Wireless Networks

Lecture 5: Physical Layer Channel Properties

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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

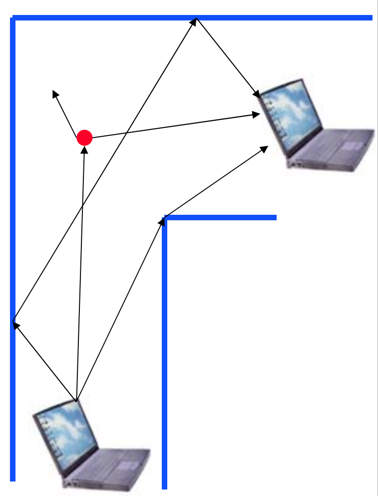
Typical Bad News Good News Story

Propagation Modes

- **Line-of-sight (LOS) propagation.**
  - » **Most common form of propagation**
  - » **Happens above ~ 30 MHz**
  - » **Subject to many forms of degradation (next set of slides)**
- **Obstacles can redirect the signal and create multiple copies that all reach the receiver**
  - » **Creates multi-path effects**
- **Refraction changes direction of the signal due to changes in density**
  - » **If the change in density is gradual, the signal bends!**

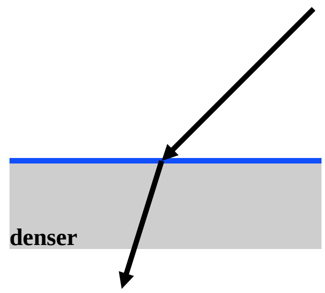
Impact of Obstacles

- **Besides line of sight, signal can reach receiver in three "indirect" ways.**
- **Reflection: signal is reflected from a large 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.**



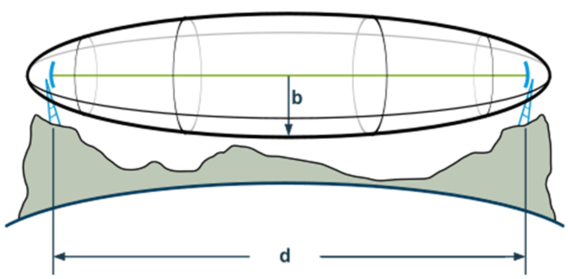
Refraction

- Speed of EM signals depends on the density of the material
  - » Vacuum: 3 x 10^8 m/sec
  - » Denser: slower
- Density is captured by refractive index
- Explains "bending" of signals in some environments
  - » E.g. sky wave propagation: Signal "bounces" off the ionosphere back to earth – can go very long distances
  - » But also local, small scale differences in the air density, temperature, etc.



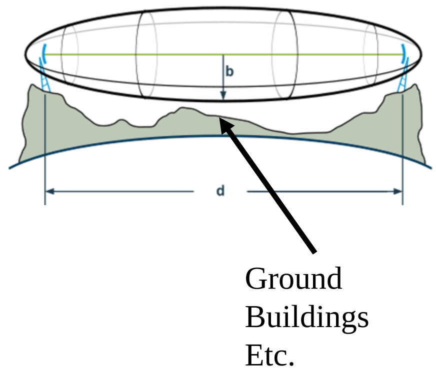
Fresnel Zones

- Sequence of ellipsoids centered around the LOS path between a transmitter and receiver
- The zones identify areas in which obstacles will have different impact on the signal propagation
  - » Capture the constructive and destructive interference due to multipath caused by obstacles

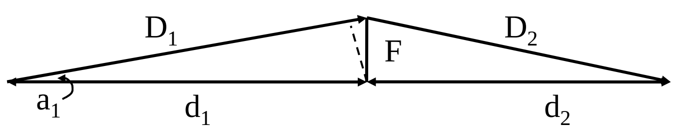


Fresnel Zones

- Zones create different phase differences between paths
  - » First zone: 0-90
  - » Second zone: 90-270
  - » Third zone: 270-450
  - » Etc.
- Odd zones create constructive interference, even zones destructive
- Also want clear path in most of the first Fresnel zone, e.g. 60%
- The radius F_n of the nth Fresnel zone depends on the distances d_1 and d_2 to the transmitter and receiver and the wavelength

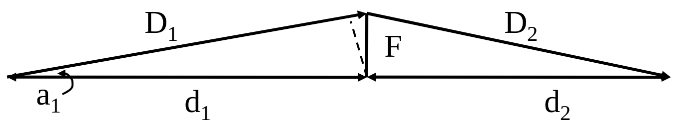


Sketch of Calculation: Difference in Path Length



- Difference in path length (a_1 is small)
  - » $D_1 - d_1 \approx F * \sin a_1$
- But for small a_1 we also have
  - » $\sin a_1 = \tan a_1 = F / d_1$
- So $D_1 - d_1 = F^2 / d_1$

Sketch of Calculation Fresnel Radios



- Given $D_1 - d_1 = F^2 / d_1$
- and $(D_1 + D_2) - (d_1 + d_1) = \lambda * n$
- $(D_1 - d_1) + (D_2 - d_2) = F^2 / d_1 + F^2 / d_2$
- or

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

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- Antennas and signal propagation
  - » How do antennas work
  - » Propagation properties of RF signals (the really sad part)
  - » Modeling the channel
- Modulation
- Diversity and coding
- OFDM

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 ½ wavelength -> big change in signal strength

Free Space Loss

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

- 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

Other LOS Factors

- Objects absorbe energy was the signal passes through them
  - » Degree of absorption depends strongly 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)
  - » Obviously objects also absorb energy

Log Distance Path Loss Model

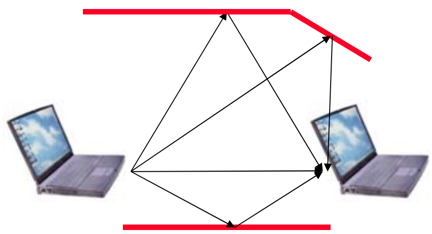
- Log-distance path los model captures free space attenuation plus additional absorption by of energy by obstacles:

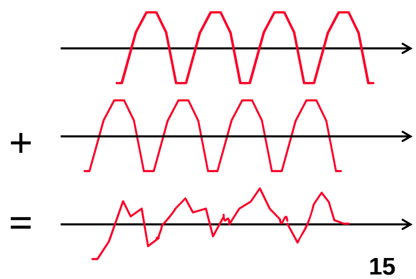
$$Loss_{db} = L_0 + 10\ n\ \log_{10}(d/d_0)$$

- 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

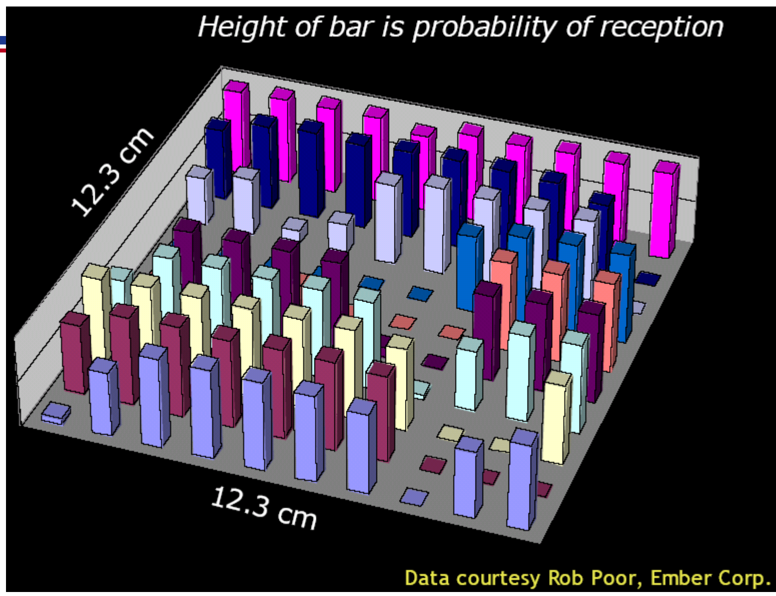
Multipath Effect

- 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 our 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





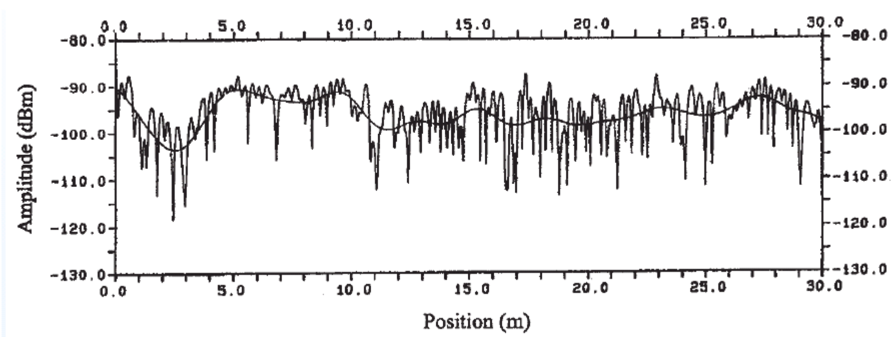
Example: 900 MHz



Fading in the Mobile Environment

- Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.
  - » Rain, moving objects, moving sender/receiver, …
- Fast: changes in distance of about half a wavelength – results in big fluctuations in the instantaneous power
- 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

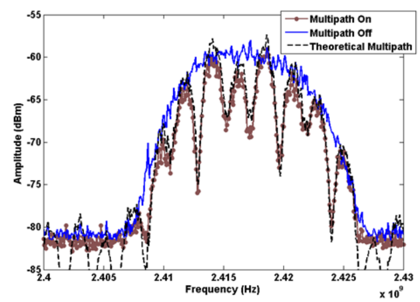
Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

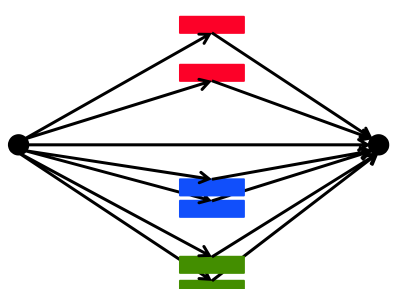
Frequency Selective versus Non-selective Fading

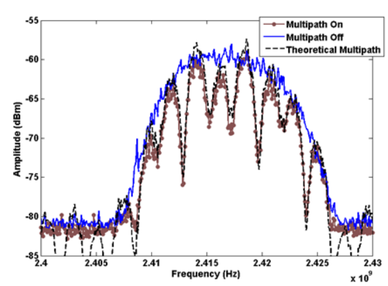
- Non-selective (flat) fading: fading affects all frequency components in the signal equally
  - » There is only a single path, or a strongly dominating path, e.g., LOS
- Selective fading: frequency components experience different degrees of fading
  - » Multiple paths with path lengths that change independently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



Some Intuition for Selective Fading

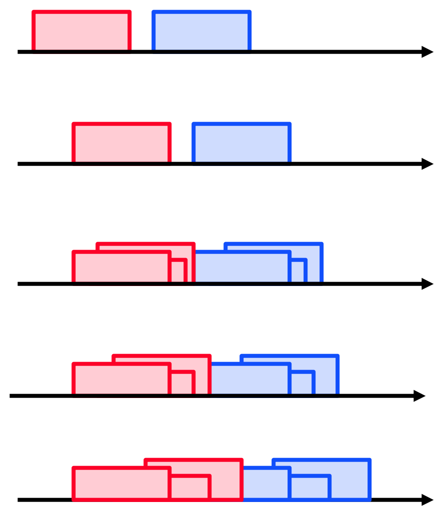
- Assume three paths between a transmitter and receiver
- The outcome is determined by the differences in path length
  - » But expressed in wavelengths → outcome depends on frequency
- As transmitter, receivers or obstacles move, the path length differences change, i.e., there is fading
  - » But changes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





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



How Bad is the Problem?

- Assume binary encoding
  - » Times will increase with more complex symbol
  - » More complex encoding also requires higher SINR
- Some bit times and distances:

Rate Mbs	Time microsec	Distance meter
1	1	300
5	0.2	60
10	0.1	30
50	0.02	6

- Distances are much longer than for fast fading!
  - » Wavelength at 2.4 GHz: 14 cm

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 – 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 $f_1 + f_2$ 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

Fairly Predictable
➢Can be planned for or avoided

↓

Noise Floor

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