18-452/18-750
Wireless Networks and Applications
Lecture 5: Physical Layer
Signal Propagation and Modulation

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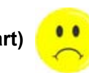
http://www.cs.cmu.edu/~prs/wirelessS17/

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- 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

Log Distance Path Loss Model

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

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

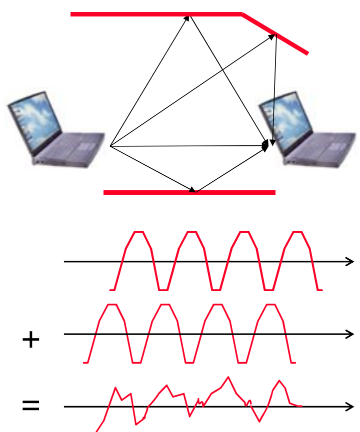
- Where L_0 is the loss at distance d_0 and n is the path loss distance component
- Value of n depends on the environment:
  - » 2 is free space model
  - » 2.2 office with soft partitions
  - » 3 office with hard partitions
  - » Higher if more and thicker obstacles

Obstacles and Atmosphere

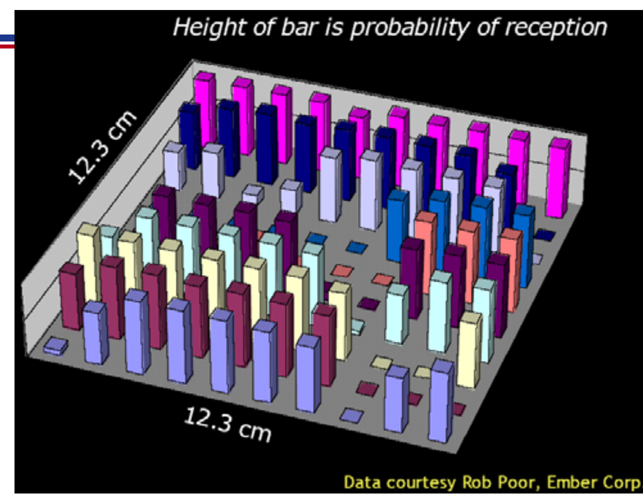
- Objects absorb energy as the signal passes through them
  - » Degree of absorption depends strongly the material
  - » Paper versus brick versus metal
- Absorption of energy in the atmosphere.
  - » Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)
- Refraction refraction 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 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



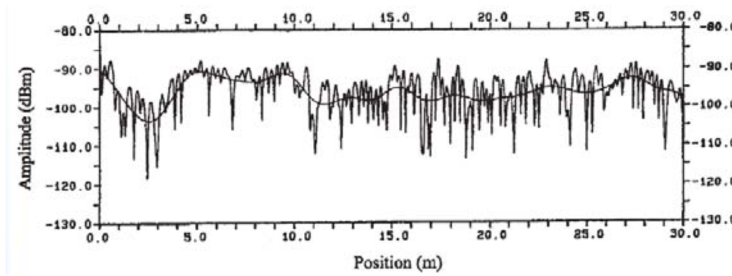
Example: 900 MHz



Fading in the Mobile Environment

- Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.
  - » Rain, moving 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

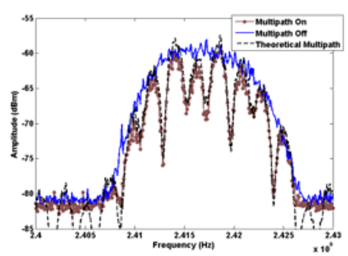
Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

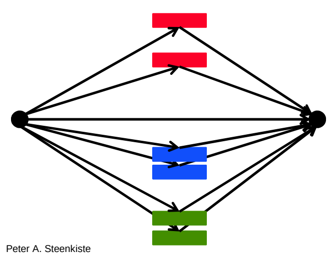
Frequency Selective versus Non-selective Fading

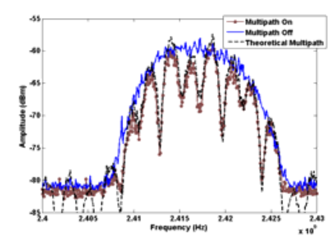
- Non-selective (flat) fading: fading affects all frequency components in the signal equally
  - » There is only a single path, or a strongly dominating path, e.g., LOS
- Selective fading: frequency components experience different degrees of fading
  - » Multiple paths with path lengths that change independently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





Multi-Path and Fading Videos

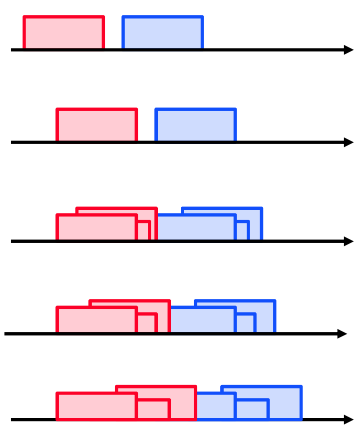
- Single path
- Multi-path
- Multi-path + mobility

Example Fading Channel Models

- 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
- 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?

- 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

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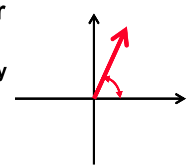
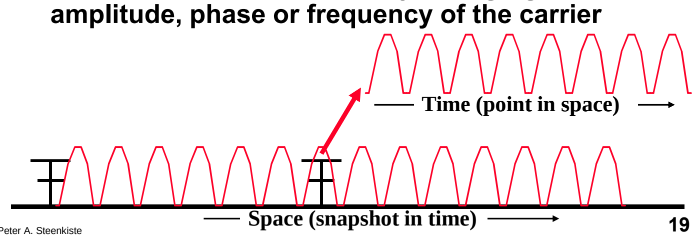
Typical Bad News Good News Story

Remember: Representing a Channel

- Communication is based on the sender transmitting the carrier signal
  - » A sine wave with an amplitude, phase, frequency
  - » A complex value at a certain point in space and time captures the amplitude and phase
  - » It changes with a frequency f



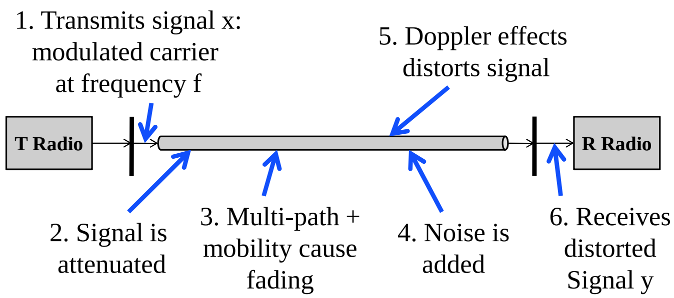
- Sender sends information by changing the amplitude, phase or frequency of the carrier



Channel State

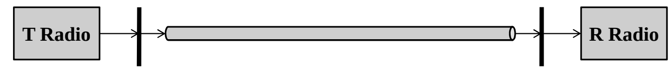
- The channel state c is a complex number that captures attenuation, multi-path, … effects
  - » Represents phase and amplitude
- c changes over time, i.e., fading
  - » Change is continuous, but represented as a sequence of values c_i
  - » The sampling rate depends on how fast c changes – must sample at twice the frequency the frequency (Nyquist)
- In general, c depends on the frequency: c(f)
  - » Frequency selective fading or attenuation, e.g., f impacts loss caused by obstacles, or signal propagation properties
  - » The dependency is must much more of a concern for wide-band channels

Channel Model



x x **c** + **n** = **y**

Power Budget



Rpower (dBm) = Tpower (dBm) + Gains (dB) – 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 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)**

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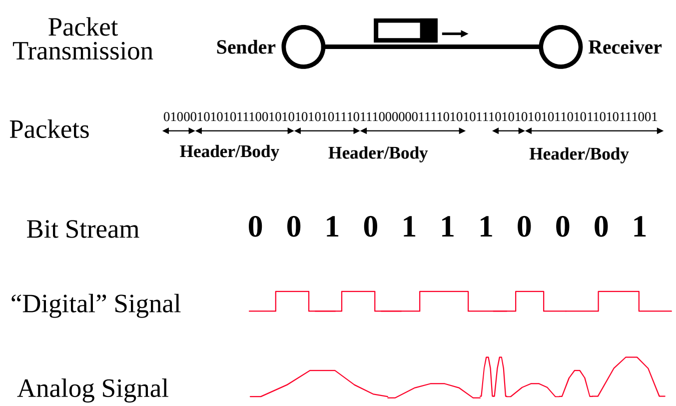
- Modulation
- Coding and diversity
- OFDM

(Limited) Goals

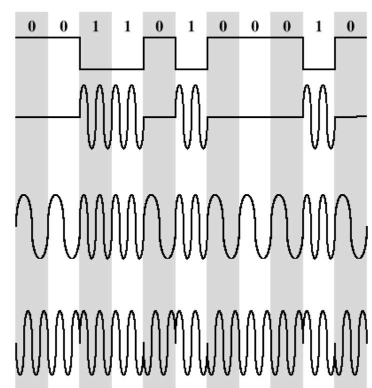
- Non-goal: turn you into electrical engineers
- Basic understanding of how modulation can be done
- Understand the tradeoffs involved in speeding up the transmission

From Signals to Packets



Basic Modulation Techniques

- Encode digital data in an analog signal
- Amplitude-shift keying (ASK)
  - » Amplitude difference of carrier frequency
- Frequency-shift keying (FSK)
  - » Frequency difference near carrier frequency
- Phase-shift keying (PSK)
  - » Phase of carrier signal shifted



Amplitude-Shift Keying

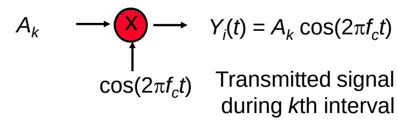
- **One binary digit represented by presence of carrier, at constant amplitude**
- **Other binary digit represented by absence of carrier**

$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ 0 & \text{binary } 0 \end{cases}$$

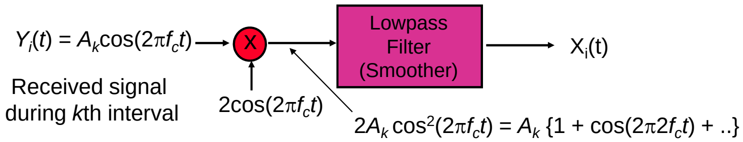
  - **where the carrier signal is $A\cos(2\pi f_c t)$**
- **Inefficient because of sudden gain changes**
  - » **Only used when bandwidth is not a concern, e.g. on voice lines (< 1200 bps) or on digital fiber**
- **A can be a multi-bit symbol**

Modulator & Demodulator

Modulate $\cos(2\pi f_c t)$ by multiplying by A_k for T seconds:



Demodulate (recover A_k) by multiplying by $2\cos(2\pi f_c t)$ for T seconds and lowpass filtering (smoothing):



Binary Frequency-Shift Keying (BFSK)

- **Two binary digits represented by two different frequencies near the carrier frequency**

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary } 1 \\ A\cos(2\pi f_2 t) & \text{binary } 0 \end{cases}$$

  - **where f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts**
- **Less susceptible to error than ASK**
- **Sometimes used for radio or on coax**
- **Demodulator looks for power around f_1 and f_2**

How Can We Go Faster?

- **Increase the rate at which we modulate the signal, or …**
- **Modulate the signal with "symbols" that send multiple bits**
  - » **I.e., each symbol represents more information**
  - » **Of course, we can also try to send symbols faster**
- **Which solution is the best depends on the many factors**
  - » **We will not worry about that in this course**

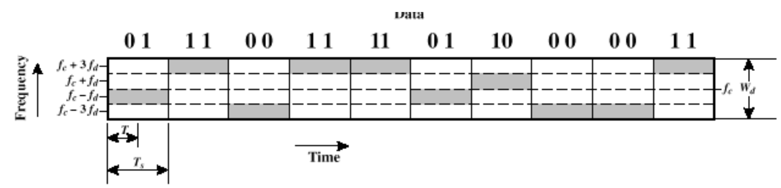
Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used
- Each symbol represents L bits

$$s_i(t) = A\cos 2\pi f_i t \quad 1 \le i \le M$$

  - $f_i = f_c + (2i - 1 - M)f_d$
  - L = number of bits per signal element
  - M = number of different signal elements = 2^L
  - f_c = the carrier frequency
  - f_d = the difference frequency
- More bandwidth efficient but more susceptible to error
  - » Symbol length is $T_s = LT$ seconds, where T is bit period

Multiple Frequency-Shift Keying (MFSK)



Phase-Shift Keying (PSK)

- Two-level PSK (BPSK)
  - » Uses two phases to represent binary digits

$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ A\cos(2\pi f_c t + \pi) & \text{binary } 0 \end{cases}$$

$$= \begin{cases} A\cos(2\pi f_c t) & \text{binary } 1 \\ -A\cos(2\pi f_c t) & \text{binary } 0 \end{cases}$$

- Differential PSK (DPSK)
  - » Phase shift with reference to previous bit
    - Binary 0 – signal of same phase as previous signal burst
    - Binary 1 – signal of opposite phase to previous signal burst

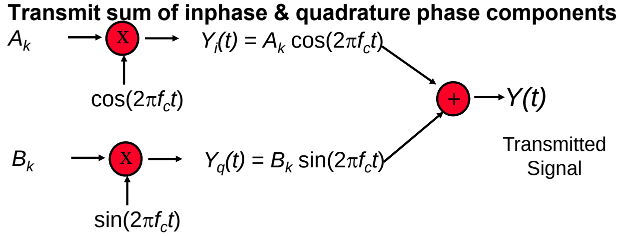
Phase-Shift Keying (PSK)

- Four-level PSK (QPSK)
  - » Each element represents more than one bit

$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

Quadrature Amplitude Modulation (QAM)

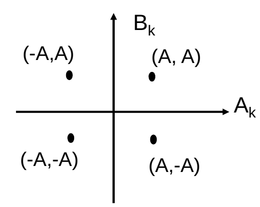
- **QAM uses two-dimensional signaling**
  - » **A_k modulates in-phase $\cos(2\pi f_c t)$**
  - » **B_k modulates quadrature phase $\sin(2\pi f_c t)$**
  - » **Transmit sum of inphase & quadrature phase components**



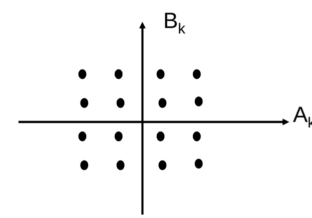
- $Y_i(t)$ and $Y_q(t)$ both occupy the bandpass channel
- QAM sends 2 pulses/Hz

Signal Constellations

- **Each pair (A_k, B_k) defines a point in the plane**
- ***Signal constellation* set of signaling points**

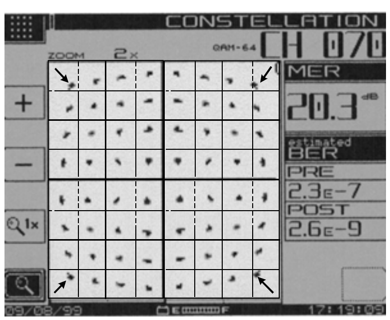


4 possible points per *T* sec.
2 bits / pulse



16 possible points per *T* sec.
4 bits / pulse

How Does Distortion Impact a Constellation Diagram?



- **Changes in amplitude, phase or frequency move the points in the diagram**
- **Large shifts can create uncertainty on what symbol was transmitted**
- **Larger symbols are more susceptible**
- **Can Adapt symbol size to channel conditions to optimize throughput**

www.cascaderange.org/presentations/Distortion_in_the_Digital_World-F2.pdf

Adapting to Channel Conditions

- **Channel conditions can be very diverse**
  - » **Affected by the physical environment of the channel**
  - » **Changes over time as a result of slow and fast fading**
- **Fixed coding/modulation scheme will often be inefficient**
  - » **Too conservative for good channels, i.e. lost opportunity**
  - » **Too aggressive for bad channels, i.e. lots of packet loss**
- **Adjust coding/modulation based on channel conditions – "rate" adaptation**
  - » **Controlled by the MAC protocol**
  - » **E.g. 802.11a: BPSK – QPSK – 16-QAM – 64 QAM**

Bad ⟷ Good

Some Examples

- **Gaussian Frequency Shift Keying.**
  - » 1/-1 is a positive/negative frequency shift from base
  - » Gaussian filter is used to smooth pulses– reduces the spectral bandwidth – "pulse shaping"
  - » Used in Bluetooth
- **Differential quadrature phase shift keying.**
  - » Variant of "regular" frequency shift keying
  - » Symbols are encoded as changes in phase
  - » Requires decoding on pi/4 phase shift
  - » Used in 802.11b networks
- **Quadrature Amplitude modulation.**
  - » Combines amplitude and phase modulation
  - » Uses two amplitudes and 4 phases to represent the value of a 3 bit sequence

Summary

- **Key properties for channels are:**
  - » Channel state that concisely captures many of the factors degrading the channel
  - » The power budget expresses the power at the receiver
  - » Channel reciprocity
- **Modulation changes the signal based on the data to be transmitted**
  - » Can change amplitude, phase or frequency
  - » The transmission rate can be increased by using symbols that represent multiple bits
    - – Can use hybrid modulation, e.g., phase and amplitude
  - » The symbol size can be adapted based on the channel conditions – results in a variable bit rate transmission
  - » Details do not matter!