CS/ECE 439: Wireless Networking

Physical Layer – Antennas and Propagation

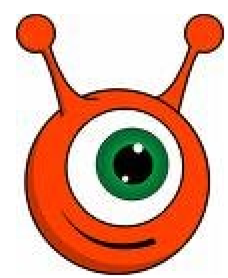
Fall 2023

GRAINGER ENGINEERING

COMPUTER SCIENCE

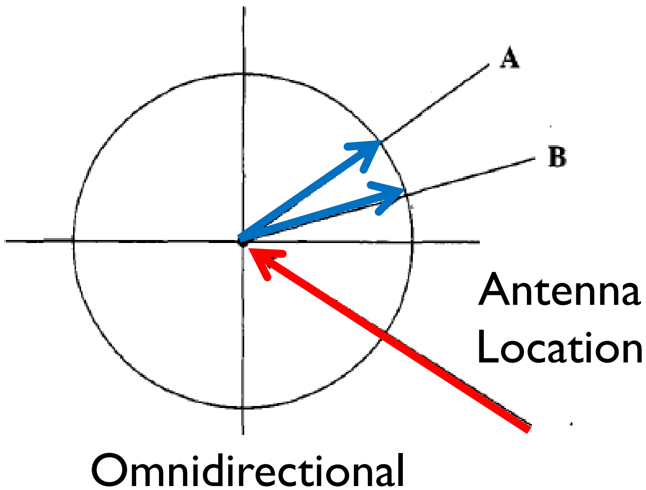
What is an Antenna?

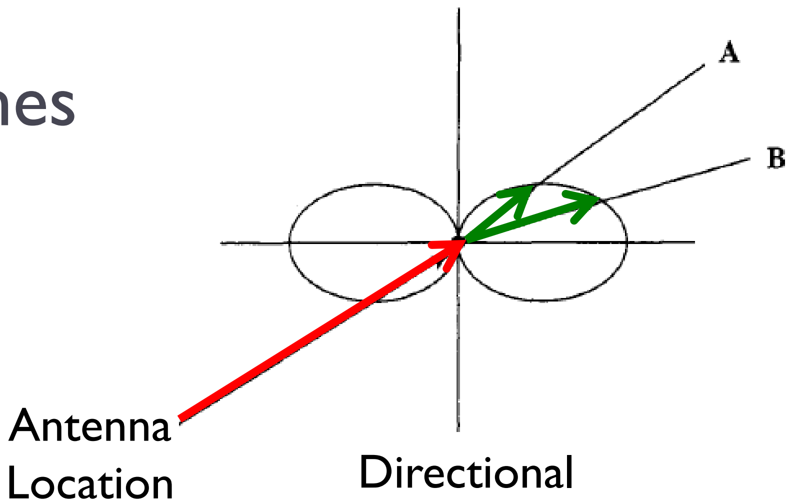
- Conductor that carries an electrical signal
  - Transmission
    - Radiates RF signal (electromagnetic energy) into space
  - Reception
    - Collects electromagnetic energy from space
  - The RF signal "is a copy of" the electrical signal in the conductor
- Two-way communication
  - Same antenna used 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

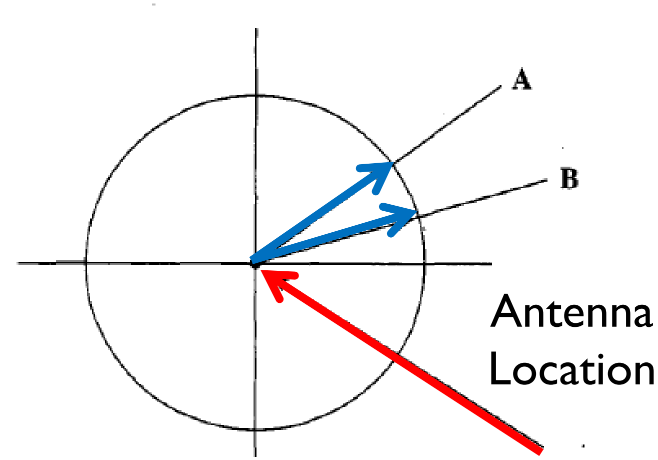
- Radiation pattern
  - Graphical representation of radiation properties of an antenna
  - Depicted as two-dimensional cross section
  - Relative distance determines relative power



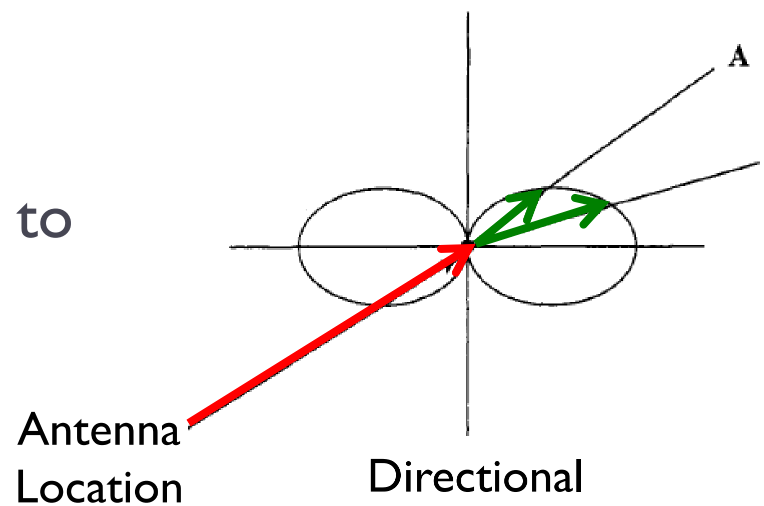


Radiation Patterns

- 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



Omnidirectional

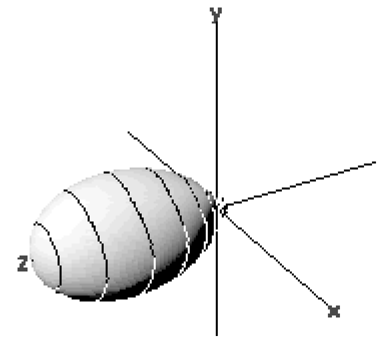


Directional

Antenna Types: Dipoles

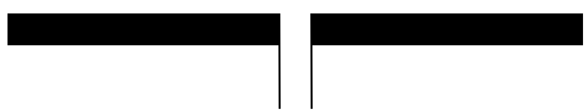
- Simplest
  - Quarter wave vertical (Marconi)
    - Automobile and portable radios
  - Half-wave dipole (Hertz)
    - Very simple and very common
    - Elements are quarter wavelength of frequency that is transmitted most efficiently
  - Donut shape
- Many other designs

Directed antenna



Simple dipole

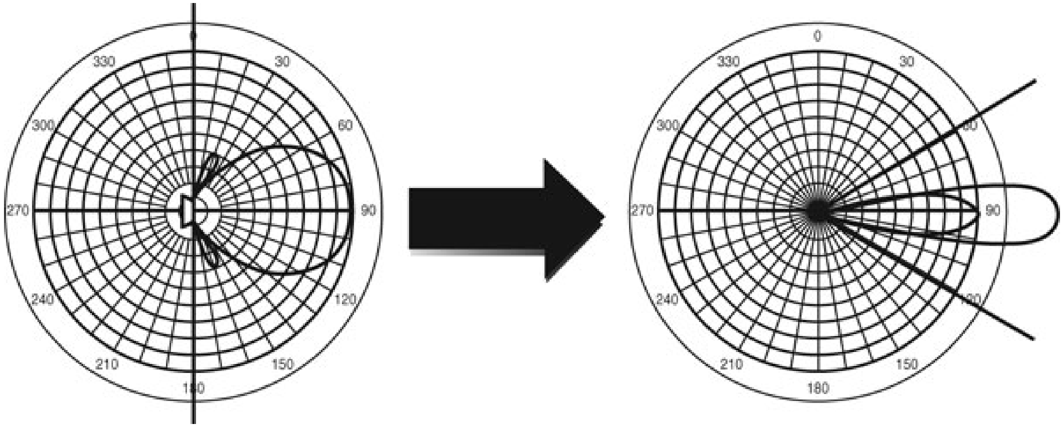
quarter wave
vertical antenna



half-wave dipole

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!



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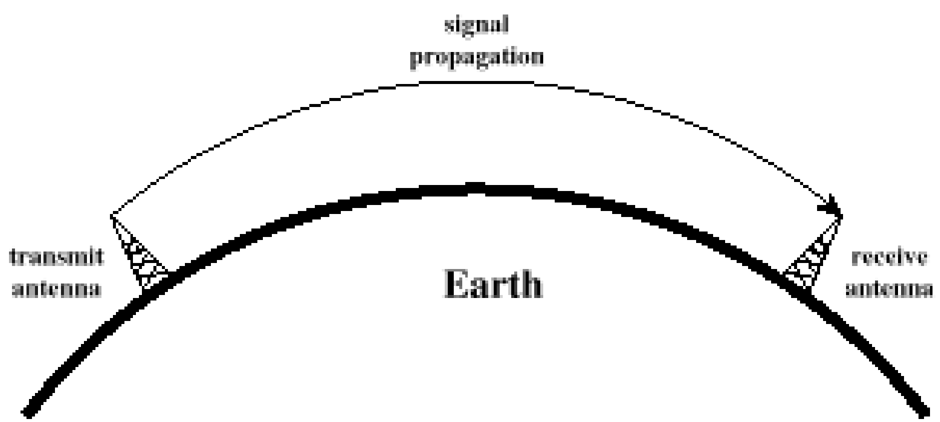
- Effective area
  - Related to physical size and shape of antenna

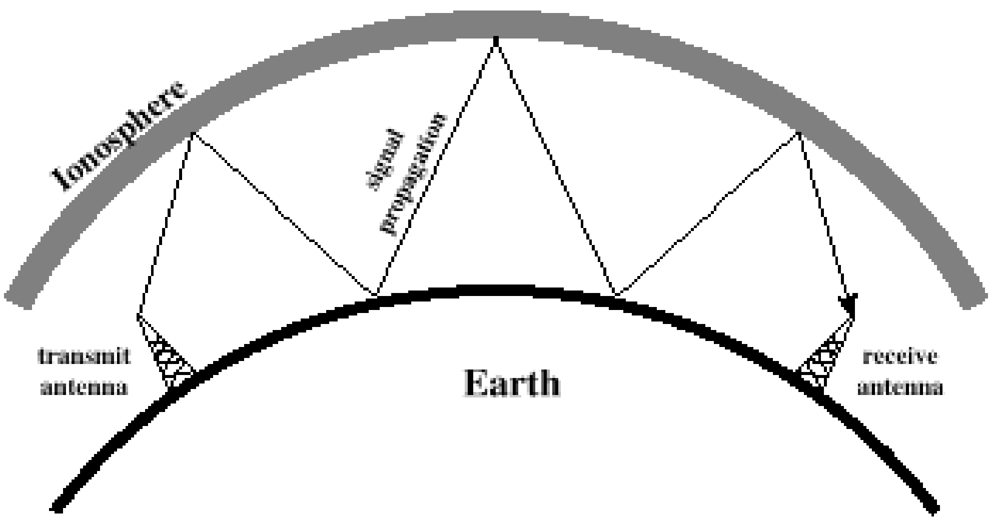
Propagation Modes

- 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



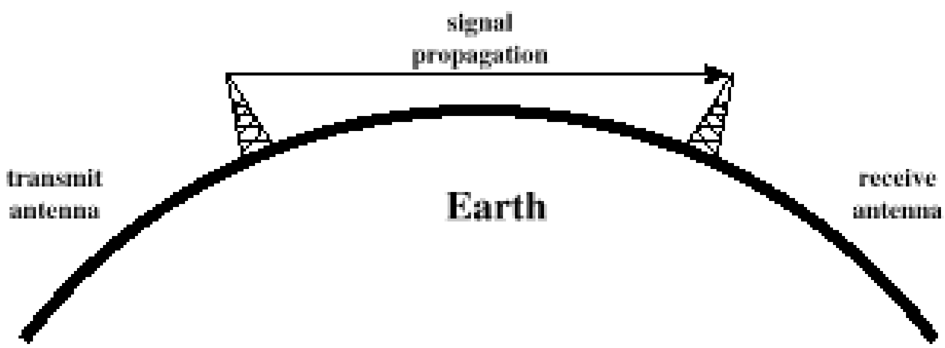
Propagation Modes

- 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 Degrades RF Signals

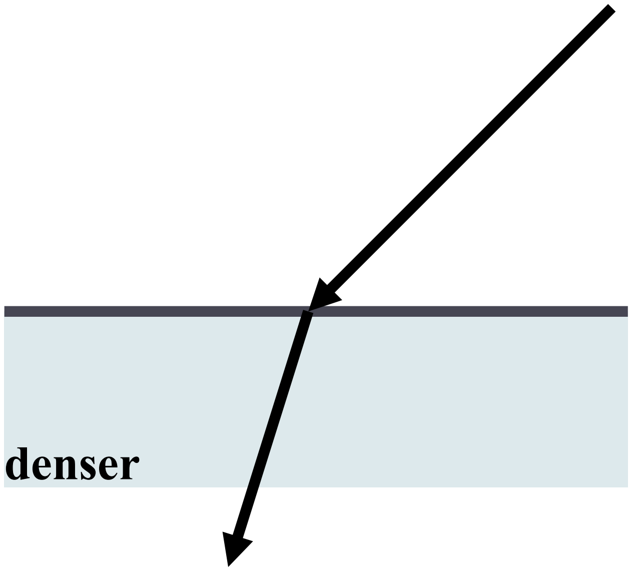
- Attenuation in free space
  - Signal gets weaker as it travels over longer distances
    - Radio signal spreads out – free space loss
    - Refraction and absorption in the atmosphere
- Obstacles can weaken signal through absorption or reflection
  - Part of the signal is redirected

Propagation Degrades RF Signals

- Multi-path effects
  - Multiple copies of the signal interfere with each other
  - Similar to an unplanned directional antenna
- Mobility
  - Moving receiver causes another form of self interference
  - Node moves ½ wavelength -> big change in signal strength

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.



LOS Wireless Transmission

- Attenuation and attenuation distortion
- Free space loss
- Noise
- Atmospheric absorption
- Multipath
- Refraction
- Thermal noise

Attenuation

- Strength of signal falls off with distance over transmission medium
- 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

$\Rightarrow$ Power control, amplifiers

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

Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors
  - Attenuation is greater at higher frequencies, causing distortion
    - Attenuation distortion

  $\Rightarrow$ Equalize attenuation
    - Amplify high frequencies more

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

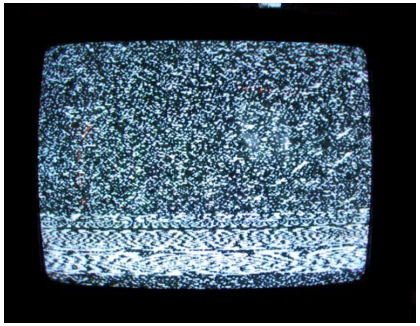
- Log-distance path loss model
  - Captures free space attenuation plus additional absorption by of energy by obstacles:

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

  - L_0 is the loss at distance d0
  - 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

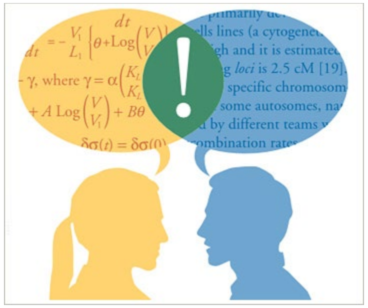
Noise Sources



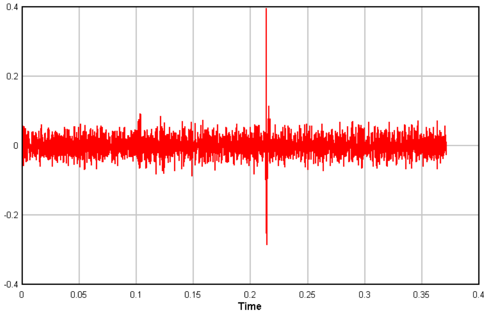
- Noise = unwanted signals!
- Thermal noise
  - Agitation of the electrons
    - Function of temperature
    - Uniform across all frequencies (white noise)
    - Affects electronic devices and transmission media
    - We're stuck with it!
      - Determines an upper bound on performance

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!

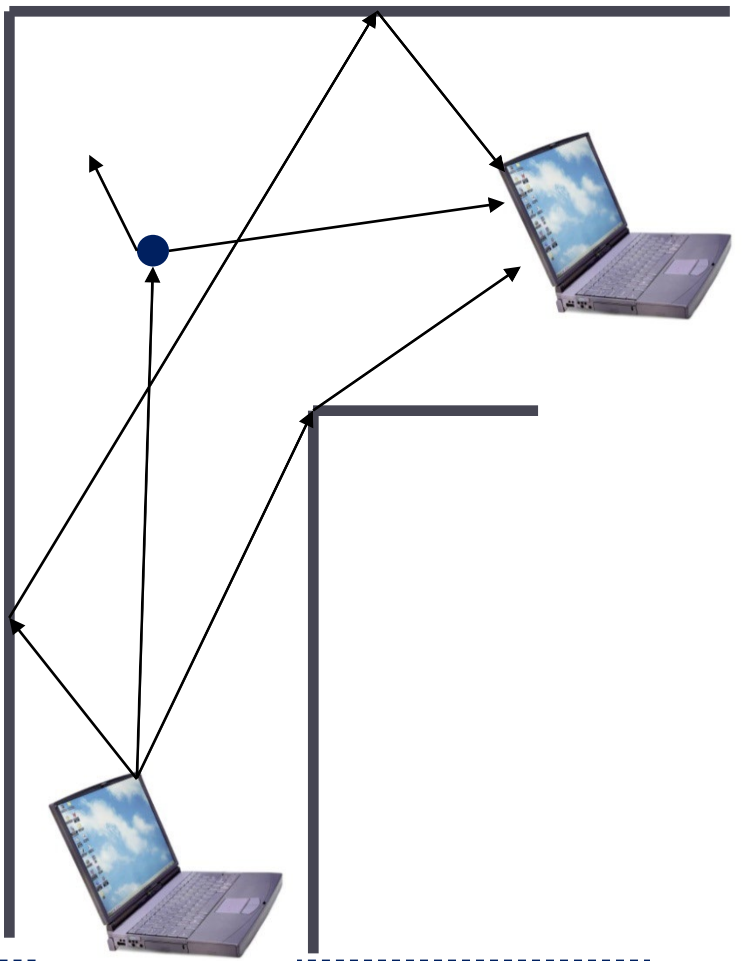


Other LOS Factors

- 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, user shorter paths or lower frequencies!
  - Obviously objects also absorb energy

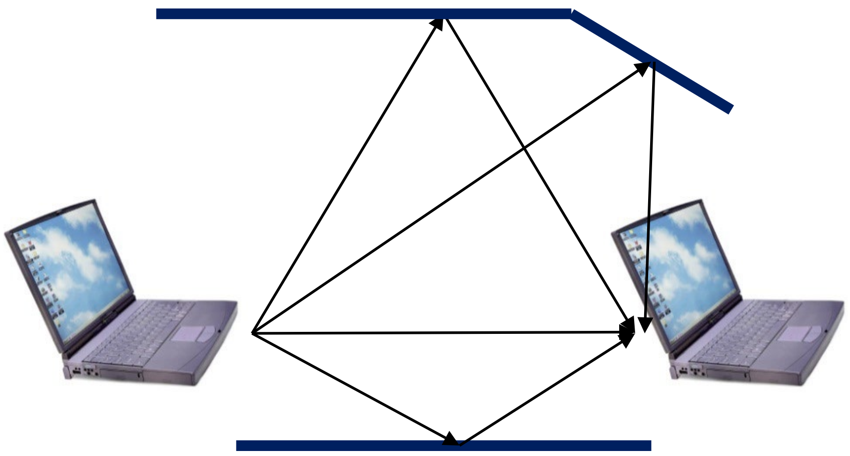
Non LOS transmissions

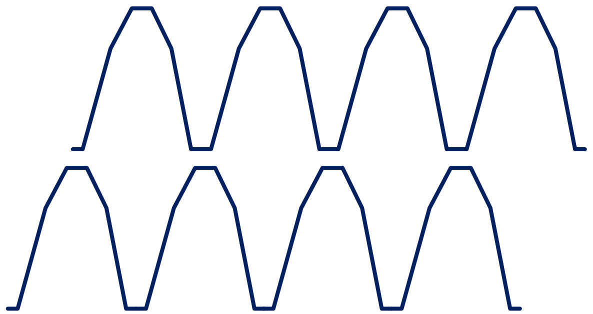
- Signal can reach receiver indirectly
  - Reflection
    - Signal is reflected from a large (relative to wavelength) object
  - Diffraction
    - Signal is scattered by the edge of a large object – "bends"
  - Scattering
    - Signal is scattered by an object that is small relative to the wavelength



Multipath Effect

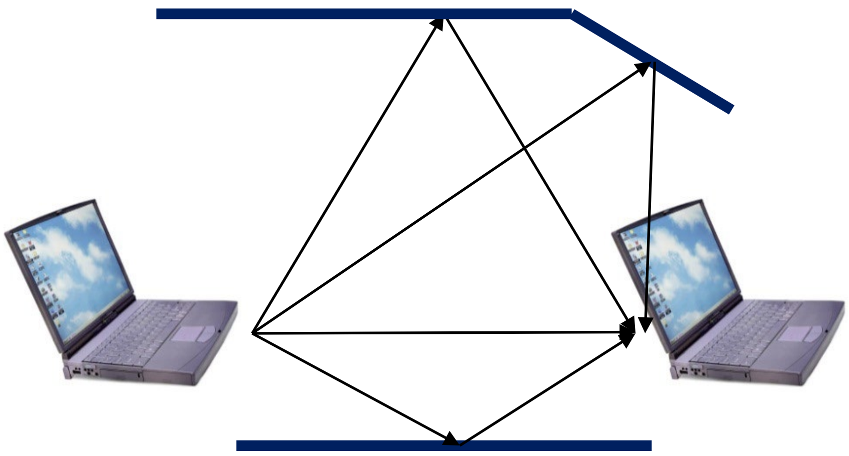
- Receiver receives multiple copies of the signal
  - Each copy follows a different path
  - Length of path determines phase-shift
- Copies can either strengthen or weaken each other
  - Depends on whether they are in our out of phase

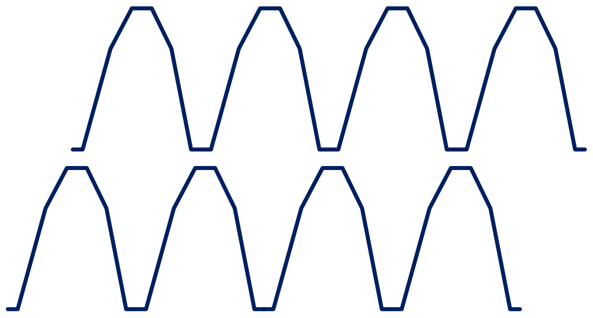




Multipath Effect

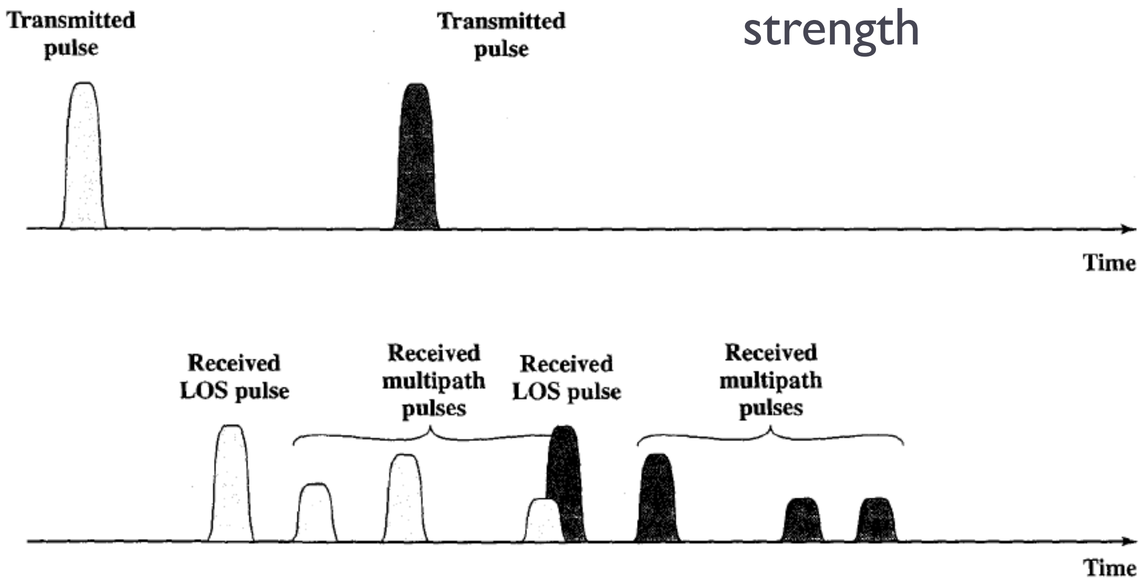
- Changes of half a wavelength affect the outcome
  - Challenging for short wavelengths
    - 2.4 Ghz → 12 cm
    - 900 MHz → ~1 ft
- Small adjustments in location or orientation of the wireless devices can result in big changes in signal strength





Inter-Symbol Interference

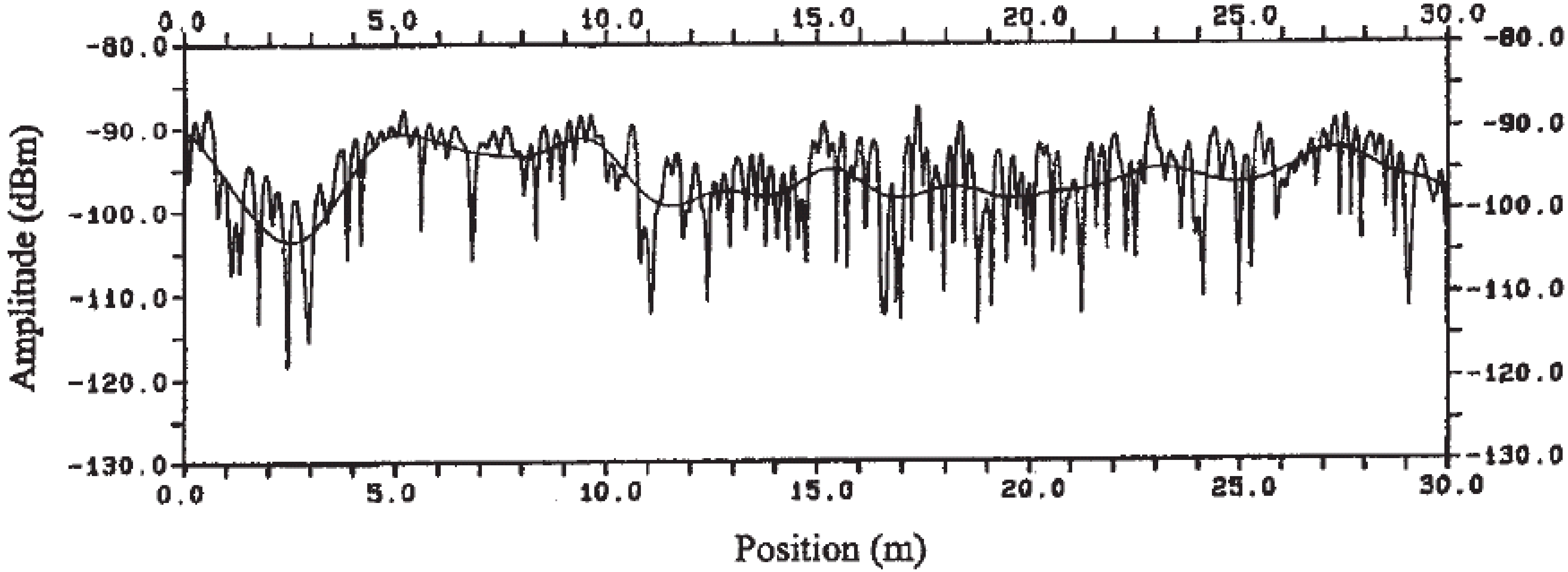
- Larger difference in path length can cause inter-symbol interference (ISI)
  - Different from effect of carrier phase differences
- Delays on the order of a symbol time result in overlap of the symbols
  - Makes it very hard for the receiver to decode
  - Corruption issue – not signal strength



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, …
- 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 - Example



- Frequency of 910 MHz or wavelength of about 33 cm

Fading Channel Models

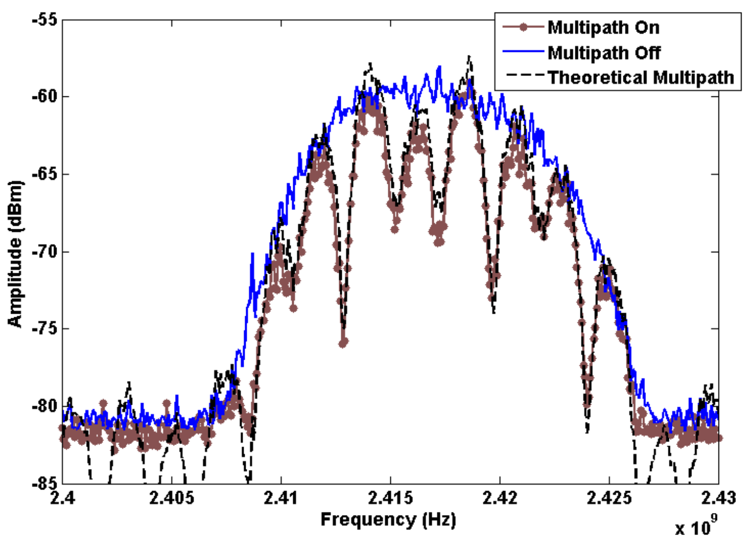
- Statistical distribution that captures the properties fading channels due to mobility
  - Fast versus slow
  - Flat versus selective
- Models depend on the physical environment
  - Obstacles in the environment
  - Movement in the environment
  - Mobility of devices
- Useful for evaluation of wireless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

Fading Channel Models

- Additive white Gaussian nose
  - 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 Raleigh 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



Doppler Effect

- Movement by the transmitter, receiver, or objects in the environment can also create a doppler shift:

$$f_m = (v / c) * f$$

- Results in distortion of signal
  - Shift may be larger on some paths than on others
  - Shift is also frequency dependent (minor)
- Effect only an issue at higher speeds:
  - Speed of light: $3 * 10^8$ m/s
  - Speed of car: 10^5 m/h = 27.8 m/s
  - Shift at 2.4 GHz is 222 Hz

Power Budget

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

- 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 in 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