rate of 4800 waveforms/s, the rate at which the power-control bits are transmitted is 800 bits/s. Thus, there are 16 such control bits in each 20 ms frame. The goal of this closed-loop power control is to correct the open-loop power-control estimate every 1.25 ms in steps of 1 dB. Later versions added the option for step sizes of 0.5 dB and 0.25 dB. The most significant benefit of such fast and accurate closed-loop power control is a significant reduction in the average transmitter power on the reverse channel. Analog mobile radios transmit enough power to maintain a link even during fading. Thus, most of the time such analog radios transmit excessive amounts of power. CDMA mobile radios operate at power levels no greater than what is needed to close the reverse link. A mobile unit using CDMA designed to meet IS-95 specifications requires approximately 20 dB to 30 dB less power than a mobile unit operating in an analog AMPS system [30].

Forward Link Control. The base station periodically reduces the power transmitted to the mobile unit. Whenever the mobile senses an increased frame-error rate, it requests additional power from the base station. Adjustments can be made periodically based on reported frame-error rates (FER).

Example 12.6 Signaling Elements (Numerology) Used in IS-95

There is a rich set of signaling elements used in CDMA systems that are designed to IS-95 specifications: data bits, channel bits, Walsh waveforms, Walsh chips, spread-spectrum chips, and BPSK waveforms. Consider a reverse traffic channel that is carrying full-rate digitized speech at 9.6 kbits/s, with a received $E_b/(N_0 + I_0) \approx E_b/I_0 = 7$ dB (assuming that $N_0 << I_0$). Find the values of the following received power-to-noise spectral-density and energy-to-noise spectral-density parameters: P_r/I_0, E_c/I_0, E_w/I_0, E_{wch}/I_0, and E_{ch}/I_0. Also, find the values of the following rates: R_c, R_w, R_{wch}, and R_{ch}, where c, w, wch, and ch represent channel bit, Walsh waveform, Walsh chip, and spread-spectrum chip, respectively. How many spread-spectrum (SS) chips correspond to one Walsh chip?

Solution

The key to this problem lies in the fundamental relationships between received power-to-noise spectral density and each of the signaling parameters, in a manner similar to that presented in Section 9.7.7. From that development, we can write

$$\frac{P_r}{I_0} = \frac{E_b}{I_0} R = \frac{E_c}{I_0} R_c = \frac{E_w}{I_0} R_w = \frac{E_{\text{wch}}}{I_0} R_{\text{wch}} = \frac{E_{\text{ch}}}{I_0} R_{\text{ch}} \tag{12.69}$$

Since E_b/N_0 is 7 dB (or 5), and the data rate R is 9600 bits/s, from Equation (12.69) we obtain

$$\frac{P_r}{I_0} = \frac{E_b}{I_0} R = 48{,}000 \text{ Hz} \quad \text{or} \quad 46.8 \text{ dB-Hz}$$

For the reverse traffic channel, the code rate is $\frac{1}{3}$. Therefore,

$$\frac{E_c}{I_0} = \left(\frac{1}{3}\right) \frac{E_b}{I_0} = \frac{5}{3} \quad \text{or} \quad 2.2 \text{ dB}$$

and

$$R_c = 3 \times R = 3 \times 9600 = 28{,}800 \text{ channel bits/s}$$

Each 64-ary Walsh waveform corresponds to 6 channel bits. Therefore,

$$\frac{E_w}{I_0} = 6 \times \frac{E_c}{I_0} = 6 \times \left(\frac{5}{3}\right) = 10 \text{ or } 10 \text{ dB}$$

and

$$R_w = \left(\frac{1}{6}\right) R_c = \left(\frac{1}{6}\right) 28{,}800 = 4800 \text{ Walsh waveforms/s}$$

A Walsh waveform is composed of 64 Walsh chips. Hence,

$$\frac{E_{\text{wch}}}{I_0} = \left(\frac{1}{64}\right) \frac{E_w}{I_0} = \left(\frac{1}{64}\right) \times 10 = \frac{10}{64} \text{ or } -8.1 \text{ dB}$$

and

$$R_{\text{wch}} = 64 \times R_w = 64 \times 4800 = 307{,}200 \text{ Walsh-chips/s}$$

In IS-95, the spread-spectrum chip rate is 1.2288 Mchips/s. Thus,

$$\frac{E_{\text{ch}}}{I_0} = \frac{P_r}{I_0} \times \left(\frac{1}{R_{\text{ch}}}\right) = \left(\frac{48{,}000}{1.2288 \times 10^6}\right) = 0.039 \text{ or } -14.1 \text{ dB}$$

SS-chips per Walsh chip: $\quad \dfrac{R_{\text{ch}}}{R_{\text{wch}}} = \dfrac{1.2288 \times 10^6}{307{,}200} = 4$

12.8.4.5 Typical Telephone Call Scenario

Turn on and Synchronization. Once power is applied to the mobile unit, the receiver scans continuously in search of available pilot signals. Such signals will be received from different base stations with different time-offsets of the short PN code (described in Section 12.8.4.1). The time-offset used by a base station differs by a multiple of 64 chips from all other base stations. Since the short code is maximal length, its 15-stage shift register produces $2^{15} - 1 = 32{,}767$ bits. After "bit stuffing" the sequence with one bit, 32,768 bits are produced before the whole process repeats itself. Thus, there are 32,768/64, or 512 available unique addresses. The 512 short PN codes can be generated by a simple time shift of a single PN sequence, because the base stations are time synchronized within a few microseconds of each other. At the chip rate of 1.2288 Mchips/s, there are 75 frames of the short code corresponding to a 2-second interval. The zero-offset address of the short code occurs on even second time marks. Consider the case of a base station whose address is represented by offset number 18. Then its transmission cycle begins at (18 × 64 chips × $(1/1.2288 \times 10^6)$ s/chip, or 937.5 μs after every even-second time mark.

Once the mobile unit completes its scan and is correlated to the strongest pilot signal, it is now synchronized with one of the 512 unique base station addresses. The mobile unit can now despread any of that base station's transmissions; however, it does not yet have system time, which is needed for access, paging, and traffic channels. Next, using the pilot signal as a reference, the mobile unit coherently demodulates the SYNC channel signal (Walsh 32), which the base station transmits continuously. The SYNC channel transmissions provide several system parameters, the key one being the state of a long code 320 ms in the future, giving the mobile unit time to decode, load its registers, and become system-time synchronized. This long code is one of a specific group of long codes used for access and paging. The mobile selects a predefined paging channel based on its serial number, and it monitors this paging channel for incoming calls. The mobile can now register with the base station, which allows for location-based paging rather than system-based paging when there is an incoming telephone call.

Idle-State Handoff. The mobile unit continually scans for alternative pilot signals. If it finds a stronger pilot signal from a different base station, the mobile locks on to the base station with the stronger pilot. Since there is no call in progress, the process simply serves to update the location of the mobile. The mobile has obtained system time from the SYNC channel. If there were only one base station, system time could be defined by whatever reference the base station chooses. With several operating base stations, the *handoff* process is facilitated if time is coordinated throughout the system. In IS-95, system time is specified to be *Universally Coordinated Time* (UTC) ± 3 μs. A practical way to implement this is with the use of a Global Positioning System (GPS) receiver at each base station.

Call Initiation. A call is initiated by the user keying in a telephone number and pushing the *send* button. This initiates an access probe. The mobile uses open-loop power control, choosing an initial transmission power level estimated from the pilot signal, as described in Section 12.8.4.4. All access channels use different long-code offsets. At the beginning of an access probe, the mobile pseudorandomly chooses one of the access channels associated with its paging channel. The transmission of an access probe is timed to begin at the start of an access channel slot, which is determined pseudorandomly. A key element of the access procedure involves the identification of the caller's serial number. Identification is needed because the base station cannot discriminate accesses from different users, since the access channel is a common channel.

The mobile-terminal time reference for transmission is determined by the earliest multipath component being used for demodulation. The mobile does not make transmission adjustments to account for propagation delay. Instead, the base station continually searches and tests for the presence of reverse channel signals. The mobile "listens" on the paging channel for a response from the base station. If there is none (collisions can occur during transmission on the access channels), the mobile attempts access again after waiting a pseudorandom time. When the mobile's access probe is successful, the base station response is a traffic channel assignment (Walsh code number).

Traffic channels use different long-code offsets than paging channels. Therefore, the mobile unit changes its long-code offset to one based on its serial number. After receiving the Walsh code assignment, the mobile begins an all-zeros data transmission on the traffic channel, and waits for a positive acknowledgment on the forward traffic channel. If the exchange is successful, the next step is ringing at the telephone that was called. Conversation can then commence.

Soft Handoff. During a call, the mobile may find an alternate strong pilot signal. It then transmits a control message to its base station, identifying the new base station with the stronger pilot signal and requesting a soft handoff. The original base station passes the request to a base station controller (BSC) that handles the radio resource control of the link; the BSC may or may not be collocated with a Mobile Switching Center (MSC) that handles the non-radio aspects of the link (e.g., switching). The BSC contacts the new base station and obtains a Walsh number assignment. This assignment is sent to the mobile via its original base station connection. During the transition, the mobile is supported by (connected to) both base stations, and a land link connection is maintained from the BSC to both base stations. The mobile combines the signals received from both base stations by using the two respective pilot signals as coherent phase references. Signal reception from two base stations simultaneously is facilitated by the Rake receiver, since the transmissions from both base stations appear as multipath components to the mobile receiver. At the BSC, where the signals are received noncoherently, the two received signals from the mobile are examined, and the better one is chosen in each 20-ms frame. The original base station drops the call when connection is firmly established in the new cell. Such dual connection, sometimes called "make before break," reduces the probability of a dropped call and of poor reception at a cell's edge.

12.9 CONCLUSION

Spread-spectrum (SS) technology has only emerged since the 1950s. Yet, this novel approach to applications, such as multiple access, ranging, and interference rejection, has rendered SS techniques extremely important to most current NASA and military communication systems. In this chapter we presented an overview enumerating the benefits and types of spread-spectrum techniques, as well as some historical background.

Since SS techniques were initially developed with military applications in mind, we started the treatment with discussions of anti-jam (AJ) systems. Pseudorandom sequences are at the heart of all present-day SS systems; we therefore treated PN generation and properties. Emphasis was placed on the two major spread-spectrum techniques; direct sequence and frequency hopping. Consideration was given to synchronization, a crucial aspect of spread-spectrum operation. Also, attention was devoted to the commercial use of spread-spectrum techniques for code-division multiple access (CDMA) systems, particularly direct-sequence CDMA, as it is specified in interim standard 95 (IS-95).

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PROBLEMS

12.1. Explain why a maximal-length n-stage linear feedback shift register can produce a sequence with a period no greater than $2^n - 1$.

12.2. Show that in a maximal-length n-stage linear feedback shift register the output stage must always be an input to the feedback network.

12.3. Consider the DS/BPSK spread-spectrum transmitter of Figure 12.9a or b. Let $x(t)$ be the sequence 1 0 0 1 1 0 0 0 1, arriving at a rate of 75 bits/s, where the leftmost bit is the earliest bit. Let $g(t)$ be generated by the shift register of Figure 12.7, with an initial state of 1 1 1 1 and a clock rate of 225 Hz.

(a) Sketch the final transmitted sequence $x(t)g(t)$.

(b) What is the bandwidth of the transmitted (spread) signal?

(c) What is the processing gain?

(d) Suppose that the estimated delay, $\hat{T}_d$, of Figure 12.9c is too large by one chip time. Sketch the despread chip sequence.

(e) Choose a decision rule for deciding on $\hat{x}(t)$ and identify the errors.

12.4. A total of 24 equal-power terminals are to share a frequency band through a code-division multiple access (CDMA) system. Each terminal transmits information at 9.6 kbits/s with a direct-sequence spread-spectrum BPSK modulated signal. Calculate the minimum chip rate of the PN code in order to maintain a bit error probability of 10^{-3}. Assume that the receiver noise is negligible with respect to the interference from the other users.

12.5. A feedback shift register PN generator produces a 31-bit PN sequence at a clock rate of 10 MHz. What are the equation and graphical form of the autocorrelation function and power spectral density of the sequence? Assume that the pulses have values of ±1.

12.6. Consider an FH/MFSK system such as the one shown in Figure 12.11. Let the PN generator be defined by a 20-stage linear feedback shift register with a maximal length sequence. Each state of the register dictates a new center frequency within the hopping band. The minimum step size between center frequencies (hop to hop) is 200 Hz. The register clock rate is 2 kHz. Assume that 8-ary FSK modulation is used and that the data rate is 1.2 kbits/s.

(a) What is the hopping bandwidth?

(b) What is the chip rate?

(c) How many chips are there in each data symbol?

(d) What is the processing gain?

12.7. The block diagram of Figure 12.16 is described in Section 12.4.5 for a fast frequency hopping (FFH) demodulator. Draw a similar block diagram for a slow frequency hopping (SFH) demodulator, and explain how it would work.

12.8. Find the mean and the standard deviation of the time needed to acquire a 10-megachip/s BPSK modulated PN code sequence using a serial search where 100 chips are examined at a time. Assume that a correct detection results when all 100 received chips match the locally generated ones. The ratio of received chip energy to noise power spectral density is 9.6 dB, and the uncertainty time between the received and local code sequences is 1 ms. Assume that the probability of false lock (false alarm) is negligible.

12.9. There are 11 equal-power terminals in a CDMA communication system, transmitting signals toward a central node. Each terminal transmits information at 1 kbit/s on a 100-kchips/s direct-sequence spreading signal using BPSK modulation.

(a) If receiver noise is negligible with respect to the interference from other users, what is the ratio of bit energy to interference power spectral density (E_b/I_0) received by a receiving terminal?

(b) What is the effect on E_b/I_0 if all users double their output power?

(c) If the users wish to expand their service to 101 equal-power users, what must be done to the spreading codes to maintain the original E_b/I_0 ratio?

12.10. A CDMA system uses direct-sequence modulation with a data bandwidth of 10 kHz and a spread bandwidth of 10 MHz. With only one signal being transmitted, the received E_b/N_0 is 16 dB.

- **(a)** If the required $(E_b/N_0 + I_0)$ is 10 dB, how many equal-power users can share the band? Do not neglect receiver noise.
- **(b)** If each user's transmitted power is reduced by 3 dB, how many equal-power users can share the band?
- **(c)** If the received $E_b/N_0 \rightarrow \infty$ for each receiver, what is the maximum number of users that can share the band?

12.11. A DS/SS system is used to combat multipath. If the path length of the multipath wave is 100 m longer than that of the direct wave, what is the minimum chip rate necessary to reject the multipath interference?

12.12. A ground-to-synchronous satellite link must be closed in a jamming environment. The data rate is 1 kbit/s and the ground station has a 60-ft antenna. Antijam protection is provided by a 10-Mbits/s direct-sequence spread-spectrum code. The jammer has a 150-ft antenna and a transmitter with 400 kW of power. Assume equal space and propagation losses. How much power is required of the earth station transmitter to achieve an E_b/J_0 of 16 dB at the satellite receiver? Assume that the receiver noise is negligible.

12.13. Input data at 75 bits/s are channel encoded using a rate $\frac{1}{2}$ encoder. The coded bits are then modulated using 8-ary FSK. The FSK symbols are then spread by frequency hopping at a rate of 2000 hops/s.

- **(a)** What is the chip rate?
- **(b)** What is the order of diversity?
- **(c)** If there are two such signals, time-division multiplexed (TDM'd) on the channel at the same hopping rate, how would this affect the chip rate, symbol rate, and order of diversity?
- **(d)** If there are 80 such signals TDM's on the channel, how would this effect the chip rate, symbol rate, and order of diversity?

12.14. A frequency hopping noncoherent binary FSK system operates at an E_b/N_0 of 30 dB with a hopping bandwidth of 2 GHz. Assume that no channel coding is used. A jammer operating over the same broadband bandwidth yields a received $J_0 = 100N_0$.

- **(a)** What is the bit error probability, P_B?
- **(b)** If the jammer becomes a partial-band jammer, what bandwidth should it occupy to be most effective?
- **(c)** What is P_B as a result of such optimum partial-band jamming?
- **(d)** What is the unjammed P_B?

12.15. A noncoherent frequency hopping 8-ary FSK system hops at 12,000 hops/s over a bandwidth of 1 MHz. The symbol rate is 3000 symbols/s. Assume that channel coding is not used. The signal power at the input of the receiver is 10^{-12} W. A partial-band noise jammer occupies 50 kHz (assumed to be entirely within the hopping bandwidth of the signal). The received jammer power is 10^{-11} W. Assume that the system temperature is 290 K. What is the probability of bit error?

12.16. A coherent DS/BPSK system is transmitting at a data rate of 10 kbits/s in the presence of a broadband jammer. Assume that the system does not use channel coding. Also assume that the propagation losses are the same for the system and the jammer.

- **(a)** If the EIRP of the communicator is 20 kW and the EIRP of the jammer is 60 kW, calculate the required spread-spectrum bandwidth to achieve a bit error probability of $P_B = 10^{-5}$.

(b) If the jammer is a pulse jammer, calculate the pulse duty cycle that results in worst-case jamming. What is the value of P_B at this duty cycle?

12.17. A communicator intends to use frequency hopping at a hop rate of 10,000 hops/s to avoid a threat of repeat-back jamming.

(a) Ignoring the curvature of the earth, and assuming that the communicator is transmitting to a satellite of geosynchronous altitude (approximately 36,000 km) that is directly overhead, compute the *radius of vulnerability*, which is the radius outside of which the communicator is unconditionally safe from repeat-back jamming by a ground-based jammer.

(b) If the communicator knows that the jammer requires a minimum of 10 μs to identify the transmission frequency and tune the jammer output, compute the radius of vulnerability conditioned on this information.

12.18. Consider an airborne repeat-back jammer as shown in Figure P12.1. The communicator is using a FH/SS system. What is the minimum hop rate required in order that the repeat-back jamming does not degrade the message? What would be the minimum required hopping rate if the communicator and jammer switched positions (i.e., fixed land jammer and airborne communicator).

12.19. Spread-spectrum techniques can be used to meet government regulations regarding flux (power) density radiating the surface of the earth. If a satellite at synchronous altitude (36,000 km) transmit 4-kbits/s data using 100 W of EIRP, what spreading bandwidth is required to maintain a flux density on the earth's surface no greater than −151 dBW/m^2 in any 4-kHz band?

12.20. A communicator uses noncoherent BFSK modulation and frequency hopping to combat the effects of a jammer. The power of the communicator's signal at the re-

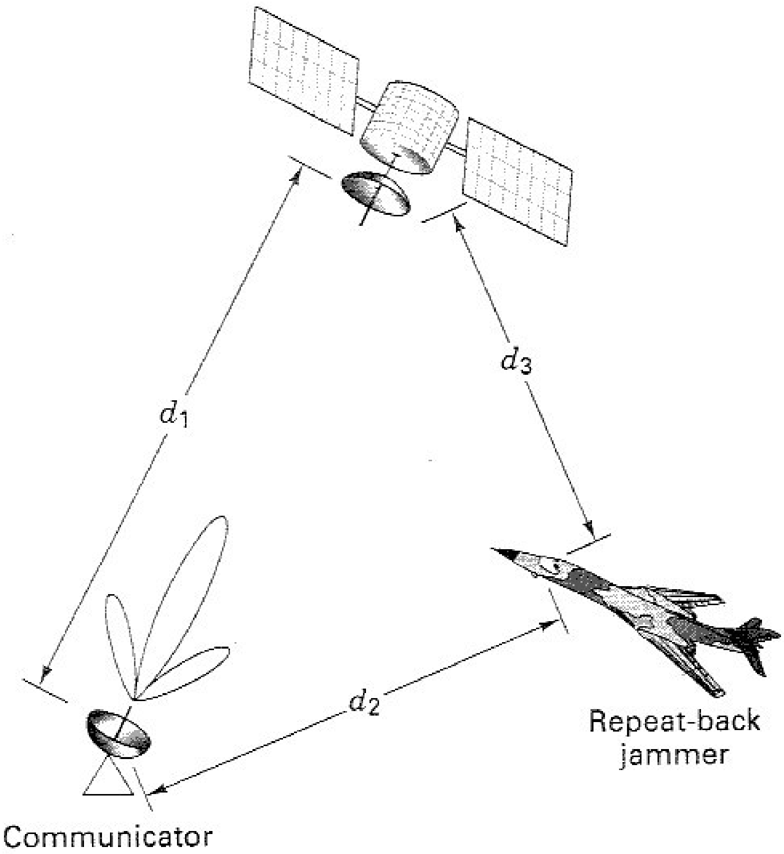

Figure P12.1

ceiver input is 10 μW. The SNR in the absence of jamming is assumed to be very large. The power of the jamming signal at the receiver input is 1 W.

(a) If the jammer jams the entire hopping bandwidth with equal amounts of Gaussian noise (the noise will be white within the band), what bandwidth expansion factor will allow the communicator to maintain a bit error probability of 10^{-4}?

(b) Assume that the jammer decides to "color" its jamming noise by reducing its energy by a fraction, α $(0 \leq \alpha \leq 1)$, in half the hop bandwidth, and increasing it by a like amount in the other half (thereby keeping its transmitted energy constant). Assuming that the communicator does not modify his hopping pattern to avoid the jammer strategy, develop an expression for the bit error probability for this case of colored jamming.

(c) Determine the fraction, α, that is optimum from the jammer standpoint for each of the limiting cases (i) when the effective SNR is large and, (ii) when it is small.

12.21. Spread-spectrum (SS) techniques can provide impressive error-performance benefits against interfering signals. One might therefore think that such SS techniques might provide similar benefits against AWGN. Explain why this is not possible.

12.22. A hand-held direct-sequence spread-spectrum (DS/SS) radio is part of a cellular CDMA system. The system specifications are as follows: data and SS-code modulation is BPSK, data rate is 8,000 bits/s, carrier frequency is 1 GHz, chip rate is 25 Mchips/s, worst-case path loss is 138.6 dB, gain of transmitting antenna is 5 dBI, receiver figure-of-merit G/T is −18 dB/K, occasional deep small-scale fading loss is 30 dB, other losses are 4 dB, required E_b/N_0 is 4 dB. The factors G_A, G_V, H_0, and γ are 2.5, 2.5, 1.6, and 1, respectively. Hint: Refer to Chapter 5 for treatment of link parameters.

(a) Find the required transmitter power P_t during deep small-scale fading.

(b) To what level can P_t be powered down when there is no small-scale fading?

(c) What is the minimum required E_{ch}/N_0 to meet the specifications?

(d) What is the processing gain?

(e) What is the maximum number of users per cell?

12.23. A direct-sequence spread-spectrum system using BPSK modulation for both the data and the code is required to support a data rate of 9600 bits/s. The received predetection power-received versus N_0 (P_r/N_0) is 48-dB Hz, and the SS-processing gain is 1000. A BCH (63, 51) error-correcting code is used. Verify that these system specifications can provide a bit-error probability of 10^{-4}. Hint: Use Equation (6.46) in Chapter 6, for computing decoded bit-error probability.

12.24. **(a)** Consider a CDMA direct-sequence cellular telephone system, where each user requires an E_b/I_0 of 6 dB for acceptable voice quality. The chip rate is 3.68 Mchips/s, and the data rate is 14.4 kbits/s. Assume that the factors γ, G_V, and H_0, are 1.5, 2.5, and 1.5, respectively, and that transmission ceases during speech pauses. How many users per cell can be supported?

(b) If a powerful error-correcting code is used to lower the required E_b/I_0 by 1 dB, how many users per cell can be supported?

12.25. A direct-sequence spread-spectrum system uses QPSK modulation for transmitting data. It is required that the bit-error probability be 10^{-5} and that $E_{ch}/I_0 \leq -30.4$ dB. Assuming perfect synchronization, what is the minimum number of chips/bit required?

12.26. A direct-sequence spread-spectrum system with a processing gain of 20 dB uses QPSK modulation for transmitting data. A rate $\frac{1}{2}$ error-correcting code is used, and the required bit-error probability is 10^{-5}. Assuming perfect synchronization, what is the minimum value of E_{ch}/I_0 and E_c/I_0 needed to support these requirements?

12.27. **(a)** A fast frequency-hopping spread-spectrum (FFH/SS) system uses 8-ary FSK modulation and a rate $\frac{1}{2}$ error-correcting code. Chips are transmitted with a repeat factor of $N = 4$. That is, each symbol is sent four times, each on a different hop. The required E_b/I_0 is 13 dB, the chip rate is 32 kchips/s, and the hopping bandwidth is 1.2 MHz. Find the data rate R, the processing gain G_p, the (P_r/I_0), the E_{ch}/I_0, the E_s/I_0, and the E_c/I_0.

(b) Will this system meet the FCC Part-15 requirements in the ISM band, for processing gain and bandwidth?

12.28. Consider a CDMA cellular telephone system designed to meet a standard similar to IS-95, with the following modifications. The spread-spectrum chip rate is 10.24 Mchips/s, and the data rate is 20 kbits/s. The reverse link uses a 256-ary Walsh waveform for modulating the rate $\frac{1}{2}$ coded data, requiring an E_b/I_0 of 6 dB. Find the values of the following received power-to-interference spectral density and energy-to-interference spectral density parameters: P_r/I_0, E_c/I_0, E_w/I_0, E_{wch}/I_0, and E_{ch}/I_0. Also, find the values of the following rates: R_c, R_w, and R_{wch}, where *c, w*, wch, and ch represent channel bit, Walsh waveform, Walsh chip, and spread-spectrum chip, respectively. What is the processing gain, and how many spread-spectrum chips correspond to one Walsh chip?

QUESTIONS

12.1. Frequency modulation (FM) and pulse code modulation (PCM) represent techniques that spread the spectrum of an information signal. Yet, such FM and PCM signals do not qualify as *spread-spectrum* signals. Why not? (See Section 12.1.)

12.2. List four *beneficial attributes* of spread-spectrum systems. (See Section 12.1.1.)

12.3. Describe three *randomness* properties that make pseudorandom signals appear to be random. (See Section 12.2.1.)

12.4. Define the term *chip,* in the context of a direct-sequence system, and in the context of a frequency-hopping system. (See Sections 12.3.2 and 12.4.4.)

12.5. What is meant by a *robust signal?* (See Section 12.4.2.)

12.6. What is the difference between *fast hopping* and *slow hopping?* (See Section 12.4.4.)

12.7. How does the *processing gain* parameter differ for direct-sequence systems compared with frequency-hopping systems? (See Sections 12.3.2 and 12.4.6.)

12.8. Explain how spread-spectrum systems can reliably receive signals that are "*buried in the noise.*" (See Example 12.5.)

12.9. For systems designed to meet IS-95, *Walsh codes* are used in the *forward* and *reverse* links for completely different functions. Explain the functions? (See Sections 12.8.4.1 and 12.8.4.2.)

EXERCISES

Using the Companion CD, run the exercises associated with Chapter 12.