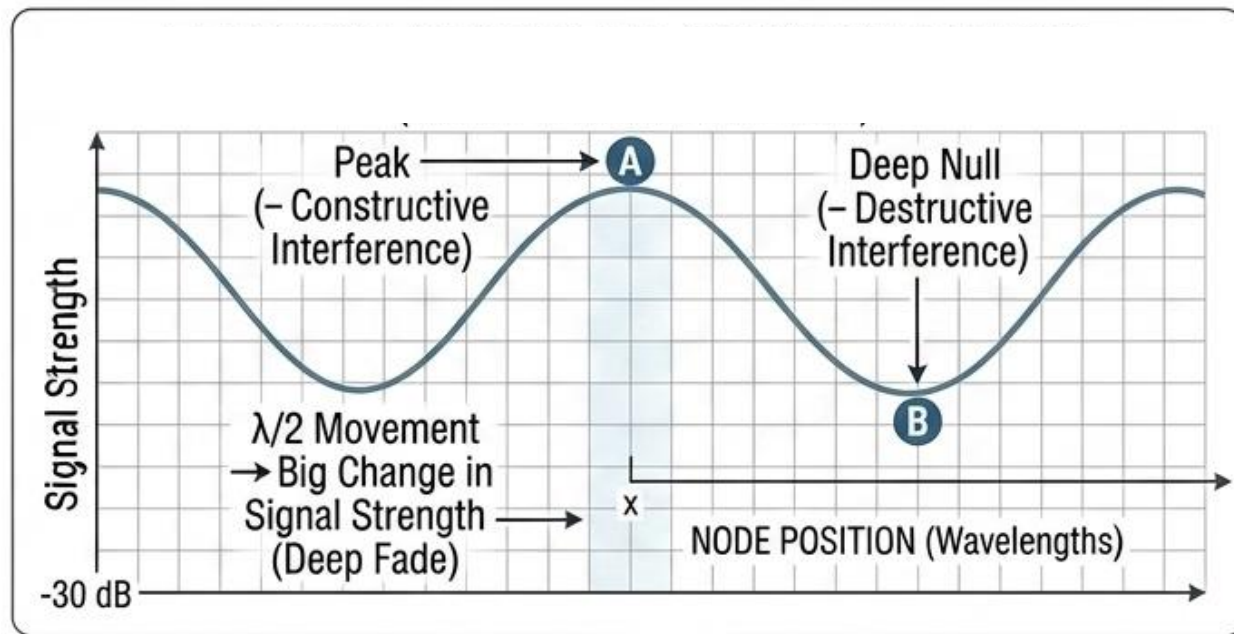
- ▶ Obstacles can change the signal through absorption or reflection
- ▶ Part of the signal is redirected



Propagation Degrades RF Signals

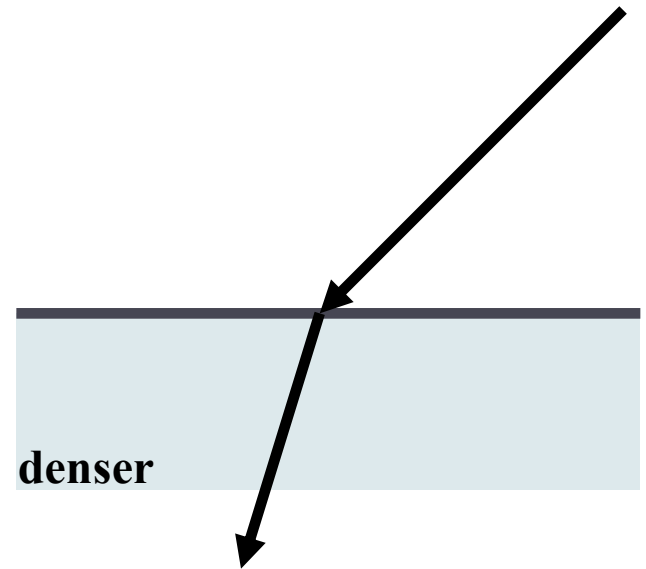
► Mobility

- Moving receiver causes another form of self interference
- Node moves $\frac{1}{2}$ wavelength $\rightarrow$ big change in signal strength



Propagation Degrades RF Signals

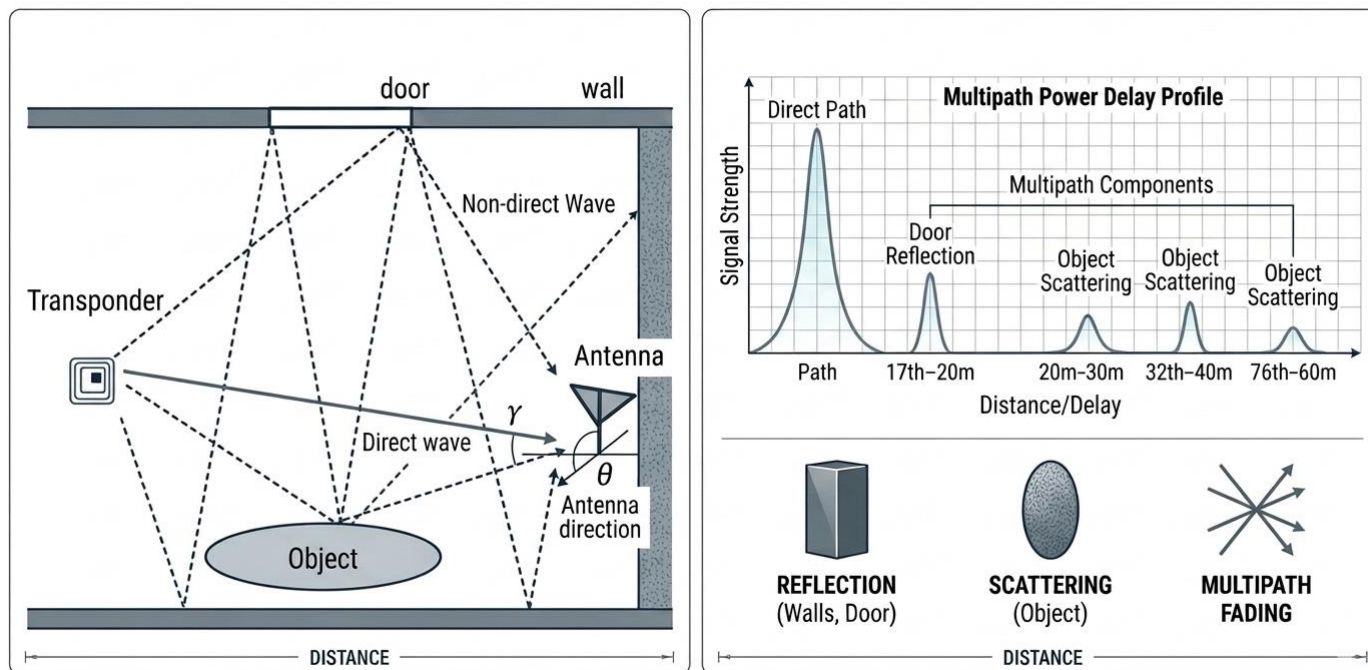
- ▶ Refraction
- ▶ Speed of EM signals depends on the density of the material
 - ▶ Vacuum: 3×10^8 m/sec
 - ▶ Denser: slower
- ▶ Density is captured by refractive index
- ▶ Explains “bending” of signals in some environments
 - ▶ e.g. sky wave propagation
 - ▶ But also local, small scale differences in the air density, temperature, etc.



Propagation Degrades RF Signals

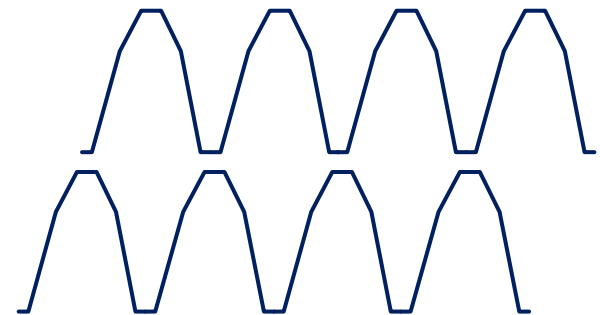
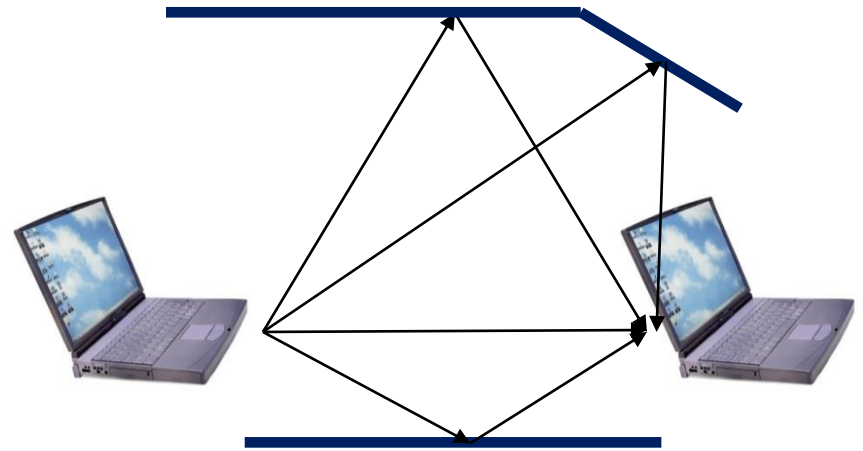
► Multi-path effects

- Multiple copies of the signal interfere with each other
- Similar to an unplanned directional antenna



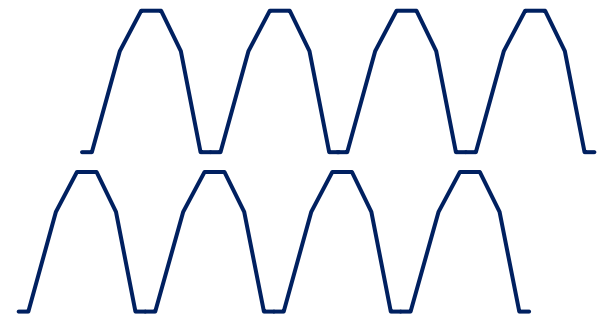
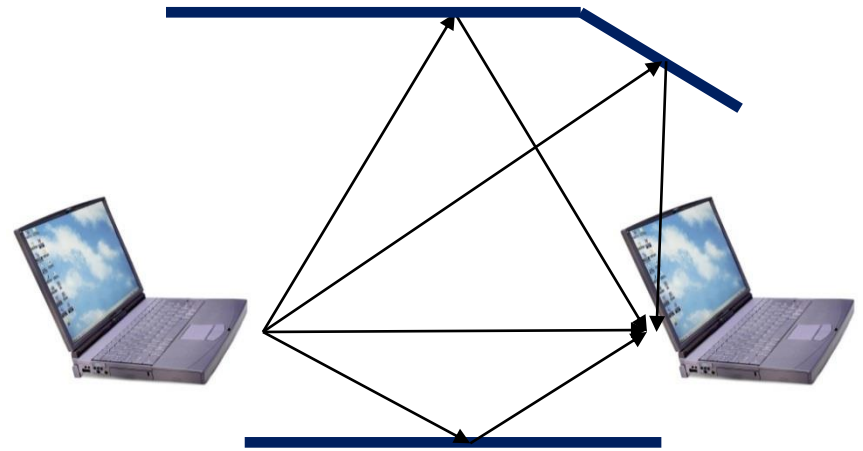
Multipath Effect

- ▶ Receiver receives multiple copies of the signal
 - ▶ Each copy follows a different path
 - ▶ Length of path determines phase-shift
- ▶ Copies can either strengthen or weaken each other
 - ▶ Depends on whether they are in or out of phase



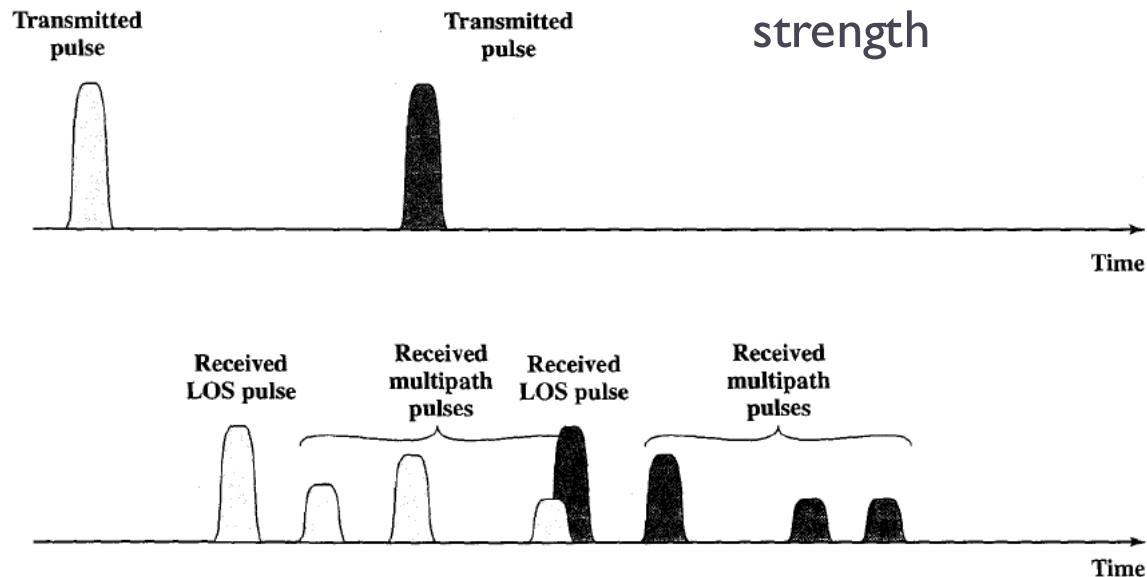
Multipath Effect

- ▶ Changes of half a wavelength affect the outcome
- ▶ Challenging for short wavelengths
 - ▶ 2.4 GHz → 12 cm
 - ▶ 900 MHz → ~1 ft
- ▶ Small adjustments in location or orientation of the wireless devices can result in big changes in signal strength



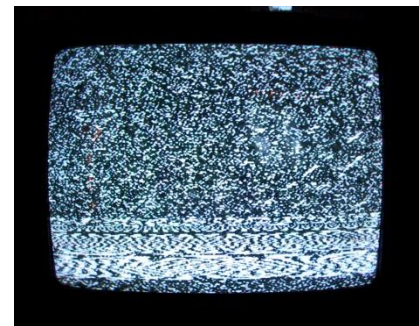
Inter-Symbol Interference

- ▶ Larger difference in path length can cause inter-symbol interference (ISI)
 - ▶ Different from effect of carrier phase differences
- ▶ Delays on the order of a symbol time result in overlap of the symbols
 - ▶ Makes it very hard for the receiver to decode
 - ▶ Corruption issue – not signal strength



Noise Sources

- ▶ Noise = unwanted signals!
- ▶ Thermal noise
 - ▶ Agitation of the electrons
 - ▶ Function of temperature
 - ▶ Uniform across all frequencies (white noise)
 - ▶ Affects electronic devices and transmission media
 - ▶ We're stuck with it!
 - Determines an upper bound on performance



Noise Sources

► Intermodulation noise

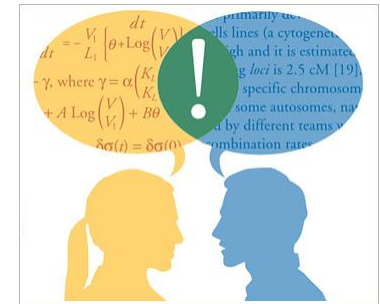
► Mixing signals on same media

- Appears as sum ($f_1 + f_2$) or difference ($f_1 - f_2$) of original frequencies

► Cross talk

► Picking up other near-by signals

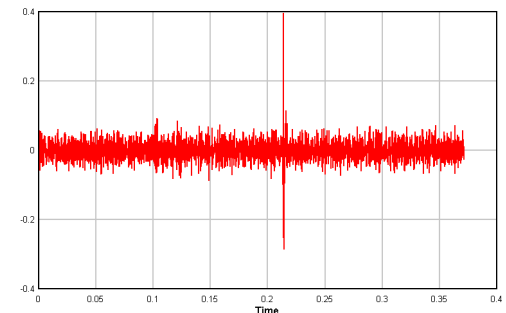
- e.g. from other source-destination pairs
- Significant in the ISM bands!



► Impulse noise

► Irregular pulses of high amplitude and short duration

- Harder to deal with
- Interference from various RF transmitters
- Should be dealt with at protocol level
- Worse for digital data!



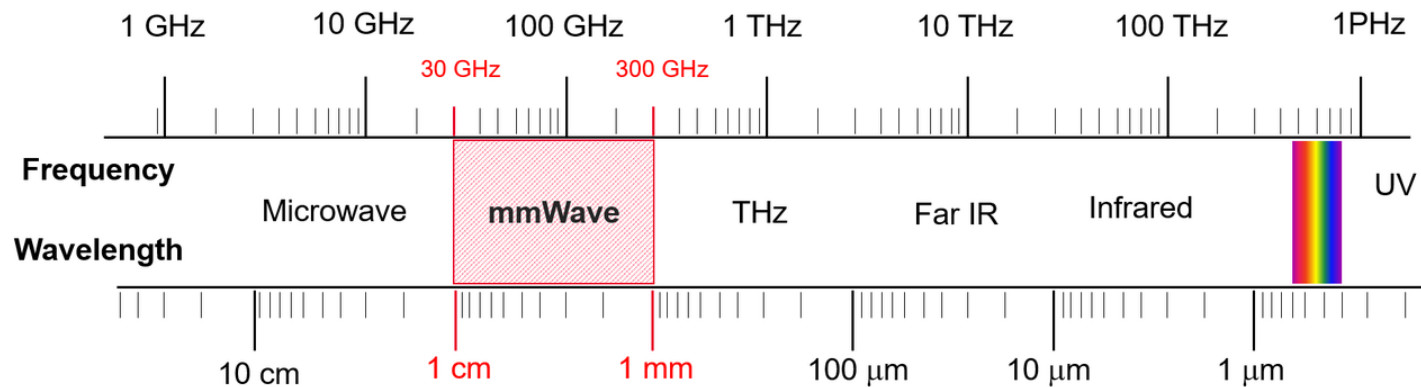
Other LOS Factors

- ▶ Absorption of energy in the atmosphere
 - ▶ Very serious at specific frequencies
 - ▶ e.g. water vapor (22 GHz) and oxygen (60 GHz)
 - ▶ If there is rain, use shorter paths or lower frequencies!
 - ▶ Obviously objects also absorb energy



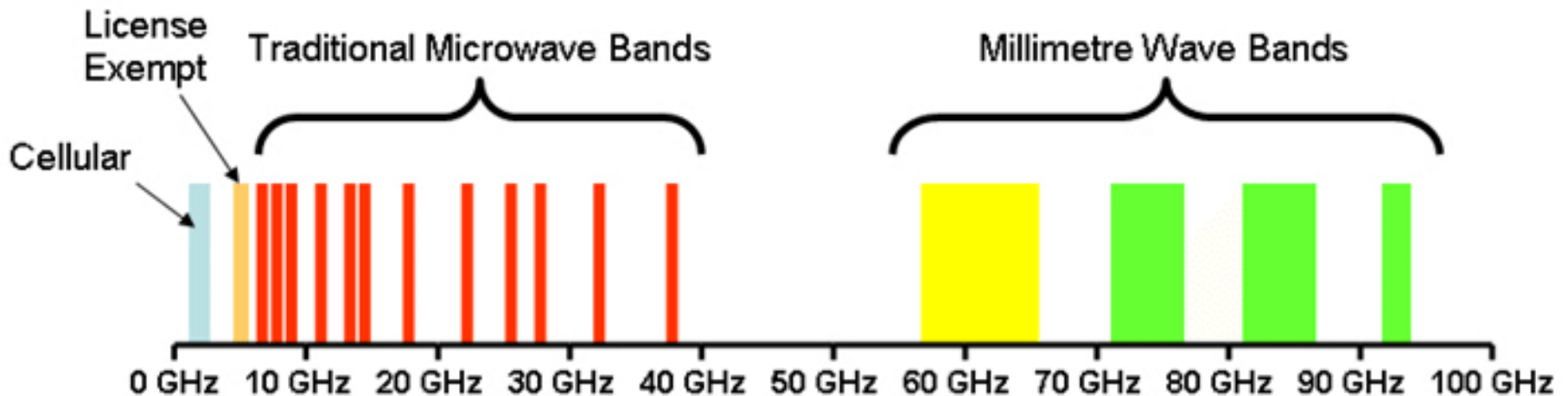
Millimeter-Wave (mmWave)

► mmWave



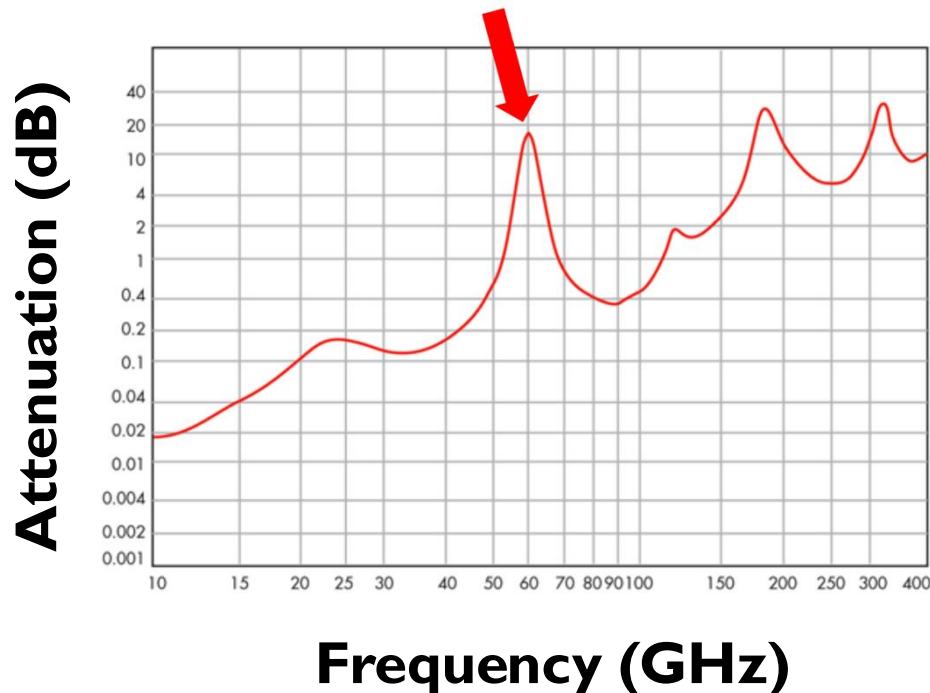
Millimeter-Wave (mmWave)

- ▶ mmWave
 - ▶ GHz of largely unlicensed spectrum available
 - ▶ vs the crowded sub-6 GHz bands



Millimeter-Wave (mmWave)

- ▶ **mmWave**
 - ▶ Millimeter waves suffer from large attenuation
 - ▶ 60 GHz sits at the oxygen absorption peak



mmWave Propagation Challenges

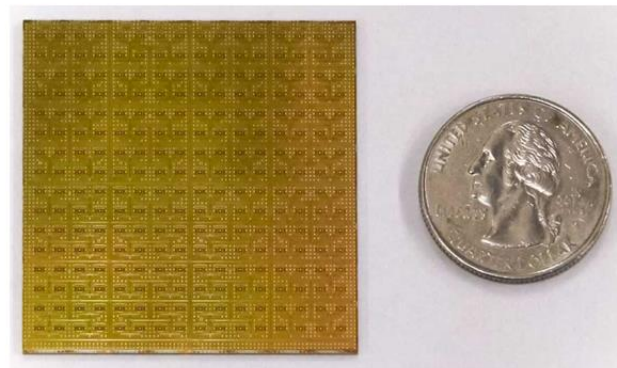
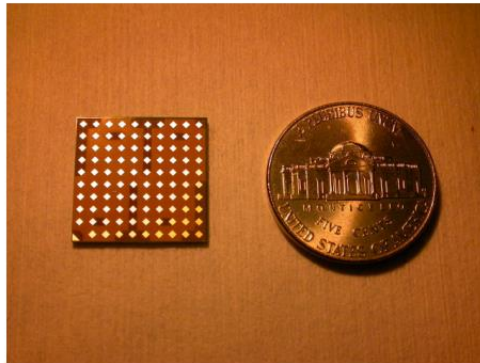
- ▶ Free-space loss $\propto \text{frequency}^2$
 - ▶ 60 GHz has $\sim 625\times$ the path loss of 2.4 GHz at the same distance
- ▶ Requires line of sight
 - ▶ A hand, a body, a wall, or heavy rain
- ▶ mmWave is essentially unusable without directional, high-gain antennas



Millimeter-Wave (mmWave)

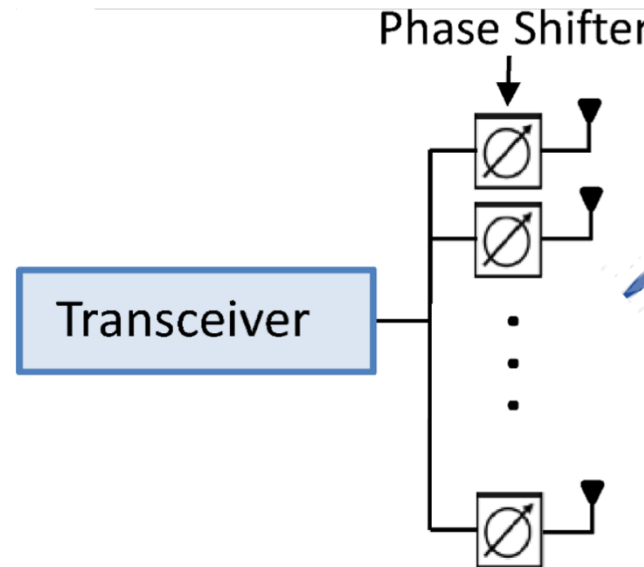
- ▶ mmWave

- ▶ radios use phased antenna arrays to focus the power along one direction



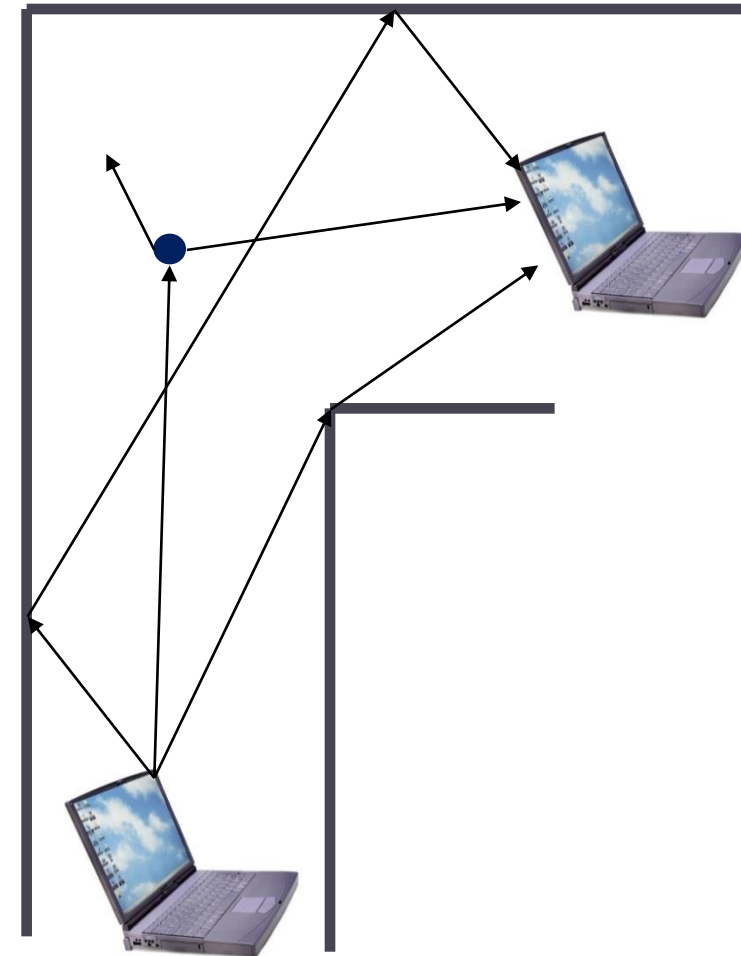
Millimeter-Wave (mmWave)

- ▶ **Small wavelength**
 - ▶ Thousands of antennas fit in a small phased array
 - ▶ Extremely narrow, pencil-thin beams
- ▶ **Narrow beams create a new problem**
 - ▶ The AP and client must point directly at each other



Non LOS transmissions

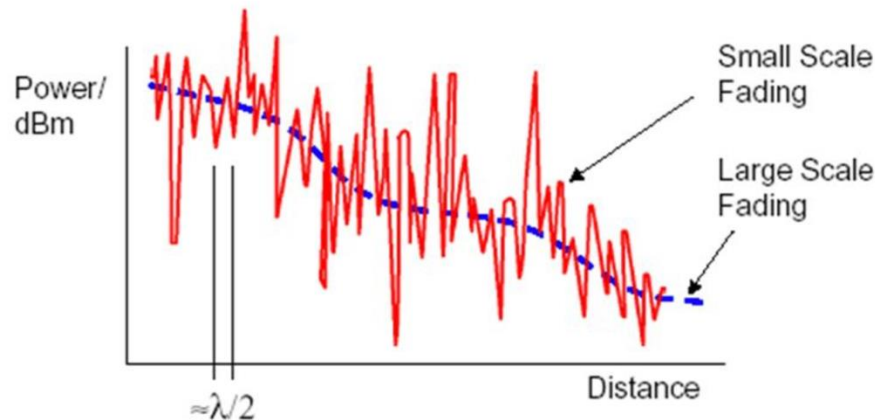
- ▶ Signal can reach receiver indirectly
- ▶ Reflection
 - ▶ Signal is reflected from a large (relative to wavelength) object
- ▶ Diffraction
 - ▶ Signal is scattered by the edge of a large object – “bends”
- ▶ Scattering
 - ▶ Signal is scattered by an object that is small relative to the wavelength



Can you still hear me ..

► Fading

- Time variation of the received signal strength
- Changes in the transmission medium or paths
 - Rain, moving objects, moving sender/receiver, ...



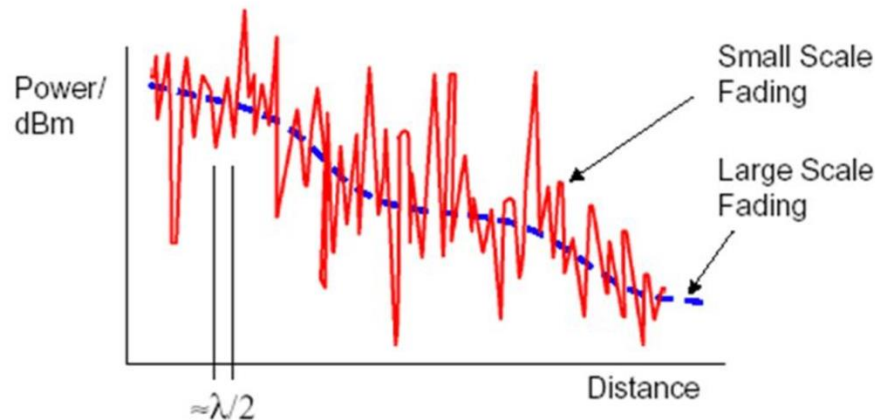
Can you still hear me ..

► Fast Fading

- Changes in distance of about half a wavelength
 - Big fluctuations in the instantaneous power

► Slow Fading

- Changes in larger distances
 - Change in the average power levels



Fading Channel Models

- ▶ Statistical distribution that captures the properties fading channels due to mobility
 - ▶ Fast versus slow
 - ▶ Flat versus selective
- ▶ Models depend on the physical environment
 - ▶ Obstacles in the environment
 - ▶ Movement in the environment
 - ▶ Mobility of devices
- ▶ Useful for evaluation of wireless technologies
 - ▶ How well does radio deal with channel impairments
 - ▶ Network simulators tend to use simpler channel models

Fading Channel Models

- ▶ Additive white Gaussian noise
 - ▶ Not representative of wireless channels
- ▶ Ricean distribution
 - ▶ LOS path plus indirect paths
 - ▶ Open space or small cells
 - ▶ K = power in dominant path/power in scattered paths
 - ▶ Speed of movement and min-speed
- ▶ Rayleigh distribution
 - ▶ Multiple indirect paths but no dominating or direct LOS path
 - ▶ Lots of scattering, e.g. urban environment, in buildings
 - ▶ Sum of uncorrelated Gaussian variables
 - ▶ $K = 0$ is Rayleigh fading
- ▶ Many others!



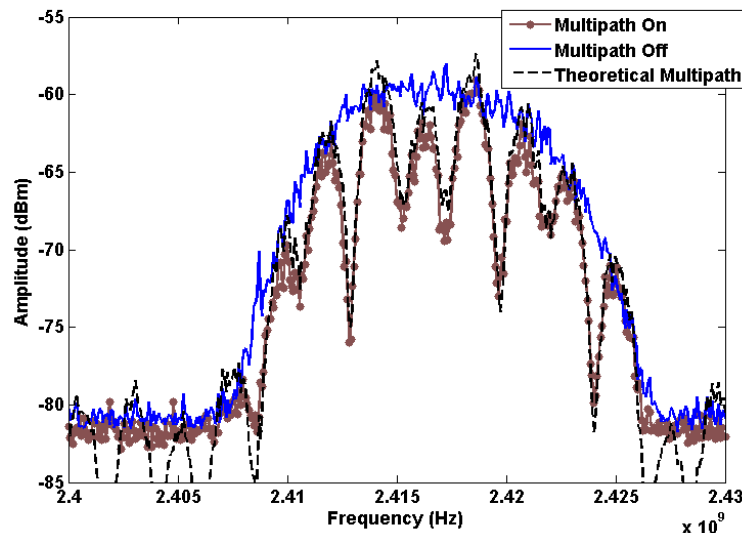
Selective versus Non-selective Fading

▶ Non-selective (flat) fading

- ▶ Affects all frequency components in the signal equally
 - ▶ e.g. when only line of sight

▶ Selective fading

- ▶ Frequency components experience different degrees of fading
 - ▶ Due to multipath
 - ▶ Region of interest is the spectrum used by the channel



Power Budget



$$R_{\text{power}} \text{ (dBm)} = T_{\text{power}} \text{ (dBm)} + \text{Gains (dB)} - \text{Losses (dB)}$$

- ▶ Receiver needs a certain SINR to be able to decode the signal
 - ▶ Required SINR depends on coding and modulation schemes, i.e. the transmit rate
- ▶ Factors reducing power budget:
 - ▶ Noise, attenuation (multiple sources), fading, ..
- ▶ Factors improving power budget:
 - ▶ Antenna gain, transmit power

Channel Reciprocity Theorem

- ▶ If the role of the transmitter and the receiver are interchanged, the instantaneous signal transfer function between the two remains unchanged
 - ▶ Informally, the properties of the channel between two antennas is the same in both directions
 - ▶ i.e. the channel is symmetric
- ▶ Channel in this case includes all the signal propagation effects and the antennas

Reciprocity Does not Apply to Wireless “Links”

- ▶ “Link” corresponds to the packet level connection between the devices
 - ▶ In other words, the throughput you get in the two directions can be different
- ▶ The reason is that many factors that affect throughput may be different on the two devices
 - ▶ Transmit power and receiver threshold
 - ▶ Quality of the transmitter and receiver (radio)
 - ▶ Observed noise
 - ▶ Interference
 - ▶ Different antennas may be used

