CS/ECE 439: Wireless Networking

Physical Layer – Coding and Modulation

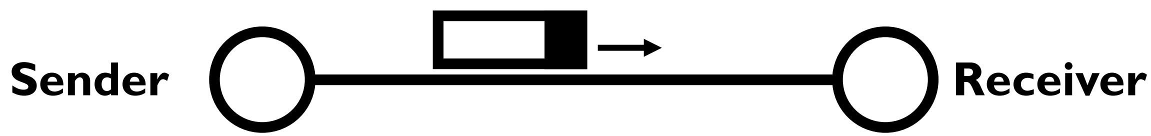
GRAINGER ENGINEERING

 Fall 2021

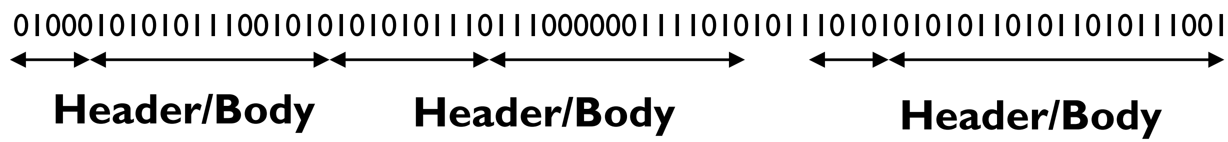
COMPUTER SCIENCE

From Signals to Packets

Packet Transmission



Packets

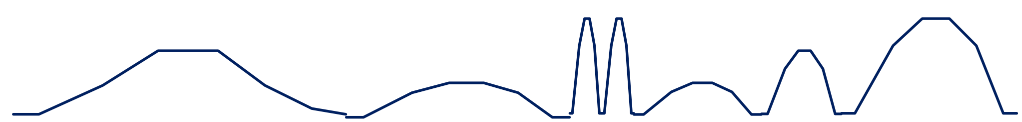


Bit Stream

0 0 1 0 1 1 1 0 0 0 1

Digital Signal

Analog Signal

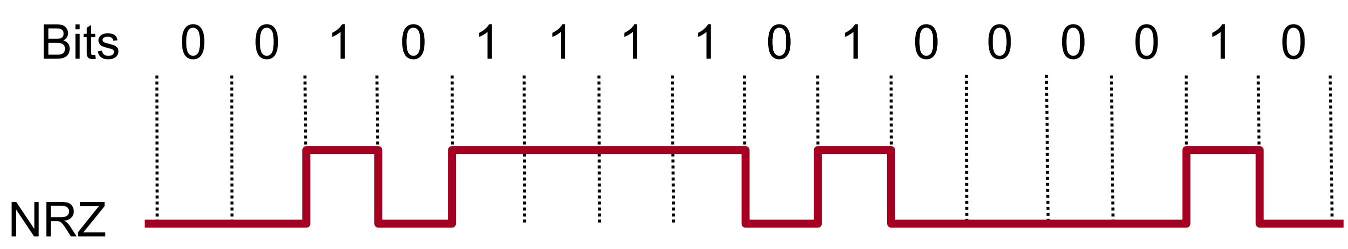


Binary Voltage Encoding

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

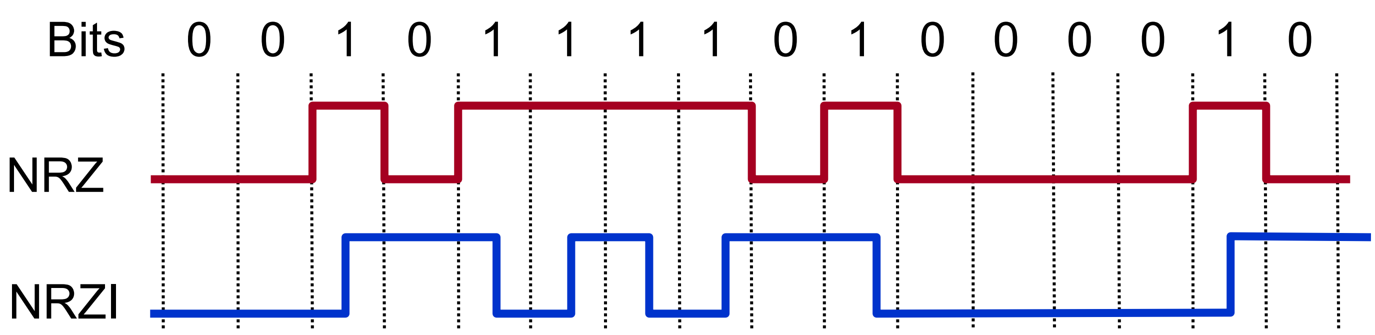
Non-Return to Zero (NRZ)

- Signal to Data
  - High ⇨ 1
  - Low ⇨ 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



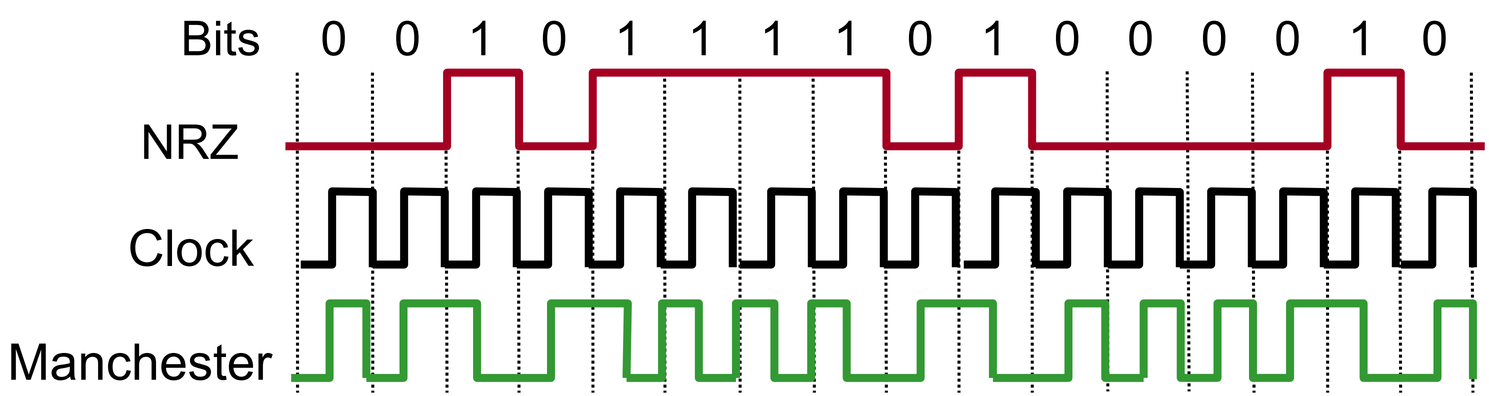
Non-Return to Zero Inverted (NRZI)

- Signal to Data
  - Transition ⇨ 1
  - Maintain ⇨ 0
- Comments
  - Solves series of 1s, but not 0s



Manchester Encoding

- Signal to Data
  - XOR NRZ data with clock
  - High to low transition ⇨ 1
  - Low to high transition ⇨ 0
- Comments
  - (used by IEEE 802.3—10 Mbps Ethernet)
  - Solves clock recovery problem
  - Only 50% efficient (½ 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

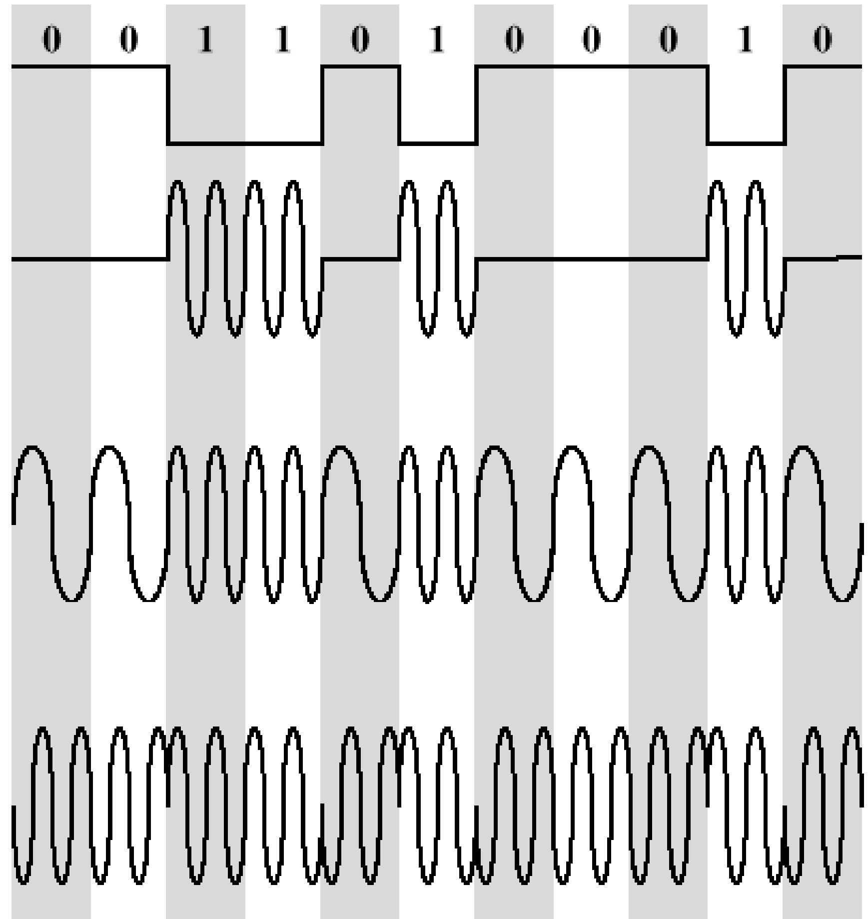
- 1000 ⇒ 10010
- 1001 ⇒ 10011
- 1010 ⇒ 10110
- 1011 ⇒ 10111
- 1100 ⇒ 11010
- 1101 ⇒ 11011
- 1110 ⇒ 11100
- 1111 ⇒ 11101

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)

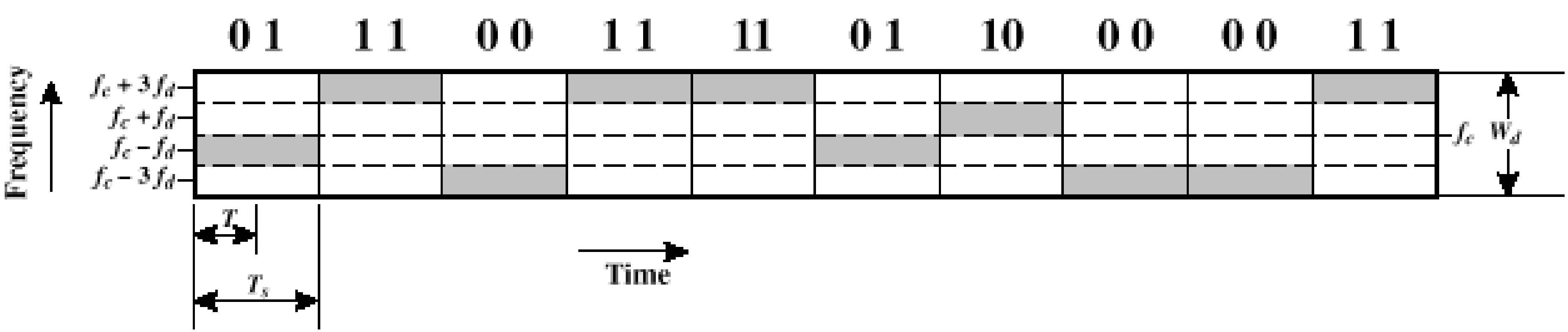
- More than two frequencies are used
  - More bandwidth efficient but more susceptible to error

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

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

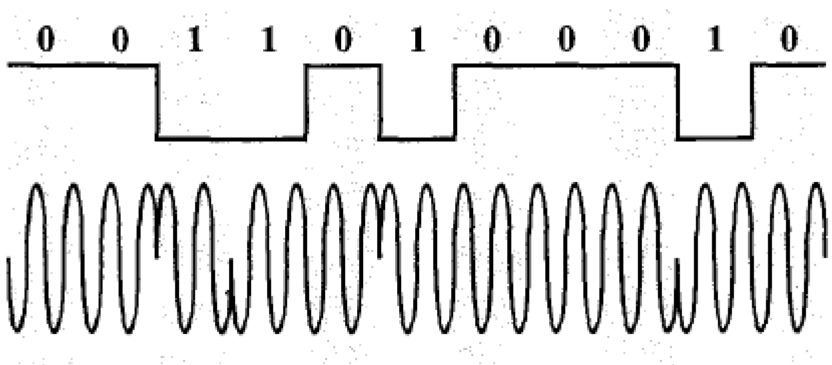
- Two-level PSK (BPSK)
  - Uses two phases to represent binary digits

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

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

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 2π (90°)

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

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

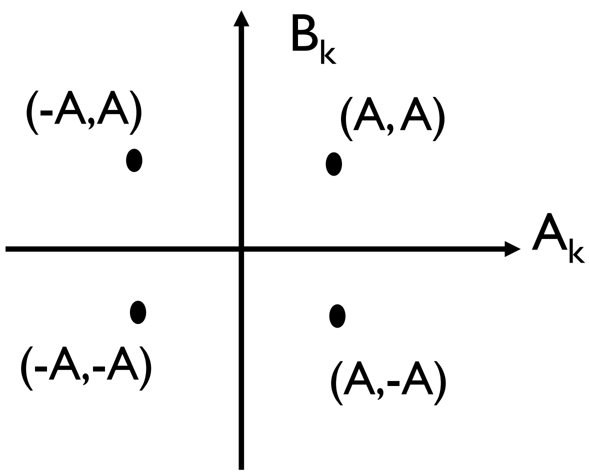
Quadrature Amplitude Modulation (QAM)

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

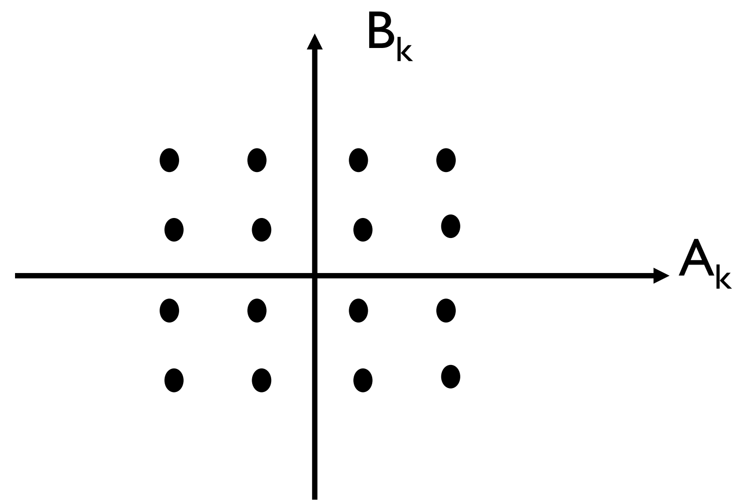
$$s(t) = A_k(t)\cos 2\pi f_c t + B_k(t)\sin 2\pi f_c t$$

Signal Constellations

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



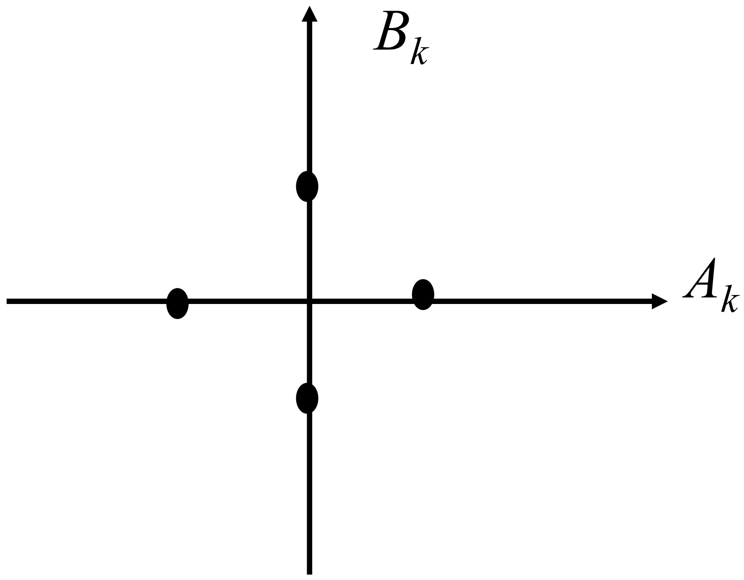
4 possible points per *T* sec.
2 bits / pulse



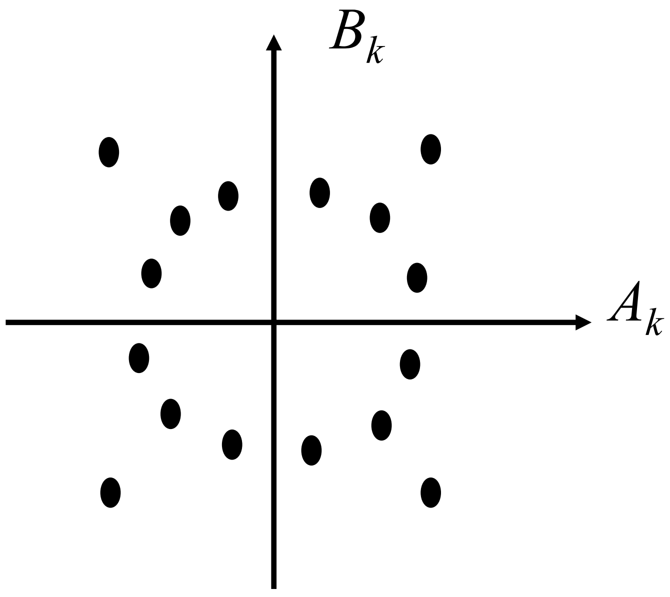
16 possible points per *T* sec.
4 bits / pulse

Other Signal Constellations

- Point selected by amplitude & phase



4 possible points per T sec.



16 possible points per T sec.

Adapting to Channel Conditions

- 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

- 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