There are many good references on analog modulation schemes for digital data. Good choices are [COUC01], [XION00], and [PROA02]; these three also provide comprehensive treatment of digital and analog modulation schemes for analog data.

An exceptionally clear exposition that covers digital-to-analog, analog-to-digital, and analog-to-analog techniques is [PEAR92]. Another comprehensive treatment of the topics in this chapter is [SKLA01].

An instructive treatment of the concepts of bit rate, baud, and bandwidth is [FREE98]. A recommended tutorial that expands on the concepts treated in this chapter relating to bandwidth efficiency and encoding schemes is [SKLA93].


**FREE98** Freeman, R. “Bits, Symbols, Baud, and Bandwidth.” *IEEE Communications Magazine*, April 1998.


### Key Terms

- amplitude modulation (AM)
- amplitude shift keying (ASK)
- angle modulation
- bit error rate (BER)
- carrier frequency
- delta modulation (DM)
- differential PSK (DPSK)
- frequency modulation (FM)
- frequency shift keying (FSK)
- modulation
- phase modulation (PM)
- phase shift keying (PSK)
- pulse code modulation (PCM)
- quadrature amplitude modulation (QAM)
- quadrature PSK (QPSK)

### Review Questions

6.1 What is differential encoding?
6.2 What function does a modem perform?
6.3 Indicate three major advantages of digital transmission over analog transmission.
6.4 How are binary values represented in amplitude shift keying, and what is the limitation of this approach?
6.5 What is NRZ-L? What is a major disadvantage of this data encoding approach?
6.6 What is the difference between QPSK and offset QPSK?
6.7 What is QAM?
6.8 What does the sampling theorem tell us concerning the rate of sampling required for an analog signal?
6.9 What are the differences among angle modulation, PM, and FM?

Problems

6.1 Figure 6.20 shows the QAM demodulator corresponding to the QAM modulator of Figure 6.10. Show that this arrangement does recover the two signals \( d_1(t) \) and \( d_2(t) \), which can be combined to recover the original input.

6.2 A sine wave is to be used for two different signaling schemes: (a) PSK; (b) QPSK. The duration of a signal element is \( 10^{-3} \) s. If the received signal is of the following form

\[
s(t) = 0.005 \sin(2\pi \cdot 10^6 t + \theta) \text{ volts}
\]

and if the measured noise power at the receiver is \( 2.5 \times 10^{-3} \) watts, determine the \( E_b/N_0 \) (in dB) for each case.

6.3 Derive an expression for baud rate \( D \) as a function of bit rate \( R \) for QPSK using the digital encoding techniques of Table 6.2.

6.4 What SNR ratio is required to achieve a bandwidth efficiency of 1.0 for ASK, FSK, PSK, and QPSK? Assume that the required bit error rate is \( 10^{-6} \).

6.5 An NRZ-L signal is passed through a filter with \( r = 0.5 \) and then modulated onto a carrier. The data rate is 2400 bps. Evaluate the bandwidth for ASK and FSK. For FSK assume that the two frequencies used are 50 kHz and 55 kHz.

6.6 Assume that a telephone line channel is equalized to allow bandpass data transmission over a frequency range of 600 to 3000 Hz. The available bandwidth is 2400 Hz. For \( r = 1 \), evaluate the required bandwidth for 2400 bps QPSK and 4800-bps, eight-level multilevel signaling. Is the bandwidth adequate?

6.7 Why should PCM be preferable to DM for encoding analog signals that represent digital data?

6.8 Are the modem and the codec functional inverses (i.e., could an inverted modem function as a codec, or vice versa)?

![Figure 6.20 QAM Demodulator](image_url)
6.9 A signal is quantized using 10-bit PCM. Find the signal-to-quantization noise ratio.

6.10 Consider an audio signal with spectral components in the range 300 to 3000 Hz. Assume that a sampling rate of 7000 samples per second will be used to generate a PCM signal.
   a. For SNR = 30 dB, what is the number of uniform quantization levels needed?
   b. What data rate is required?

6.11 Find the step size \( \delta \) required to prevent slope overload noise as a function of the frequency of the highest-frequency component of the signal. Assume that all components have amplitude \( A \).

6.12 A PCM encoder accepts a signal with a full-scale voltage of 10 V and generates 8-bit codes using uniform quantization. The maximum normalized quantized voltage is \( 1 - 2^{-8} \). Determine (a) normalized step size, (b) actual step size in volts, (c) actual maximum quantized level in volts, (d) normalized resolution, (e) actual resolution, and (f) percentage resolution.

6.13 The analog waveform shown in Figure 6.21 is to be delta modulated. The sampling period and the step size are indicated by the grid on the figure. The first DM output and the staircase function for this period are also shown. Show the rest of the staircase function and give the DM output. Indicate regions where slope overload distortion exists.

6.14 Consider the angle-modulated signal
   \[
   s(t) = 10 \cos[(10^8)\pi t + 5 \sin(2\pi(10^5)t)]
   \]
   Find the maximum phase deviation and the maximum frequency deviation.

6.15 Consider the angle-modulated signal
   \[
   s(t) = 10 \cos[2\pi(10^6)t + 0.1 \sin(10^5)\pi t]
   \]
   a. Express \( s(t) \) as a PM signal with \( n_2 = 10 \).
   b. Express \( s(t) \) as an FM signal with \( n_2 = 10\pi \).

6.16 Let \( m_1(t) \) and \( m_2(t) \) be message signals and let \( s_1(t) \) and \( s_2(t) \) be the corresponding modulated signals using a carrier frequency of \( f_c \).

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**Figure 6.21** Delta Modulation Example
a. Show that if simple AM modulation is used, then \( m_1(t) + m_2(t) \) produces a modulated signal equal that is a linear combination of \( s_1(t) \) and \( s_2(t) \). This is why AM is sometimes referred to as linear modulation.

b. Show that if simple PM modulation is used, then \( m_1(t) + m_2(t) \) produces a modulated signal that is not a linear combination of \( s_1(t) \) and \( s_2(t) \). This is why angle modulation is sometimes referred to as nonlinear modulation.