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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 biphas-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	Appendix A—Review	Chapter 4
Chapter 2—Last Half	Chapter 3	Chapter 6—PLL
Appendix A for Review	Chapter 5	Chapter 7
Chapter 3	Chapter 6—Review PLL	Chapter 8
Chapter 5	Chapter 7	Chapter 9
Chapter 7	Chapter 8	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.

Finally, a sincere word of thanks goes to our wives Sandy and Ann for putting up with a project which to them seemed nebulous and endless at times. Without their encouragement and support, this book could not have been written.

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

CONTENTS

1	BASIC CONCEPTS OF DIGITAL DATA TRANSMISSION	1
1-1	Introduction	1
1-2	Glossary of Terms	3
1-3	Further Consideration of Digital Communication System Design	5
1-3.1	General Considerations	5
1-3.2	Error-Free Capacity of a Communication System	7
1-3.3	The Source in a Digital Communication System	9
1-3.4	The Transmitter in a Digital Communication System	15
1-3.5	The Channel	23
1-3.6	The Receiver	36
1-4	Prologue	37
	References	39
	Problems	39
2	SIGNALS AND SYSTEMS: OVERVIEW	43
2-1	Review of Signal and Linear System Theory	43
2-1.1	Introduction	43
2-1.2	Classification of Signals	43

2-1.3	Fundamental Properties of Systems	45	
2-1.4	Complex Exponentials as Eigenfunctions for a Fixed, Linear System; Transfer Function	47	
2-1.5	Orthogonal Function Series	48	
2-1.6	Complex Exponential Fourier Series	50	
2-1.7	Fourier Transform	53	
2-1.8	Signal Spectra	57	
2-1.9	Energy Relationships	58	
2-1.10	System Analysis	61	
2-1.11	Other Applications of the Fourier Transform	64	
2-2	Complex Envelope Representation of Signals and Systems		67
2-2.1	Narrowband Signals	67	
2-2.2	Narrowband Signals and Narrowband Systems	69	
2-3	Signal Distortion and Filtering		72
2-3.1	Distortionless Transmission and Ideal Filters	73	
2-3.2	Group and Phase Delay	73	
2-3.3	Nonlinear Systems and Nonlinear Distortion	81	
2-4	Practical Filter Types and Characteristics		86
	References		100
	Problems		101

3 PERFORMANCE CHARACTERIZATION OF DIGITAL DATA TRANSMISSION SYSTEMS

3-1	Introduction		105
3-2	Detection of Binary Signals in White, Gaussian Noise		106
3-2.1	Receiver Structure and Analysis	106	
3-2.2	The Matched Filter	109	
3-2.3	Application of the Matched Filter to Binary Data Detection	112	
3-2.4	Correlator Realization of Matched Filter Receivers	115	
3-3	Quadrature-Multiplexed Signaling Schemes: QPSK, OQPSK, and MSK		117
3-3.1	Quadrature Multiplexing	117	
3-3.2	Quadrature and Offset-Quadrature Phase-Shift Keying	118	
3-3.3	Minimum-Shift Keying	120	
3-3.4	Performance of Digital Quadrature Modulation Systems	120	
3-4	Power Spectra for BPSK, QPSK, OQPSK, and MSK		124
3-5	Serial Modulation and Detection of MSK		128
3-5.1	Serial Approach	129	
3-5.2	Terminology and Trellis Diagrams	130	
3-6	Signaling Through Bandlimited Channels		133
3-6.1	System Model	133	
3-6.2	Designing for Zero ISI: Nyquist's Pulse-Shaping Criterion	135	
3-6.3	Optimum Transmitting and Receiving Filters	136	

3-6.4	Quadrature Bandpass Systems and Multiple Amplitude Systems	141
3-6.5	Shaped Transmitted Signal Spectra	142
3-6.6	Duobinary Signaling	143
3-7	The Use of Eye Diagrams for System Characterization	146
3-8	Equalization in Digital Data Transmission Systems	147
3-8.1	Zero Forcing Equalizers	147
3-8.2	LMS Equalizer Application	151
3-8.3	Adaptive Weight Adjustment	155
3-8.4	Other Equalizer Structures	157
3-9	Degradations due to Realization Imperfections in Digital Modulation Systems	158
3-9.1	Phase and Amplitude Imbalance in BPSK	159
3-9.2	Phase and Amplitude Unbalance in QPSK Modulation	160
3-9.3	Power Loss due to Filtering the Modulated Signal	162
3-9.4	Imperfect Phase Reference at a Coherent Demodulator	162
3-9.5	Degradation due to a Nonideal Detection Filter	166
3-9.6	Degradation due to Predetection Filtering	169
3-9.7	Degradation due to Transmitter, or Channel Filtering; Non-Matched Detector	170
3-9.8	Degradation due to Bit Synchronizer Timing Error	171
3-10	Modulator Structures for QPSK, OQPSK, and MSK	174
3-11	Envelope Functions for BPSK, QPSK, OQPSK, and MSK	177
	References	179
	Problems	180

4 SIGNAL-SPACE METHODS IN DIGITAL DATA TRANSMISSION 184

4-1	Introduction	184
4-2	Optimum Receiver Principles in Terms of Vector Spaces	186
4-2.1	Maximum a Posteriori Detectors	186
4-2.2	Vector-Space Representation of Signals	188
4-2.3	MAP Detectors in Terms of Signal Spaces	192
4-2.4	Performance Calculations for MAP Receivers	195
4-3	Performance Analysis of Coherent Digital Signaling Schemes	198
4-3.1	Coherent Binary Systems	198
4-3.2	Coherent M -ary Orthogonal Signaling Schemes	200
4-3.3	M -ary Phase-Shift Keying	204
4-3.4	Multi-amplitude/Phase-Shift Keyed Systems	207
4-3.5	Bandwidth Efficiency of M -ary Digital Communication Systems	211
4-4	Signaling Schemes Not Requiring Coherent References at the Receiver	213
4-4.1	NFSK	213
4-4.2	DPSK	215

4-5	Efficient Signaling for Message Sequences	222
4-5.1	Summary of Block-Orthogonal and M -ary Signaling Performance	222
4-5.2	Channel Coding Theorem	224
4-6	Multi-h Continuous Phase Modulation	228
4-6.1	Description of the Multi- h CPM Signal Format	229
4-6.2	Performance Bounds [12]	233
4-6.3	Calculation of Power Spectra for Multi- h CPM Signals	236
4-6.4	Synchronization Considerations for Multi- h CPM Signals	243
4-6.5	Application of the Viterbi Algorithm to Detection of Multi- h CPM Signals	246
	References	250
	Problems	251

5 GENERATION OF COHERENT REFERENCES **254**

5-1	Introduction	254
5-2	Description of Phase Noise and its Properties	255
5-2.1	General Considerations	255
5-2.2	Phase and Frequency Noise Power Spectra	255
5-2.3	Allan Variance	259
5-2.4	Effect of Frequency Multipliers and Dividers on Phase-Noise Spectra	260
5-3	Phase-Lock Loop Models and Characteristics of Operation	261
5-3.1	Synchronized Mode: Linear Operation	261
5-3.2	Effects of Noise	266
5-3.3	Phase-Locked-Loop Tracking of Oscillators with Phase Noise	270
5-3.4	Phase Jitter Plus Noise Effects	271
5-3.5	Transient Response	272
5-3.6	Phase-Locked-Loop Acquisition	275
5-3.7	Other Configurations	278
5-3.8	Effects of Transport Delay	281
5-4	Frequency Synthesis	281
5-4.1	Digital Synthesizers	281
5-4.2	Direct Synthesis	283
5-4.3	Phase-Locked Frequency Synthesizers	287
	References	289
	Problems	290

6 SYNCHRONIZATION OF DIGITAL COMMUNICATION SYSTEMS **293**

6-1	The General Problem of Synchronization	293
6-2	Application of the MAP and ML Principles to Estimation of Signal Parameters	296
6-2.1	Preliminary Definitions and Relationships	296
6-2.2	Expressions for Estimation of Continuous Waveform Parameters	298

6-2.3	Generalization of the Estimator Equations to Multiple Symbol Intervals and Multiple Parameters	302	
6-2.4	Data-Aided Versus Non-Data-Aided Synchronization	309	
6-2.5	Joint Estimation of Parameters	309	
6-2.6	Open-Loop Versus Closed-Loop Structures	311	
6-2.7	Practical Timing Epoch Estimators	312	
6-3	Synchronization Methods Based on Properties of Wide-Sense Cyclostationary Random Processes		314
6-3.1	Carrier Recovery Circuits	315	
6-3.2	Delay and Multiply Circuits for Symbol Clock Estimation	319	
	References		325
	Problems		325

7 INTRODUCTION TO SPREAD SPECTRUM SYSTEMS 327

7-1	Introduction		327
7-2	Two Communications Problems		328
7-2.1	Pulse-Noise Jamming	328	
7-2.2	Low Probability of Detection	330	
7-3	Direct-Sequence Spread Spectrum		332
7-3.1	BPSK Direct-Sequence Spread Spectrum	332	
7-3.2	QPSK Direct-Sequence Spread Spectrum	340	
7-3.3	MSK Direct-Sequence Spread Spectrum	344	
7-4	Frequency-Hop Spread Spectrum		348
7-4.1	Coherent Slow-Frequency-Hop Spread Spectrum	348	
7-4.2	Noncoherent Slow-Frequency-Hop Spread Spectrum	352	
7-4.3	Noncoherent Fast-Frequency-Hop Spread Spectrum	354	
7-5	Hybrid Direct-Sequence/Frequency-Hop Spread Spectrum		355
7-6	Complex-Envelope Representation of Spread-Spectrum Systems		357
	References		361
	Problems		361

8 BINARY SHIFT REGISTER SEQUENCES FOR SPREAD-SPECTRUM SYSTEMS 365

8-1	Introduction		365
8-2	Definitions, Mathematical Background, and Sequence Generator Fundamentals		366
8-2.1	Definitions	366	
8-2.2	Finite-Field Arithmetic	368	
8-2.3	Sequence Generator Fundamentals	375	
8-3	Maximal-Length Sequences		385
8-3.1	Properties of m -Sequences	385	
8-3.2	Power Spectrum of m -Sequences	387	
8-3.3	Tables of Polynomials Yielding m -Sequences	388	

8-3.4	Partial Autocorrelation Properties of m -Sequences	392	
8-3.5	Power Spectrum of $c(t)c(t + \epsilon)$	396	
8-3.6	Generation of Specific Delays of m -Sequences	396	
8-4	Gold Codes		404
8-5	Rapid Acquisition Sequences		407
8-6	Nonlinear Code Generators		411
	References		415
	Problems		416

9 CODE TRACKING LOOPS 419

9-1	Introduction		419
9-2	Optimum Tracking of Wideband Signals		420
9-3	Baseband Full-Time Early-Late Tracking Loop		423
9-4	Full-Time Early-Late Noncoherent Tracking Loop		433
9-5	Tau-Dither Early-Late Noncoherent Tracking Loop		447
9-6	Double-Dither Early-Late Noncoherent Tracking Loop		456
9-7	Full-Time Early-Late Noncoherent Tracking Loop with Arbitrary Data and Spreading Modulation		459
9-8	Code Tracking Loops for Frequency-Hop Systems		467
9-9	Summary		478
	References		480
	Problems		480

10 INITIAL SYNCHRONIZATION OF THE RECEIVER SPREADING CODE 484

10-1	Introduction		484
10-2	Problem Definition and the Optimum Synchronizer		486
10-3	Serial Search Synchronization Techniques		488
10-3.1	Calculation of the Mean and Variance of the Synchronization Time	488	
10-3.2	Modified Sweep Strategies	492	
10-3.3	Continuous Linear Sweep of Uncertainty Region	494	
10-3.4	Detection of a Signal in Additive White Gaussian Noise (Fixed Integration Time, Multiple Dwell, and Sequential Detectors)	501	
10-4	Synchronization Using a Matched Filter		538
10-5	Synchronization by Estimating the Received Spreading Code		540
10-6	Tracking Loop Pull-In		543
10-7	Summary		547
	References		550
	Problems		551

11 PERFORMANCE OF SPREAD-SPECTRUM SYSTEMS IN A JAMMING ENVIRONMENT 555

11-1	Introduction		555
11-2	Spread-Spectrum Communication System Model		556

11-3 Performance of Spread-Spectrum Systems Without Coding	561
11-3.1 Performance in AWGN or Barrage Noise Jamming	562
11-3.2 Performance in Partial Band Jamming	570
11-3.3 Performance in Pulsed Noise Jamming	582
11-3.4 Performance in Single-Tone Jamming	586
11-3.5 Performance in Multiple-Tone Jamming	597
11-3.6 Conclusions	602
References	602
Problems	604
 12 PERFORMANCE OF SPREAD-SPECTRUM SYSTEMS WITH FORWARD ERROR CORRECTION	 606
12-1 Introduction	606
12-2 Elementary Block Coding Concepts	607
12-2.1 Optimum Decoding Rule	609
12-2.2 Calculation of Error Probability	612
12-3 Elementary Convolutional Coding Concepts	616
12-3.1 Decoding of Convolutional Codes	618
12-3.2 Error Probability for Convolutional Codes	620
12-4 Results for Specific Error Correction Codes	620
12-4.1 BCH Codes	621
12-4.2 Reed-Solomon Codes	622
12-4.3 Maximum Free-Distance Convolutional Codes	624
12-4.4 Repeat Coding for the Hard Decision FH/MFSK Channel	624
12-5 Interleaving	630
12-6 Random Coding Bounds	632
References	633
Problems	634
 13 EXAMPLE SPREAD-SPECTRUM SYSTEMS *	 635
13-1 Introduction	635
13-2 Space Shuttle Spectrum Depsreader	636
13-3 TDRSS User Transponder	640
13-4 Global Positioning System	644
13-5 Joint Tactical Information Distribution System	647
References	649
 APPENDICES	
 A PROBABILITY AND RANDOM VARIABLES	 650
A-1 Probability Theory	650
A-2 Random Variables, Probability Density Functions, and Averages	654
A-3 Characteristic Function and Probability Generating Functions	658

A-4	Transformations of Random Variables	653
A-5	Central Limit Theorem	667
A-6	Random Processes	668
A-7	Input/Output Relationships for Fixed Linear Systems with Random Inputs; Power Spectral Density	674
A-8	Examples of Random Processes	681
A-9	Narrowband Noise Representation	685
	References	687
	Problems	687
B	CHARACTERIZATION OF INTERNALLY GENERATED NOISE	691
C	COMMUNICATION LINK PERFORMANCE CALCULATIONS	697
D	OVERVIEW OF THE VITERBI ALGORITHM	704
E	GAUSSIAN PROBABILITY FUNCTION	713
F	POWER SPECTRAL DENSITIES FOR SEQUENCES OF RANDOM BINARY DIGITS AND RANDOM TONES	716
G	CALCULATION OF THE POWER SPECTRUM OF THE PRODUCT OF TWO M-SEQUENCES	720
H	EVALUATION OF PHASE DISCRIMINATOR OUTPUT AUTOCORRELATION FUNCTIONS AND POWER SPECTRA	728
	INDEX	740

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.