Wireless Networks

Lecture 6: Physical Layer
Channel Model and Modulation

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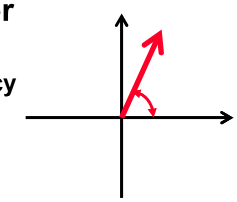
Outline

- 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

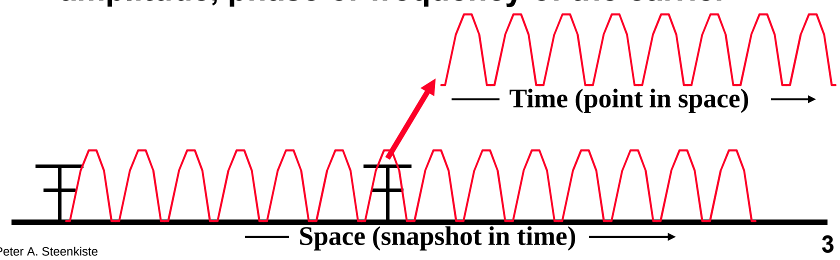
Typical Bad News Good News Story

Remember: Representing a Channel

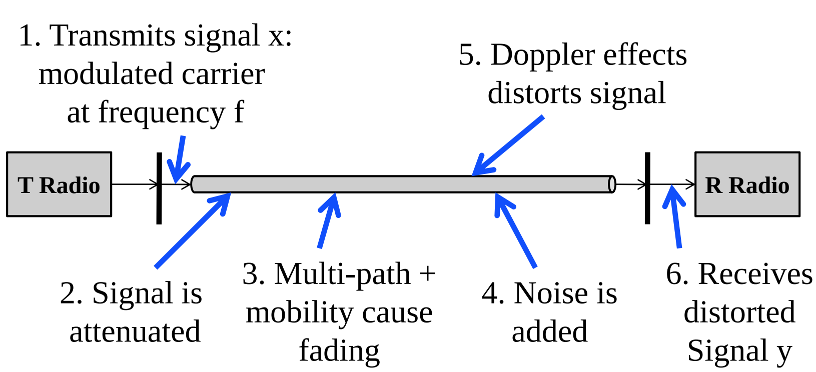
- Communication is based on the sender transmitting the carrier signal
  - » A sine wave with an amplitude, phase, frequency
  - » A complex value at a certain point in space and time captures the amplitude and phase
  - » It changes with a frequency f



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



Channel Model

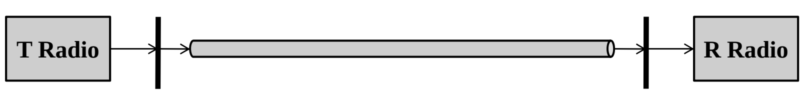


x x **c** + **n** = **y**

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

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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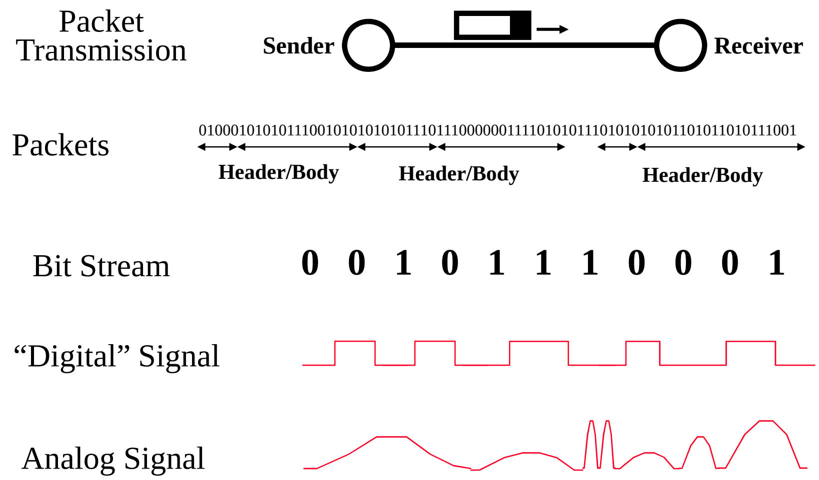
- Modulation
- Coding and diversity
- OFDM

(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



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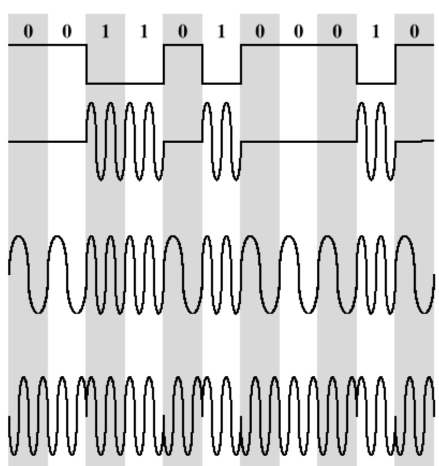
Basic Modulation Techniques

- 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



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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

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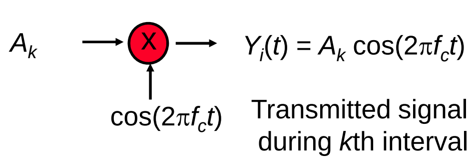
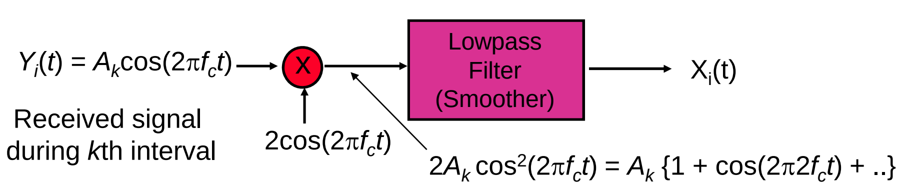
Modulator & Demodulator

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):



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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

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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

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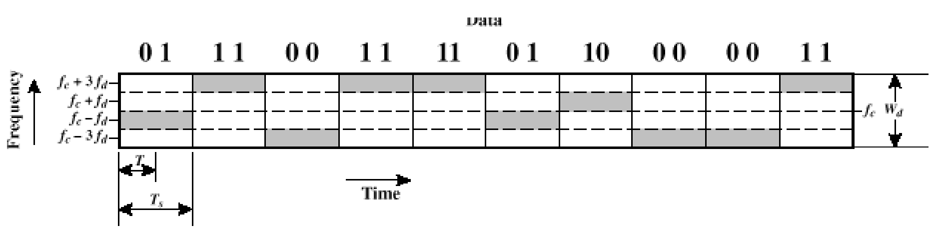
Multiple Frequency-Shift Keying (MFSK)

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

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

  - L = number of bits per signal element
  - M = number of different signal elements = 2^L
  - $f_i = f_c + (2i - 1 - M)f_d$
  - 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**

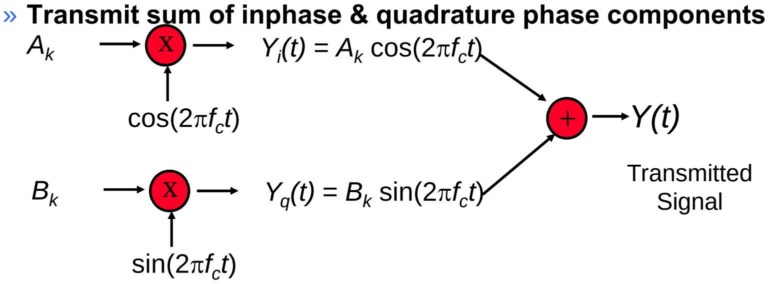
Phase-Shift Keying (PSK)

- **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)

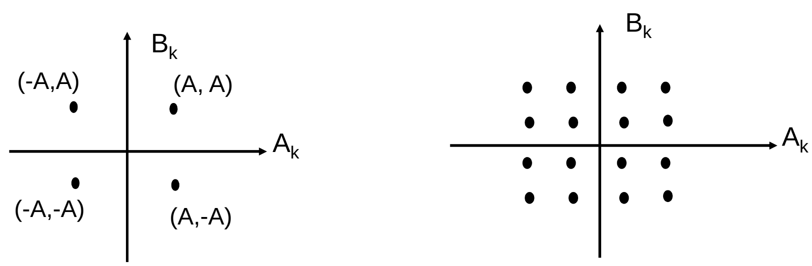
- **QAM uses two-dimensional signaling**
  - » A_k **modulates in-phase** $\cos(2\pi f_c t)$
  - » B_k **modulates quadrature phase** $\sin(2\pi f_c t)$
  - » **Transmit sum of inphase & quadrature phase components**



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

Signal Constellations

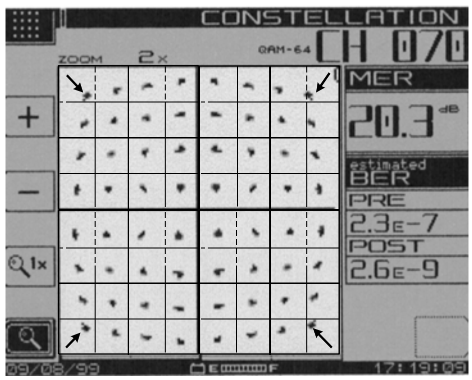
- **Each pair (A_k, B_k) defines a point in the plane**
- ***Signal constellation*** **set of signaling points**



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!