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

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http://www.cs.cmu.edu/~prs/wirelessS18/

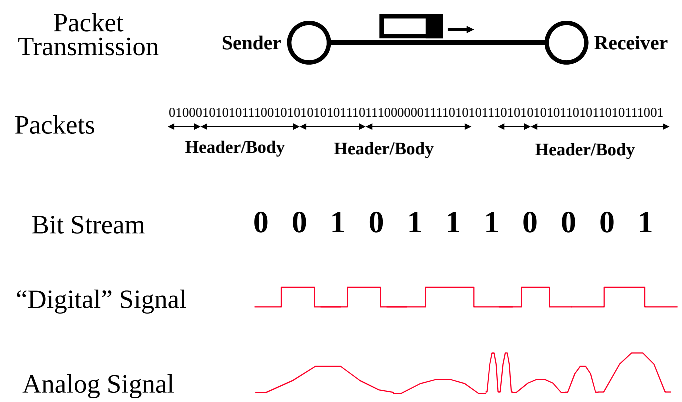
Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Coding and diversity
- OFDM

(Limited) Goals

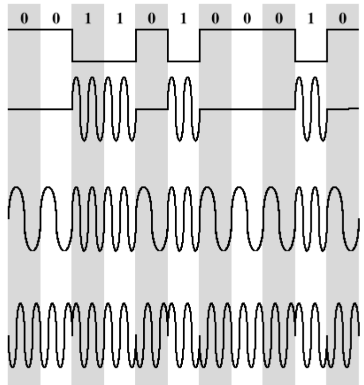
- Non-goal: turn you into electrical engineers
- Basic understanding of how modulation can be done
- Understand the tradeoffs involved in speeding up the transmission

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

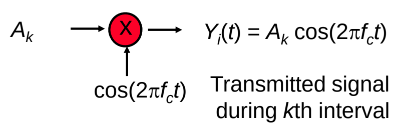
- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

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

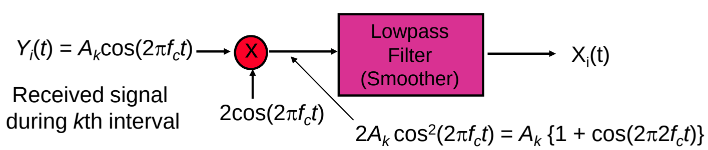
- – where the carrier signal is $A\cos(2\pi f_c t)$
- Inefficient because of sudden gain changes
  - » Only used when bandwidth is not a concern, e.g. on voice lines (< 1200 bps) or on digital fiber
- A can be a multi-bit symbol

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 …
  - » I.e., a higher frequency base signal
  - » Signal time becomes short
- Modulate the signal with "symbols" that send multiple bits
  - » I.e., each symbol represents more information
  - » Longer signal time but more sensitive to distortion
- Which solution is the best depends on the many factors
  - » We will not worry about that in this course

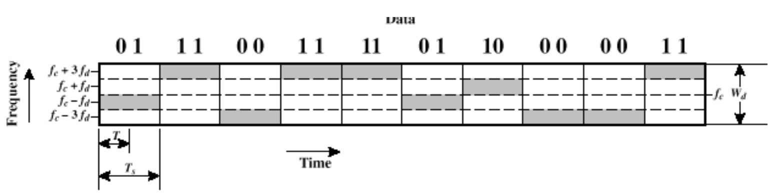
Multiple Frequency-Shift Keying (MFSK)

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

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

- – $f_i = f_c + (2i - 1 - M)f_d$
- – 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

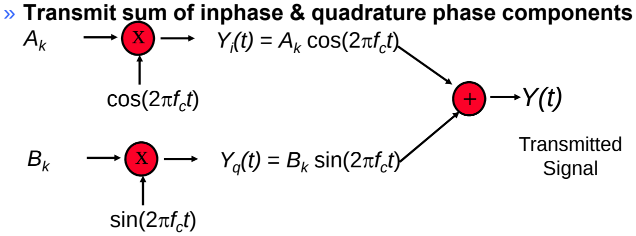
Phase-Shift Keying (PSK)

- **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)

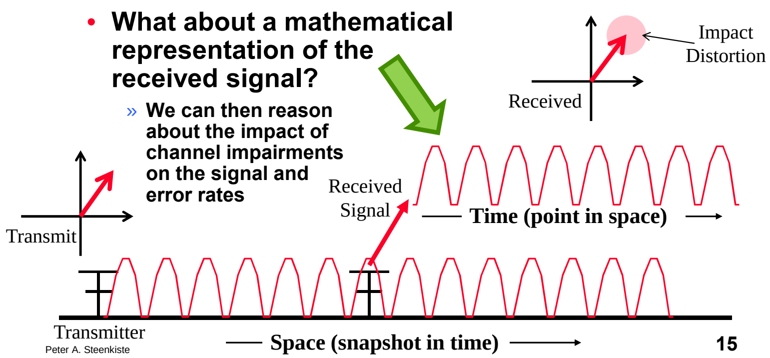
- **QAM uses two-dimensional signaling**
  - » **A_k modulates in-phase $\cos(2\pi f_c t)$**
  - » **B_k modulates quadrature phase $\sin(2\pi f_c t)$**
  - » **Transmit sum of inphase & quadrature phase components**



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

Time and Point View of Signal

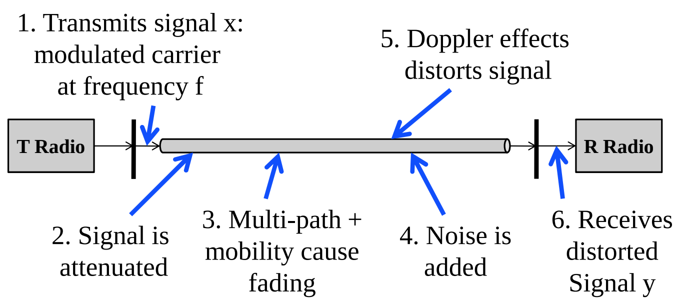
- **Remember: communication is based on the transmission of a modulated carrier signal**
  - » **Focus on amplitude-phase modulation – very common!**
- **What about a mathematical representation of the received signal?**
  - » **We can then reason about the impact of channel impairments on the signal and error rates**



Channel State

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

Channel Model



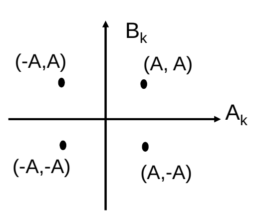
x x **c** + **n** = **y**

Tradeoff: Bit Rate versus Error Rate - Informal

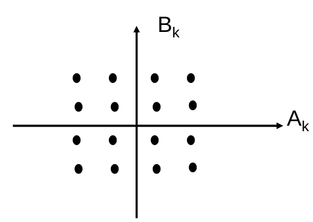
- **Amplitude and phase modulation places transmitted signals into 2D space**
  - » **Represented by a complex number**
- **Channel distortion "moves" the symbol**
  - » **Large shift can map it onto another symbol**
- **Large symbols means denser packing of symbols in the plane** — Good channels
  - » **Results in high bit rate but distortions are more likely to result in errors**
- **Smaller symbols are more conservative**
  - » **Lower bit rate but more resistant to errors** — Bad channels

Signal Constellations

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

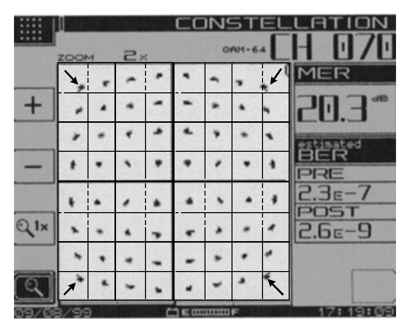


4 possible points per *T* sec.
2 bits / pulse



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

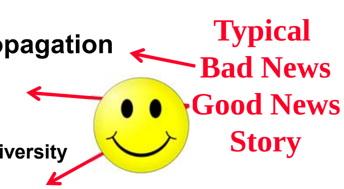
- Gaussian Frequency Shift Keying.
  - » 1/-1 is a positive/negative frequency shift from base
  - » Gaussian filter is used to smooth pulses– reduces the spectral bandwidth – "pulse shaping"
  - » Used in Bluetooth
- Differential quadrature phase shift keying.
  - » Variant of "regular" frequency shift 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!

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
  - » Space, time and frequency diversity
- OFDM



Diversity Techniques

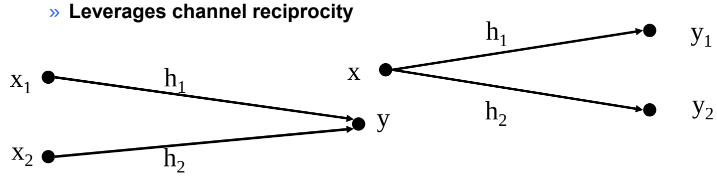
- The quality of the channel depends on time, space, and frequency
- Space diversity: use multiple nearby antennas and combine signals
  - » Both at the sender and the receiver
- Time diversity: spread data out over time
  - » Useful for burst errors, i.e., errors are clustered in time
- Frequency diversity: spread signal over multiple frequencies
  - » For example, spread spectrum
- Distribute data over multiple “channels”
  - » “Channels” experience different frequency selective fading, so only part of the data is affected

Space Diversity

- Use multiple antennas that pick up/transmit the signal in slightly different locations
- If antennas are sufficiently separated, instantaneous channel conditions are independent
  - » Antennas should be separated by ½ wavelength or more
- If one antenna experiences deep fading, the other antenna has a strong signal
- Represents a wide class of techniques
  - » Use on transmit and receive side - channels are symmetric
  - » Level of sophistication of the algorithms used
  - » Can use more than two antennas!

Selection Diversity

- Receiver diversity: receiver picks the antenna with the best SNR
  - » Very easy
- Transmit diversity: sender picks the antenna that offers the best channel to the receiver
  - » Transmitter can learn the channel conditions based on signals sent by the receiver
  - » Leverages channel reciprocity



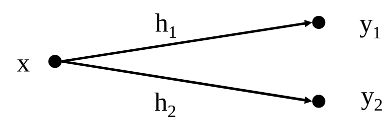
Simple Algorithm in (older) 802.11

- Combine transmit + receive selection diversity
  - » Assume packets are acknowledged – why?
- How to explore all channels to find the best one … or at least the best transmit antenna
- Receiver:
  - » Uses the antenna with the strongest signal
  - » Always use the same antenna to send the acknowledgement – gives feedback to the sender
- Sender:
  - » Picks an antenna to transmit and learns about the channel quality based on the ACK
  - » Needs to occasionally try the other antenna to explore the channel between all four channel pairs

Receiver Diversity
Can we Do Better?

- But why not use both signals?
  - » 2 Signals contain more information than 1
  - » What can go wrong?
- Simply adding the two signals has drawbacks:
  - » Signals may be out of phase, e.g. kind of like multi-path; can reduce the signal strength!
  - » We want to make sure we do not amplify the noise
- Maximal ratio combining: combine signals with a weight that is based on their SNR
  - » Weight will favor the strongest signal (highest SNR)
  - » Also: equal gain combining as a quick and dirty alternative

Receiver Diversity Optimization



$$\vec{y} = \vec{h} * x + \vec{n}$$

$$\vec{h} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix}$$

- Multiply $\vec{y}$ with the complex conjugate $\vec{h}^*$ of the channel vector $\vec{h}$
  - » Aligns the phases of the two signals so they amplify each other
  - » Scales the signals with their magnitude so the effect of noise is not amplified
- Can learn $\vec{h}$ based on training data

The Details

- Complex conjugates: same real part but imaginary parts of opposite signs

$$\vec{h}^* * \vec{y} = \vec{h}^* * (\vec{h} * x + \vec{n})$$

$$\text{Where } h^* = [h_1^* \;\; h_2^*] = [\, a_1+b_1 i \;\; a_2-b_2 i]$$

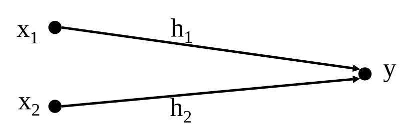
- Result:

  signal x is scaled by $a_1^2 + b_1^2 + a_2^2 + b_2^2$

  noise becomes: $h_1^* * n_1 + h_2^* * n_2$

Transmit Diversity

- Same as receive diversity but the transmitter has multiple antennas
- Maximum ratio combining: sender “precodes” the signal
  - » Pre-align the phases at receiver and distribute power over the transmit antennas (total power fixed)
- How does transmitter learn channel?
  - » Channel reciprocity: learn from packets received Y



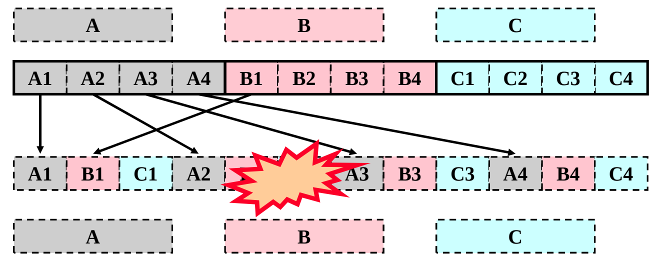
$$y = \vec{h} * \vec{x} + n$$

Adding Redundancy

- Protects digital data by introducing redundancy in the transmitted data.
  - » Error detection codes: can identify certain types of errors
  - » Error correction codes: can fix certain types of errors
- Block codes provide Forward Error Correction (FEC) for blocks of data.
  - » (n, k) code: n bits are transmitted for k information bits
  - » Simplest example: parity codes
  - » Many different codes exist: Hamming, cyclic, Reed-Solomon, …
- Convolutional codes provide protection for a continuous stream of bits.
  - » Coding gain is n/k
  - » Turbo codes: convolutional code with channel estimation

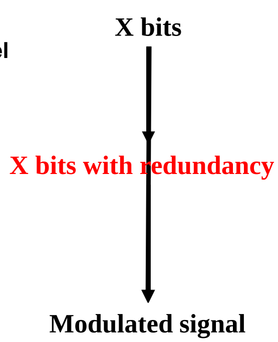
Combine Redundancy with Time Diversity

- Fading can cause burst errors: a relatively long sequence of bits is corrupted
- Spread blocks of bytes out over time so redundancy can help recover from the burst
  - » Example: only need 3 out of 4 to recover the data



Bits, Symbols, and Chips

- Redundancy and time diversity can be added easily at the application layer
- Can we do it lower in the stack?
  - » Need to adapt quickly to the channel
- So far: use bits to directly modulate the signal
- Idea: add a coding layer – provides a level of indirection
- Can add redundancy and adjust level of redundancy quickly based on channel conditions



Discussion

- Error coding increases robustness at the expense of having to send more bits
  - » Technically this means that you need more spectrum
- But: since you can tolerate some errors, you may be able to increase the bit rate through more aggressive modulation
- Coding and modulation combined offer a lot of flexibility to optimize transmission
- Next steps:
  - » Apply a similar idea to frequency diversity
  - » Combine coding with frequency and time diversity in OFDM

Summary

- Space diversity really helps in overcoming fading
  - » Very widely deployed
  - » Will build on this when we discuss MIMO
- Coding is also an effective way to improve throughput
  - » Widely used in all modern standards
  - » Coding, combined with modulation, can be adapt quickly to channel conditions