Preface

The continuing vitality of spread-spectrum communication systems and the development of new mathematical methods for their analysis provided the motivation to undertake this new edition of the book. This edition is intended to enable readers to understand the current state-of-the-art in this field. Almost twenty percent of the material in this edition is new, including several new sections, a new chapter on adaptive arrays and filters, and a new chapter on code-division multiple-access networks. The remainder of the material has been thoroughly revised, and I have removed a considerable amount of material that has been superseded by more definitive results.

This book provides a comprehensive and intensive examination of spread-spectrum communication systems that is suitable for graduate students, practicing engineers, and researchers with a solid background in the theory of digital communication. As the title indicates, this book stresses principles rather than specific current or planned systems, which are described in many less advanced books. The principal goal of this book is to provide a concise but lucid explanation of the fundamentals of spread-spectrum systems with an emphasis on theoretical principles and methods of mathematical analysis that will facilitate future research. The choice of specific topics to include was tempered by my judgment of their practical significance and interest to both researchers and system designers. The book contains many improved derivations of the classical theory and presents the latest research results that bring the reader to the frontier of the field. The analytical methods and subsystem descriptions are applicable to a wide variety of communication systems. Problems at the end of each chapter are intended to assist readers in consolidating their knowledge and to provide practice in analytical techniques. The listed references are ones that I recommend for further study and as sources of additional references.

A spread-spectrum signal is one with an extra modulation that expands the signal bandwidth greatly beyond what is required by the underlying coded-data modulation. Spread-spectrum communication systems are useful for suppressing interference and jamming, making secure communications difficult to detect and process, accommodating fading and multipath channels, and providing a multiple-access capability without requiring synchronization across the entire network. The most practical and dominant spread-spectrum systems are direct-sequence and frequency-hopping systems.
There is no fundamental theoretical barrier to the effectiveness of spread-spectrum communications. That remarkable fact is not immediately apparent since the increased bandwidth of a spread-spectrum signal might require a receive filter that passes more noise power than necessary to the demodulator. However, when any signal and white Gaussian noise are applied to a filter matched to the signal, the sampled filter output has a signal-to-noise ratio that depends solely on the energy-to-noise-density ratio. Thus, the bandwidth of the input signal is irrelevant, and spread-spectrum signals have no inherent limitations.

Chapter 1 reviews fundamental results of coding and modulation theory that are essential to a full understanding of spread-spectrum systems. Channel codes, which are also called error-correction or error-control codes, are vital in fully exploiting the potential capabilities of spread-spectrum systems. Although direct-sequence systems can greatly suppress interference, practical systems require channel codes to deal with the residual interference and channel impairments such as fading. Frequency-hopping systems are designed to avoid interference, but the possibility of hopping into an unfavorable spectral region usually requires a channel code to maintain adequate performance. In this chapter, coding and modulation theory are used to derive the required receiver computations and the error probabilities of the decoded information bits. The emphasis is on the types of codes and modulation that have proved most useful in spread-spectrum systems.

Chapter 2 presents the fundamentals of direct-sequence systems. Direct-sequence modulation entails the direct addition of a high-rate spreading sequence with a lower-rate data sequence, resulting in a transmitted signal with a relatively wide bandwidth. The removal of the spreading sequence in the receiver causes a contraction of the bandwidth that can be exploited by appropriate filtering to remove a large portion of the interference. This chapter describes basic spreading sequences and waveforms and provides a detailed analysis of how the direct-sequence receiver suppresses various forms of interference.

Chapter 3 presents the fundamentals of frequency-hopping systems. Frequency hopping is the periodic changing of the carrier frequency of a transmitted signal. This time-varying characteristic potentially endows a communication system with great strength against interference. Whereas a direct-sequence system relies on spectral spreading, spectral despreading, and filtering to suppress interference, the basic mechanism of interference suppression in a frequency-hopping system is that of avoidance. When the avoidance fails, it is only temporary because of the periodic changing of the carrier frequency. The impact of the interference is further mitigated by the pervasive use of channel codes, which are more essential for frequency-hopping than for direct-sequence systems. The basic concepts, spectral and performance aspects, and coding and modulation issues are presented. The effects of partial-band interference and jamming are examined, and the most important issues in the design of frequency synthesizers are described.

Chapter 4 focuses on synchronization. A spread-spectrum receiver must generate a spreading sequence or frequency-hopping pattern that is synchronized with the received sequence or pattern; that is, the corresponding chips or dwell intervals must precisely or nearly coincide. Any misalignment causes the signal amplitude at the
demodulator output to fall in accordance with the autocorrelation or partial autocorrelation function. Although the use of precision clocks in both the transmitter and the receiver limit the timing uncertainty in the receiver, clock drifts, range uncertainty, and the Doppler shift may cause synchronization problems. Code synchronization, which is either sequence or pattern synchronization, might be obtained from separately transmitted pilot or timing signals. It may be aided or enabled by feedback signals from the receiver to the transmitter. However, to reduce the cost in power and overhead, most spread-spectrum receivers achieve code synchronization by processing the received signal. Both acquisition, which provides coarse synchronization, and tracking, which provides fine synchronization, are described in this chapter. The emphasis is on the acquisition system because this system is almost always the dominant design issue and most expensive component of a complete spread-spectrum system.

Adaptive filters and adaptive arrays have numerous applications as components of communication systems. Chapter 5 focuses on those adaptive filters and adaptive arrays that are amenable to exploiting the special spectral characteristics of spread-spectrum signals to enable interference suppression beyond that inherent in the despreading or dehopping. Adaptive filters for the rejection of narrowband interference or primarily for the rejection of wideband interference are presented. Adaptive arrays for both direct-sequence systems and frequency-hopping systems are described and shown to potentially provide a very high degree of interference suppression.

Chapter 6 provides a general description of the most important aspects of fading and the role of diversity methods in counteracting it. Fading is the variation in received signal strength due to a time-varying communications channel caused by the interaction of multipath components of the transmitted signal that are generated and altered by changing physical characteristics of the propagation medium. The principal means of counteracting fading are diversity methods, which are based on the exploitation of the latent redundancy in two or more independently fading copies of the same signal. The rake demodulator, which is of central importance in most direct-sequence systems, is shown to be capable of exploiting undesired multipath signals rather than simply attempting to reject them. The multicarrier direct-sequence system is shown to be a viable alternative method of exploiting multipath signals.

Multiple access is the ability of many users to communicate with each other while sharing a common transmission medium. Wireless multiple-access communications are facilitated if the transmitted signals are orthogonal or separable in some sense. Signals may be separated in time (time-division multiple access or TDMA), frequency (frequency-division multiple access or FDMA), or code (code-division multiple access or CDMA). Chapter 7 presents the general characteristics of spreading sequences and frequency-hopping patterns that are suitable for CDMA systems, which comprise direct-sequence CDMA (DS-CDMA) and frequency-hopping CDMA (FH-CDMA) systems. The use of spread-spectrum modulation in CDMA allows the simultaneous transmission of signals from multiple users in the same frequency band. All signals use the entire allocated spectrum, but the spreading sequences or frequency-hopping patterns differ. Information theory indicates that in an isolated cell, CDMA systems
achieve the same spectral efficiency as TDMA or FDMA systems only if optimal multiuser detection is used. However, even with single-user detection, CDMA has advantages for mobile communication networks because it eliminates the need for frequency and time-slot coordination, allows carrier-frequency reuse in adjacent cells, imposes no sharp upper bound on the number of users, and provides resistance to interference and interception. Multiuser detectors, which have great potential usefulness but are fraught with practical difficulties, are described and assessed.

The impact of multiple-access interference in mobile ad hoc and cellular networks with DS-CDMA and FH-CDMA systems is analyzed in Chap. 8. Phenomena and issues that become prominent in mobile networks using spread spectrum include exclusion zones, guard zones, power control, rate control, network policies, sectorization, and the selection of various spread-spectrum parameters. The outage probability, which is the fundamental network performance metric, is derived for both ad hoc and cellular networks and both DS-CDMA and FH-CDMA systems. Acquisition and synchronization methods that are needed within a cellular DS-CDMA network are addressed.

Chapter 9 examines the role of iterative channel estimation in the design of advanced spread-spectrum systems. The estimation of channel parameters, such as the fading amplitude and the power spectral density of the interference and noise, is essential to the effective use of soft-decision decoding. Channel estimation may be implemented by the transmission of pilot signals that are processed by the receiver, but pilot signals entail overhead costs, such as the loss of data throughput. Deriving maximum-likelihood channel estimates directly from the received data symbols is often prohibitively difficult. There is an effective alternative when turbo or low-density parity-check codes are used. The expectation-maximization algorithm, which is derived and explained, provides an iterative approximate solution to the maximum-likelihood equations and is inherently compatible with iterative demodulation and decoding. Two examples of advanced spread-spectrum systems that apply iterative channel estimation, demodulation, and decoding are described and analyzed in this chapter. These systems provide good illustrations of the calculations required in the design of advanced systems.

The ability to detect the presence of spread-spectrum signals is often required by cognitive radio, ultra-wideband, and military systems. Chapter 10 presents an analysis of the detection of spread-spectrum signals when the spreading sequence or the frequency-hopping pattern is unknown and cannot be accurately estimated by the detector. Thus, the detector cannot mimic the intended receiver, and alternative procedures are required. The goal is limited in that only detection is sought, not demodulation or decoding. Nevertheless, detection theory leads to impractical devices for the detection of spread-spectrum signals. An alternative procedure is to use a radiometer or energy detector, which relies solely on energy measurements to determine the presence of unknown signals. The radiometer has applications not only as a detector of spread-spectrum signals, but also as a sensing method in cognitive radio and ultra-wideband systems.
Four Appendices contain mathematical details about Gaussian processes and the central limit theorem, special functions, signal characteristics, and basic probability distributions.

In writing this book, I have relied heavily on notes and documents prepared and the perspectives gained during my work at the US Army Research Laboratory. I am thankful to my colleagues Matthew Valenti, Hyuck Kwon, and Yingtao Niu for their trenchant and excellent reviews of selected chapters of the original manuscript. I am grateful to my wife, Nancy, who provided me not only with her usual unwavering support but also with extensive editorial assistance.