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
# Data Transmission Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Units</th>
<th>Definition</th>
</tr>
</thead>
<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
Definition of Digital Signal Encoding Formats

Nonreturn to Zero-Level (NRZ-L)
- 0 = high level
- 1 = low level

Nonreturn to Zero Inverted (NRZI)
- 0 = no transition at beginning of interval (one bit time)
- 1 = transition at beginning of interval

Bipolar-AMI
- 0 = no line signal
- 1 = positive or negative level, alternating for successive ones

Pseudoternary
- 0 = positive or negative level, alternating for successive zeros
- 1 = no line signal

Manchester
- 0 = transition from high to low in middle of interval
- 1 = transition from low to high in middle of interval

Differential Manchester
- Always a transition in middle of interval
- 0 = transition at beginning of interval
- 1 = no transition at beginning of interval

B8ZS
- Same as bipolar AMI, except that any string of eight zeros is replaced by a string with two code violations

HDB3
- Same as bipolar AMI, except that any string of four zeros is replaced by a string with one code violation
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
NRZ

NRZ-L

NRZI

0 1 0 0 1 1 0 0 0 1 1
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)
Manchester Encoding

Manchester Encoding

bit sent

signal

baseline

time interval(s)
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

5 bits = 5 μsec

1 1 1 1 1 1

NRZI

1 bit = 1 μsec
1 signal element = 1 μsec

Manchester

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 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

- B = Valid bipolar signal
- V = Bipolar violation

(Bpolar-AMI  V  B  0  V  B  0  V  B)

(B8ZS  V  B  0  V  B)

(HDB3  V  B  0  V  B)

(odd number of 1s since last substitution)
Test your understanding and see solutions on next slide

0  1  0  0  1  1  0  0  0  1  1

NRZ-L

0  1  0  0  1  1  0  0  0  1  1

NRZI

0  1  0  0  1  1  0  0  0  1  1

Bipo.AMI

0  1  0  0  1  1  0  0  0  1  1

Pseudoternary

0  1  0  0  1  1  0  0  0  1  1

Manchester

0  1  0  0  1  1  0  0  0  1  1

Differential Manchester
NRZ-L

NRZI

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

Pseudoternary
(most recent preceding 0 bit has negative voltage)

Manchester

Differential Manchester
Test your understanding and see solutions on next slide

Bipol.
AMI
B8ZS
HDB3
B = Valid bipolar signal
V = Bipolar violation

Bipolar-AMI

B8ZS

HDB3

(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

(a) 

\[ v_d(t) \quad \text{(Data signal)} \rightarrow \text{Bandpass filter} \rightarrow \text{PSTN} \rightarrow \text{Lowpass filter} \rightarrow v_d'(t) \]

\[ v_c(t) \quad \text{(Carrier signal)} \]

(b) 

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

- \[ v_d(t) \]
- \[ v_c(t) \]
- \[ v_{\text{ASK}}(t) \]

Hal96 fig 2.18
Amplitude Shift Keying

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

\[ f_0 = \text{Fundamental frequency component} = 1/2 \text{ bit rate (Hz)} \]
How does ASK work?

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

\[ v_d(t) = \frac{1}{2} + \frac{2}{\pi} \left\{ \cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + \frac{1}{5} \cos 5\omega_0 t - \ldots \right\} \]

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

\[ = \frac{1}{2} \cos \omega_c t + \frac{2}{\pi} \left\{ \cos \omega_c t \cdot \cos \omega_0 t - \frac{1}{3} \cos \omega_c t \cdot \cos 3\omega_0 t + \ldots \right\} \]

Now, we know that

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

Therefore we have:

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

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

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

Hal96 fig 2.19
Frequency Shift Keying

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

\[ f_0 = \text{Fundamental frequency component} = \frac{1}{4} \text{ bit rate (Hz)} \]

\[ f_s = \text{Frequency shift} \]

Hal96 fig 2.19
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 \( v_{d'}(t) = 1 - v_d(t) \)

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

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

Therefore we have:

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

\[ - \frac{1}{3} \cos (\omega_1 - 3\omega_0) t + \cos (\omega_1 + 3\omega_0) t + \ldots \right\} \]

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

\[ - \frac{1}{3} \cos (\omega_2 - 3\omega_0) t + \cos (\omega_2 + 3\omega_0) t + \ldots \right\} \]
Phase Shift Keying

(a)

Data signal $v_d(t)$

Carrier $v_c(t)$

Phase coherent $v_{PSK}(t)$

Differential $v_{PSK}'(t)$

Time, $t$

t

t

t

Hal96 fig 2.21
Phase Shift Keying

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

\[ f_0 = \text{Fundamental frequency component} = 1/2 \text{ bit rate (Hz)} \]

Hal96 fig 2.21
How does PSK work?

Carrier and bipolar data signal

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

\[ v_d(t) = \frac{4}{\pi} \left\{ \cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + \frac{1}{5} \cos 5\omega_0 t - \ldots \right\} \]

\[ v_{PSK}(t) = v_c(t) \cdot v_d(t) = \frac{4}{\pi} \left\{ \cos \omega_c t \cdot \cos \omega_0 t - \frac{1}{3} \cos \omega_c t \cdot \cos 3\omega_0 t + \ldots \right\} \]

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

\[ v_{PSK}(t) = \frac{2}{\pi} \left\{ \cos(\omega_c - \omega_0)t + \cos(\omega_c + \omega_0)t \right. \]

\[ \left. - \frac{1}{3} \cos(\omega_c - 3\omega_0)t + \cos(\omega_c + 3\omega_0)t + \ldots \right\} \]
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 1200 bps 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
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

- $s(t) = A \cos\left(2\pi f_c t + \frac{\pi}{4}\right)$
- $s(t) = A \cos\left(2\pi f_c t + \frac{3\pi}{4}\right)$
- $s(t) = A \cos\left(2\pi f_c t - \frac{3\pi}{4}\right)$
- $s(t) = A \cos\left(2\pi f_c t - \frac{\pi}{4}\right)$
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
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 the same carrier frequency.
  - Use two copies of carrier, one shifted 90°.
  - Each carrier is ASK modulated.
  - Two independent signals over the 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
Figure 15.15  16-QAM Constellation
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

Figure 5.16 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
PCM Example

<table>
<thead>
<tr>
<th>PAM value</th>
<th>1.1</th>
<th>9.2</th>
<th>15.2</th>
<th>10.8</th>
<th>5.6</th>
<th>2.8</th>
<th>2.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>quantized code number</td>
<td>1</td>
<td>9</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CS4:</td>
<td>PCM code</td>
<td>0001</td>
<td>1001</td>
<td>1111</td>
<td>1010</td>
<td>0101</td>
<td>0010</td>
</tr>
</tbody>
</table>
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
Typical Companding Functions

Graph showing companding functions with labels:
- Strong companding
- Moderate companding
- No companding

Y-axis: Output signal magnitude
X-axis: Input signal magnitude
Delta Modulation

- Analog input is approximated by a staircase function
- Move up or down one level ($\delta$) at each sample interval
- Binary behavior
  - Function moves up or down at each sample interval
Delta Modulation - example
Delta Modulation - Operation

(a) Transmission

(b) Reception
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 (DSBTC) 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