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DIGITAL COMMUNICATIONS AND SPREAD SPECTRUM SYSTEMS

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PREFACE

The goal of this book is to carry the treatment of the implementation of digital communication systems a step beyond that given in most introductory communications systems texts. As such, it is intended for a second course in communications systems at the senior and first year graduate levels, for continuing education (short) courses, or for self study by communications engineers in industry. Previous background assumed on the part of the student is an introductory course in communications systems which has included a coverage of spectral analysis, linear system theory, basic modulation theory, and an introduction to probability and random processes. This material is included in review form in the book for the benefit of those students who have not been recently exposed to it.

A feature of the book is a treatment of digital communications techniques that includes both theoretical development and the consideration of various types of system degradations from ideal performance. These include hardware impairments introduced at the modulator and demodulator as well as channel-induced impairments.

A second feature of the book is the treatment of spread spectrum systems, including the basic spread spectrum concept, codes for spread spectrum systems, initial code synchronization and tracking, error correction coding as applied to spread spectrum systems, and performance characteristics of spread spectrum systems.

The organization of the book is as follows. The first two chapters deal with introductory and review material, the next four with topics of general concern in digital communications, and the last seven with spread spectrum communication system theory and analysis. The structure of the book allows for considerable flexibility in course arrangement, and several possible course outlines are given at the end of this preface. Each chapter includes an ample supply of problems and references for use in further study. A solutions manual is available from the publisher as an aid to the instructor.

Chapter 1 begins with an introduction to the field of digital communications, giving several reasons for the increasing popularity and use of digital communications systems. A general block diagram for a digital communications system is given and the functions of the various blocks are discussed in detail. Also introduced at this point is the concept of error-free capacity of a communication system and the power-bandwidth tradeoff which is of importance in most communication system designs. In connection with the discussion of digital information sources, the concept of a measure of average information, or entropy, is discussed, and the process whereby the theoretically maximum average source-information rate can be approached by employing variable-length coding of the source output for *redundancy reduction* is illustrated. Moving next to the transmitter, the concept of adding redundancy to the digital data stream for error correction is introduced. The use of *modulation* to suitably prepare the data for transmission through the channel is also discussed and several examples of modulation schemes are given. The final operation performed in the transmitter may involve power amplification with the possible introduction of nonlinearities and filtering.

Two approaches or levels are available for characterizing the next major component of a communication system, the channel. These two approaches are the waveform description and the transition probability description. Both are discussed and the features of both are illustrated through examples. At the waveform level of description, the most prevalent form of perturbation on the transmitted signal is thermal noise generated *internally* to the communication system. Accordingly, a brief treatment of the means for characterizing thermal noise is given in Appendix B, including the concepts of noise figure and noise temperature. Also briefly summarized in Chapter 1 are *external perturbations* on the transmitted signal.

The final important communication system component discussed in Chapter 1 is the receiver. Because the remainder of the book is concerned with the details of designing the *demodulation* and *detection* functions of the receiver, this section is relatively brief. The broad coverage of general digital communication system concepts given in Chapter 1 provides the overall perspective of the areas of digital communications systems analysis and design discussed in detail in the remainder of the book.

The next chapter of the book, "Signals and Systems Overview," is intended as a review and to establish notation for the remainder of the book. However, it may also be used as a first-time coverage of the material with some expansions made by the instructor. Features of Chapter 2 are fairly comprehensive treatments of the effects of nonideal filter effects on modulated signals, nonlinear device characterization including mixers, and practical filter characteristics. Appendix A treats probability concepts, random signal characterization, and systems analysis involving random signals to provide a quick review for those requiring it.

Chapter 3 gives a treatment of basic digital data transmission concepts. The infinite bandwidth, additive white Gaussian noise (AWGN) channel is considered first. This leads to the concept of a matched filter receiver, or the alternative implementation as a correlation receiver. Several basic digital modulation methods are introduced as special cases, including biphase-shift keying (BPSK), amplitude-shift keying (ASK), frequency-shift keying (FSK), quadriphase shift keying (QPSK), and minimum-shift keying (MSK). Both the parallel and serial approaches are discussed for the latter. Bandwidths for BPSK, QPSK, and MSK are derived and compared. Following the consideration of the infinite bandwidth case, signal designs and receiver implementations for finite bandwidth channels are analyzed. This makes use of the early work by Nyquist in regard to intersymbol-interference-free transmission and the later invention by Lender of duobinary signaling. Chapter 3 closes with a consideration of several implementation questions such as nonideal filtering, carrier tracking, symbol clock tracking, and the attendant degradation introduced by nonideal realizations of these functions.

Chapter 4, which can be omitted in an introductory course, approaches the signal detection problem using the maximum *a posteriori* (MAP) criterion and vector space representation of signals. This provides a general framework for the consideration of virtually any digital signaling scheme operating in an AWGN environment. Use of the union bound in providing tight upper bounds for the probability of error for M-ary digital modulation schemes is introduced. Several special cases are considered including M-ary orthogonal signaling, M-ary phase-shift keying, and combined amplitude- and phase-shift keying. The subject of introducing coding to achieve efficient transmission of message sequences through AWGN channels at any rate below *channel capacity* is discussed. Contrary to intuitive notions, Shannon's *capacity theorem* shows that it is possible to simultaneously achieve bandwidth and power efficiency. The next section introduces a scheme which can simultaneously achieve good bandwidth and power efficiency; it is referred to as multi-h continuous phase modulation. An overview of the Viterbi algorithm as an implementation of the MAP estimator of a Markov sequence is provided in Appendix C. Its many applications include the decoding of convolutional codes and multi-h signals. The latter application is covered in Chapter 4.

Another important aspect of digital communication system design is that of generation of coherent references. Chapter 5 provides an overview of this area including basic phase-lock loop theory and frequency synthesizer design.

Any digital communication system requires the synchronization of clocks. These include the carrier oscillators at transmitter and receiver in a coherent communication system, the symbol timing clocks, code timing in systems employing coding, and frame timing in systems where the data is transmitted in blocks or frames. The consideration of synchronization techniques could well occupy an entire book. Accordingly, Chapter 6 can be considered only an introduction to this important area.

The remaining chapters of the book deal with spread spectrum communication systems. Chapter 7 introduces the concept of spread spectrum and the reasons for its use. The most widely used types of spread spectrum modulation are described including *direct sequence* (DS), *frequency hopped* (FH), and hybrid DS/FH spread spectrum.

The generation of pseudo-random digital sequences is important in any spread spectrum system implementation. Chapter 8 provides a comprehensive introduction to the generation of pseudo-noise (PN) sequences by means of linear feedback shift registers and the properties of PN sequences. Other types of sequences such as Gold codes, rapid acquisition codes, and nonlinear codes are considered at the end of the chapter. The latter are particularly important in spread spectrum systems where security is an issue.

An important function in any spread spectrum system is synchronization of the locally generated despreading code with the spreading code generated at the transmitter. This synchronization problem can be divided into two parts, initial synchronization and tracking. The former is the most complex to analyze mathematically. Code tracking is therefore considered in Chapter 9, with acquisition taken up in Chapter 10, even though code acquisition must chronologically precede tracking in the spread spectrum communication process. The two main code tracking methods used are referred to as the *full-time early-late tracking loop* and the *tau-dither early-late tracking loop*. With suitable manipulations and definitions of the signal and noise processes within the loop, both techniques can be reduced to conventional phase-lock loop type implementations. Once this point is reached, the treatment of code tracking loops can make use of standard phase-lock-loop analysis techniques. Also included in Chapter 9 are introductions to frequency hop tracking loops, and the double dither loop.

Initial synchronization of the spreading waveform is perhaps the most difficult spread spectrum problem. Chapter 10 treats this subject comprehensively. Beginning with the simplest technique using a swept serial search, the discussion progresses through a general analysis of stepped serial search, a discussion of multiple-dwell detection techniques, and finally to a detailed analysis of sequential detection techniques. In all cases, the student is presented with analytical techniques which enable calculation of the mean and sometimes the variance of the synchronization time. Chapter 10 finishes with a short discussion of matched filter synchronization techniques.

The analysis of the performance of spread spectrum systems in a jamming environment is the subject of Chapter 11. The chapter begins with a discussion of the system model including barrage noise, partial band noise, pulsed noise, tone, multiple tone, and repeater jamming. Following this, the most commonly used digital modulation techniques, including BPSK/BPSK,* QPSK/BPSK, FH/DPSK, and FH/MFSK, are evaluated in most types of jamming. It is concluded that error correction coding is an essential component of any spread spectrum system to provide adequate protection to jamming. Accordingly, Chapter 12 treats the performance of spread spectrum systems which employ forward error correction. Some important coding schemes, including Reed–Solomon, BCH, and convolutional, are presented. The concepts of channel capacity and computational cut-off rate as applied to spread spectrum systems are introduced to provide performance bounds for coded systems. Chapter 12 provides the reader with computational techniques which may be used to evaluate system error performance.

The discussion of spread spectrum systems is concluded in Chapter 13 with descriptions of some currently operational systems. Examples are given which apply the analytical techniques of Chapters 7–12 to actual systems.

Chapters 1–6 were written by Rodger E. Ziemer; Chapters 7–13 were written by Roger L. Peterson.

Parts of the book have been taught to engineers in industry, and portions have been used in note form as a basis for courses ranging from the senior undergraduate level to graduate level. The success of these courses has resulted from being able to select appropriate chapters from the text in order to tailor the course content to the needs and backgrounds of the students taking the particular course. Examples of chapter selections for several possible courses are given in the following table.

*Spreading Modulation/Data Modulation

Introductory Semester Course on Digital Communications for Undergraduates	Two Twenty Hour Short Courses on Spread Spectrum for Engineers in Industry	Semester Advanced Course on Digital Detection and Spread Spectrum for Graduate Students
	PART 1	
Chapter 1 Chapter 2—Last Half Appendix A for Review Chapter 3 Chapter 5 Chapter 7	Appendix A—Review Chapter 3 Chapter 5 Chapter 6—Review PLL Chapter 7 Chapter 8	Chapter 4 Chapter 6—PLL Chapter 7 Chapter 8 Chapter 9 Chapter 10 Chapter 11 Chapter 12 Chapter 13
	PART 2	
	Chapter 9 Chapter 10 Chapter 11 Chapter 12 Chapter 13	

The authors wish to express their thanks to the many people who have contributed to the development of this book. Thanks are due first of all to Carl Ryan, who sowed the seeds for this book while both authors worked for him in 1980–1981, and to students who took classes in which parts of the book were used in note form. These include engineers at Motorola Inc., Government Electronics Group, Scottsdale, Arizona, and students at the University of Missouri–Rolla (UMR) Electrical Engineering Department, Rolla, Missouri; the UMR Graduate Engineering Center, St. Louis, Missouri; and the Electrical Engineering Department at the University of Colorado at Colorado Springs. We also thank our colleagues at both the University of Missouri–Rolla, The University of Colorado at Colorado Springs (UCCS), and Motorola who have provided helpful suggestions. Professors J. B. Anderson, Prakash Narayan, Allan R. Hambley, Leon Couch, David L. Landis, and John N. Daigle reviewed the manuscript. Two persons in particular deserve mentioning: John Liebetreu and Mark Wickert, both of whom suffered through the book in note form at UMR and both of whom checked portions of it when a course was taught at UCCS. All errors which inevitably remain are solely the responsibility of the authors, however. The expert and fast typing of Kathy Collins at UMR is also gratefully acknowledged. Other typists who put considerable effort into various stages of the manuscript are Diane Borque and Lorrie Evans. Alice Astuto of Macmillan spent innumerable hours obtaining the permissions required for this book.

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R.E.Z.
R.L.P.

CONTENTS

CHAPTER 1

Basic Concepts of Digital Data Transmission

1-1 INTRODUCTION

This book is concerned with the transmission of information by electrical means using *digital communication techniques*. Information may be transmitted from one place to another using either digital or analog communication systems. In a digital system, the information is processed so that it can be represented by a sequence of discrete messages. Each message is one of a finite set of messages. For example, the information at the output of a sensor may be a voltage waveform whose amplitude at any given time instant may assume a continuum of values. This waveform may be processed by sampling at appropriately spaced time instants, quantizing these samples, and converting each quantized sample to a binary number (i.e., an analog-to-digital converter). Each sample value is therefore represented by a sequence of ones and zeros, and the communication system associates the message 1 with a transmitted signal $s_1(t)$ and the message 0 with a transmitted signal $s_0(t)$. During each signaling interval either the message 0 or 1 is transmitted with no other possibilities. In practice, the transmitted signals $s_0(t)$ and $s_1(t)$ may be two different phases, say $\pm\pi/2$, or two different amplitudes, say 0 and A, of a sinusoidal carrier. In an analog communication system the sensor output would be used directly to modify some characteristic of the transmitted signal, such as amplitude, phase, or frequency.