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 the 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

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)
Manchester Encoding

Manchester Encoding

bit sent

signal

baseline

time interval(s)
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
Modulation Rate

5 bits = 5 μsec

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
B8ZS and HDB3

Bipolar-AMI

B8ZS

HDB3

B = Valid bipolar signal
V = Bipolar violation

(odd number of 0s since last substitution)
Test your understanding and see solutions on next slide.
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

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

Bipol.
AMI
B8ZS
HDB3
Bipolar-AMI

B8ZS

HDB3

(odd number of 1s since last substitution)

B = Valid bipolar signal
V = Bipolar violation

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

0 0 0 V B 0 V B

0 0 0 V B 0 0 V B 0 0 V
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)

$v_d(t)$ (Data signal)

$v_c(t)$ (Carrier signal)

$v_{ASK}(t)$

Bandpass filter

PSTN

Lowpass filter

$v_d'(t)$

(b)

$1$

$0$

$1$

$1$

$0$

$0$

$1$

$v_d(t)$

Time, $t$

$v_c(t)$

$t$

$0$

$1$

$0$

$1$

$0$

$0$

$1$

$v_{ASK}(t)$

Hal96 fig 2.18
Amplitude Shift Keying

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

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

Hal96 fig 2.18
How does ASK work?

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

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

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

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

Now, we know that

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

Therefore we have:

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

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

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

(a)

Data signal \( v_d(t) \)

Carrier 1 \( v_1(t) \)

Carrier 2 \( v_2(t) \)

\( v_{FSK}(t) \)

Time, t

1 0 1 1 0 0 1

Hal96 fig 2.19
Frequency Shift Keying

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

$f_0 = $ Fundamental frequency component = $1/4$ bit rate (Hz)

$f_s = $ 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 \( v_d'(t) = 1 - v_d(t) \)

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

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

Therefore we have:

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

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

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

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

Hal96 fig 2.21
How does PSK work?

Carrier and bipolar data signal

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

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

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

\[ = \frac{4}{\pi} \{\cos \omega_c t \cdot \cos \omega_0 t - \frac{1}{3} \cos \omega_c t \cdot \cos 3\omega_0 t + \ldots\} \]

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

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

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

\[ I(t) \quad a_n = \pm 1 \]

\[ Q(t) \quad b_n = \pm 1 \]

2-bit serial-to-parallel converter

R/2 bps

carrier oscillator

\( \cos(2\pi f_c t) \sqrt{2} \)

\( \sin(2\pi f_c t) \sqrt{2} \)

\( -\pi/2 \)

\( + \)

signal out

\( s(t) \)

Delay

QPSK only
Examples of QPSF Waveforms

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<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>
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<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
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<tr>
<td>Q</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

input signal

I(t)

\[1 \quad 3 \quad 5 \quad 7 \quad 9\]

Q(t)

\[2 \quad 4 \quad 6 \quad 8 \quad 10\]

phase of output signal

\[-\pi/4, \quad \pi/4, \quad -3\pi/4, \quad 3\pi/4, \quad \pi/4\]
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 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

Analog data (voice) → Digitizer → Digital data → Modulator

Modulator → Analog data (ASK)
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

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
- Discrete-time continuous-amplitude signal (PAM pulses)
- Discrete-time discrete-amplitude signal (PCM pulses)
- 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

![Companding Functions Graph]

- **Strong companding**
- **Moderate companding**
- **No companding**

**Axes:**
- **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

![Diagram of Delta Modulation](link-to-diagram)

### Explanation

- **Signal Amplitude**
- **Analog input**
- **Staircase function**
- **Step size** \( \delta \)
- **Overload noise**
- **Quantizing noise**
- **Sampling time** \( T_s \)

**Delta modulation output**:
- 1
- 0
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