Chapter 5: Signal Encoding Techniques

Encoding Techniques

- Digital data, digital signal
- Analog data, digital signal
- Digital data, analog signal
- Analog data, analog signal
Digital Data, Digital Signal

• Digital signal
  — Discrete, discontinuous voltage pulses
  — Each pulse is a signal element
  — Binary data encoded into signal elements

Terms (1)

• Unipolar
  — All signal elements have same sign

• Polar
  — One logic state represented by positive voltage the other by negative voltage

• Data rate
  — Rate of data transmission in bits per second

• Duration or length of a bit
  — Time taken for transmitter to emit the bit
Terms (2)

- **Modulation rate**
  - Rate at which the signal level changes
  - Measured in baud = signal elements per second

- **Mark and Space**
  - Binary 1 and Binary 0 respectively

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**Data Transmission Terms**

<table>
<thead>
<tr>
<th>Term</th>
<th>Units</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Data element</td>
<td>Bits</td>
<td>A single binary one or zero</td>
</tr>
<tr>
<td>Data rate</td>
<td>Bits per second (bps)</td>
<td>The rate at which data elements are transmitted</td>
</tr>
</tbody>
</table>
| Signal element                | Digital: a voltage pulse of constant amplitude  
                                   | Analog: a pulse of constant frequency, phase, and amplitude                | That part of a signal that occupies the shortest interval of a signaling code |
| Signaling rate or modulation rate | Signal elements per second (baud) | The rate at which signal elements are transmitted                          |
Interpreting Signals

- **Need to know**
  - Timing of bits - when they start and end
  - Signal levels
- **Factors affecting successful interpreting of signals**
  - Signal to noise ratio
  - Data rate
  - Bandwidth
  - Synchronization

Comparison of Encoding Schemes (1)

- **Signal Spectrum**
  - Lack of high frequencies reduces required bandwidth
  - Lack of DC component allows AC coupling via transformer, providing isolation
  - Concentrate power in the middle of the bandwidth

- **Clocking**
  - Synchronizing transmitter and receiver
  - External clock
  - Sync mechanism based on signal
Comparison of Encoding Schemes (2)

• Error detection
  — Can be built in to signal encoding

• Signal interference and noise immunity
  — Some codes are better than others

• Cost and complexity
  — Higher signal rate (& thus data rate) lead to higher costs
  — Some codes require signal rate greater than data rate

Encoding Schemes

• Nonreturn to Zero-Level (NRZ-L)
• Nonreturn to Zero Inverted (NRZI)
• Bipolar -AMI
• Pseudoternary
• Manchester
• Differential Manchester
• B8ZS
• HDB3
**Nonreturn to Zero-Level (NRZ-L)**

- Two different voltages for 0 and 1 bits
- Voltage constant during bit interval
  - no transition, i.e. no return to zero voltage
  - in general, absence of voltage for "0, constant positive voltage for 1
  - More often, negative voltage for “1” value and positive for the “0”
- This is NRZ-L
Nonreturn to Zero Inverted

- Nonreturn to zero inverted on ones
  - Constant voltage pulse for duration of bit
  - Data encoded as presence or absence of signal transition at beginning of bit time

  - Transition denotes a binary 1
    - (low to high or high to low)
  - No transition denotes binary 0

  - An example of differential encoding

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NRZ

| 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 |

NRZ-L

NRZI
Differential Encoding

- Data represented by changes rather than levels
  - More reliable detection of transition rather than level
  - In complex transmission layouts it is easy to lose sense of polarity

NRZ pros and cons

- Pros
  - Easy to engineer
  - Make good use of bandwidth

- Cons
  - dc component
  - Lack of synchronization capability

- Used for magnetic recording
- Not often used for signal transmission
Multilevel Binary

- Use more than two levels
- Bipolar-AMI
  - "0" represented by no line signal
  - "1" represented by positive or negative pulse
  - "1" pulses alternate in polarity
  - No loss of sync if a long string of "1"s ("0" still a problem)
  - No net dc component
  - Lower bandwidth
  - Easy error detection

Pseudoternary

- "1" represented by absence of line signal
- "0" represented by alternating positive and negative
- No advantage or disadvantage over bipolar-AMI
Bipolar-AMI and Pseudoternary

Bipolar-AMI
(most recent preceding 1 bit has negative voltage)

Pseudoternary
(most recent preceding 0 bit has negative voltage)

Trade-Off for Multilevel Binary

• Not as efficient as NRZ
  — Each signal element only represents one bit
  — 3 level system could represent \( \log_2 3 = 1.58 \) bits
  — Receiver must distinguish between three levels (+A, -A, 0)
  — Requires approx. 3dB more signal power for same probability of bit error
Manchester Encoding

• Transition in middle of each bit period
• Transition serves as clock and data
• Low to high represents one
• High to low represents zero
• Used by IEEE 802.3 (CSMA/CD, i.e. Ethernet)
Differential Manchester

- Mid-bit transition is clocking only
- Transition at start of a bit period represents zero
- No transition at start of a bit period represents one
- Note: this is a differential encoding scheme
- Used by IEEE 802.5 (token ring)

Differential Manchester Encoding

BTW: does anything seem wrong here?
Biphase Pros and Cons

Manchester and Diff. Manchester are called *Biphase*

- **Con**
  - At least one transition per bit time and possibly two
  - Maximum modulation rate is twice NRZ
  - Requires more bandwidth

- **Pros**
  - Synchronization on mid bit transition (self clocking)
  - No dc component
  - Error detection
    - Absence of expected transition

Modulation Rate
**Scrambling**

- Use scrambling to replace sequences that would produce constant voltage
- **Filling sequence**
  - Must produce enough transitions to sync
  - Must be recognized by receiver and replace with original
  - Same length as original
- No dc component
- No long sequences of zero level line signal
- No reduction in data rate
- Error detection capability

**B8ZS**

- Bipolar With 8 Zeros Substitution
- Based on bipolar-AMI
- If octet of all zeros and last voltage pulse preceding was positive encode as 000+-0--
- If octet of all zeros and last voltage pulse preceding was negative encode as 000-+0+-
- Causes two violations of AMI code
- Unlikely to occur as a result of noise
- Receiver detects and interprets as octet of all zeros
Data Encoding

- **HDB3 - (High Density Bipolar 3)**
  - Commonly used in Europe and Japan
  - Similar to bipolar AMI, except that any string of four zeros is replaced by a string with one code violation

  - **Rules:**
    - replace every string of 4 zeros by 000V
      - V is a code violation
    - this might result in DC components if consecutive strings of 4 zeros are encoded -- in this case the pattern B00V is used
      - B is a level inversion and
      - V is the code violation
    - general rule: use patterns 000V and B00V such that the violations alternate, thereby avoiding DC components

![Figure 5.6 Encoding Rules for B8ZS and HDB3](image)
Test your understanding and see solutions on next slide

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</table>

NRZ-L
NRZI
Bipolar-AMI
Pseudoternary
Manchester
Differential Manchester
Test your understanding and see solutions on next slide

Bipol. AMI

B8ZS

HDB3

B = Valid bipolar signal
V = Bipolar violation

(odd number of 1s since last substitution)
Digital Data, Analog Signal

- Public telephone system
  - 300Hz to 3400Hz
  - Use modem (modulator-demodulator)
- Amplitude shift keying (ASK)
- Frequency shift keying (FSK)
- Phase shift keying (PSK)

Amplitude Shift Keying

![Amplitude Shift Keying Diagram](image)

Hal96 fig 2.18
Amplitude Shift Keying

- Amplitude Modulation
  - carrier frequency
  - signal to be modulated
  - spectrum

![Diagram of frequency spectrum with labels](image)

Now, we know that

\[ 2 \cos A \cos B = \cos(A - B) + \cos(A + B) \]

Therefore we have:

\[ v_{\text{ASK}}(t) = \frac{1}{2} \cos \omega_c t \]

\[ + \frac{1}{\pi} \{ \cos(\omega_c - \omega_0) t + \cos(\omega_c + \omega_0) t \} \]

\[ - \frac{1}{3} \left[ \cos(\omega_c - 3\omega_0) t + \cos(\omega_c + 3\omega_0) t \right] + ... \]
Frequency Shift Keying

- Frequency Modulation
  - different carrier frequencies
  - signal to be modulated
  - spectrum

\[ f_0 \text{ = Fundamental frequency component = 1/4 bit rate (Hz)} \]
\[ f_s \text{ = Frequency shift} \]
How does FSK work?

\[ v_{FSK}(t) = \cos \omega_1 t \cdot v_d(t) + \cos \omega_2 t \cdot v_d(t) \]

The two carriers are \( \omega_1 \) and \( \omega_2 \) and \( v_d(t) = 1 - v_d(t) \)

\[ v_{FSK}(t) = \cos \omega_1 t \left\{ \frac{1}{2} + \frac{2}{\pi} (\cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + ...) \right\} \]

\[ + \cos \omega_2 t \left\{ \frac{1}{2} - \frac{2}{\pi} (\cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + ...) \right\} \]

Therefore we have:

\[ v_{FSK}(t) = \frac{1}{2} \cos \omega_1 t + \frac{1}{\pi} \left\{ \cos (\omega_1 - \omega_0) t + \cos (\omega_1 + \omega_0) t \right\} \]

\[ - \frac{1}{3} \cos (\omega_1 - 3\omega_0) t + \cos (\omega_1 + 3\omega_0) t + ... \}

\[ + \frac{1}{2} \cos \omega_2 t + \frac{1}{\pi} \left\{ \cos (\omega_2 - \omega_0) t + \cos (\omega_2 + \omega_0) t \right\} \]

\[ - \frac{1}{3} \cos (\omega_2 - 3\omega_0) t + \cos (\omega_2 + 3\omega_0) t + ... \}

Phase Shift Keying

(a)

Data signal \( v_d(t) \)

Carrier \( v_c(t) \)

Phase coherent \( v_{psk}(t) \)

Differential \( v_{psk}(t) \)

Time, t

180° 180° 0° 180° 0° 180°

90° 270° 270° 90° 90° 270°

Hal96 fig 2.21
Phase Shift Keying

- Phase Modulation
  - phase of carrier defines data
  - two versions
  - phase coherent
  - differential
  - spectrum

How does PSK work?

Carrier and bipolar data signal

\[ v_c(t) = \cos \omega_c t \]

\[ v_d(t) = \frac{4}{\pi} \{ \cos \omega_d t - \frac{1}{3} \cos 3\omega_d t + \frac{1}{5} \cos 5\omega_d t - \ldots \} \]

\[ v_{PSK}(t) = v_c(t) \cdot v_d(t) \]

\[ = \frac{4}{\pi} \{ \cos \omega_c t \cdot \cos \omega_d t - \frac{1}{3} \cos \omega_c t \cdot \cos 3\omega_d t + \ldots \} \]

With the usual simplification \( 2 \cos A \cos B = \cos(A - B) + \cos(A + B) \) we get:

\[ v_{PSK}(t) = \frac{1}{\pi} \{ \cos(\omega_c - \omega_d) t + \cos(\omega_c + \omega_d) t \]

\[ - \frac{1}{3} \cos(\omega_c - 3\omega_d) t + \cos(\omega_c + 3\omega_d) t + \ldots \} \]
Phase Shift Keying

- Multilevel Phase Modulation Methods
  - use multiple phases
  - e.g. 4-PSK or quadrature phase shift keying QPSK
    - \((0^\circ, 90^\circ, 180^\circ, 270^\circ)\)
  - 4-PSK phase-time diagram
  - 4-PSK phase diagram
  - 16-QAM phase diagram

Spread Spectrum

- Spread spectrum digital communication systems
  - developed initially for military
    - spread the signal to make it hard to jam
    - became known as “frequency-hopping”
    - switches through a pseudo random sequence of frequency assignments
Data Signaling

- Transmitting on Analog Lines
  - If we use existing telephone lines (PSTN) we have to consider that they were created for voice with effective bandwidth from 300Hz to 3400Hz or total of 3000Hz.
  
  - We have to concern ourselves with two forms of data.
    - Analog data
    - Digital data

(a) ASK

(b) BFSK

(c) BPSK
Amplitude Shift Keying

- Values represented by different amplitudes of carrier
- Usually, one amplitude is zero — i.e. presence and absence of carrier is used
- Susceptible to sudden gain changes
- Inefficient
- Up to 1200bps on voice grade lines
- Used over optical fiber

Binary Frequency Shift Keying

- Most common form FSK is binary FSK (BFSK)
- Two binary values represented by two different frequencies (near carrier)
- Less susceptible to error than ASK
- Up to 1200bps on voice grade lines
- High frequency radio
Multiple FSK

- More than two frequencies used
- More bandwidth efficient
- More prone to error
- Each signalling element represents more than one bit

**Figure 5.9 MFSK Frequency Use (M = 4)**

FSK on Voice Grade Line

**Figure 5.8 Full-Duplex FSK Transmission on a Voice-Grade Line**
**Phase Shift Keying**

- Phase of carrier signal is shifted to represent data
- Binary PSK
  - Two phases represent two binary digits
- Differential PSK
  - Phase shifted relative to previous transmission rather than some reference signal

**Binary PSK**

![Binary PSK Diagram]
Quadrature (four-level) PSK

- More efficient use by each signal element representing more than one bit
  - e.g. shifts of $\pi/2$ ($90^\circ$)
  - Each element represents two bits
  - Can use 8 phase angles and have more than one amplitude
  - 9600bps modem use 12 angles, four of which have two amplitudes

- Offset QPSK (OQPSK)
  - also called “orthogonal QPSK”
  - Delay in Q stream

Example QPSK

- signals

<table>
<thead>
<tr>
<th>Signal</th>
<th>Equation</th>
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</thead>
<tbody>
<tr>
<td>11</td>
<td>$s(t) = A \cos(2\pi f_c t + \frac{\pi}{4})$</td>
</tr>
<tr>
<td>01</td>
<td>$s(t) = A \cos(2\pi f_c t + \frac{3\pi}{4})$</td>
</tr>
<tr>
<td>00</td>
<td>$s(t) = A \cos(2\pi f_c t - \frac{3\pi}{4})$</td>
</tr>
<tr>
<td>10</td>
<td>$s(t) = A \cos(2\pi f_c t - \frac{\pi}{4})$</td>
</tr>
</tbody>
</table>
QPSK signal: \[ s(t) = \frac{1}{\sqrt{2}} I(t) \cos 2\pi f_c t - \frac{1}{\sqrt{2}} Q(t) \sin 2\pi f_c t \]

Figure 5.12 Example of QPSK and OQPSK Waveforms
Performance of Digital to Analog Modulation Schemes

- **Bandwidth**
  - ASK and PSK bandwidth directly related to bit rate
  - FSK bandwidth is larger. Why?
  - Note the difference in the derivation of the math in Stallings compare to the previous arguments based on the spectrum.

- In the presence of noise, bit error rate of PSK and QPSK are about 3dB superior to ASK and FSK

Quadrature Amplitude Modulation

- QAM used on asymmetric digital subscriber line (ADSL) and some wireless

- Combination of ASK and PSK

- Send two different signals simultaneously on same carrier frequency
  - Use two copies of carrier, one shifted 90°
  - Each carrier is ASK modulated
  - Two independent signals over same medium
    - binary 0 = absence of signal, binary 1 = carrier
    - same holds for path that uses the shifted carrier
  - Demodulate and combine for original binary output
QAM Modulator

QAM signal: \[ s(t) = d_1(t) \cos 2\pi f_c t + d_2(t) \sin 2\pi f_c t \]

QAM Levels

• Two level ASK
  — Each of two streams in one of two states
  — Four state system
• Essentially this is a four level ASK
  — Combined stream in one of 16 states
• 64 and 256 state systems have been implemented
• Improved data rate for given bandwidth
  — Increased potential error rate
Analog Data, Digital Signal

- Digitization
  - Conversion of analog data into digital data
  - Digital data can then be transmitted using NRZ-L
  - Digital data can then be transmitted using code other than NRZ-L
  - Digital data can then be converted to analog signal
  - Analog to digital conversion done using a codec
  - Pulse code modulation
  - Delta modulation
Digitizing Analog Data

Sampling theorem

- If a signal is sampled at regular intervals at a rate higher than twice the highest signal frequency, the samples contain all the information of the original signal
  - in short: sample with rate more than twice the highest signal frequency
  - e.g. Voice data limited to below 4000Hz, thus, require 8000 sample per second
  - the samples are analog samples
    - think of a slice of the signal
  - the signal can be reconstructed from the samples using a lowpass filter
**PAM and PCM**

- **Pulse Amplitude Modulation (PAM)**
  - “get slices of analog signals”

- **Pulse Code Modulation (PCM)**
  - “assign digital code to the analog slice”
  - \( n \) bits give \( 2^n \) levels, e.g. 4 bit give 16 levels

- Quantizing error
  - error depends on granularity of encoding
  - it is impossible to recover original exactly

- Example
  - 8000 samples per second of 8 bits each gives 64kbps

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**PCM Example**

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<thead>
<tr>
<th>Code number</th>
<th>Normalized magnitude</th>
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<tr>
<td>0</td>
<td>16</td>
</tr>
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</table>

- **PAM value**
  - 1.1 9.2 15.2 10.8 5.6 2.8 2.7
- **quantized code number**
  - 1 9 15 10 5 2 2

<table>
<thead>
<tr>
<th>PCM code</th>
<th>PAM value</th>
<th>quantized code number</th>
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CS420/520 Axel Krings  
Page 67  
Sequence 5
**Nonlinear Encoding**

- Quantization levels not evenly spaced
- Reduces overall signal distortion
- Can also be done by companding
Effect of Non-Linear Coding

(a) Without nonlinear encoding
(b) With nonlinear encoding

Typical Companding Functions
**Delta Modulation**

- Analog input is approximated by a staircase function
- Move up or down one level (δ) at each sample interval
- Binary behavior
  - Function moves up or down at each sample interval

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**Delta Modulation - example**
Delta Modulation - Operation

Delta Modulation - Performance

- Good voice reproduction
  - PCM - 128 levels (7 bit)
  - Voice bandwidth 4kHz
  - Should be 8000 x 7 = 56kbps for PCM
- Data compression can improve on this
  - e.g. Interframe coding techniques for video
Analog Data, Analog Signals

- Why modulate analog signals?
  - Higher frequency can give more efficient transmission
  - Permits frequency division multiplexing (chapter 8)
- Types of modulation
  - Amplitude
  - Frequency
  - Phase

Analog Modulation

Carrier

Modulating sine-wave signal

Amplitude-modulated (DSB/C) wave

Phase-modulated wave

Frequency-modulated wave
Summary

- looked at signal encoding techniques
  - digital data, digital signal
  - analog data, digital signal
  - digital data, analog signal
  - analog data, analog signal