Principles of Spread-Spectrum Communication Systems

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Fourth Edition

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To my family

Preface

The continuing vitality of spread-spectrum communication systems and my desire to expand the scope of the content motivated me to undertake this fourth edition of *Principles of Spread-Spectrum Communication Systems*. This edition is intended to enable readers to understand the current state-of-the-art spread-spectrum communication systems. This edition includes new or enhanced sections on code tracking, the normalized LMS algorithm, frequency-hopping diversity, direct-sequence multicode and multiple-input multiple-output systems, interference cancelers, optimal frequency-hopping patterns, complementary codes, Laplace transforms and characteristic functions, orthonormal functions, and Hermitian positive-definite matrices. The remainder of the material has been thoroughly revised to improve the presentation.

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, 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, bringing 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 of analytical techniques. The listed references are those I recommend for further study and as sources of additional references.

A *spread-spectrum signal* is a signal with extra modulation that expands the signal bandwidth greatly beyond what is required by the underlying channel code and modulation. Spread-spectrum communication systems are useful for suppressing interference and jamming, making it difficult to detect and process secure communications, 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. This remarkable fact is not immediately apparent because the increased bandwidth of a spread-spectrum signal necessitates a receive filter that passes more noise power 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. In this chapter, coding and modulation theory are used to derive the required receiver computations and the error probabilities of the decoded information bits. *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 limit the effects of 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.

Chapter 2 presents the fundamentals of direct-sequence systems. This chapter describes basic spreading sequences and waveforms and provides a detailed analysis of how the direct-sequence receiver suppresses various forms of interference. *Direct-sequence modulation* entails the direct addition of a high-rate spreading sequence and 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 applying appropriate filtering to remove a large portion of the interference.

Chapter 3 covers 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 systems 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 multitone jamming are examined, and the most important issues in the design of frequency synthesizers are described.

The methods of code synchronization for both direct-sequence and frequency-hopping systems are presented in Chapter 4. A spread-spectrum receiver requires *code synchronization* to generate a spreading sequence or frequency-hopping pattern that is synchronized with the received sequence or pattern. After code synchronization, the received and receiver-generated 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. A practical implementation of code synchronization is greatly facilitated by dividing synchronization into two operations: acquisition and tracking. *Code acquisition* provides coarse synchronization by limiting the possible timing offsets of the receiver-generated chips or dwell intervals to a finite number of quantized candidates. Code acquisition is almost always the dominant design issue and most expensive component of a complete spread-spectrum system. Following code acquisition, *code tracking* is activated to provide fine synchronization by which synchronization errors are further reduced or at least maintained within certain bounds. *Symbol synchronization*, which is needed to provide timing pulses for symbol detection to the decoder, is derived from the code-synchronization system. Although the use of precision clocks in both the transmitter and the receiver limit the timing uncertainty of sequences or patterns in the receiver, clock drifts, range uncertainty, and the Doppler shift may cause synchronization problems.

Adaptive filters and adaptive arrays have numerous applications as components of communication systems. Chapter 5 covers 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. The least-mean-square (LMS), normalized LMS, and Frost algorithms are derived, and conditions for the convergence of their mean weight vectors are determined. 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 changes in the physical characteristics of the propagation medium, which alter the interaction of multipath components of the transmitted signal. 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 basic concept of diversity is that even if some copies are degraded, there is a high probability that others will not be. Both direct-sequence and frequency-hopping signals are shown to provide diversity. 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 and frequency-domain equalization are shown to be alternative methods of advantageously processing 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 *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. The vast potential and practical difficulties of spread-spectrum multiuser detectors, such as optimal, decorrelating, minimum mean-square error, or adaptive detectors, are described and assessed. The tradeoffs and design issues of direct-sequence multiple-input multiple-output with spatial multiplexing or beamforming are determined.

The impact of multiple-access interference on mobile ad hoc and cellular networks with DS-CDMA and FH-CDMA systems are analyzed in Chapter 8. Phenomena and issues that become prominent in mobile networks using a 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. 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 general sensing method in cognitive radio and ultra-wideband systems.

Eight appendices contain important mathematical details about Gaussian processes and the central limit theorem, the moment-generating function and the Laplace transform, the Fourier transform and the characteristic function, deterministic and random signal characteristics, probability distribution functions, orthonormal functions and parameter estimation, Hermitian positive-definite matrices, and special functions.

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 and Hyuck Kwon for their thorough reviews 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.

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