CS/ECE 439: Wireless Networking

Physical Layer – Coding and Modulation
From Signals to Packets

Packet Transmission

Sender → Receiver

Packets

Header/Body

Bit Stream

0 0 1 0 1 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

Bits: 0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0

NRZ
Non-Return to Zero Inverted (NRZI)

- **Signal to Data**
  - Transition $\Rightarrow 1$
  - Maintain $\Rightarrow 0$

- **Comments**
  - Solves series of 1s, but not 0s

```
Bits 0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0
NRZ
NRZI
```
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 (½ bit per transition)

![Bits](0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0)

- **NRZ**
- **Clock**
- **Manchester**
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 $\Rightarrow$ 11110
- 0001 $\Rightarrow$ 01001
- 0010 $\Rightarrow$ 10100
- 0011 $\Rightarrow$ 10101
- 0100 $\Rightarrow$ 01010
- 0101 $\Rightarrow$ 01011
- 0110 $\Rightarrow$ 01100
- 0111 $\Rightarrow$ 01101
- 0110 $\Rightarrow$ 01110
- 0111 $\Rightarrow$ 01111

At most 2 trailing 0s

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

At most 1 leading 0

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

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4B/5B – Control Symbols

- 11111 ⇒ idle
- 11000 ⇒ start of stream 1
- 10001 ⇒ start of stream 2
- 01101 ⇒ end of stream 1
- 00111 ⇒ end of stream 2
- 00100 ⇒ transmit error
- Other ⇒ 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

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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

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

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

[Diagram showing frequency and time]
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 Diagram](image-url)
Phase-Shift Keying (PSK)

- Four-level PSK (QPSK)
  - Each element represents more than one bit
  - Ex. Phase shift of multiples of $2\pi$ (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