10. Spread-spectrum communications systems are useful for providing resistance to jamming, to provide a means for masking the transmitted signal from unwanted interceptors, to provide resistance to multipath, to provide a way for more than one user to use the same time–frequency allocation, and to provide range-measuring capability.
11. The two major types of spread-spectrum systems are DSSS and FHSS. In the former, a spreading code with rate much higher than the data rate multiplies the data sequence, thus spreading the spectrum, while for FHSS, a synthesizer driven by a pseudorandom code generator provides a carrier that hops around in a pseudorandom fashion. A combination of these two schemes, referred to as *hybrid spread spectrum*, is also another possibility.
12. Spread spectrum performs identically to whatever data-modulation scheme is employed without the spectrum spreading as long as the background is additive white Gaussian noise and synchronization is perfect.
13. The performance of a spread-spectrum system in interference is determined in part by its processing gain, which can be defined as the ratio of bandwidth of the spread system to that for an ordinary system employing the same type of data modulation as the spread-spectrum system. For DSSS the processing gain is the ratio of the data bit duration to the spreading code bit (or chip) duration.
14. An additional level of synchronization, referred to as *code synchronization*, is required in a spread-spectrum system. The serial search method is perhaps the simplest in terms of hardware and to explain, but it is relatively slow in achieving synchronization.
15. Multicarrier modulation is a modulation scheme where the data to be transmitted is multiplexed on several subcarriers that are summed before transmission. Each transmitted symbol is thereby longer by a factor of the number of subcarriers used than would be the case if the data were transmitted serially on a single carrier. This makes MCM more resistant to multipath than a serial transmission system, assuming both to be operating with the same data rate.
16. A special case of MCM wherein the subcarriers are spaced by $1/T$, where $T$ is the symbol duration is called OFDM. Orthogonal frequency division multiplexing is often implemented by means of the inverse DFT at the transmitter and by a DFT at the receiver.
17. Satellite communications systems provide a specific example to which the digital modulation schemes considered in this chapter can be applied. Two general types of relay satellite configurations were considered in the last section of this chapter: bent-pipe and OBP (or demod–remod). In the OBP system, the data on the uplink are demodulated and detected and then used to remodulate the downlink carrier. In the bent-pipe relay, the uplink transmissions are translated in frequency, amplified, and retransmitted on the downlink. Performance characteristics of both types of links were considered by example.



18. Cellular radio provides an example of a communications technology that has been accepted faster and more widely by the public then first anticipated. First-generation systems were fielded in the early 1980s and used analog modulation. Second-generation systems were fielded in the mid-1990s. The introduction of 3G systems started around the year 2000. All 2G and 3G systems utilize digital modulation, with many based on CDMA.

## Further Reading

In addition to the references given in Chapter 8, for a fuller discussion and in-depth treatment of the digital modulation techniques presented here, see Ziemer and Peterson (2001), and Peterson et al. (1995) for further discussion on spread spectrum and cellular communications. Another comprehensive reference is Proakis (2007).

## Problems

### Section 9.1

**9.1.** An $M$-ary communication system transmits at a rate of 4000 symbols per second. What is the equivalent bit rate in bits per second for $M = 4$? $M = 8$? $M = 16$? $M = 32$? $M = 64$? Generate a plot of bit rate versus $\log_2 M$.

**9.2.** A serial bit stream, proceeding at a rate of 10 kbps from a source, is given as

101110 000111 010011 (spacing for clarity)

Number the bits from left to right starting with 1 and going through 18 for the right most bit. Associate the odd-indexed bits with $d_1(t)$ and the even-indexed bits with $d_2(t)$ in Figure 9.1.

**a.** What is the symbol rate for $d_1$ or $d_2$?

**b.** What are the successive values of $\theta_i$ given by (9.2) assuming QPSK modulation? At what time intervals may $\theta_i$ switch?

**c.** What are the successive values of $\theta_i$ given by (9.2) assuming OQPSK modulation? At what time intervals may $\theta_i$ switch values?

**9.3.** Quadriphase-shift keying is used to transmit data through a channel that adds Gaussian noise with power spectral density $N_0 = 10^{-11}$ V$^2$/Hz. What are the values of the quadrature-modulated carrier amplitudes required to give $P_{E,\text{symbol}} = 10^{-5}$ for the following data rates?

**a.** 5 kbps

**b.** 10 kbps

**c.** 50 kbps

**d.** 100 kbps

**e.** 0.5 Mbps

**f.** 1 Mbps

**9.4.** Show that the noise components $N_1$ and $N_2$ for QPSK, given by (9.6) and (9.8), are uncorrelated; that is, show that $E[N_1 N_2] = 0$. (Explain why $N_1$ and $N_2$ are zero mean.)

**9.5.** A QPSK modulator produces a phase imbalanced signal of the form

$$x_c(t) = Ad_1(t)\cos\left(2\pi f_c t + \frac{\beta}{2}\right)$$

$$-Ad_2(t)\sin\left(2\pi f_c t - \frac{\beta}{2}\right)$$

**a.** Show that the integrator outputs of Figure 9.2, instead of (9.5) and (9.7), are now given by

$$V'_1 = \frac{1}{2}AT_s\left(\pm\cos\frac{\beta}{2} \pm \sin\frac{\beta}{2}\right)$$

$$V'_2 = \frac{1}{2}AT_s\left(\pm\sin\frac{\beta}{2} \pm \cos\frac{\beta}{2}\right)$$

where the $\pm$ signs depend on whether the data bits $d_1(t)$ and $d_2(t)$ are $+1$ or $-1$.

**b.** Show that the probability of error per quadrature channel is