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

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 zero, constant positive voltage for one
  - 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

NRZ

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

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
**Biphase**

- **Manchester**
  - 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)

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**Manchester Encoding**
Biphase

- 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**

- **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

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**Modulation Rate**

- NRZI
- Manchester

- 5 bits = 5 μsec

- 1 bit = 1 μsec
- 1 signal element = 0.5 μsec
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 000V 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

B8ZS and HDB3

<table>
<thead>
<tr>
<th>Bipolar-AMI</th>
<th>B8ZS</th>
<th>HDB3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 0</td>
<td>0 0 0 0 0 V B 0 V B</td>
<td>0 0 0 0 V B 0 0 V B</td>
</tr>
</tbody>
</table>

- B = Valid bipolar signal
- V = Bipolar violation

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**Sequence 5**
Test your understanding and see solutions on next slide

NRZ-L

NRZI

Bipo.AMI

Pseudoternary

Manchester

Differential Manchester

0 1 0 0 1 1 0 0 0 1 1
Test your understanding and see solutions on next slide

1 1 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 0

- Bipol.
- AMI
- B8ZS
- HDB3

B = Valid bipolar signal
V = Bipolar violation

CS420/520 Axel Krings
Page 31
Sequence 5

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1 1 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 1 0

- Bipolar-AMI
- B8ZS
- HDB3

CS420/520 Axel Krings
Page 32
Sequence 5
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

![Diagram of amplitude shift keying](Ha96 fig 2.18)
Amplitude Shift Keying

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

How does ASK work?

\[ v_c(t) = \cos(\omega_c t) \]
\[ v_s(t) = \frac{2}{\pi} \left\{ \cos(\omega_c t - \frac{1}{3} \cos(3\omega_c t + \frac{1}{5} \cos(5\omega_c t - \ldots) \right\} \]

\[ v_{\text{ASK}}(t) = v_c(t) \cdot v_s(t) \]
\[ = \frac{1}{2} \cos(\omega_c t + \frac{2}{\pi} \left\{ \cos(\omega_c t \cdot \cos(\omega_n t + \frac{1}{3} \cos(\omega_n t \cdot \cos(3\omega_n t + \ldots) \right\} \]

Now, we know that

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

Therefore we have:

\[ v_{\text{ASK}}(t) = \frac{1}{2} \cos(\omega_c t + \frac{1}{\pi} \left( \cos(\omega_c - \omega_n) t + \cos(\omega_c + \omega_n) t \right) \]
\[ = \frac{1}{2} \left\{ \cos(\omega_c - 3\omega_n) t + \cos(\omega_c + 3\omega_n) t \right\} + \ldots \]}
Frequency Shift Keying

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

$f_c = \text{Fundamental frequency component} = 1/4 \ \text{bit rate (Hz)}$

$f_s = \text{Frequency shift}$
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 \( v_d(t) = 1 - v_d(t) \)

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

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

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 + \ldots \}

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

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

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Phaseshift Keying

![Phase Shift Keying](image)

- **Data signal**
- **Carrier**
- **Phase coherent**
- **Differential**

Hal96 fig 2.21
Phase Shift Keying

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

![Diagram](Hal96 fig 2.21)

How does PSK work?

Carrier and bipolar data signal

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

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

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

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

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
**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

FSK on Voice Grade Line

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

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

0 0 1 1 0 1 0 0 0 1 0
Quadrature (four-level) PSK

- More efficient use by each signal element representing more than one bit
  - e.g. shifts of \( \pi/2 \) (90°)
  - 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

  11 \[ s(t) = A \cos(2 \pi f_c t + \frac{\pi}{4}) \]

  01 \[ s(t) = A \cos(2 \pi f_c t + \frac{3\pi}{4}) \]

  00 \[ s(t) = A \cos(2 \pi f_c t - \frac{3\pi}{4}) \]

  10 \[ s(t) = A \cos(2 \pi f_c t - \frac{\pi}{4}) \]
QPSK and OQPSK Modulators

QPSK signal:

\[ s(t) = \frac{1}{\sqrt{2}} I(t) \cos(2\pi f_c t) - \frac{1}{\sqrt{2}} Q(t) \sin(2\pi f_c t) \]

binary 1 and 0

Examples of QPSK Waveforms

<table>
<thead>
<tr>
<th>bit number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Q</td>
<td>1</td>
<td>Q</td>
<td>1</td>
<td>Q</td>
<td>1</td>
<td>Q</td>
<td>1</td>
<td>Q</td>
</tr>
</tbody>
</table>

input signal

\[ I(t) \]

\[ Q(t) \]

phase of output signal

\[ \pm \pi/4, \pi/4, -3\pi/4, 3\pi/4, \pi/4 \]
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 compared 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

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**Digitizing Analog Data**

![Diagram of digitizing analog data](image-url)
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
PCM Example

<table>
<thead>
<tr>
<th>Code number</th>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>( T_s \pi )</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized magnitude</td>
<td>16</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</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   |

CS4: PCM code: 0001 1001 1111 1010 0101 0010 0010

PCM Block Diagram

Continuous-time, continuous-amplitude (analog) input signal → PAM sampler
Discrete-time continuous-amplitude signal (PAM pulses) → Quantizer
Discrete-time discrete-amplitude signal (PCM pulses) → Encoder
Digital bit stream output signal
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
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
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
**Summary**

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