Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
  - How do antennas work
  - Propagation properties of RF signals
  - Modeling the channel
- Modulation
- Diversity and coding
- OFDM

Free Space Loss

\[
\text{Loss} = \frac{P_t}{P_r} = \frac{(4\pi d)^2}{G_t G_r \lambda^2} = \frac{(4\pi f d)^2}{G_t G_r c^2}
\]

- Loss increases quickly with distance \((d^2)\).
- Need to consider the gain of the antennas at transmitter and receiver.
- Loss depends on frequency: higher loss with higher frequency.
  - Can cause distortion of signal for wide-band signals
  - Impacts transmission range in different spectrum bands

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.
  - Reflection redirects part of the signal
- Multi-path effects: multiple copies of the signal interfere with each other at the receiver
  - Similar to an unplanned directional antenna
- Mobility: moving the radios or other objects changes how signal copies add up
  - Node moves \(\frac{1}{2}\) wavelength \(\rightarrow\) big change in signal strength
Log Distance Path Loss Model

- Log-distance path loss model captures free space attenuation plus additional absorption by energy by obstacles:
  \[ \text{Loss}_{\text{db}} = L_0 + 10 n \log_{10}(d/d_0) \]
- Where \( L_0 \) is the loss at distance \( d_0 \) and \( n \) is the path loss distance component
- Value of \( n \) depends on the environment:
  - 2 is free space model
  - 2.2 office with soft partitions
  - 3 office with hard partitions
  - Higher if more and thicker obstacles

Obstacles and Atmosphere

- Objects absorb energy as the signal passes through them
  - Degree of absorption depends strongly on the material
  - Paper versus brick versus metal
- Absorption of energy in the atmosphere.
  - Very serious at specific frequencies, e.g., water vapor (22 GHz) and oxygen (60 GHz)
- Refraction refraction in the atmosphere
  - Pockets of air can have different properties, e.g., humidity, temperature, ...
  - Redirects the signal in unpredictable ways
  - Can reduce energy and increase path length

Multipath Effect

- Receiver receives multiple copies of the signal, each following a different path
- Copies can either strengthen or weaken each other
  - Depends on whether they are in or out of phase
- Changes of half a wavelength affect the outcome
  - Short wavelengths, e.g. 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

Example: 900 MHz

Height of bar is probability of reception

Data courtesy Rob Poor, Ember Corp.
Channel Sounding

- Measure response of channel to an impulse
  - Signals from multiple paths is spread in time in time
  - Many frequencies
- Typically interested in response across frequency range
  - Delay spread, delay spread and impact on phase

Fading in the Mobile Environment

- Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.
  - Rain, moving obstacles, moving sender/receiver, ...
- Slow: changes the paths that make up the received signal – results in a change in the average power levels around which the fast fading takes place
  - Mobility affects path length and the nature of obstacles
- Fast: changes in distance of about half a wavelength – results in big fluctuations in the instantaneous power

Fading - Example

- Frequency of 910 MHz or wavelength of about 33 cm

Frequency Selective versus Non-selective Fading

- Non-selective (flat) fading: fading affects all frequency components in the signal equally
  - There is only a single path, or a strongly dominating path, e.g., LOS
- Selective fading: frequency components experience different degrees of fading
  - Multiple paths with path lengths that change independently
  - Region of interest is the spectrum used by the channel
Some Intuition for Selective Fading

- Assume three paths between a transmitter and receiver
  - The outcome is determined by the differences in path length
    » But expressed in wavelengths → outcome depends on frequency
  - As transmitter, receivers or obstacles move, the path length differences change, i.e., there is fading
    » But changes depend on wavelength, i.e. fading is frequency selective
- Significant concern for wide-band channels

Example Fading Channel Models

- Ricean distribution: LOS path plus indirect paths
  » Open space or small cells
  » $K = \frac{\text{power in dominant path}}{\text{power in scattered paths}}$
  » Speed of movement and min-speed
- Raleigh 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
- Nakagami can be viewed as generalization: sum of independent Raleigh paths
  » Clusters or reflectors resulting paths with Raleigh fading, but with different path lengths
- Many others!

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
  » Significant concern for high bit rates (short symbol times)

How Bad is the Problem?

- ISI depends on the symbol time
  » Time to send a single or multi-bit symbol
  » i.e., property of the baseband signal
- Fast fading depends on wavelength of carrier wave
  » Distances are much shorter!
Doppler Effect

- Movement by the transmitter, receiver, or objects in the environment can also create a doppler shift:
  \[ f_m = \frac{v}{c} \times f \]
- 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: \( 3 \times 10^8 \) m/s
  » Speed of car: \( 10^5 \) m/h = 27.8 m/s
  » Shift at 2.4 GHz is 222 Hz – increases with frequency
  » Impact is that signal “spreads” in frequency domain

Noise Sources

- Thermal noise: caused by agitation of the electrons
  » Function of temperature
  » Affects electronic devices and transmission media
- Intermodulation noise: result of mixing signals
  » Appears at \( f_1 \pm f_2 \) and \( f_1 - f_2 \) (when is this useful?)
- Cross talk: picking up other signals
  » E.g. from other source-destination pairs
- 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

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Power Budget

- 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 gains, 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 (spatial diversity - see later)

Summary

- The wireless signal can be several degraded as it travels to the receiver:
- Attenuation increases with the distance to the receiver and as a result of obstacles
- Reflections create multi-path effects that cause distortion and inter-symbol interference
- Mobility causes slow and fast fading
  - Fast fading is often frequency selective
- For higher speeds the Doppler effect can be a concern