From Signals to Packets

Packet Transmission

Sender → Receiver

Packets

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<tr>
<th>Bit Stream</th>
<th>Digital Signal</th>
<th>Analog Signal</th>
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<td>0 0 1 0 1 1 1 1 0 0 0 0 1</td>
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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

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

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

\[
D = \frac{R}{L} = \frac{R}{\log_2 M}
\]

- $D = \text{modulation rate, baud}$
- $R = \text{data rate, bps}$
- $M = \text{number of different signal elements} = 2^L$
- $L = \text{number of bits per signal element}$
Performance

- \( B_T \): Bandwidth of modulated signal
- \( R \): Bit rate
  - \( 0 < r < 1 \); related to how signal is filtered

- ASK, PSK: \( B_T = (1+r)R \)
- FSK: \( B_T = 2DF + (1+r)R \)
  - \( DF = f_2 - f_c = f_c - f_1 \)
Performance

- $B_T$: Bandwidth of modulated signal
- $R$: Bit rate
  - $0 < r < 1$; related to how signal is filtered

- **MPSK**
  $$B_T = \left( \frac{1+r}{L} \right) R = \left( \frac{1+r}{\log_2 M} \right) R$$

- **MFSK**
  $$B_T = \left( \frac{(1+r)M}{\log_2 M} \right) R$$

- $L$: Number of bits encoded per signal element
- $M$: Number of different signal elements
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
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