Lecture 03-9: Physical Layer Modulation

CS 356R

Intro to Wireless Networks

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Outline

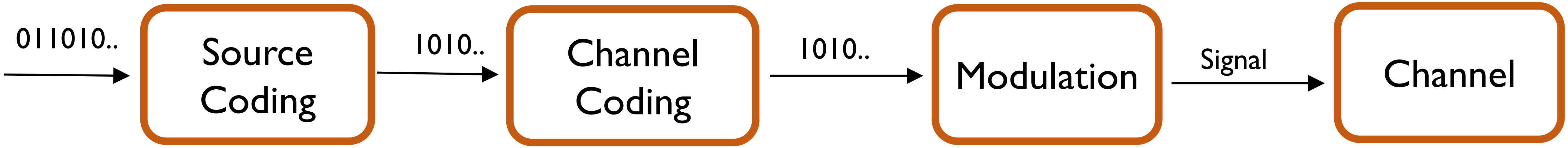
1. Sender-side Digital Communication Overview

So far…

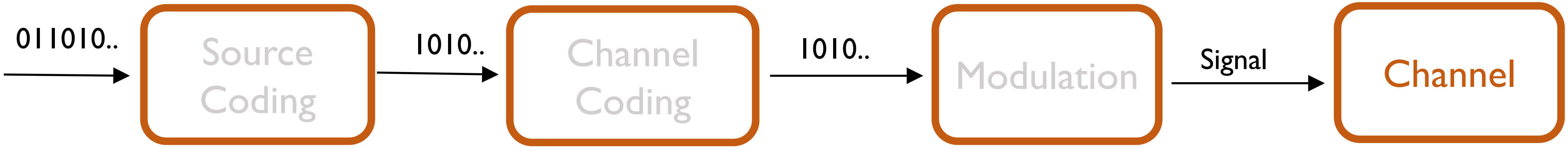
- **We learned about signals**
  - Amplitude, frequency, phase
  - Time domain <-> Frequency domain
  - Fourier Transform, DFT, FFT vs Inverse FT, IDFT, IFFT
- **But, data in software is represented in as bit streams**

How to convert the bit stream into signals?

How data is sent: sender side story



Channel



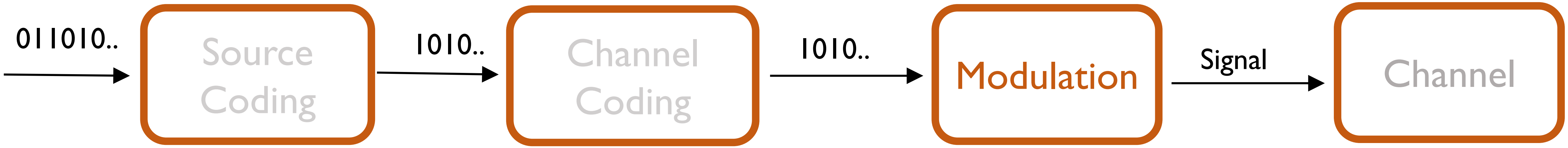
Two types of signals

- **Base-band signal**
  - Carries the original information without any shifting to higher frequency or modulation
  - Short-distance, susceptible to interference
  - Ex) voice, telephone wire
- **Passband signal**
  - Shifts baseband signal to higher frequency range called carrier frequency
  - Receiver has to shift the frequency back to original

Why we need to shift the signal to higher carrier frequency?

- A baseband signal can be transmitted over a pair of wires
  - Such as coaxial cables, or optical fibers.
- But in wireless communication, a baseband signal cannot be transmitted over a radio link or a satellite
- Why? Physically impossible or too expensive
  - The baseband signal that starts from 0 Hz and spans low-frequency would require a large antenna to radiate the signal
  - The size antenna is inversely proportional to the frequency
  - The higher the frequency, the shorter the antenna can be made.

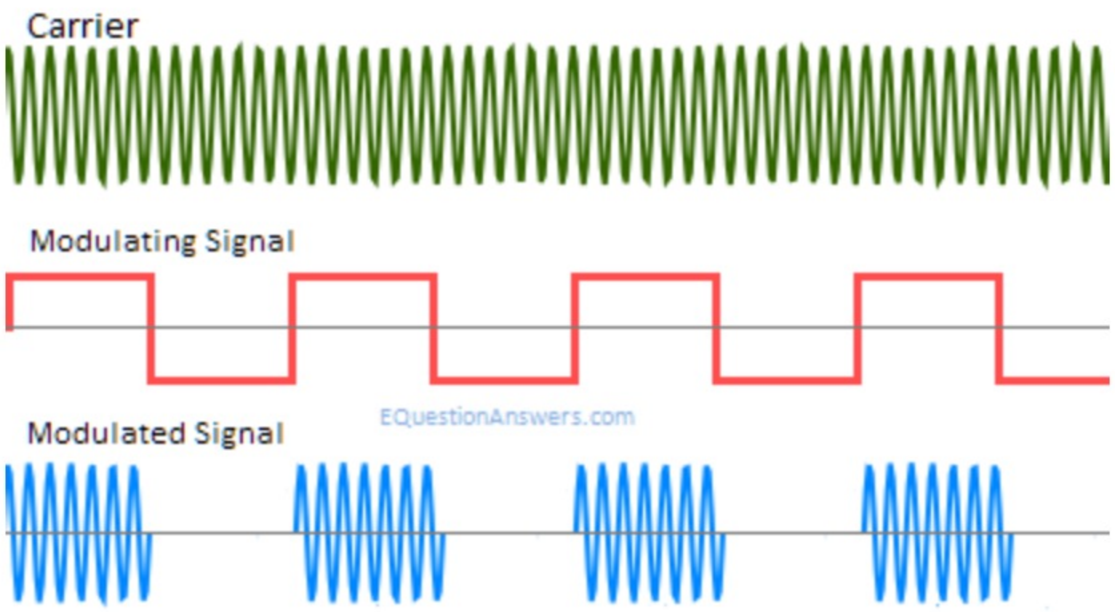
Modulation



- Two input
  - Modulating signal that contains actual data (ex, bit stream from computer)
  - Carrier signal
- Output
  - Modulated signal
- Varies one or more properties of a carrier signal according to modulating signal
  - Amplitude, phase, frequency

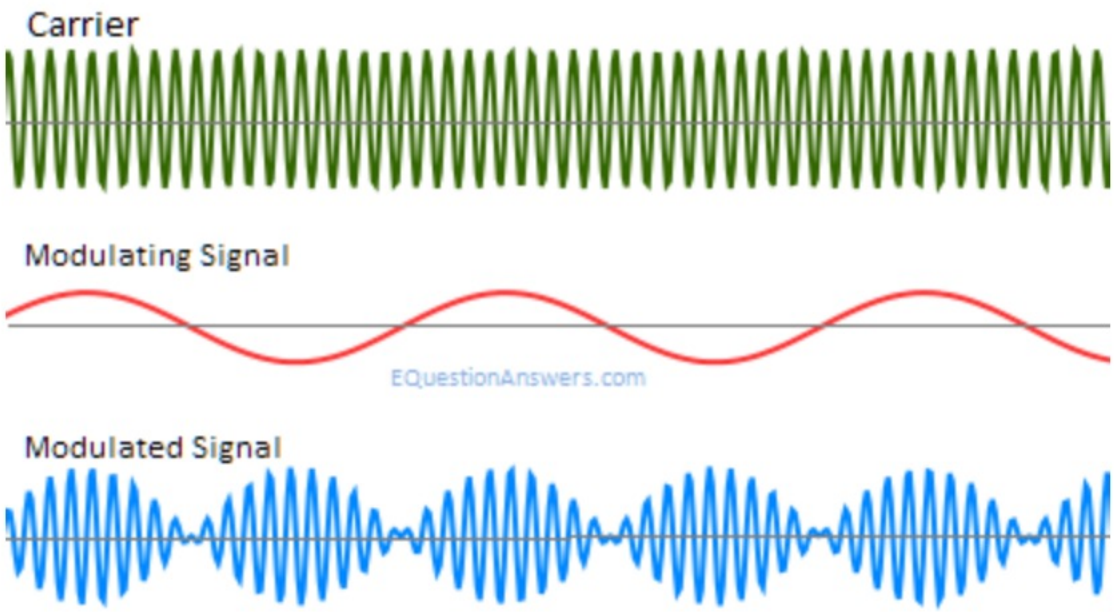
Modulation varying Amplitude

- Digital modulation



Amplitude Shift Key (ASK)
aka On Off Key (OOK)

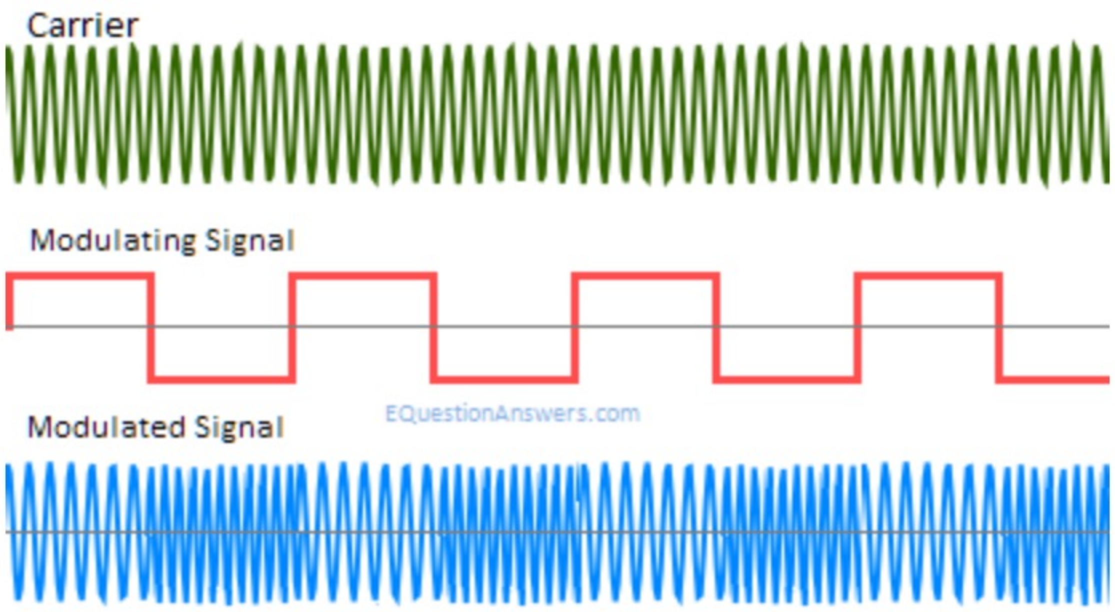
- Analog modulation



Amplitude Modulation (AM)

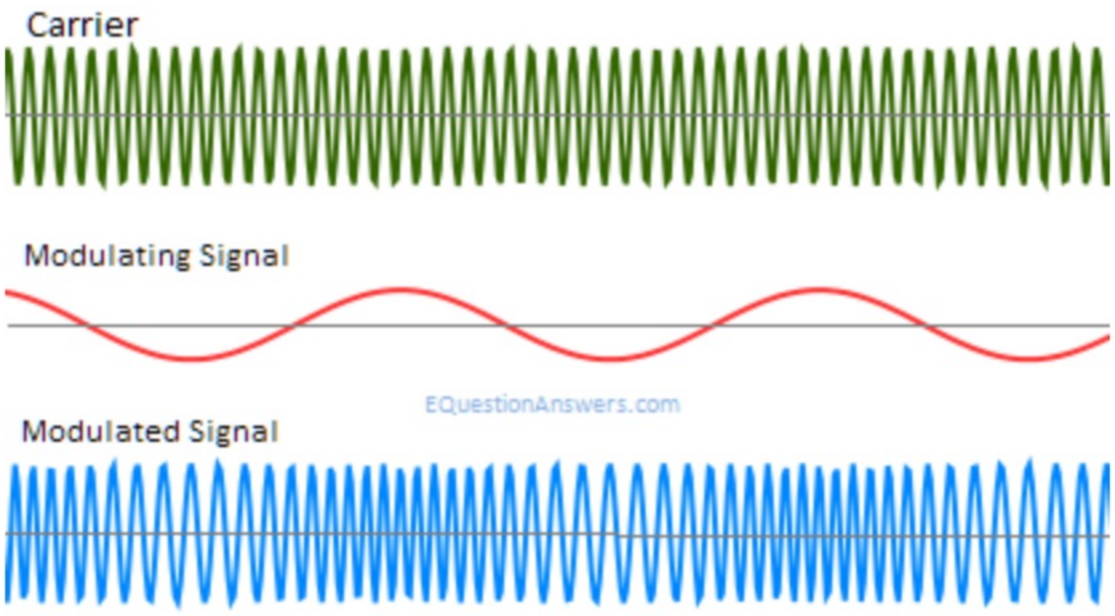
Modulation varying Frequency

- Digital modulation



Frequency Shift Key (FSK)

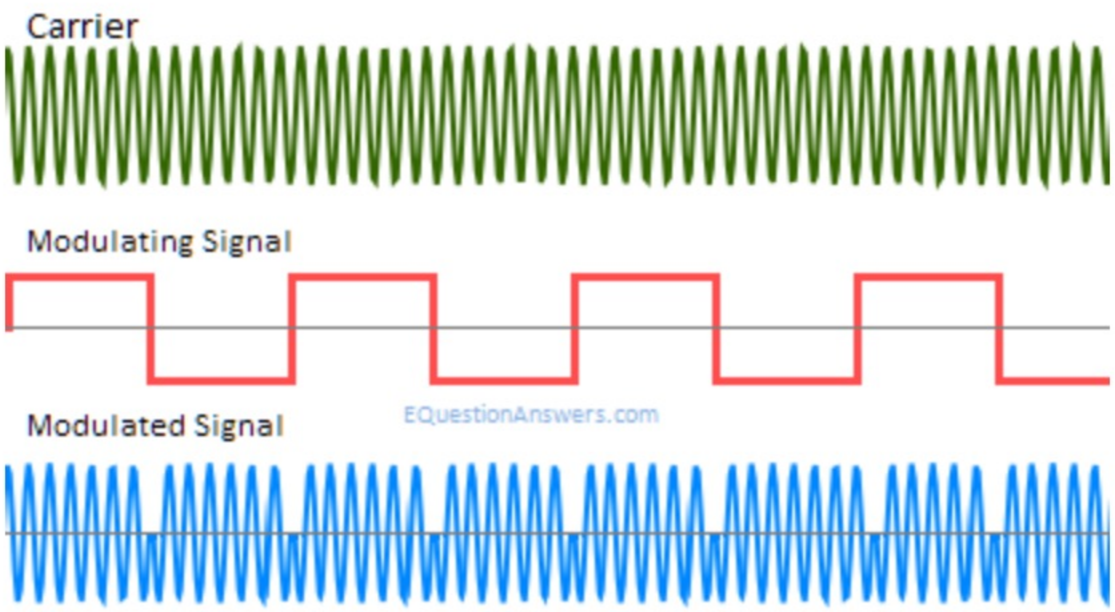
- Analog modulation



Frequency Modulation (FM)

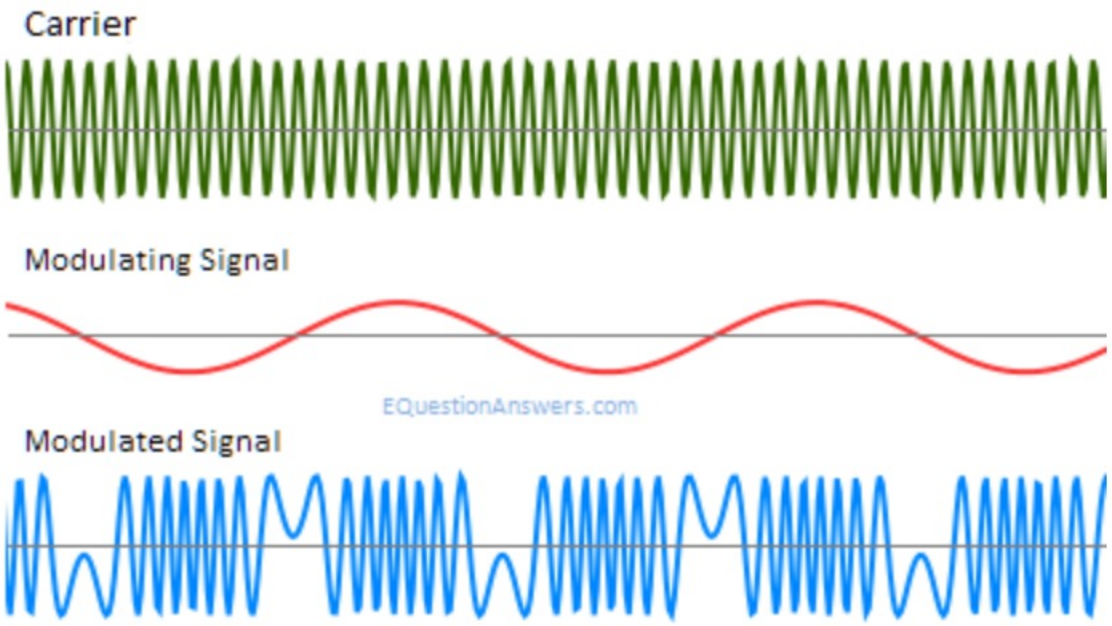
Modulation varying Phase

- Digital modulation



Phase Shift Key (PSK)

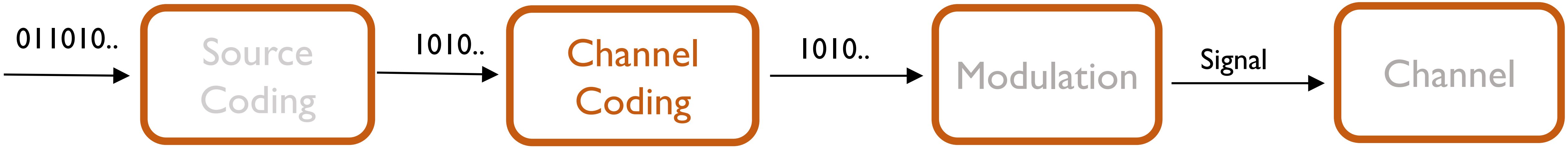
- Analog modulation



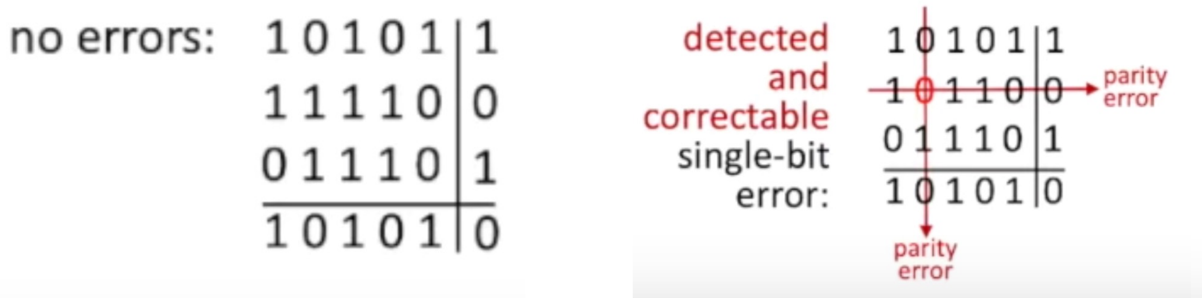
Phase Modulation (PM)

More modulation schemes to come …

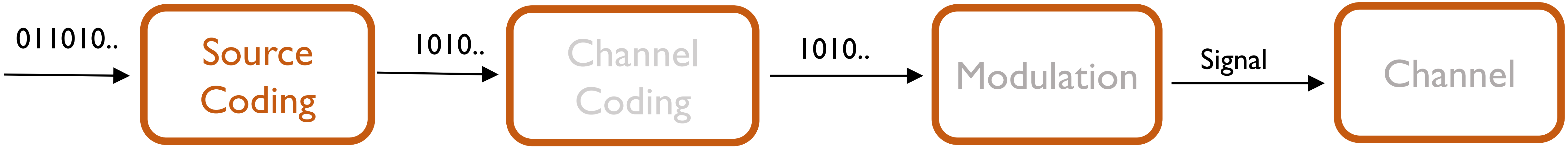
Channel Coding



- Aka Forward Error Correction
- Sender adds redundant information
  so that error can be detected and corrected without retransmission
- Combats bit errors over channel
- Ex) 2-D parity

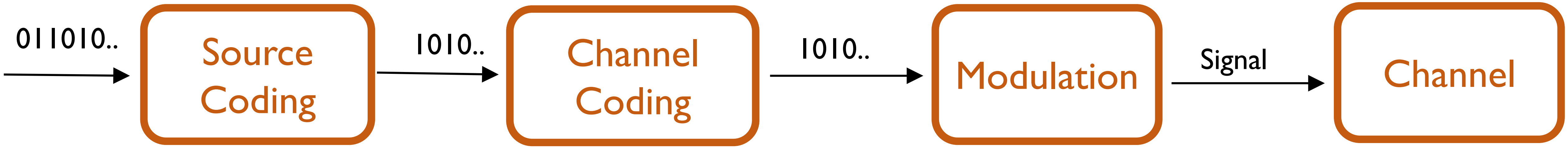


Source Coding

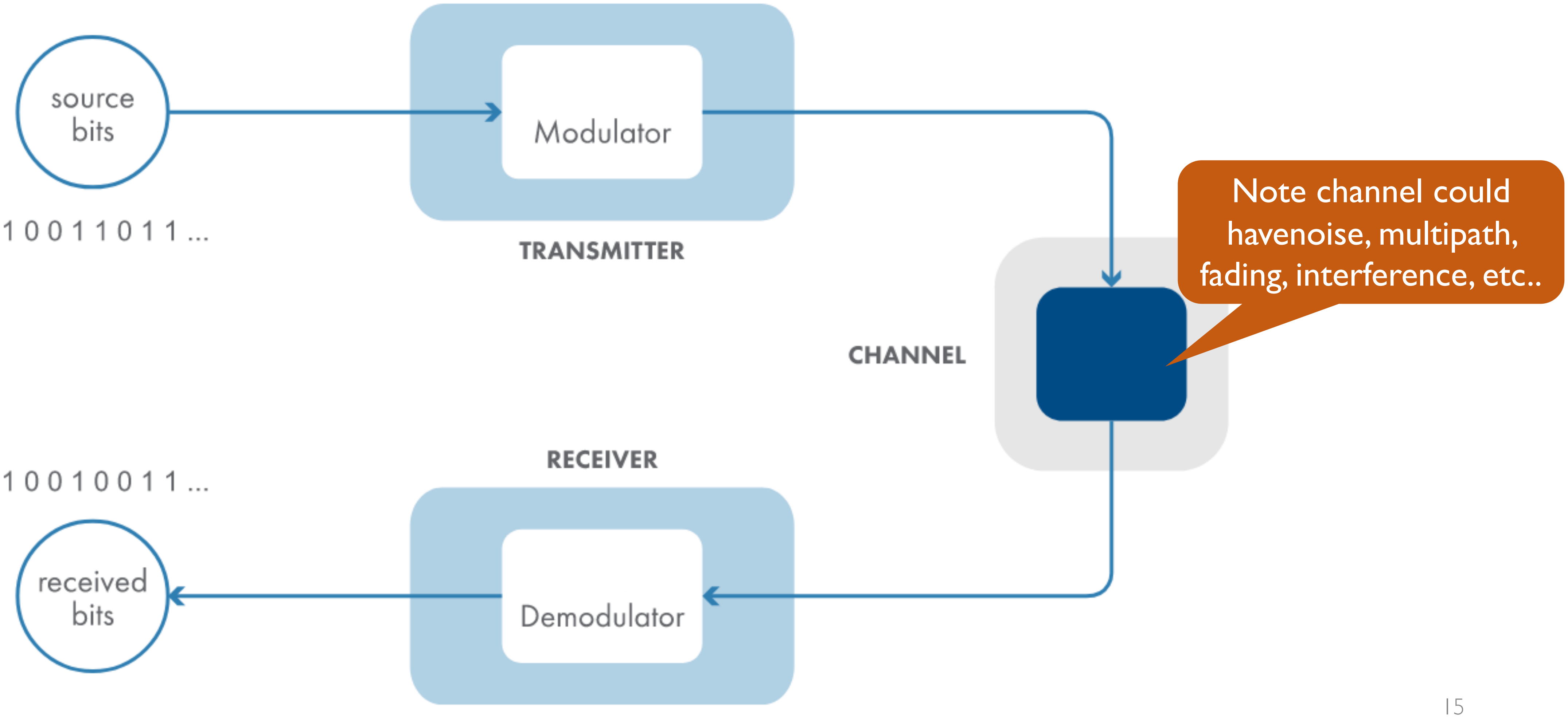


- Removing redundant or extra data that is not needed
- Decrease number of bits to reduce bandwidth
- Ex) Instead of sending 200 0's but encode number of 0's followed by 0
  - 200 0's : 200 bits
  - 0 11001000: 9 bits

The sender side story



Fuller story



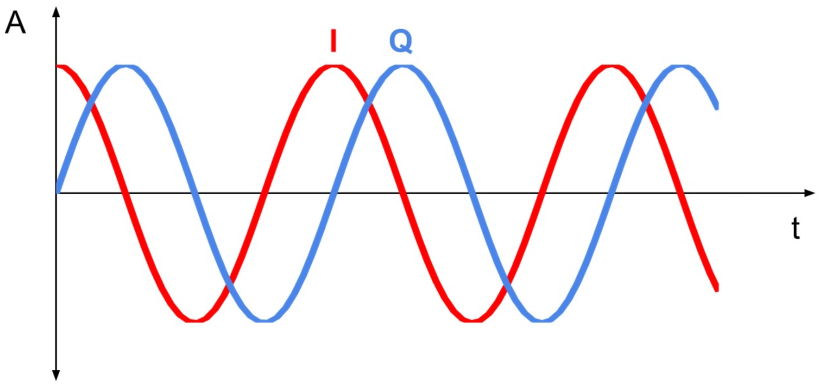
As promised,
let's talk about other modulation schemes

Outline

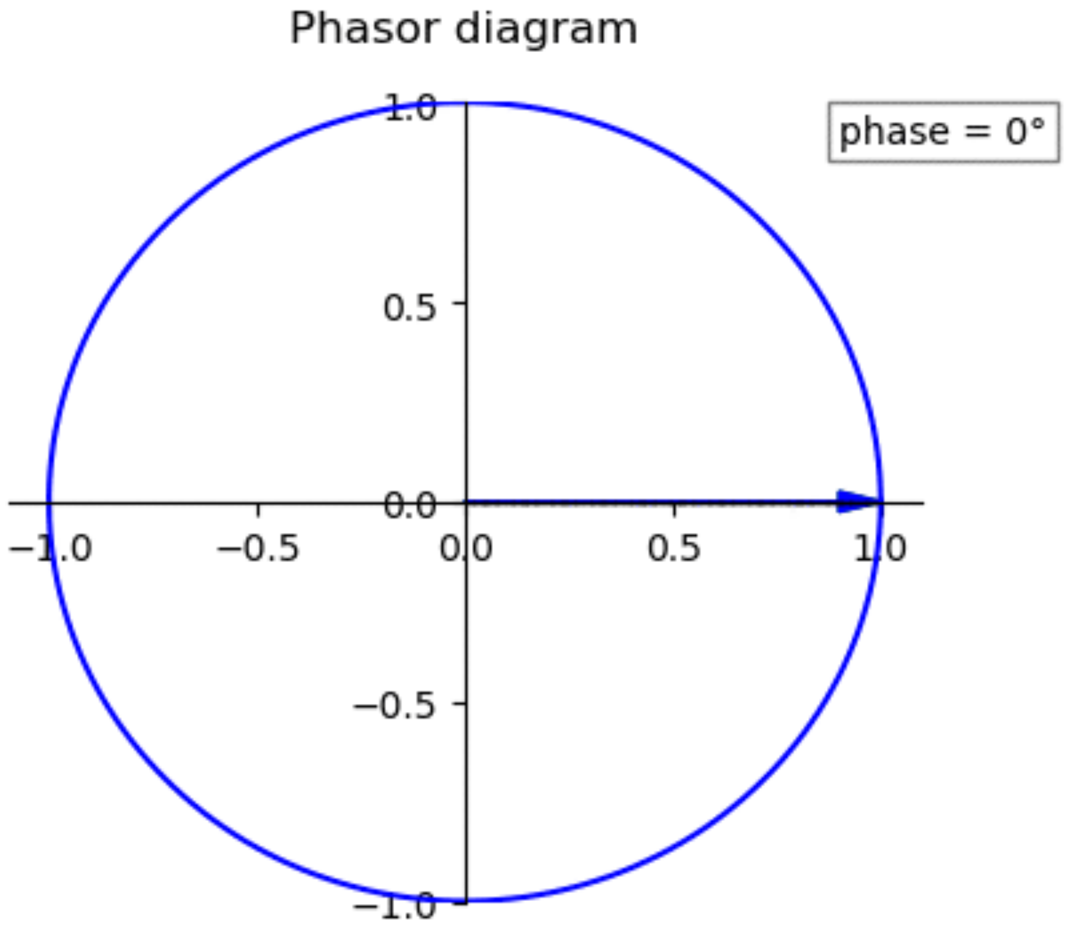
1. Sender-side Digital Communication Overview
2. Quadrature Modulation

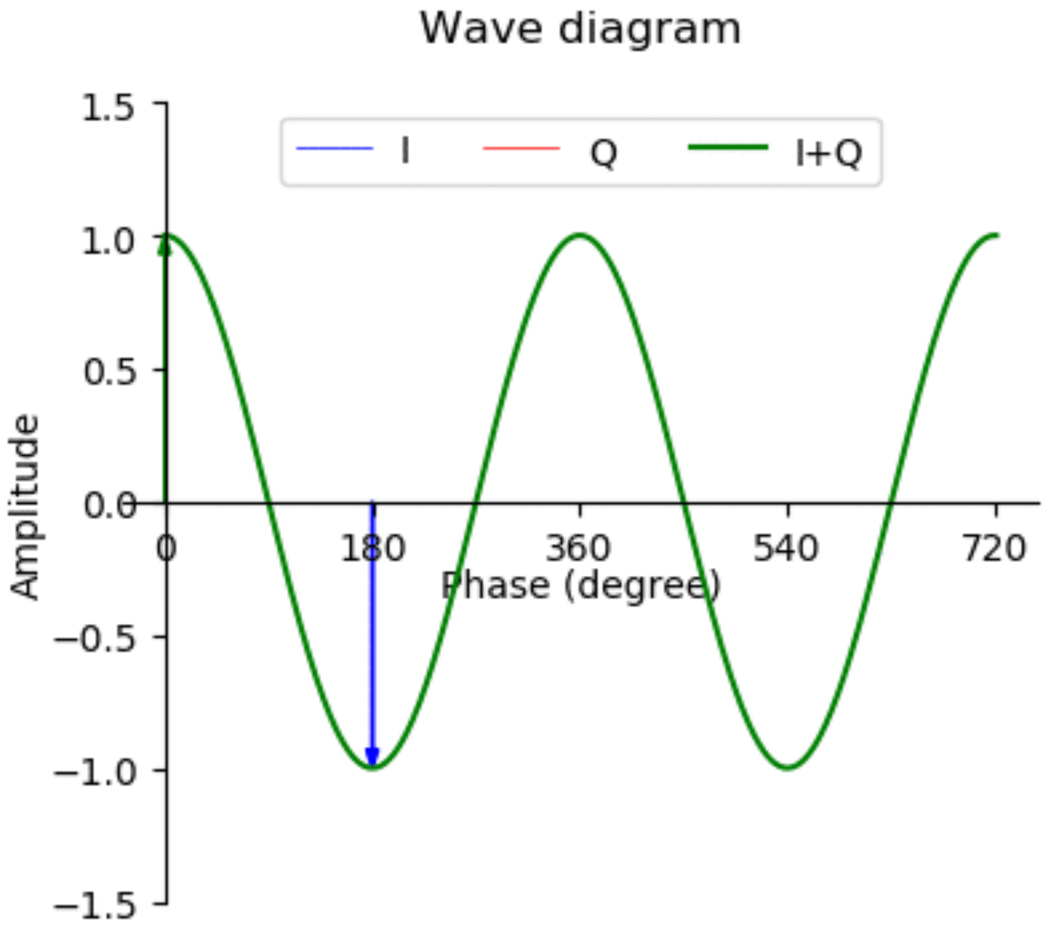
Quadrature Modulation is used to implement various modulation schemes

- Quadrature modulation uses quadrature signals
- What is Quadrature Signal?
  - Two signals are said to be Quadrature Signal when they are 90° apart in phase
  - Ex) sine and cosine waves are in quadrature
- By convention, they are called I and Q signa
  - I signal = I × cos (2 π f t)
    where I is the amplitude of "in-phase" signal
  - Q signal = Q × sin (2 π f t)
    where Q is the amplitude of "90°-shifted" signal

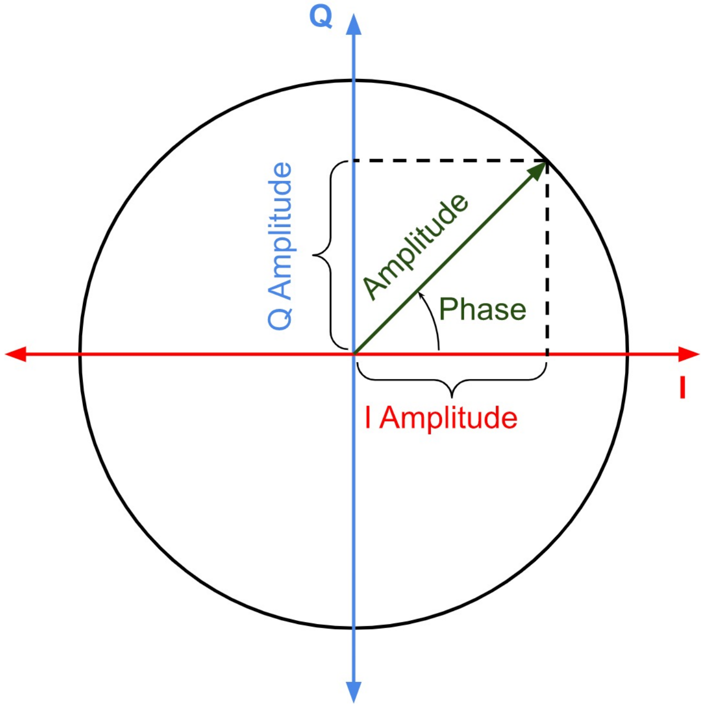


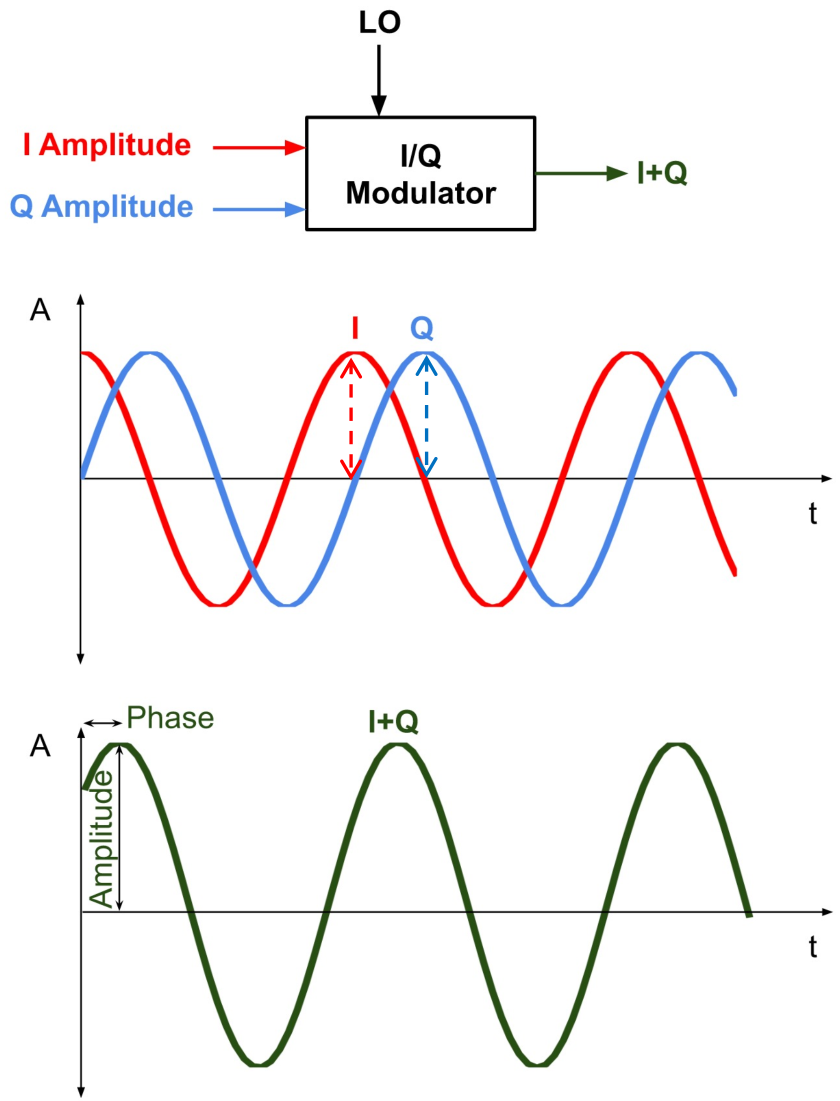
Adding `I` and Q signal



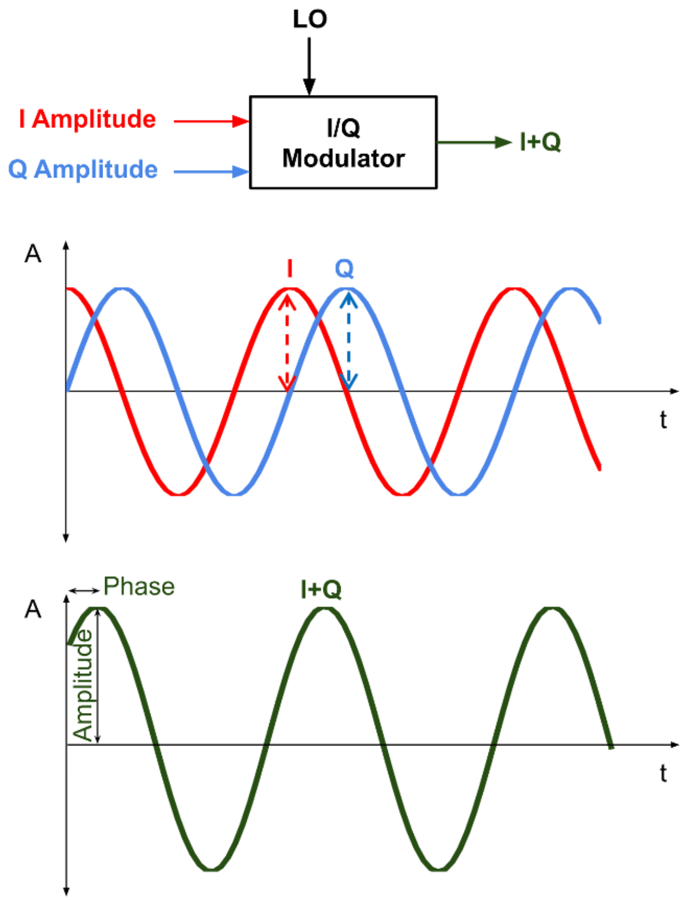


Adding I and Q signal





Varying I and Q and adding the signals up can implement various modulation



- **Amplitude modulation**
  - Vary I and Q the same amount
  - $I_{sig} + Q_{sig}$ will have varying amplitude
- **Phase modulation**
  - Vary I and Q differently
  - Ex 1) With I=0 and Q=1, we can obtain phase shift of 45°
  - Ex 2) With I=1 and Q=0, we can obtain phase shift of -45°
  - Plugging in varying I and Q will give phase modulation
- **Frequency modulation**
  - Freq modulation is a form of a phase modulation
  - Ex) $\cos(2\pi(f + \Delta)t)$ with varying Δ which can be re-written as $\cos(2\pi f t + \varphi)$ where $\varphi = 2\pi\Delta t$

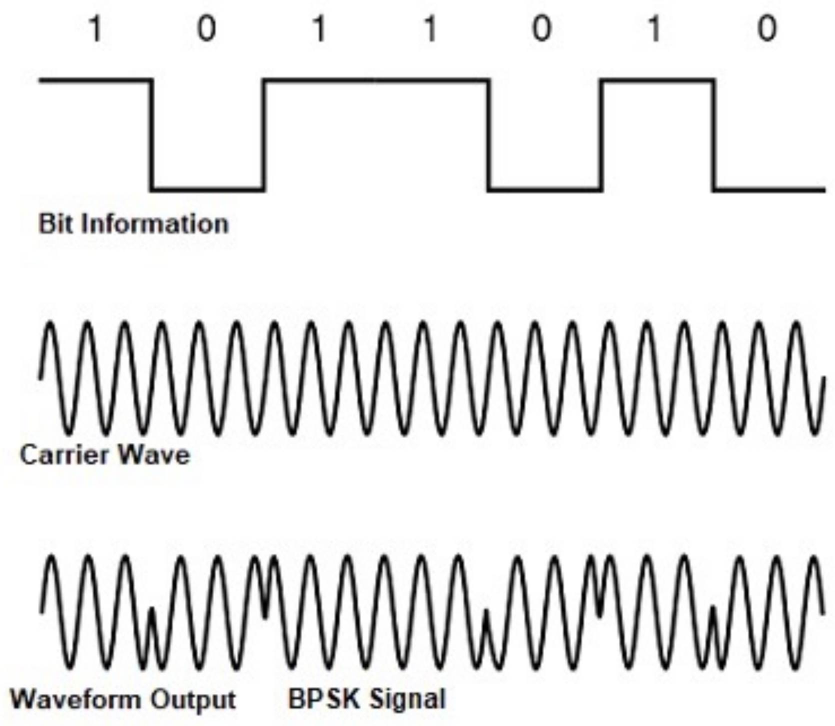
I(t) & Q(t) variations enables any combination of amplitude, phase, frequency modulation

Outline

1. Sender-side Digital Communication Overview
2. Quadrature Modulation
3. Binary Phase Shift Keying (BPSK)

Binary Phase Shift Keying (BPSK)

- Modulating signal S(t) is binary: 0 or 1
- Modulated signal M(t) should have
  - No phase shift if S(t) = 1
  - 180° phase shift if S(t) = 0

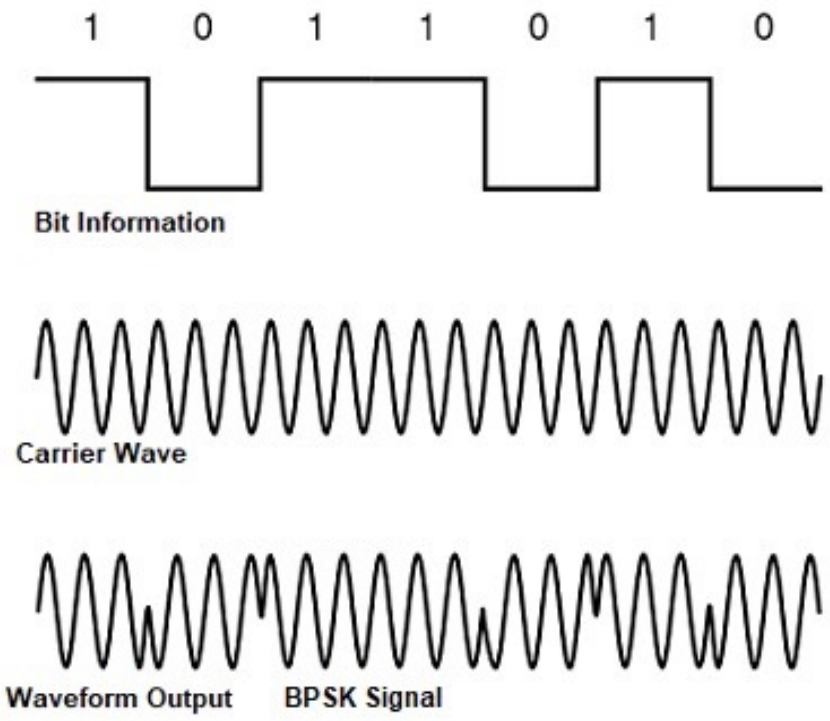


How to implement BPSK
using Quadrature signal (ie, I & Q signal)?

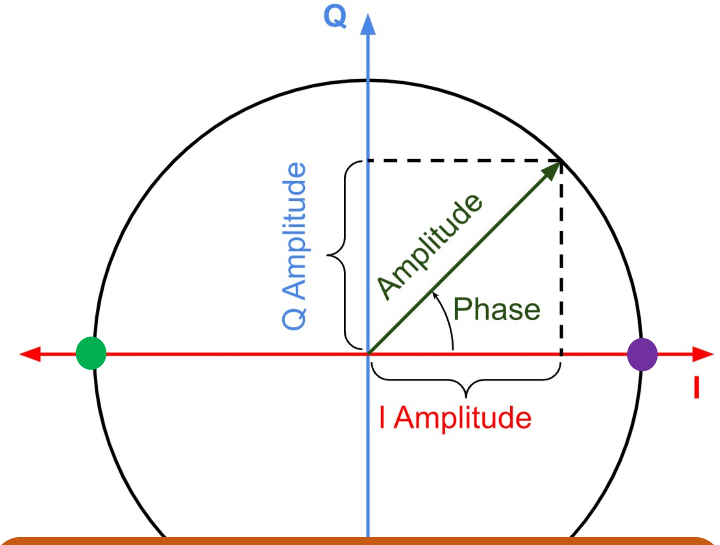
Implement BPSK using Quadrature Signal

- Encoding scheme
  - I(t) = +1 if S(t) is 1
    -1 if S(t) is 0
  - Q(t) = 0 always

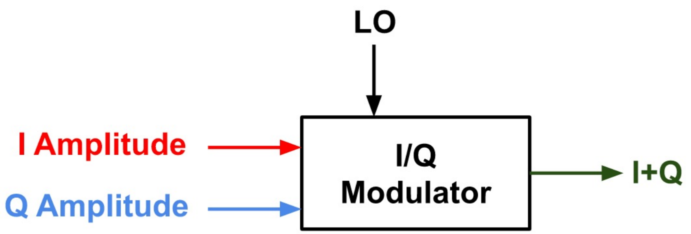
- I signal = +1 x cos (2 π fc t) if S(t) = 1
  -1 x cos (2 π fc t) if S(t) = 0
  - Note fc is the carrier frequency
- Q signal = 0

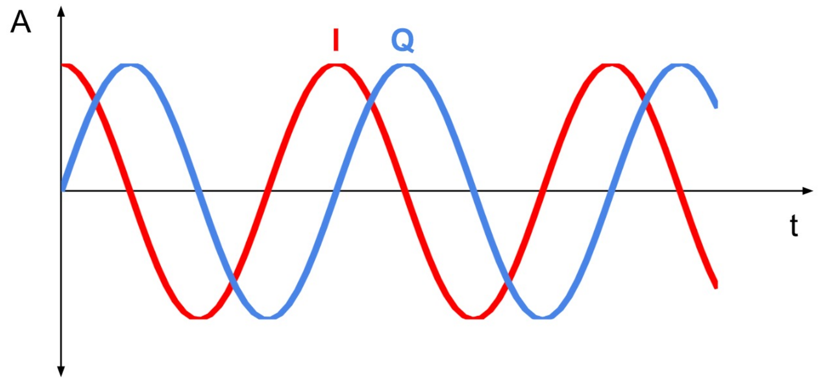


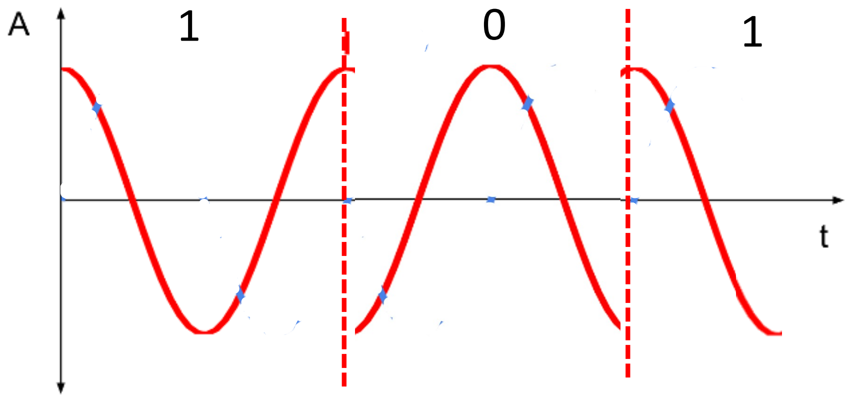
Binary Phase Shift Keying (BPSK)



Note only 2 pts
in the phasor diagram





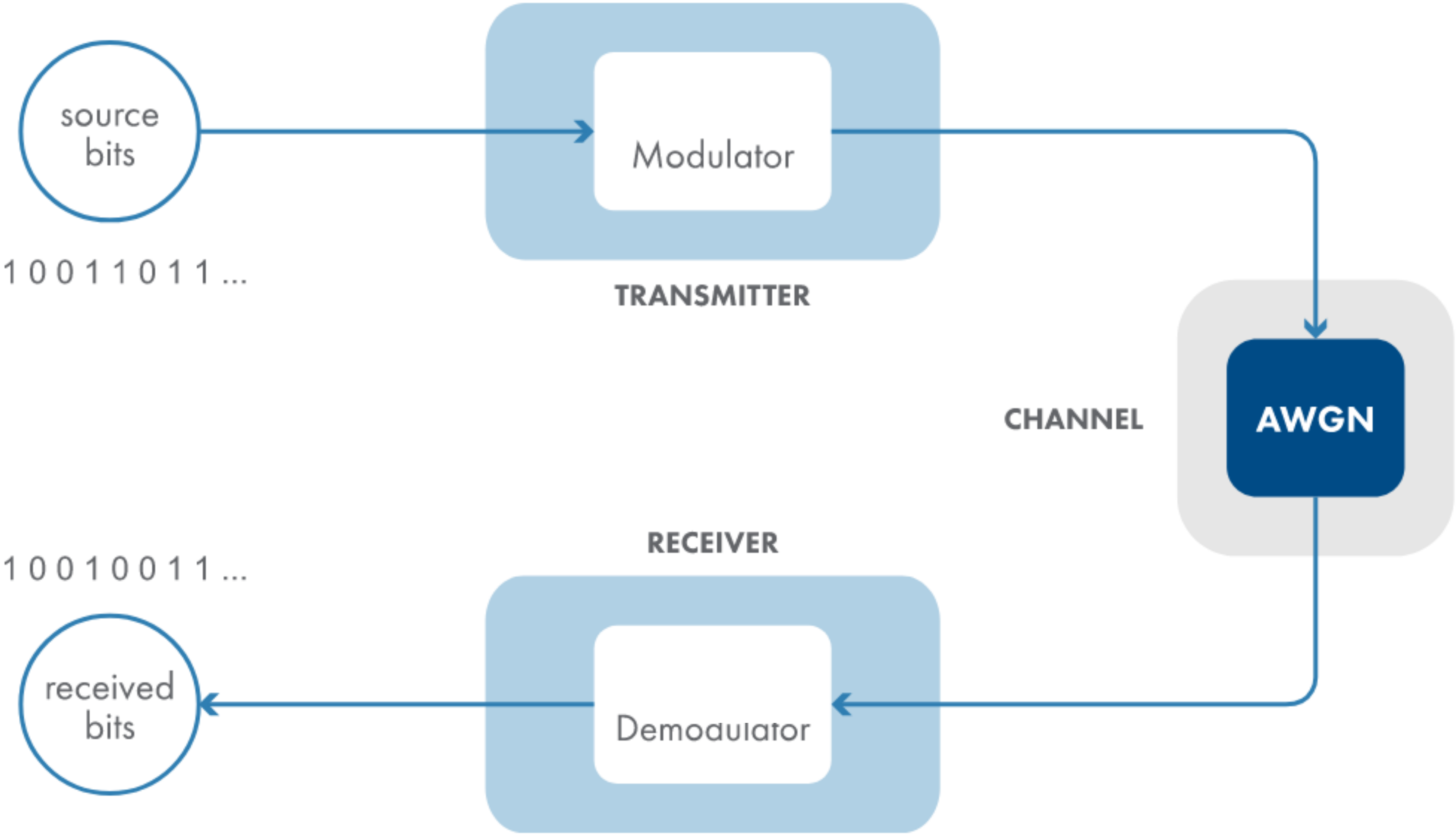


I Amplitude (V)	Q Amplitude (V)	I+Q	
		Amplitude (V)	Phase (°)
1	0	1	0
0	1	1	90
-1	0	1	180
0	-1	1	270

Matlab example

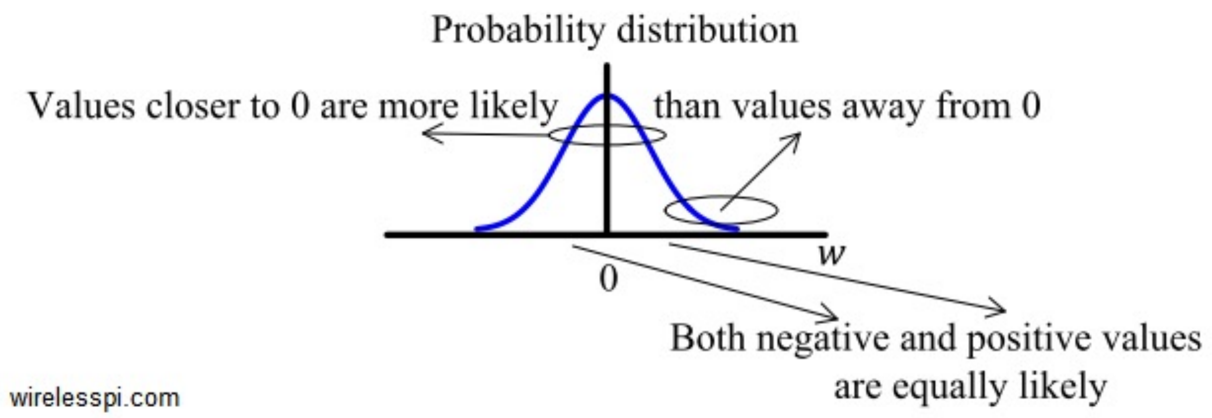
- BPSK example

Let's assume channel has noise



Additive White Gaussian Noise (AWGN)

- Additive: because it is added to any noise that might be intrinsic
- White: because it has uniform power across the frequency
- Gaussian: because it has a normal distribution in the time domain with an average time domain value of zero



Pro/Cons of BPSK

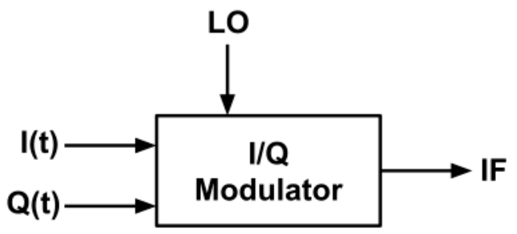
- Only 2 points in the phasor diagram (constellation)
  - Each point in phasor diagram represents 1 symbol
  - 1 symbol in this case is 1 bit only
  - Data rate (bits/sec) is the same as symbol rate (symbols/sec)
- This means low data rate
- Bit error rate is relatively low even with lower SNR as +1 and -1 are relatively far apart

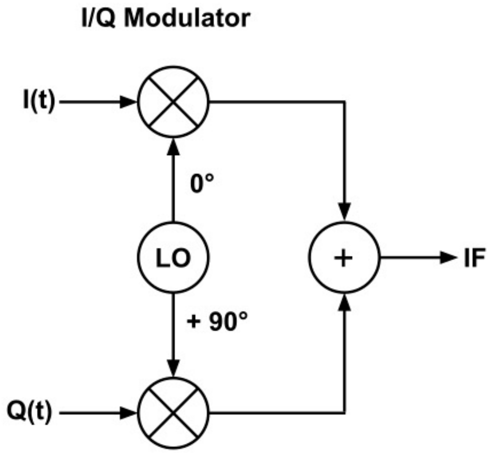
Outline

1. Sender-side Digital Communication Overview
2. Quadrature Modulation
3. Binary Phase Shift Keying (BPSK)
4. Quadrature Phase Shift Keying (QPSK)

Recap

- Bit stream has to be modulated into signal
  - Including frequency modulation into higher carrier frequency
- I/Q modulator is used to systematically generate various modulation
  - In-phase and Quadrature are 90 degree apart

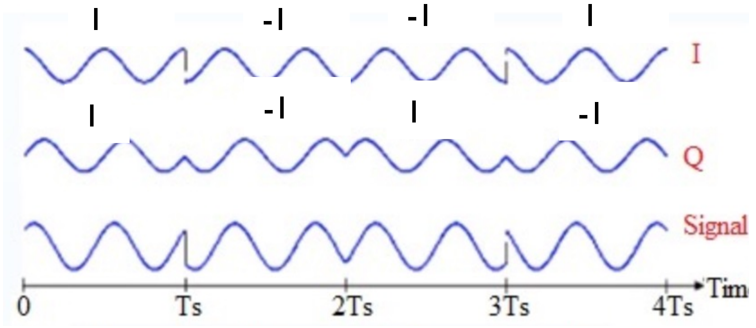




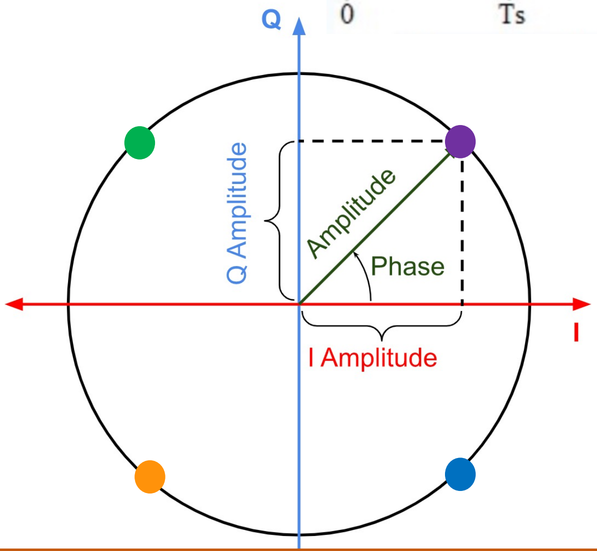
- Implementing QPSK with I/Q modulator

Quadrature Phase Shift Key (QPSK) with I/Q modulation

- We can implement QPSK by changing both I value and Q value to be +1/-1
  - +1/+1 : cos(wt)+sin(wt) = sqrt(2)*sin(wt+1*π/4)
  - -1/+1: -cos(wt)+sin(wt) == sqrt(2)*sin(wt+3*π/4)
  - -1/-1: -cos(wt)-sin(wt) == sqrt(2)*sin(wt+5*π/4)
  - +1/-1: cos(wt)-sin(wt) == sqrt(2)*sin(wt+7*π/4)



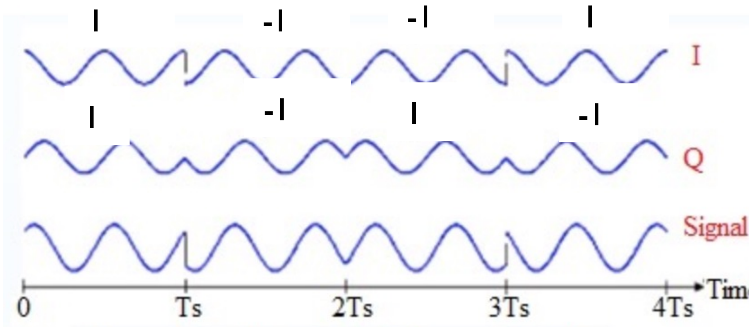
I	Q	Phase Shift
+1	+1	45°
-1	+1	135°
-1	-1	225°
+1	-1	315°



Let's find some cool facts represented here

Fact #1: There are 4 symbols in QPSK

- These waveforms are called symbols
  - Symbol1: cos(wt)+sin(wt) = sqrt(2)*sin(wt+1*π/4)
  - Symbol2: -cos(wt)+sin(wt) == sqrt(2)*sin(wt+3*π/4)
  - Symbol3: -cos(wt)-sin(wt) == sqrt(2)*sin(wt+5*π/4)
  - Symbol4: cos(wt)-sin(wt) == sqrt(2)*sin(wt+7*π/4)



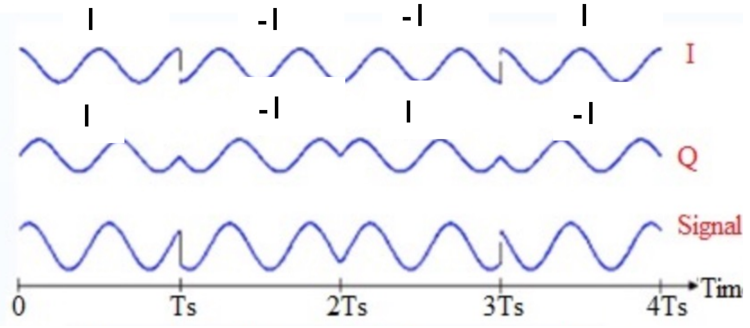
T is symbol duration

- Symbol is a state/waveform that persists over a fixed period of time (symbol duration)
  - Symbol is a unit of "data" in physical layer

In QPSK, 4 phase shifts are the 4 states where each state is a symbol

Fact #2: Each symbol can be represented as a point in phasor diagram

- 4 symbols of QPSK
  - Symbol1: cos(wt)+sin(wt) = sqrt(2)*sin(wt+1*π/4)
  - Symbol2: -cos(wt)+sin(wt) == sqrt(2)*sin(wt+3*π/4)
  - Symbol3: -cos(wt)-sin(wt) == sqrt(2)*sin(wt+5*π/4)
  - Symbol4: cos(wt)-sin(wt) == sqrt(2)*sin(wt+7*π/4)



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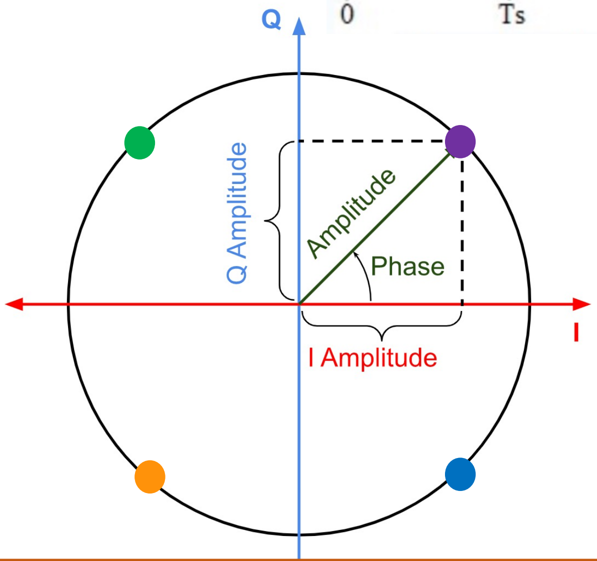
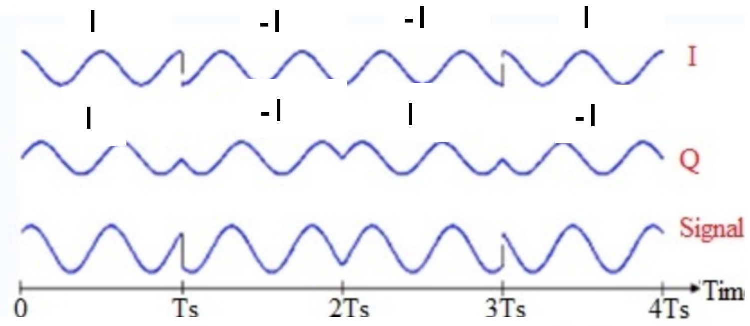


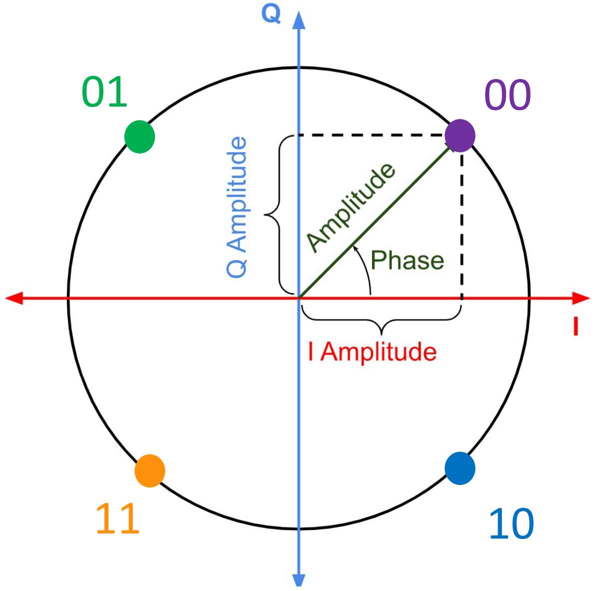
One symbol is mapped to one pts (state) in phasor diagram

Fact #3: With 4 symbols in QPSK can represent 2 bits per symbol

- 4 symbols of QPSK can represent 00, 01, 10, 11
  - Symbol1: cos(wt)+sin(wt) = sqrt(2)*sin(wt+1***π/4**)
  - Symbol2: -cos(wt)+sin(wt) == sqrt(2)*sin(wt+3***π/4**)
  - Symbol3: -cos(wt)-sin(wt) == sqrt(2)*sin(wt+5***π/4**)
  - Symbol4: cos(wt)-sin(wt) == sqrt(2)*sin(wt+7***π/**



- One possible mapping could be…



With N symbols, each symbol can represent $\log_2 N$ bits

Say we have M-order modulation scheme

- M-order modulation: a modulation with M different symbols
  - In QPSK, M = 4
- M means
  - number of symbols or states
  - number of pts in phasor diagram
- $\log_2 M$ is the num bits that one symbol can pack
  - M=4, 2 bits/symbol (00, 01, 10, 11)
  - M=8, 3 bits/symbol (000, 001, 010, 011, 100, 101, 110, 111)
  - M=16, 4 bits/symbol (0000, 0001, 0010, 0011, …)

Higher M is more bits can be sent with the same number of symbols

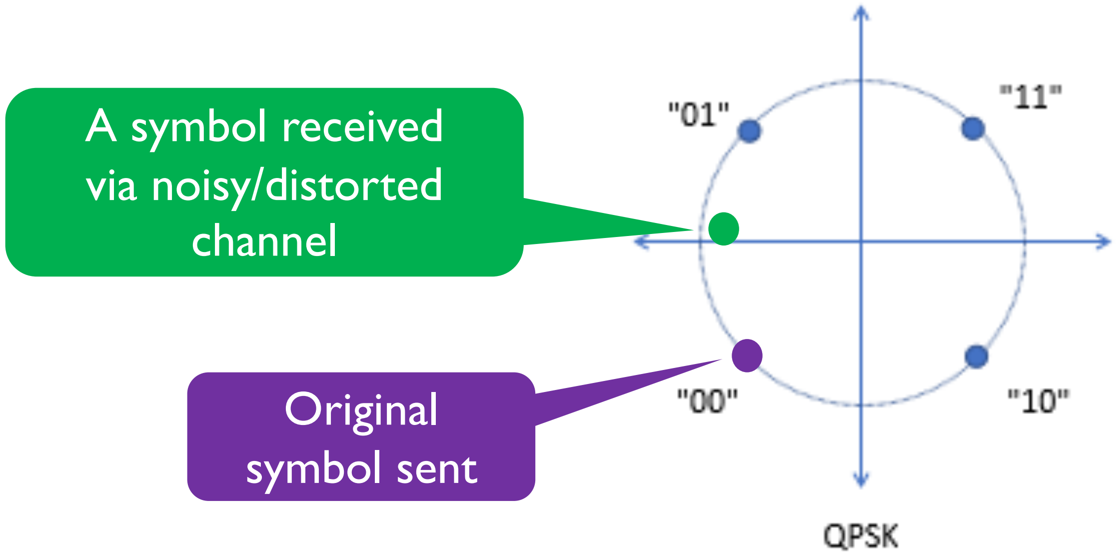
Mapping the bits to a symbol

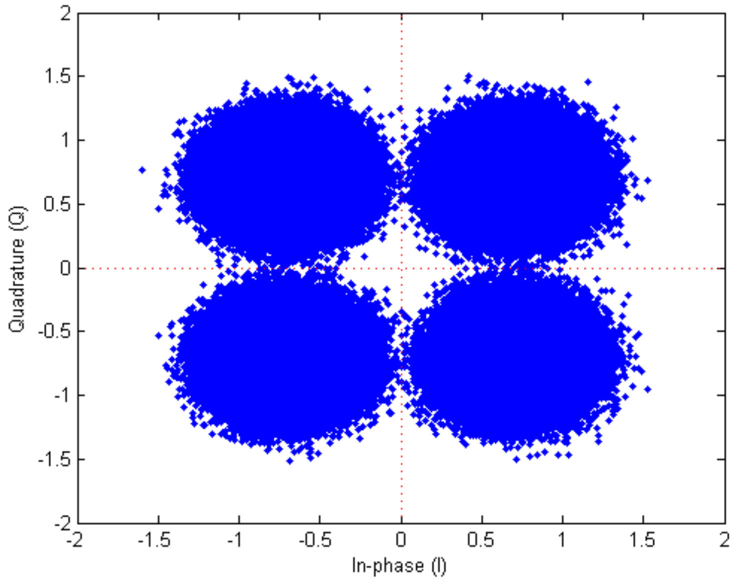
- Can we map bits arbitrarily to each symbol?
- Or would mapping have some impact on the performance?
    - In this case Bit Error Rate

But first,
what is a bit error? And when does it happen?

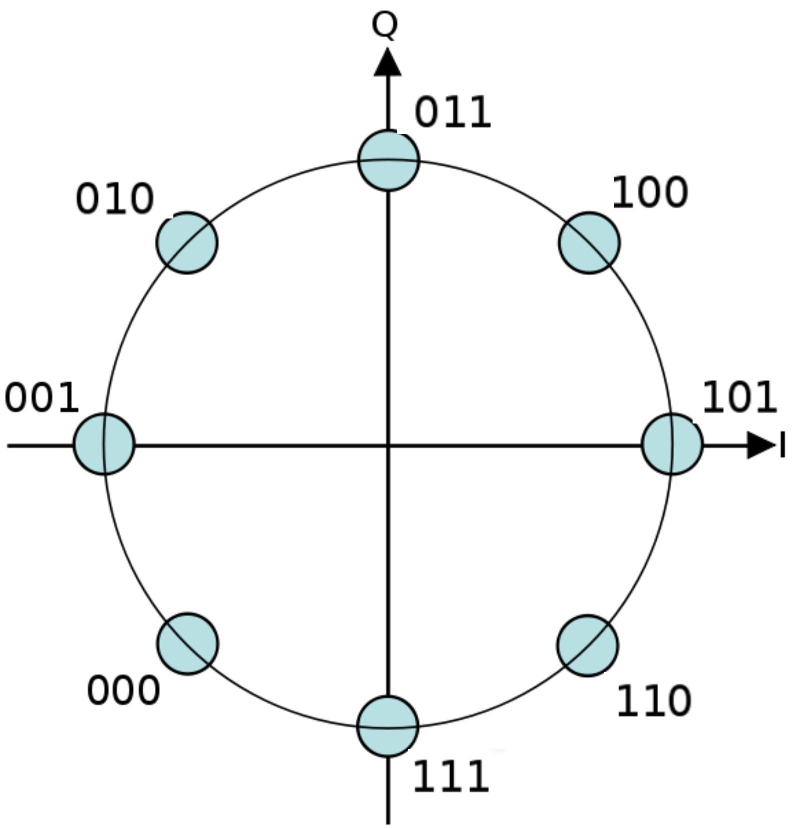
A bit error happens when a point "leaks" into adjacent area

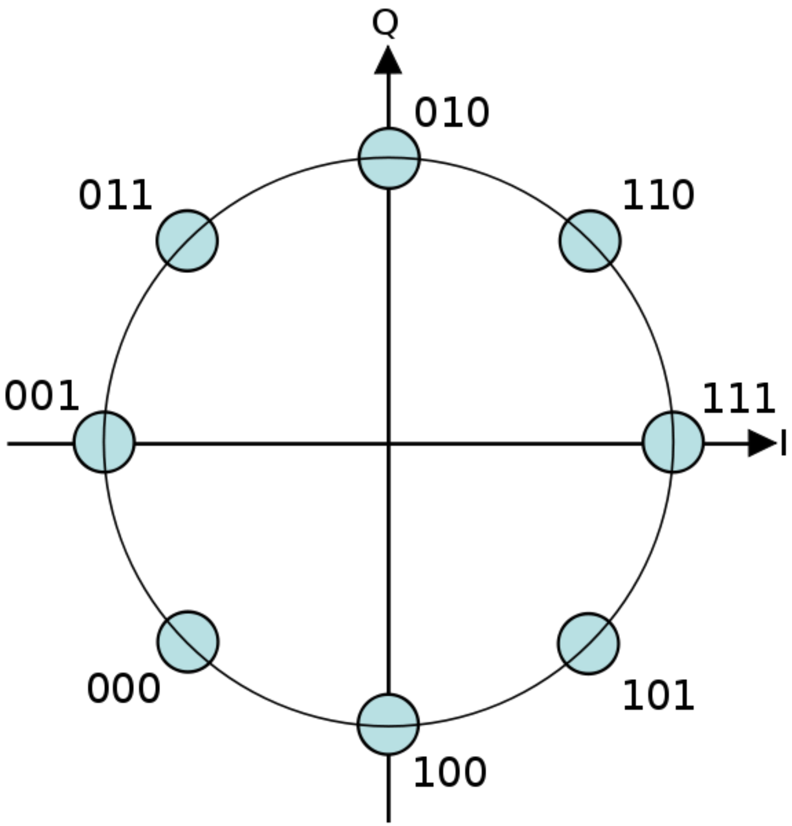
- The demodulated symbol goes onto the "other side" of the area
  - Ex) Original data sent was 00 (2-bit symbol) but misread as 01
- Due to noise, channel distortion, etc





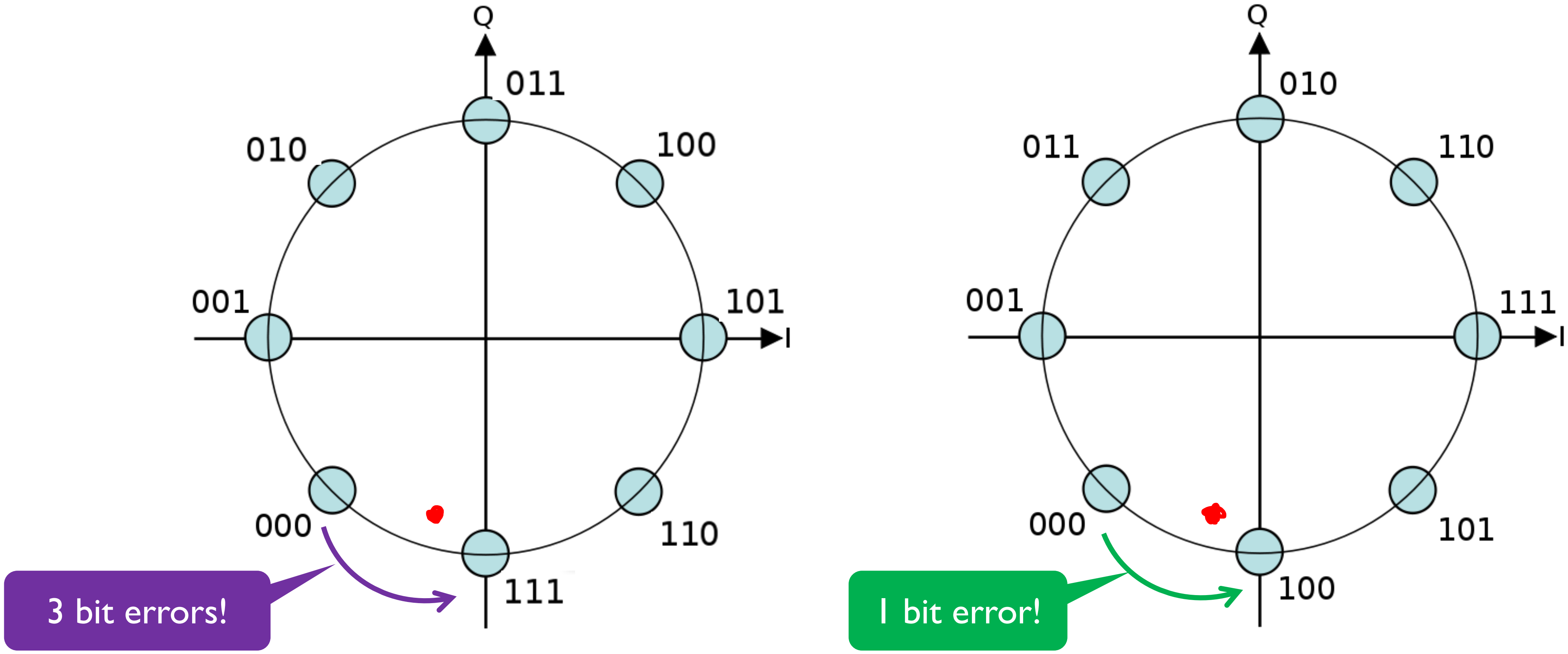
Which one will have lower BER?





Hint: which one is easier?
A symbol leaking into one of adjacent symbol vs
A symbol leaking into a symbol that is further away?

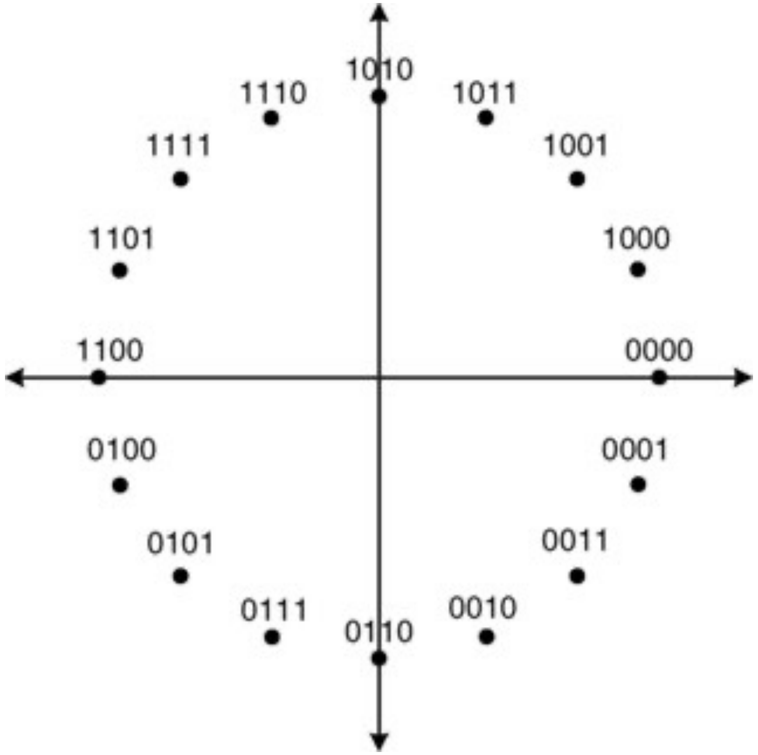
Minimizing the impact of leakage among adjacent area is critical to reduce BER

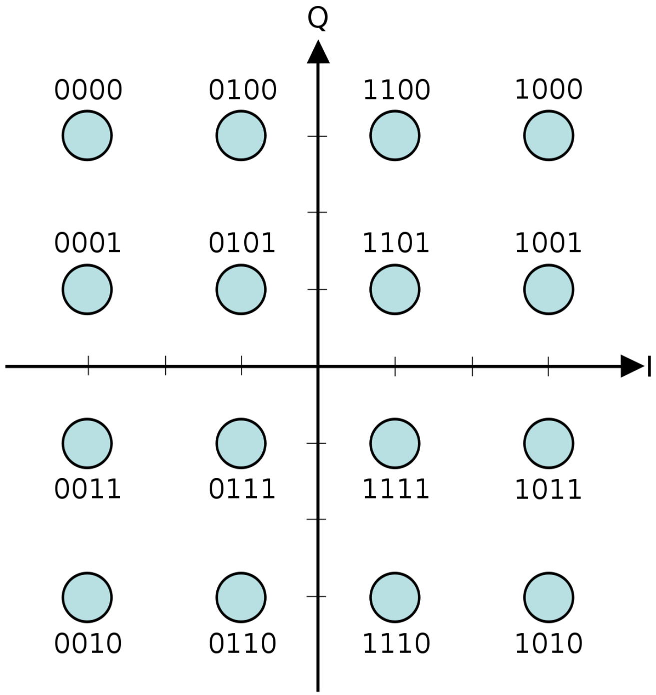


Minimize the difference btw mapped bits of adjacent points

Gray coding minimizes BER

- Mapped bits are just 1 hamming distance away from the adjacent points
  - Hamming distance: the number of bit positions in which the two bits are different





BPSK vs QPSK example

Heads-up

- More modulations to come to combat
  - Inter-symbol interference
  - Multi-path
  - etc
- Other schemes (such as filters) will be used to further improve the performance

Backup Slides