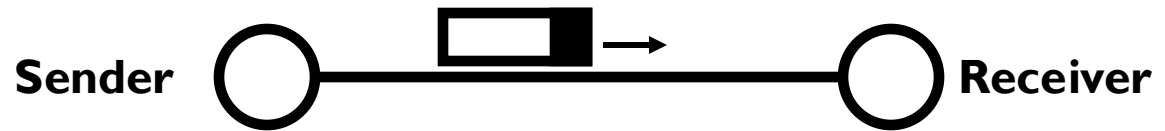


# CS/ECE 439: Wireless Networking

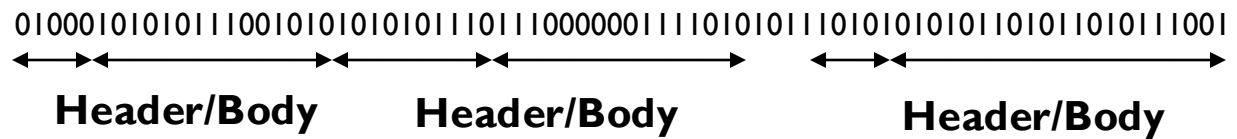
## Physical Layer – Coding and Modulation

# From Signals to Packets

Packet  
Transmission



Packets



Bit Stream

0 0 1 0 1 1 1 0 0 0 1

Digital Signal



Analog Signal



# Binary Voltage Encoding

---

- ▶ **Common binary voltage encodings**
  - ▶ Non-return to zero (NRZ)
  - ▶ NRZ inverted (NRZI)
  - ▶ Manchester (used by IEEE 802.3—10 Mbps Ethernet)
  - ▶ 4B/5B



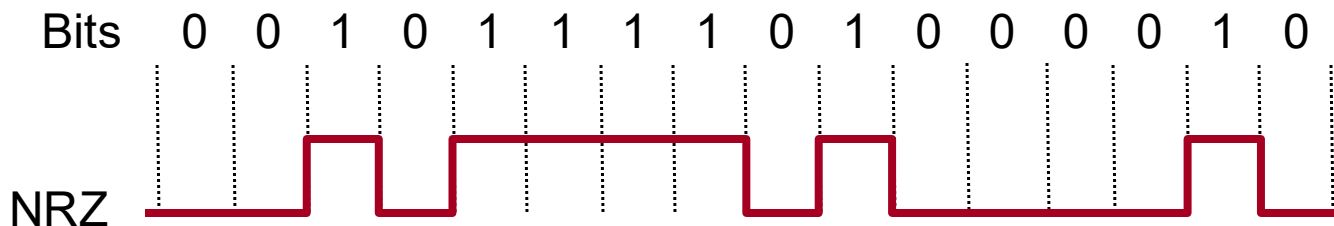
# Non-Return to Zero (NRZ)

## ▶ Signal to Data

- ▶ High  $\Rightarrow$  1
- ▶ Low  $\Rightarrow$  0

## ▶ Comments

- ▶ Transitions maintain clock synchronization
- ▶ Long strings of 0s confused with no signal
- ▶ Long strings of 1s causes baseline wander
- ▶ Both inhibit clock recovery



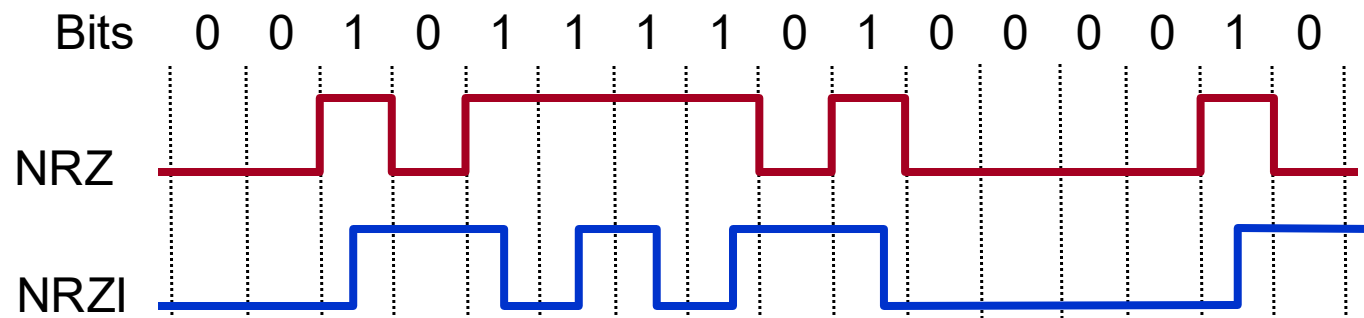
# Non-Return to Zero Inverted (NRZI)

## ► Signal to Data

- Transition  $\Rightarrow$  1
- Maintain  $\Rightarrow$  0

## ► Comments

- Solves series of 1s, but not 0s



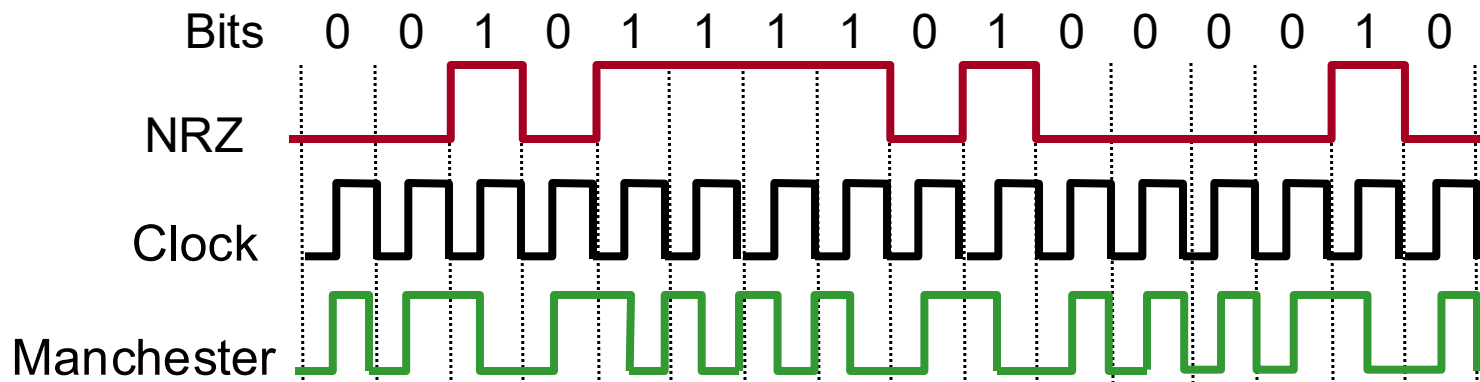
# Manchester Encoding

## ► Signal to Data

- XOR NRZ data with clock
- High to low transition  $\Rightarrow$  1
- Low to high transition  $\Rightarrow$  0

## ► Comments

- (used by IEEE 802.3—10 Mbps Ethernet)
- Solves clock recovery problem
- Only 50% efficient (  $\frac{1}{2}$  bit per transition)



# 4B/5B

---

- ▶ **Signal to Data**
  - ▶ Encode every 4 consecutive bits as a 5 bit symbol
- ▶ **Symbols**
  - ▶ At most 1 leading 0
  - ▶ At most 2 trailing 0s
  - ▶ Never more than 3 consecutive 0s
  - ▶ Transmit with NRZI
- ▶ **Comments**
  - ▶ 16 of 32 possible codes used for data
  - ▶ At least two transitions for each code
  - ▶ 80% efficient



# 4B/5B – Data Symbols

At most 1 leading 0

▶ 0000	⇒	11110
▶ 0001	⇒	01001
▶ 0010	⇒	10100
▶ 0011	⇒	10101
▶ 0100	⇒	01010
▶ 0101	⇒	01011
▶ 0110	⇒	01110
▶ 0111	⇒	01111

At most 2 trailing 0s

■ 1000	⇒	10010
■ 1001	⇒	10011
■ 1010	⇒	10110
■ 1011	⇒	10111
■ 1100	⇒	11010
■ 1101	⇒	11011
■ 1110	⇒	11100
■ 1111	⇒	11101



## 4B/5B – Control Symbols

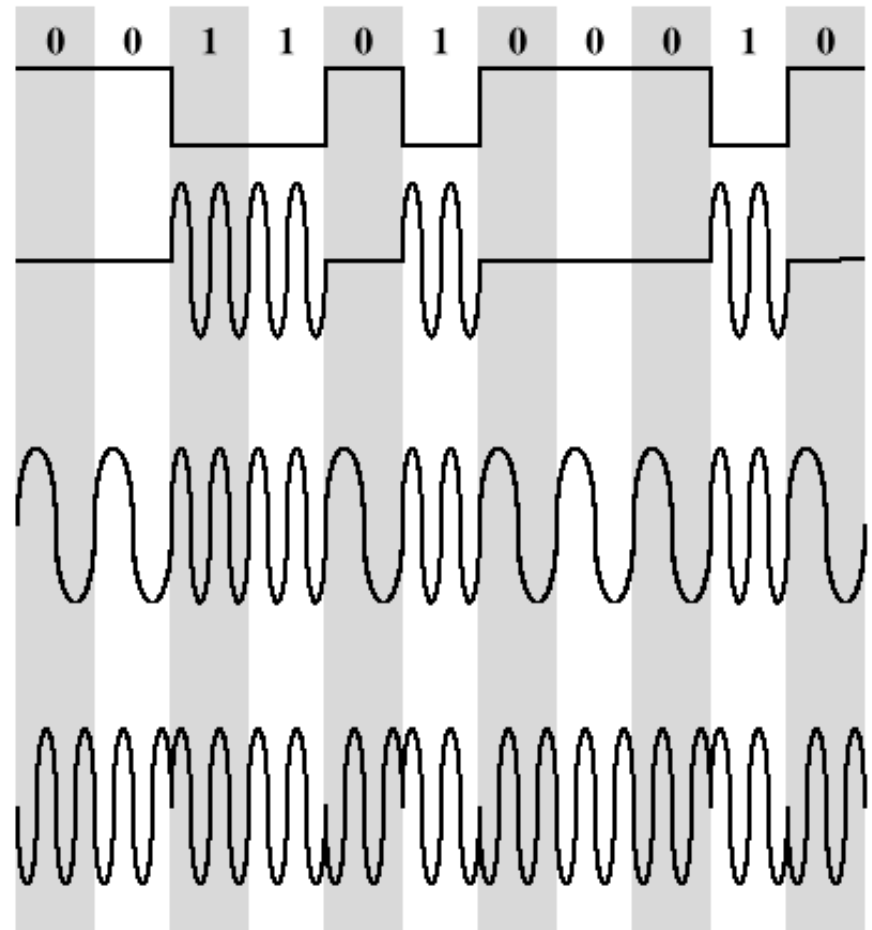
---

- ▶ 11111  $\Rightarrow$  idle
- ▶ 11000  $\Rightarrow$  start of stream 1
- ▶ 10001  $\Rightarrow$  start of stream 2
- ▶ 01101  $\Rightarrow$  end of stream 1
- ▶ 00111  $\Rightarrow$  end of stream 2
- ▶ 00100  $\Rightarrow$  transmit error
- ▶ Other  $\Rightarrow$  invalid



# 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

---

- ▶ **Binary digit (1)**
  - ▶ Represented by presence of carrier, at constant amplitude
- ▶ **Binary digit (0)**
  - ▶ 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  $A \cos(2\pi f_c t)$
- ▶ **Inefficiencies**
  - ▶ Sudden gain changes
  - ▶ Only used when bandwidth is not a concern, e.g. on voice lines (< 1200 bps) or on digital fiber



# Binary Frequency-Shift Keying (BFSK)

---

- ▶ Binary digits (0 and 1)
  - ▶ 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 (3 to 30 MHz) or coax
- ▶ Demodulator looks for power around  $f_1$  and  $f_2$



# Multiple Frequency-Shift Keying (MFSK)

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- ▶ More than two frequencies are used
  - ▶ More bandwidth efficient but more susceptible to error

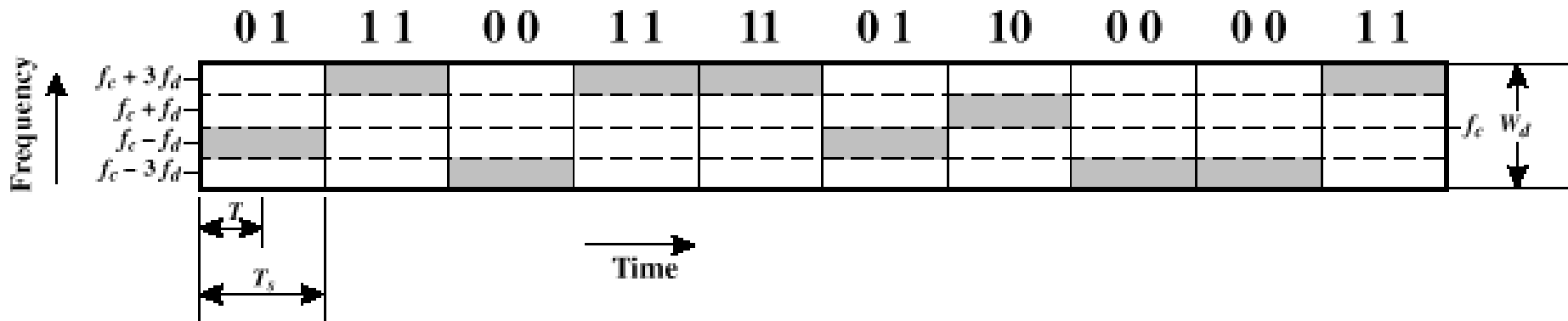
$$s_i(t) = A \cos 2\pi f_i t \quad 1 \leq i \leq M$$

- ▶  $f_i = f_c + (2i - 1 - M)f_d$
- ▶  $f_c$  = the carrier frequency
- ▶  $f_d$  = the difference frequency
- ▶  $M$  = number of different signal elements =  $2^L$
- ▶  $L$  = number of bits per signal element



# Multiple Frequency-Shift Keying (MFSK)

- ▶ More than two frequencies are used
  - ▶ More bandwidth efficient but more susceptible to error
- ▶ Each symbol represents  $L$  bits
  - ▶ Symbol length is  $T_s = LT$  seconds, where  $T$  is the bit period



# Phase-Shift Keying (PSK)

---

## ► Two-level PSK (BPSK)

- Uses two phases to represent binary digits

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

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



# Phase-Shift Keying (PSK)

## ► Differential PSK (DPSK)

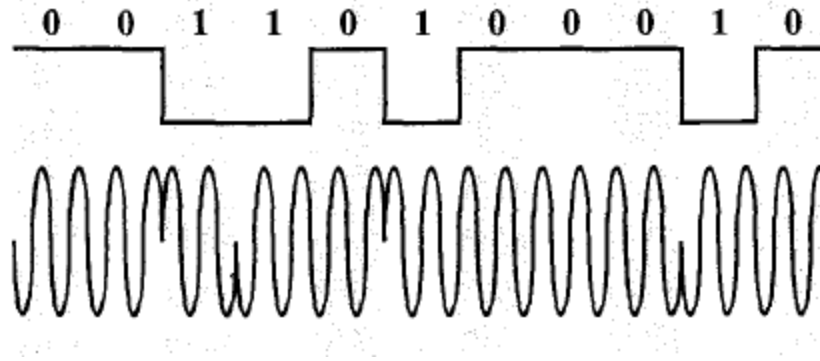
### ► Phase shift with reference to previous bit

#### ► 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
- Ex. Phase shift of multiples of  $2\pi$  ( $90^\circ$ )

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



# Phase-Shift Keying (PSK)

---

## ▶ Multilevel PSK

- ▶ Each angle has more than one amplitude
- ▶ Multiple signals elements

$$D = \frac{R}{L} = \frac{R}{\log_2 M}$$

- ▶  $D$  = modulation rate, baud
- ▶  $R$  = data rate, bps
- ▶  $M$  = number of different signal elements =  $2^L$
- ▶  $L$  = number of bits per signal element



# Quadrature Amplitude Modulation (QAM)

---

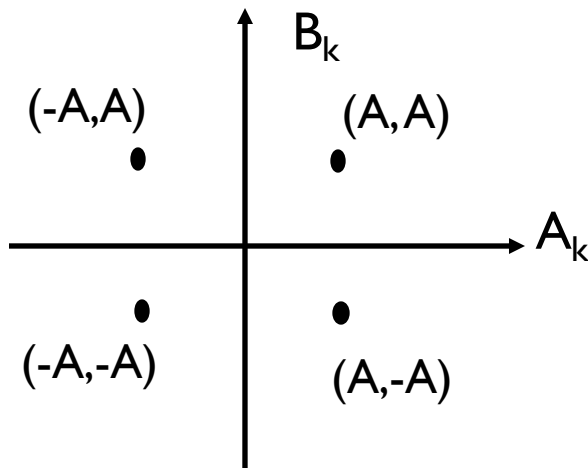
- ▶ **QAM uses two-dimensional signaling**
  - ▶ ASK and PSK
  - ▶  $A_k$  modulates in-phase  $\cos(2\pi f_c t)$
  - ▶  $B_k$  modulates quadrature phase  $\sin(2\pi f_c t)$

$$s(t) = A_k(t) \cos 2\pi f_c t + B_k(t) \sin 2\pi f_c t$$

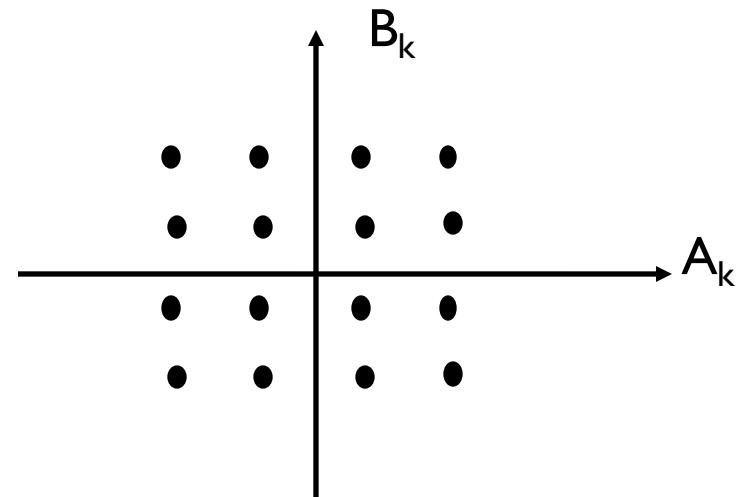


# Signal Constellations

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



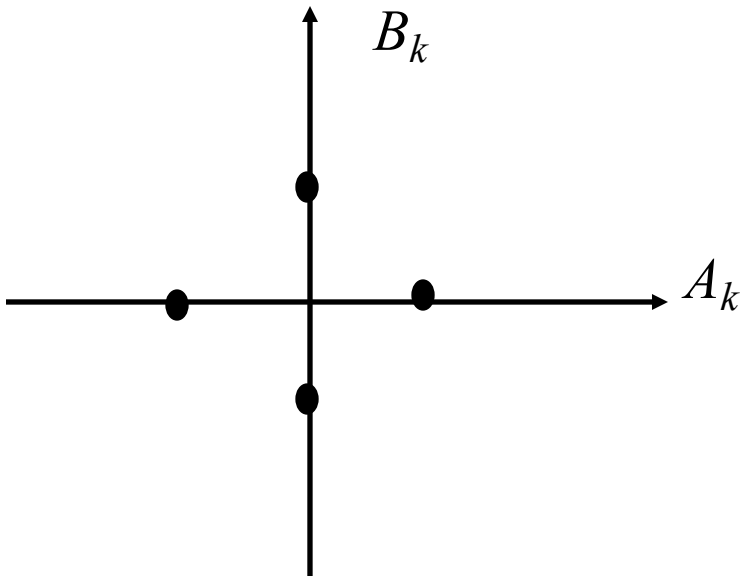
4 possible points per  $T$  sec.  
2 bits / pulse



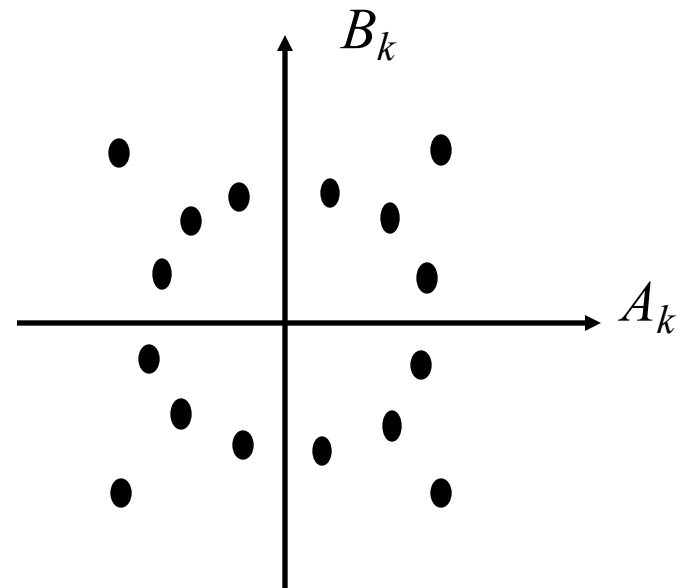
16 possible points per  $T$  sec.  
4 bits / pulse

# Other Signal Constellations

- Point selected by amplitude & phase



4 possible points per  $T$  sec.



16 possible points per  $T$  sec.

# Adapting to Channel Conditions

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- ▶ Channel conditions vary
  - ▶ Physical environment of the channel
  - ▶ Changes over time (slow and fast fading)
- ▶ Fixed coding/modulation scheme will often be inefficient
  - ▶ Too conservative for good channels
  - ▶ Too aggressive for bad channels
- ▶ 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

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- ▶ **Gaussian Frequency Shift Keying**
  - ▶  $f_{\pm}$  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

