This lecture is being recorded

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/wireless21/

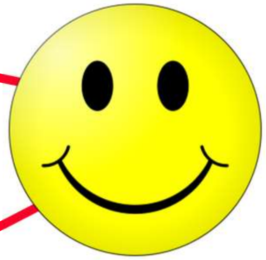
Announcements

- **Waiting list status**
  - » **Only two people left!**
  - » **There are several open slots so everybody will be able to get in**
- **We will post the Project 1 handout today**

Outline

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

Typical Bad News



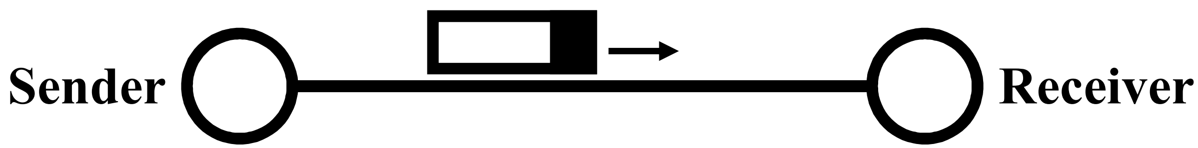
Good News Story

(Limited) Goals

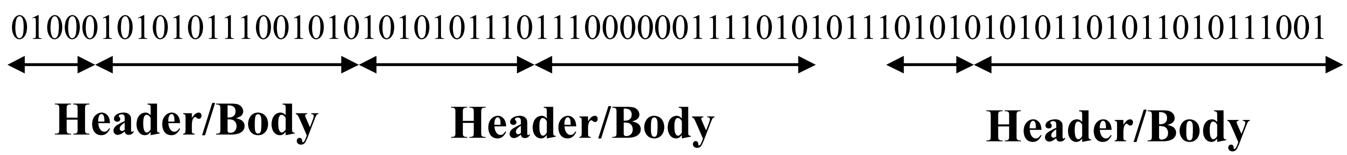
- Non-goal: turn you into electrical engineers
  - » Of course, some of you already are electrical engineers
- Basic understanding of how modulation can be done
- Understand the tradeoffs involved in increasing the bit rate

From Signals to Packets

Packet Transmission



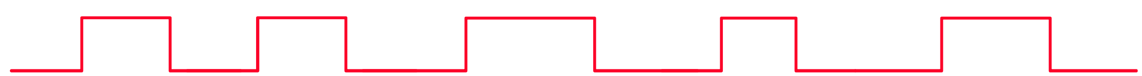
Packets



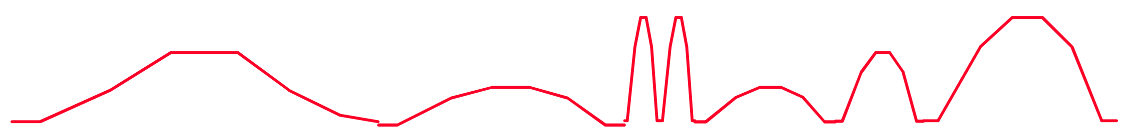
Bit Stream

0 0 1 0 1 1 1 0 0 0 1

"Digital" Signal

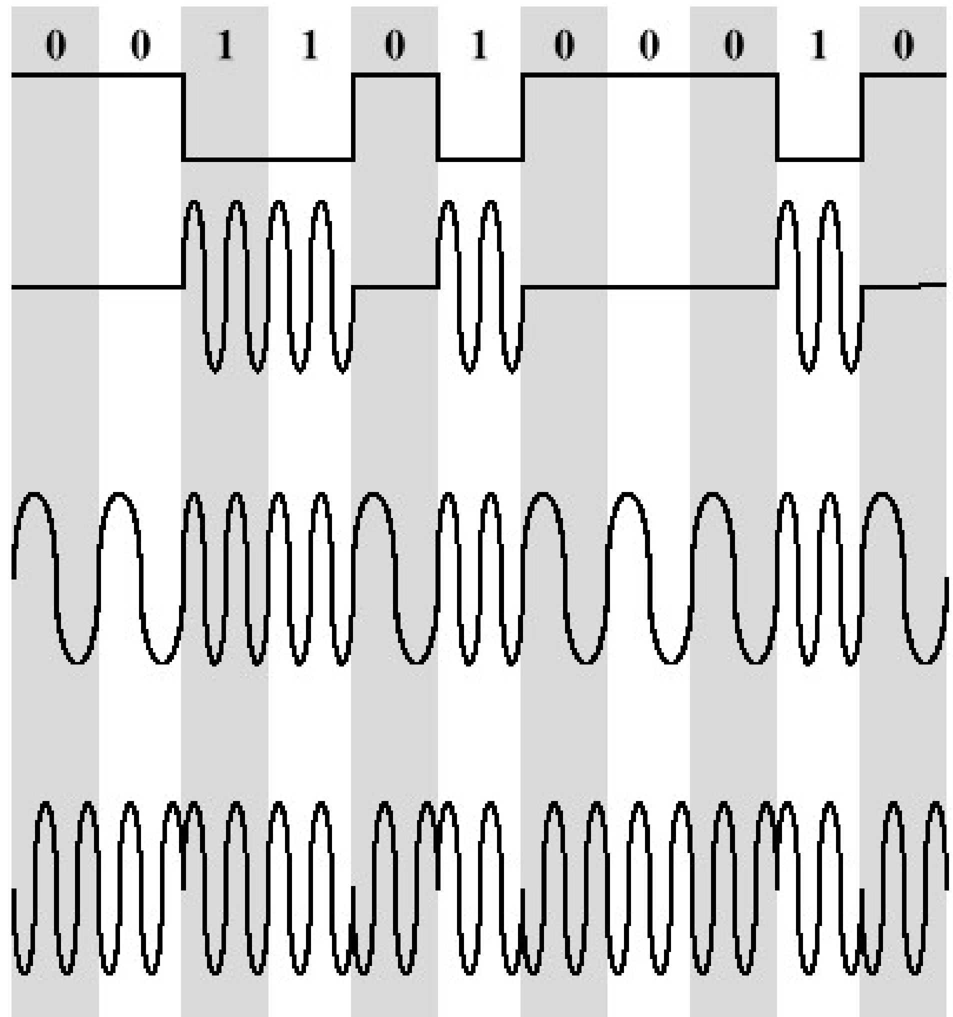


Analog Signal



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

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

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**

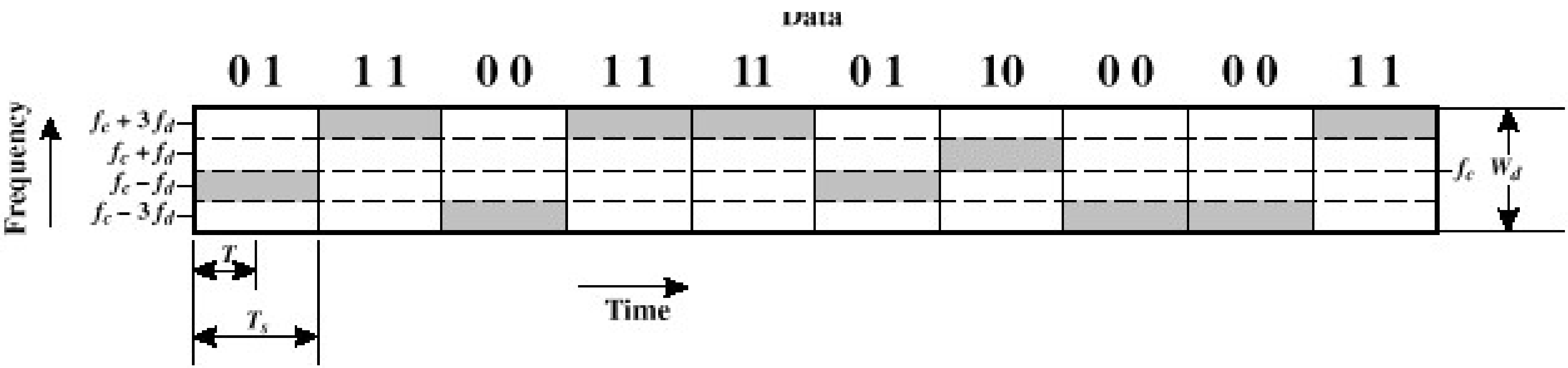
Multiple Frequency-Shift Keying (MFSK)

- 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
Four Level PSK

- **Each element represents 2 (or more) bits**

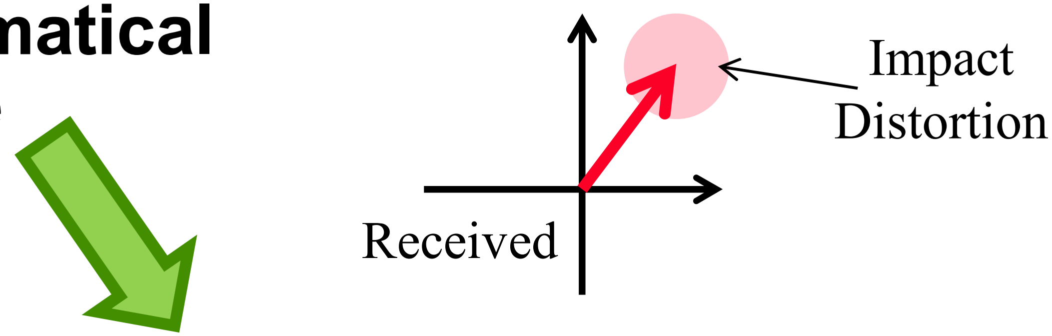
$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

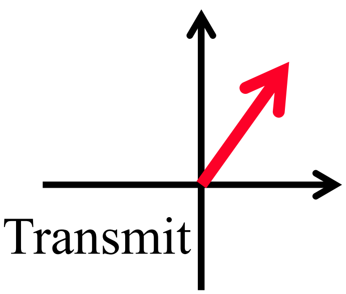
Quadrature Amplitude Modulation - QAM

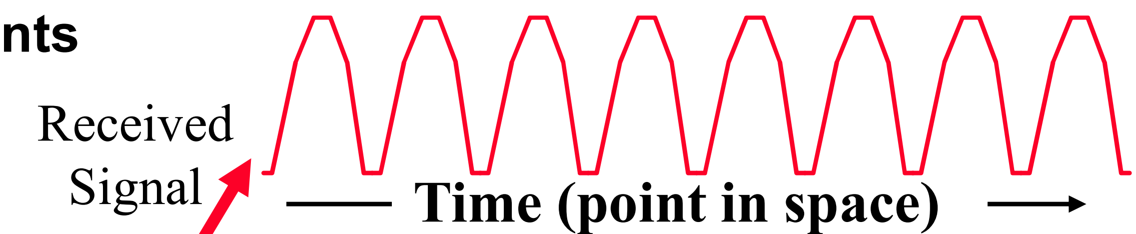
- Modulation is based on both the phase and amplitude
- Has many benefits
  - » Since two signal properties are used, it can be used for a wide range of symbol sizes
  - » It has a simple mathematical representation (next slide)
  - » Bonus: it has a very intuitive presentation (figures)
- QAM is the dominating modulation technique for modern, high performance wireless technologies
  - » 4G, 5G, all recent WiFi standards

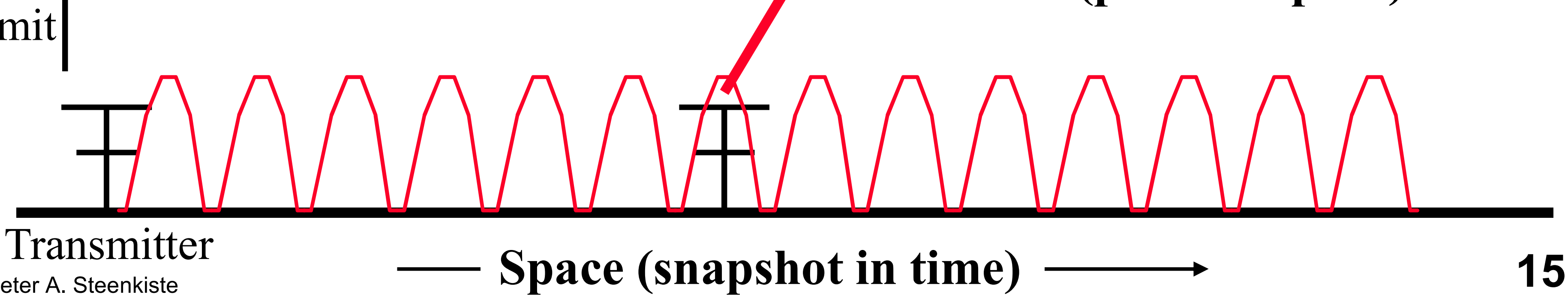
Time and Point View of Signal

- 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





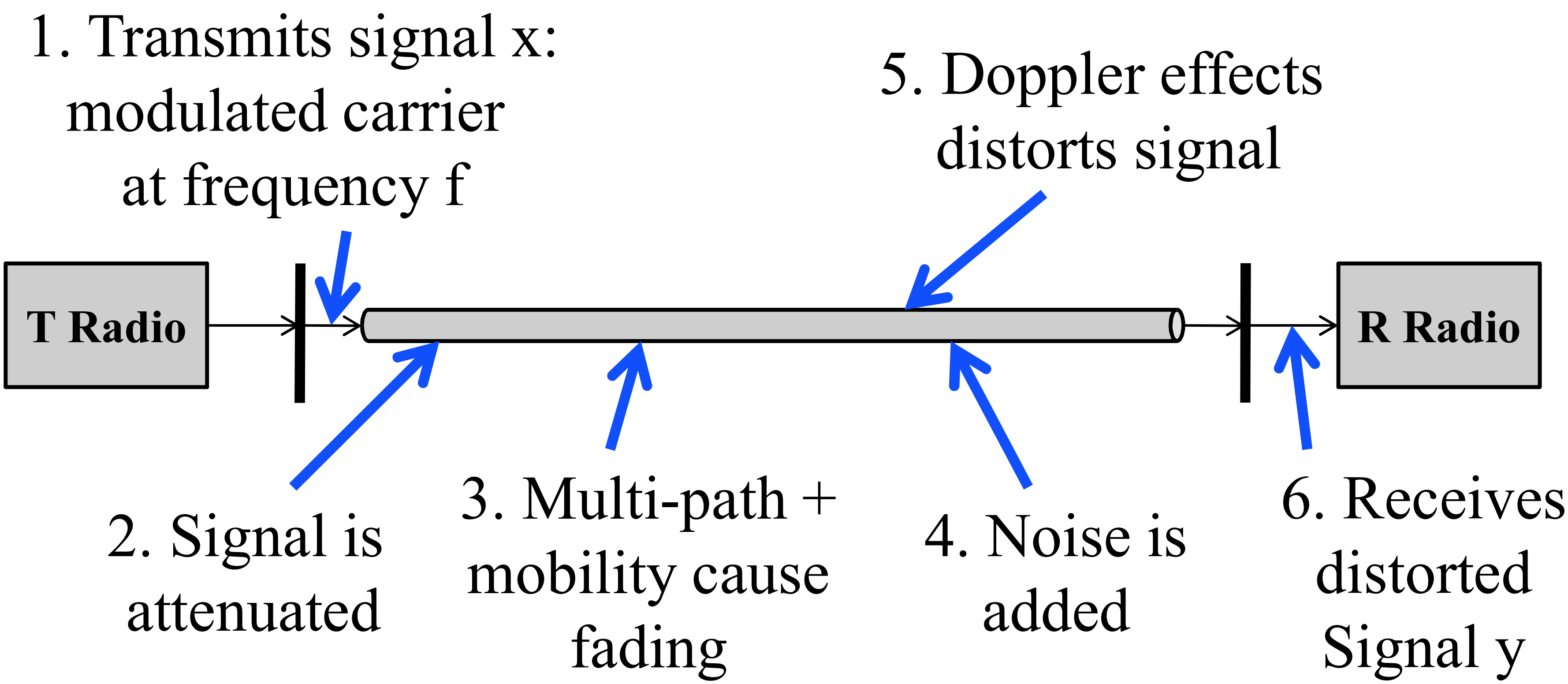




QAM Signals and Channel State

- A signal is a complex number that represents the signal's amplitude and phase
- The channel state captures how it changes a signal's attenuation and phase
  - » The two main channel properties relevant to wireless communication
- c changes over time due to mobility: c(t),
  - » Change is continuous; captured as a sequence of samples c_i
- c typically depends on carrier frequency: c(f)
  - » Frequency selective fading or attenuation
  - » The dependency on f is a concern for wide-band signals
- c is sampled in frequency and time domains

Channel Model



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

Tradeoff: Bit Rate versus Error Rate - Informal

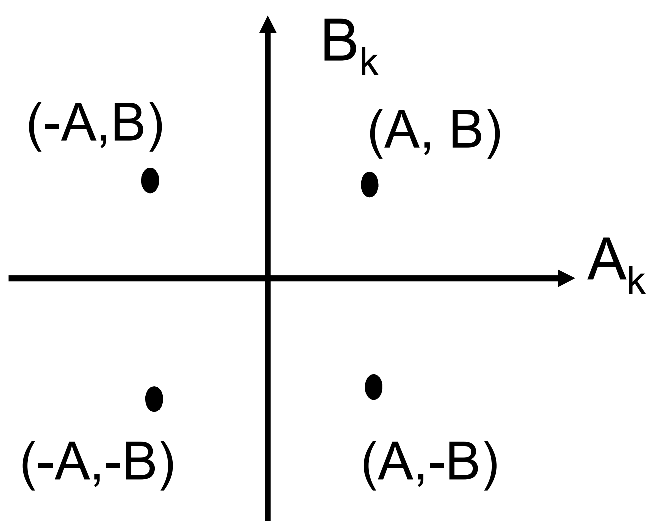
- Amplitude and phase modulation places transmitted symbols into 2D space
  - » Represented by a complex number
- Channel distortion “moves” the symbol
  - » Large shift can map it onto another symbol
- Large symbols means denser packing of symbols in the plane

  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

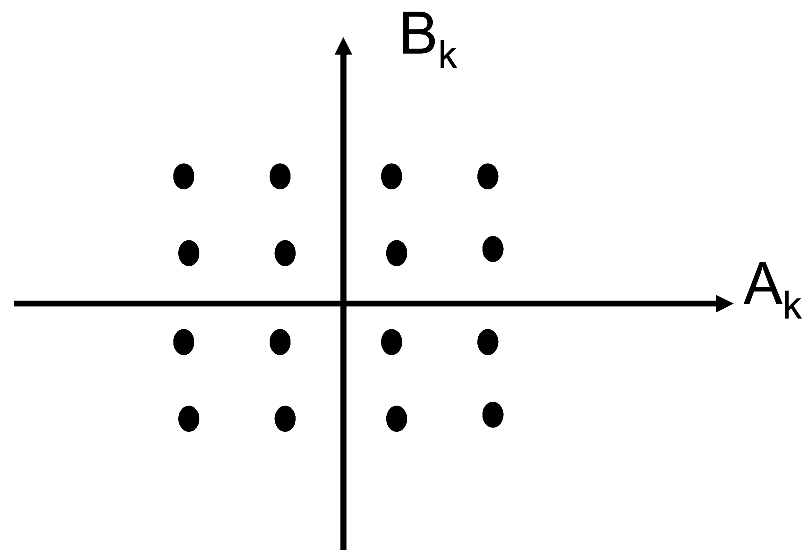
  Bad channels

Signal Constellations

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

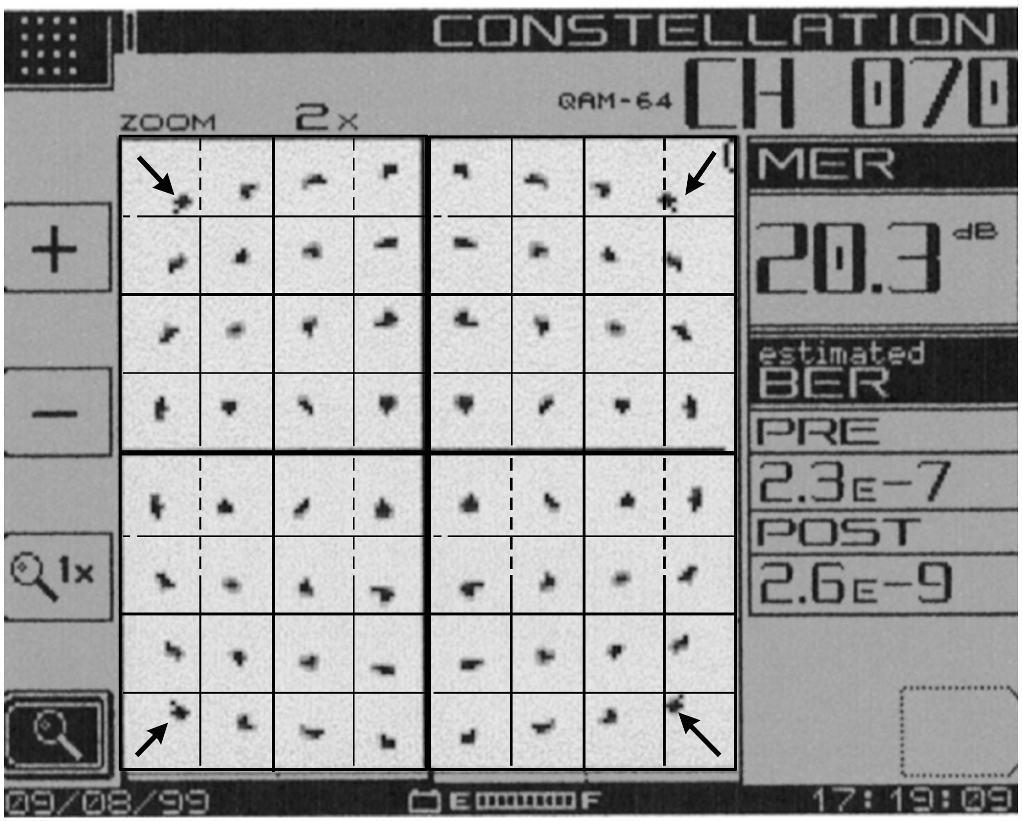


4 possible points per *T* sec.
2 bits QAM (see earlier slide)



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

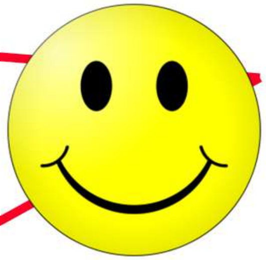
Bad ⟷ Good Channel

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



Typical
Bad News
Good News
Story

Diversity Techniques

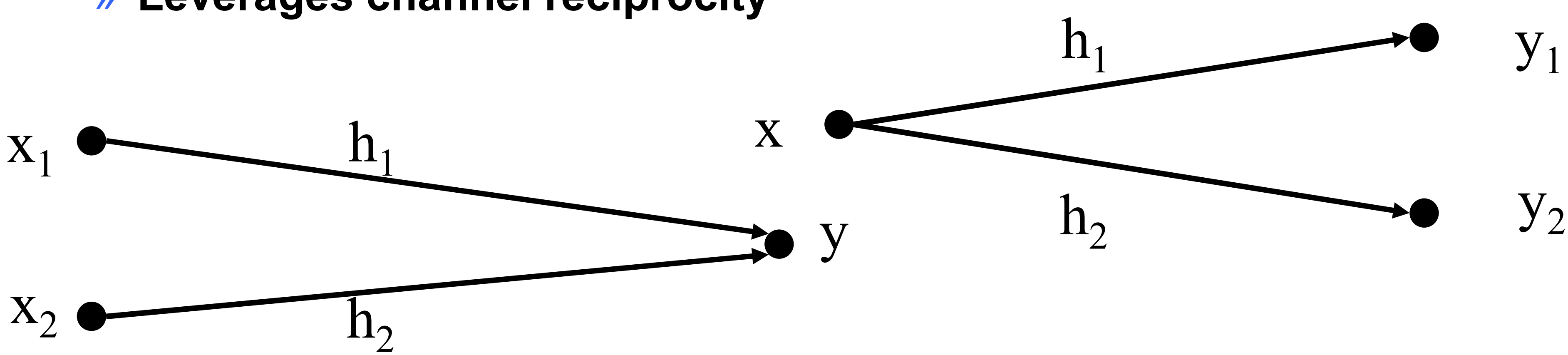
- The quality of the channel depends on time, space, and frequency
- Space diversity: use multiple nearby antennas and combine signals
  - » Both at the sender and the receiver
- Time diversity: spread data out over time
  - » Useful for burst errors, i.e., errors are clustered in time
- Frequency diversity: 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!

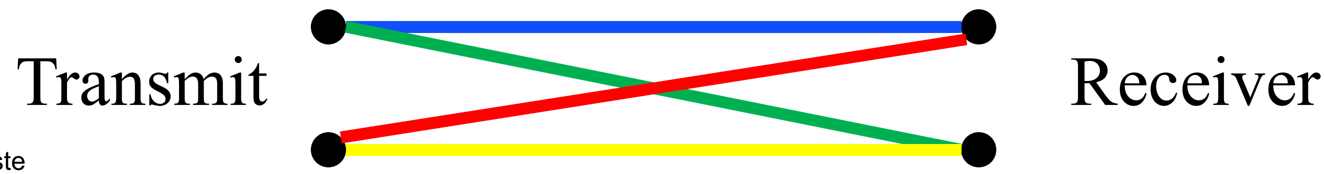
Selection Diversity

- 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

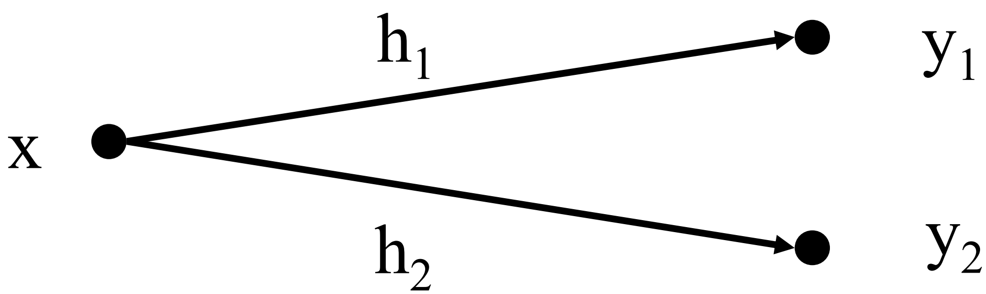
- Combine transmit + receive selection diversity
  - Assume packets are acknowledged – why?
- How to explore all channels to find the best one … or at least the best transmit antenna
- Receiver:
  - Uses the antenna with the strongest signal
  - Always use the same antenna to send the acknowledgement – 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



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

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

- **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

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

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

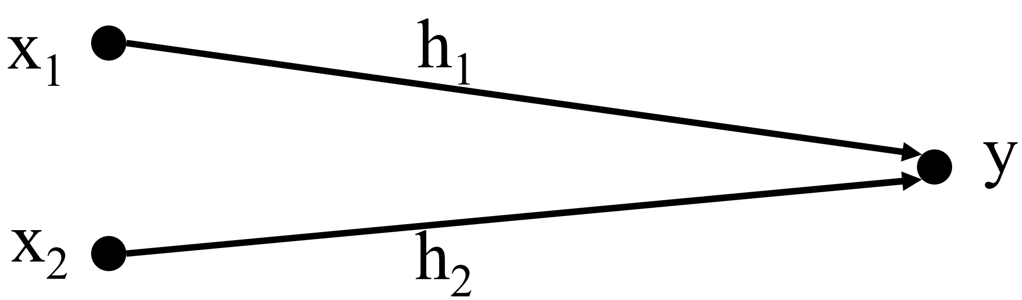
- Result:

  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 state?**
  - » **Channel reciprocity: learn from packets received Y**



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

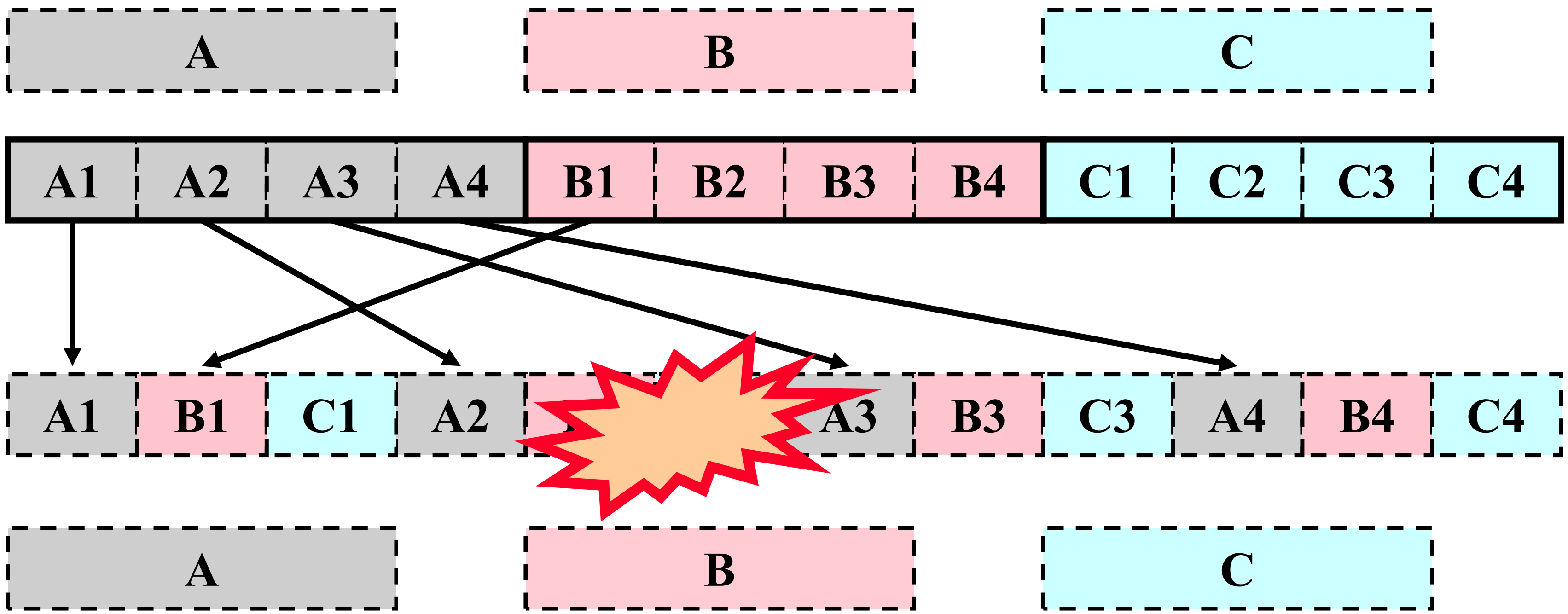
$$\vec{x} \rightarrow \vec{h}^* * x$$

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

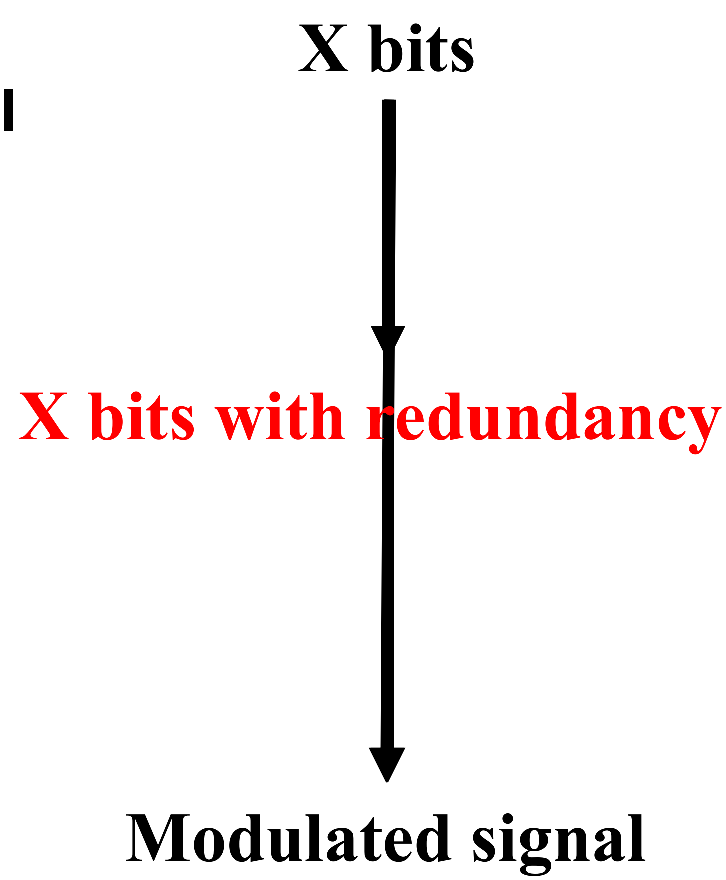
Combine Redundancy with Time Diversity

- 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 - spread spectrum
  - » Combine coding with frequency and time diversity - 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