CS 498wn: 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 Diagram](image)
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**

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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 $\frac{1}{2}$ wavelength $\rightarrow$ big change in signal strength
Refraction

- Speed of EM signals depends on the density of the material
  - Vacuum: $3 \times 10^8$ 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
  - 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
  ⇒ Equalize attenuation
    - Amplify high frequencies more
Free Space Loss

- Loss increases quickly with distance \((d^2)\)
  - Ideal:
    \[
    \text{Loss} = \frac{P_t}{P_r} = \frac{(4\pi d)^2}{(G_r G_t \lambda^2)} = \frac{(4\pi f d)^2}{(G_r G_t c^2)}
    \]
  - 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 obstacles:
    \[ \text{Loss}_{\text{db}} = L_0 + 10 \times n \log_{10}(d/d_0) \]
  - \( L_0 \) 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
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
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 noise
  - Not representative of wireless channels
- Ricean distribution
  - LOS path plus indirect paths
    - Open space or small cells
    - \( K = \text{power in dominant path/power in scattered paths} \)
    - 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:
  \[ f_m = \left( \frac{v}{c} \right) \cdot f \]

- 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: \( 3 \cdot 10^8 \text{ m/s} \)
  - Speed of car: \( 10^5 \text{ m/h} = 27.8 \text{ m/s} \)
  - Shift at 2.4 GHz is 222 Hz
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 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