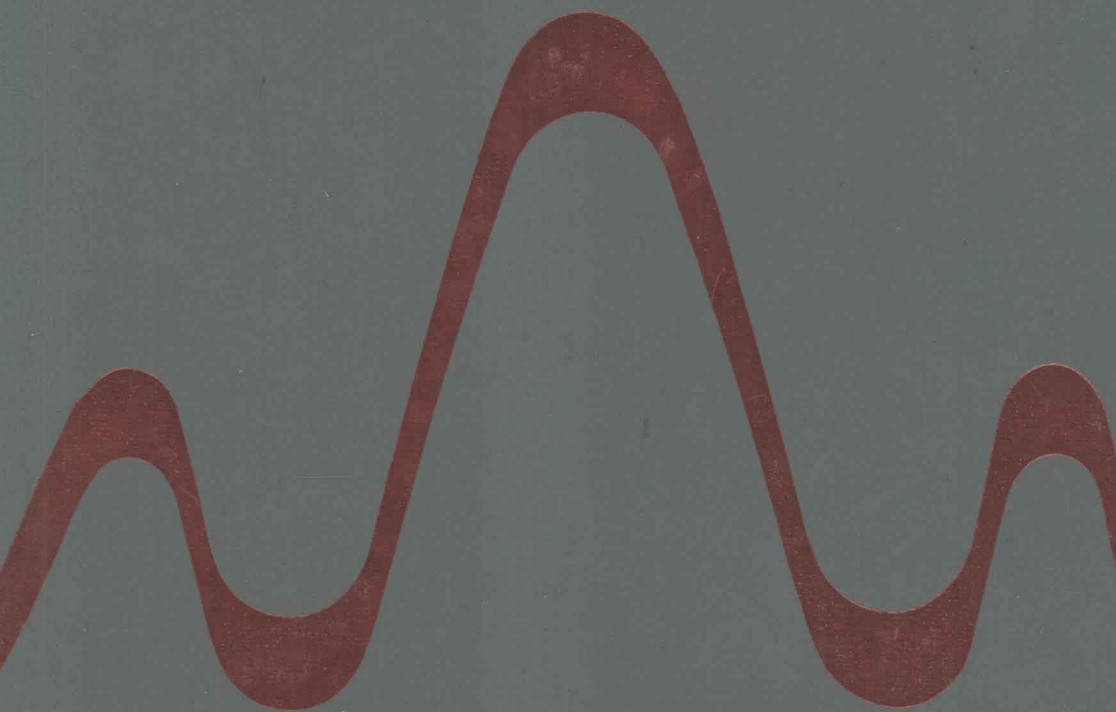


MODERN COMMUNICATIONS AND SPREAD SPECTRUM

George R. Cooper
Clare D. McGillem



MODERN COMMUNICATIONS AND SPREAD SPECTRUM

George R. Cooper

Clare D. McGillem

*School of Electrical Engineering
Purdue University*

McGraw-Hill Book Company

New York St. Louis San Francisco Auckland Bogotá Hamburg
Johannesburg London Madrid Mexico Montreal New Delhi
Panama Paris São Paulo Singapore Sydney Tokyo Toronto

This book was set in Times Roman by Doyle Photosetting.
The editor was Sanjeev Rao;
the production supervisor was Leroy A. Young.
The cover was designed by Nadja Furlan Lorbek.
Project supervision was done by Cobb/Dunlop Publisher Services Incorporated.
R. R. Donnelley & Sons Company was printer and binder.

MODERN COMMUNICATIONS AND SPREAD SPECTRUM

Copyright©1986 by McGraw-Hill, Inc. All rights reserved.
Printed in the United States of America. Except as permitted under the
United States Copyright Act of 1976, no part of this publication may be
reproduced or distributed in any form or by any means, or stored in a data
base or retrieval system, without the prior written permission of the publisher.

1234567890 DOCDOC 898765

ISBN 0-07-012951-7

Library of Congress Cataloging in Publication Data

Cooper, George R.
Modern communications and spread spectrum.
(McGraw-Hill series in electrical engineering.
Communications and information theory)
Includes bibliographies and index.
1. Telecommunication. 2. Signal processing.
3. Spread spectrum communications. I. McGillem, Clare D.
II. Title. III. Series.
TK5102.5.C66 1986 621.38 84-20092
ISBN 0-07-012951-7

MODERN COMMUNICATIONS AND SPREAD SPECTRUM

McGraw-Hill Series in Electrical Engineering

Consulting Editor

Stephen W. Director, *Carnegie-Mellon University*

Circuits and Systems
Communications and Signal Processing
Control Theory
Electronics and Electronic Circuits
Power and Energy
Electromagnetics
Computer Engineering
Introductory
Radar and Antennas
VLSI

Previous Consulting Editors

Ronald M. Bracewell, Colin Cherry, James F. Gibbons, Willis W. Harman, Hubert Heffner, Edward W. Herold, John G. Linvill, Simon Ramo, Ronald A. Rother, Anthony E. Siegman, Charles Susskind, Frederick E. Terman, John G. Truxal, Ernst Weber, and John R. Whinnery

Communications and Signal Processing

Consulting Editor

Stephen W. Director, Carnegie-Mellon University

Antoniou: *Digital Filters: Analysis and Design*

Candy: *Signal Processing: The Model-Based Approach*

Carlson: *Communications Systems: An Introduction to Signals and Noise in Electrical Communication*

Cherin: *An Introduction to Optical Fibers*

Cooper and McGillem: *Modern Communications and Spread Spectrum*

Davenport: *Probability and Random Processes: An Introduction for Applied Scientists and Engineers*

Drake: *Fundamentals of Applied Probability Theory*

Guiasu: *Information Theory with New Applications*

Keiser: *Optical Fiber Communications*

Melsa and Cohn: *Decision and Estimation Theory*

Papoulis: *Probability, Random Variables, and Stochastic Processes*

Papoulis: *Signal Analysis*

Papoulis: *The Fourier Integral and Its Applications*

Peebles: *Probability, Random Variables, and Random Signal Principles*

Proakis: *Digital Communications*

Schwartz: *Information Transmission, Modulation, and Noise*

Schwartz and Shaw: *Signal Processing*

Shooman: *Probabilistic Reliability: An Engineering Approach*

Smith: *Modern Communication Circuits*

Taub and Schilling: *Principles of Communication Systems*

Viterbi and Omura: *Principles of Digital Communication and Coding*

PREFACE

Although continuous evolution marks the technology and practice of communication engineering, a large segment of basic theory remains unchanged, and this provides the basis for evaluating new techniques and new systems. One of the main objectives of this text is to furnish an introduction to the basic principles of communication systems that is appropriate for a first-year graduate-level course. This proves to be more difficult than it might seem upon first consideration. The main problem is the diverse backgrounds of the students who are likely to take such a course. If the students have just completed their undergraduate program, they undoubtedly have had an introductory course in communication engineering that covers various modulation techniques. However, the degree of mathematical and statistical sophistication employed varies greatly with the undergraduate text used in the course, and with whether or not the students have had any previous exposure to the theory of probability and random processes. Compounding the problem is the likelihood that a number of students may be transferring from another specialty or another discipline, and although quite mature academically, may not be familiar with communication system principles.

The first seven chapters of this text are intended to address this problem. They were designed to cover topics relating to analog and digital communications in such a manner that they can be followed by students who have never taken a communications course and still provide sufficient breadth and depth of coverage to complement and extend the material normally presented in an undergraduate course. The text is written on the assumption that the reader understands something of modulation theory and is familiar with such techniques of linear system analysis as Fourier transforms and convolutions, and also is acquainted with probability and random processes. These techniques and concepts are reviewed as part of the text but it will be necessary for a student unfamiliar with them to do additional outside reading. It has been found that graduate students who are interested in this material generally will do the extra work necessary to overcome the lack of a previous communications course. The goal of this type of

course is to bring the participating students to a more or less equal level of sophistication relative to the terminology, implementation, and analysis of communication systems so that subsequent courses can be based on a presumption that such an equality exists.

Because of the enormous variety of specialized modulation systems that have been developed over the years, it is not possible to provide coverage that is in any sense comprehensive. Rather the most widely used techniques and some of their variations are considered, and various systems are compared in terms of error probability, performance in the presence of noise, effects of system instabilities, and system complexity. The methods of analysis are intended to be correct and understandable, but no attempt has been made to demonstrate that they are mathematically rigorous.

A second purpose of this text is to provide a comprehensive introduction to the new and rapidly growing area of spread-spectrum communications. This material is presented at the same level as the first portion of the text, and is appropriate for a graduate-level course. The presentation is self-contained and offers a coherent development of the theory not previously available. References to a number of specialized topics are included to permit more in-depth study of spread-spectrum communications if desired.

A third purpose of this text is to furnish a reference source for practicing engineers from which they can gain ready access to many of the analytical results available for the analysis of communication systems. This should prove particularly valuable with regard to the material on spread-spectrum communications.

Relevant problems are included at the end of each chapter, and answers to a number of them can be found at the end of the book.

George R. Cooper
Clare D. McGillem

CONTENTS

	Preface	xv
Chapter 1	Basic Communication Principles	1
1-1	Introduction	1
1-2	Baseband Signal Characteristics	3
	Baseband Signals	3
	Voice Signals	3
	Television	7
	Data and Digital Computers	9
1-3	Noise in Communication Systems	9
	Sources of Noise	9
	Single-Frequency Sinusoid	11
	Thermal Noise	12
	Shot Noise and Flicker Noise	14
	Impulse Noise	14
	Other Noise	15
	Noise Figure and Noise Calculations	15
1-4	Communication Channels	20
	Free Space Channels	20
	Propagation Over the Earth's Surface	22
	Antenna Gain and Beam Width	25
	Multipath	27
1-5	Analog Modulation Systems	28
	Linear Modulation	28
	Angle Modulation	34
	Linear Pulse Modulation	38
	Nonlinear Pulse Modulation	40
1-6	Digital Modulation Systems	41
	Pulse-Code Modulation	41
	Differential Pulse-Code Modulation	43
	Delta Modulation	43

1-7	References	44
1-8	Problems	44
Chapter 2	Fundamentals of Signal Processing	49
2-1	Linear System Analysis	49
	Impulse Response	49
	Transfer Function	51
	Relationship Between Impulse Response and Transfer Function	53
2-2	Transmission of Random Processes Through Linear Systems	55
	Time-Domain Analysis of Linear Systems with Random Inputs	58
	Frequency-Domain Analysis of Linear Systems with Random Inputs	60
	System and Signal Bandwidths	61
2-3	Narrow-Band Gaussian Noise	64
	Spectral Density of the In-Phase and Quadrature Components	68
	Envelope of Narrow-Band Noise	70
	PDF of the Power of Narrow-Band Noise	71
	Sine Wave Plus Narrow-Band Noise	71
2-4	Filtering of Modulated Signals	73
2-5	Nonlinear Processing	76
	Frequency Translation	76
	Limiting	77
	Square-Law Detector	78
2-6	Optimum Filtering	82
	Wiener Filters	82
	Matched Filters	88
2-7	Message Digitization	91
	Sampling	91
	Quantizing	94
	Channel Encoding	101
2-8	References	103
2-9	Problems	103
Chapter 3	Analog Signal Detection	108
3-1	Demodulation of AM, DSB/SC, and SSB Signals	108
	Receiver Noise	108
	Product Demodulator	109
	Envelope Detection	115
3-2	Demodulation of Angle-Modulated Signals	119
	FM Demodulation	119
	PM Demodulation	124
	FM SNR Improvement Using Preemphasis/Deemphasis	125
	Angle Demodulation by Feedback Tracking	126
	Phase-Tracking Loop	129

	Tracking Loop Design	137
	Zero-Crossing Detector	139
3-3	References	141
3-4	Problems	141
Chapter 4	Detection of Binary Signals at Baseband	147
4-1	Optimum Detection Methods	147
4-2	Binary Signal Decoding at Baseband	152
4-3	Signal Selection for Binary Systems	159
	PCM Pulses	161
	Coded PCM Pulses	161
	PRK Pulses	162
4-4	Effects of Bit Timing Errors for Antipodal Signals	163
	Timing Errors in PCM	164
4-5	Detection in Nonwhite Noise	165
	Matched Filter in Nonwhite Noise	165
	Example of Detection in Nonwhite Noise	167
	Singular Detection in Nonwhite Noise	169
4-6	Band-Limiting Effects	170
	Probability of Error with Intersymbol Interference	171
	Example of Intersymbol Interference	173
	Minimizing Intersymbol Interference	174
	Partial Response (Duobinary) Signaling	177
4-7	References	178
4-8	Problems	178
Chapter 5	Detection of Binary Signals at Radio Frequency	183
5-1	Coherent Detection	183
	On-Off Keying	183
	Phase Shift Keying	184
	Effect of Bit Timing Errors on PSK	185
	Frequency Shift Keying	186
5-2	Noncoherent Detection	189
	Pulse-Position Modulation	192
	Frequency Shift Keying	193
	On-Off Keying	195
5-3	Differential Phase Shift Keying (DPSK)	198
5-4	References	199
5-5	Problems	199
Chapter 6	M-ary Signals	202
6-1	Orthogonal Representations	202
	Example of an Orthonormal Representation	203
	Gram-Schmidt Procedure	206
	Signal Space Concepts	209

6-2	<i>M</i> -ary Orthogonal Signals	210
	Multiple Frequency Shift Keying (MFSK)	210
	Quantized Pulse-Position Modulation (QPPM)	212
	Orthogonal Binary Vectors	213
6-3	Signals Related to Orthogonal Signals	214
	Nonorthogonal Binary Vectors	214
	Biorthogonal Signals	215
	Transorthogonal or Simplex Signals	216
	Construction of Simplex Signals	217
	Signals from Quadrature Functions	219
6-4	Coherent Detection of <i>M</i> -ary Signals	221
	Correlation Receiver	224
6-5	Performance of Orthogonal Signals	227
	Union Bound for Orthogonal Signals	231
6-6	Detection of Nonorthogonal <i>M</i> -ary Signals	233
	Coherent Detection of Biorthogonal Signals	233
	Coherent Detection of Simplex Signals	235
	Coherent Detection of Polyphase Signals	235
	Coherent Detection of Quadriphase Signals (QPSK)	237
	Offset QPSK (OQPSK)	238
	Phase Reference Errors	241
	Differential Quadriphase (DQPSK)	242
6-7	Noncoherent Detection of <i>M</i> -ary Signals	242
	Amplitude Shift Keying (Baseband Model)	244
	Amplitude and Phase Shift Keying (APK)	246
6-8	References	247
6-9	Problems	247

Chapter 7 Comparison of Digital Communication Systems 252

7-1	Methods of Comparison	252
7-2	Theoretical Limits on Performance	261
7-3	Bandwidth Expansion Factor	264
7-4	References	267
7-5	Problems	267

Chapter 8 Fundamentals of Spread Spectrum 268

8-1	General Concepts	268
8-2	Direct Sequence (DS) Pseudonoise (PN)	269
	Biphase Modulation	271
	Quadriphase Modulation	273
	PN Signal Characteristics	274
	Direct-Sequence Receiver	275
8-3	Frequency Hopping	276
	The Frequency-Hopping Transmitter	276
	The Frequency-Hopping Receiver	278
	The "Near-Far" Problem	279
8-4	Time Hopping	279

8-5	Comparison of Modulation Methods	281
	Direct-Sequence (PN) Systems	281
	Frequency-Hopping (FH) Systems	281
	Time-Hopping (TH) Systems	281
8-6	Hybrid Spread-Spectrum Systems	282
	Example of PN/FH System	282
8-7	Chirp Spread Spectrum	282
8-8	Baseband Modulation Techniques	283
	Digital Methods	283
	Sampled Analog Methods	284
8-9	References	284
8-10	Problems	285

Chapter 9 Analysis of Direct-Sequence Spread-Spectrum Systems 289

9-1	Properties of PN Sequences	289
	Aperiodic Sequences	290
	Periodic Sequences	290
9-2	Classes of Periodic Sequences	291
	Maximal-Length Linear Shift Register Sequences	
	(m Sequences)	291
	Quadratic Residue Sequences ($q-r$ Sequences)	292
	Hall Sequences	292
	Twin Primes	292
9-3	Properties of m Sequences	293
9-4	Partial Correlation	294
9-5	PN Signals from PN Sequences	296
9-6	Partial Correlation of PN Signals	298
9-7	The PN Signal	299
9-8	Despreading the PN Signal	302
9-9	Interference Rejection	305
9-10	Output Signal-to-Noise Ratio	307
9-11	Antijam Characteristics	308
9-12	Interception	309
9-13	Energy and Bandwidth Efficiency	311
9-14	References	313
9-15	Problems	313

Chapter 10 Analysis of Avoidance-Type Spread-Spectrum Systems 319

10-1	The Frequency-Hopped Signal	319
10-2	Interference Rejection in a Frequency-Hopping Receiver	321
10-3	The Time-Hopped Signal	323
10-4	References	324
10-5	Problems	325

Chapter 11	Generation of Spread-Spectrum Signals	326
11-1	Shift-Register-Sequence Generators	326
11-2	Discrete-Frequency Synthesizers	331
	Direct Method (Add and Divide)	331
	Indirect Method	334
	General Comments	335
11-3	SAW Device PN Generators	337
11-4	Charge-Coupled Devices	340
11-5	Digital Tapped Delay Lines	342
11-6	References	342
11-7	Problems	342
Chapter 12	Detection of Spread-Spectrum Signals	345
12-1	Coherent Direct-Sequence Receivers	345
12-2	Other Methods of Carrier Tracking	347
12-3	Delay-Lock Loop Analysis	349
12-4	Tau-Dither Loop	352
12-5	Coherent Carrier Tracking	353
12-6	Noncoherent Frequency-Hop Receiver	354
12-7	Acquisition of Spread-Spectrum Signals	355
12-8	Acquisition by Cell-by-Cell Searching	356
12-9	Reduction of Acquisition Time	364
	Acquisition-Aiding Waveforms	364
	Acquisition-Aiding Techniques	364
12-10	Acquisition with Matched Filters	366
12-11	Matched Filters for PN Sequences	369
12-12	Matched Filters for Frequency-Hopped Signals	370
12-13	Matched Filters with Acquisition-Aiding Waveforms	372
12-14	References	373
12-15	Problems	373
Chapter 13	Application of Spread Spectrum to Communications	376
13-1	General Capabilities of Spread Spectrum	376
13-2	Multiple-Access Considerations	378
	Number of Active Users—Equal Powers	382
	Number of Active Users—Unequal Powers	383
	Bandwidth-Limited Channels	385
	Power-Limited Channels	385
	Hard-Limited Channels	386
13-3	Energy and Bandwidth Efficiency in Multiple Access	387
13-4	Selective Calling and Identification	392
13-5	Antijam Considerations	395
	Jamming Direct-Sequence Systems	396
	Jamming Frequency-Hopping Systems	398
	Pulse Jamming	399
13-6	Error-Correction Coding	400
13-7	Intercept Considerations (AI)	403

13-8	Miscellaneous Considerations	404
	Automatic Data-Rate Control	404
	Code Breaking	405
13-9	Examples of Spread-Spectrum Systems	406
13-10	References	407
13-11	Problems	407
Appendix A	Mathematical Tables	412
A-1	Trigonometric Identities	412
A-2	Bessel Function Identities	413
A-3	Hilbert Transforms	414
A-4	Approximations	415
A-5	Derivatives	415
A-6	Indefinite Integrals	416
A-7	Definite Integrals	417
A-8	Fourier Transform of Operations	418
A-9	Fourier Transforms	419
A-10	Correlation Function-Spectral Density Pairs	420
A-11	Probability Functions	421
Appendix B	The Q Function	423
	Answers to Selected Problems	426
	Index	429

BASIC COMMUNICATION PRINCIPLES

1-1 INTRODUCTION

Communication systems of all types have many functional elements in common. Because of this it is often possible to adapt methods of analysis or implementation from one system to another. A very general type of communication system is illustrated in block diagram form in Fig. 1-1. Not all of the elements shown here would be present in every system, and there may be special elements in some systems (e.g., a diversity receiver) not represented here. However, most systems will contain most of the elements shown in Fig.1-1.

To permit the easy identification of where various specialized subsystems (discussed in detail later in the text) fit into an overall system, it is helpful to consider briefly the nature and function of each of the elements in the generalized system. The signal source and transducer together form the message source. The message

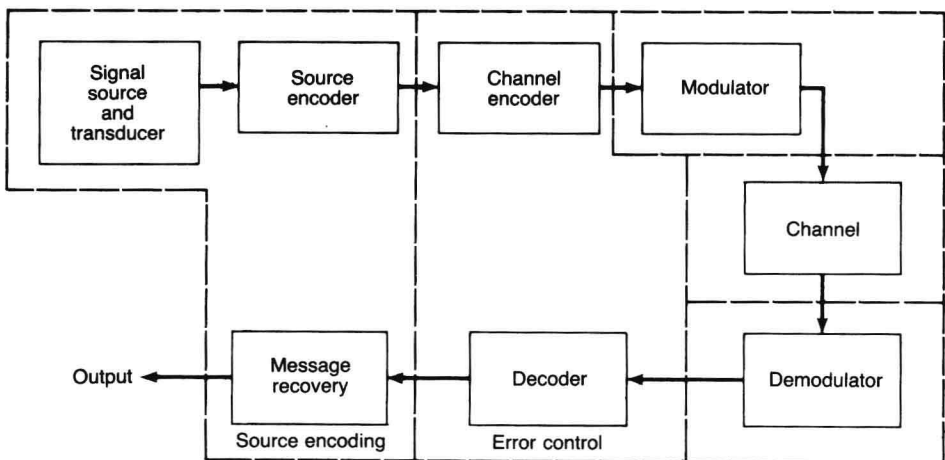


Figure 1-1 Generalized communication system.

might be an acoustic voice signal converted to an electrical waveform by a microphone, an optical image transduced by a television camera, or a measurement of some physical quantity converted to an electric signal by an appropriate sensor. Once the message is available, the source encoder modifies its structure for utilization in the particular communication system being used. This may include such operations as sampling and quantizing, companding, encrypting, or any of a variety of processes for dimensionality reduction.

The output of the source encoder goes to the channel encoder, which modifies the signal in such a way as to make its transmission through the channel more efficient. An example of a channel encoder is a processor that accepts a stream of binary signals and puts them into a series of groups with additional control symbols added so that the occurrence of an error during transmission and reception can be detected, or even corrected if desired. The channel encoder adds controlled redundancy to the transmitted message in order to accomplish error-free transmission through the channel. This added redundancy requires that extra information be transmitted along with the message and thus leads to a trade-off between speed of transmission (or bandwidth for a fixed speed) and error performance.

The modulator converts the encoded message into a signal suitable for transmission through the channel. For communications applications this channel can take many forms, ranging from free space to water to glass fibers. Generally the encoded message will be attached to a high-frequency carrier for transmission through the channel. The particular method of modulating the carrier with the message as well as the physical characteristics of the carrier itself are strongly dependent on the channel characteristics. In this book it is assumed that the channel is the atmosphere surrounding the earth and that the carrier is a radiated electromagnetic wave in the radio-frequency (RF) spectrum. However, many of the principles governing this type of carrier and channel carry over into other carriers such as acoustic or light waves and other channels such as water or waveguides. System noise is generally assumed to be part of the channel characterization. In the case of radio communications, this noise includes receiver noise generated within the system as well as external noise such as interference, intentional or otherwise, that may be present. To model a channel properly, it is necessary to be able to predict, either deterministically or probabilistically, what output will occur for a given input.

The remainder of the system in Fig. 1-1 demodulates and decodes the received signal and delivers it to the user. The design of these components is strongly dependent on the characteristics of the transmission system, but there are still a number of trade-offs that must be made among such things as cost, immunity to jamming, and ease of operation before a final design is possible.

In the following chapters, many of the alternatives available to the system designer are discussed. Performance is the principal criterion for comparing different approaches. The performance criteria considered include energy efficiency, peak-to-average power requirement, and error performance for various channels. The primary emphasis is on digital communications. However, to permit comparison with alternate and competitive analog communication systems, the