FIFTE DE

Digital Communications

John G. Proakis

Masoud Salehi



MCGRAW-HILL INTERNATIONAL EDITION

Digital Communications

Fifth Edition

John G. Proakis

Professor Emeritus, Northeastern University Department of Electrical and Computer Engineering, University of California, San Diego

Masoud Salehi

Department of Electrical and Computer Engineering, Northeastern University

> ĐẠI HỌC QUỐC GIA HA NỘI TRUNG TẨM THỐNG TIN THƯ VIỆN

A-CLO/ 000430



Boston Burr Ridge, IL Dubuque, IA Madison, WI New York San Francisco St. Louis Bangkok Bogotá Caracas Kuala Lumpur Lisbon London Madrid Mexico City Milan Montreal New Delhi Santiago Seoul Singapore Sydney Taipei Toronto

BRIEF CONTENTS

Preface		xvi
Chapter 1	Introduction	tornet 1
Chapter 2	Deterministic and Random Signal Analysis	17
Chapter 3	Digital Modulation Schemes	95
Chapter 4	Optimum Receivers for AWGN Channels	160
Chapter 5	Carrier and Symbol Synchronization	290
Chapter 6	An Introduction to Information Theory	330
Chapter 7	Linear Block Codes	400
Chapter 8	Trellis and Graph Based Codes	491
Chapter 9	Digital Communication Through Band-Limited Channels	597
Chapter 10	Adaptive Equalization	689
Chapter 11	Multichannel and Multicarrier Systems	737
Chapter 12	Spread Spectrum Signals for Digital Communications	762
Chapter 13	Fading Channels I: Characterization and Signaling	830
Chapter 14	Fading Channels II: Capacity and Coding	899
Chapter 15	Multiple-Antenna Systems	966
Chapter 16	Multiuser Communications	1028
Chapter 10		
Appendices		
Appendix A	Matrices	1085
Appendix B	Error Probability for Multichannel Binary Signals	1090
Appendix C	Error Probabilities for Adaptive Reception of <i>M</i> -Phase Signals	1096
Appendix D	Square Root Factorization	1107
References a	nd Bibliography	1109
Index		1142

Preface			X	vi
Chapter 1	Intr	oduction		1
	1.1	Elements of a Digital Communication System		1
	1.2	Communication Channels and Their Characteristics		3
	1.3	Mathematical Models for Communication Channels		10
	1.4	A Historical Perspective in the Development of		
		Digital Communications		12
	1.5	Overview of the Book		15
	1.6	Bibliographical Notes and References		15
Chapter 2	Dete	erministic and Random Signal Analysis		17
	2.1	Bandpass and Lowpass Signal Representation		18
		2.1–1 Bandpass and Lowpass Signals / 2.1–2 Lowpass		
		Equivalent of Bandpass Signals / 2.1–3 Energy		
		Considerations / 2.1-4 Lowpass Equivalent of a		
		Bandpass System		
	2.2	Signal Space Representation of Waveforms		28
		2.2-1 Vector Space Concepts / 2.2-2 Signal Space		
		Concepts / 2.2-3 Orthogonal Expansions of Signals /		
	2.2	2.2–4 Gram-Schmidt Procedure		40
	2.3	Some Useful Random Variables Bounds on Tail Probabilities		56
	2.5	Limit Theorems for Sums of Random Variables		63
	2.6	Complex Random Variables		63
	2.0	2.6–1 Complex Random Vectors		
	2.7	Random Processes		66
	slee	2.7-1 Wide-Sense Stationary Random Processes / 2.7-2		
		Cyclostationary Random Processes / 2.7-3 Proper and		
		Circular Random Processes / 2.7-4 Markov Chains		
	2.8	Series Expansion of Random Processes		74
		2.8–1 Sampling Theorem for Band-Limited Random		
		Processes / 2.8-2 The Karhunen-Loève Expansion		1
	2.9	Bandpass and Lowpass Random Processes		18

Vi

	2.10	Bibliographical Notes and References Problems	82 82
Chapter 3	Dig	ital Modulation Schemes	95
	3.1	Representation of Digitally Modulated Signals	95
	3.2	Memoryless Modulation Methods	97
		3.2-1 Pulse Amplitude Modulation (PAM) / 3.2-2 Phase	
		Modulation / 3.2–3 Quadrature Amplitude	
	22	Modulation / 3.2-4 Multidimensional Signaling	303
	3.3	Signaling Schemes with Memory 3.3–1 Continuous-Phase Frequency-Shift Keying	114
		(CPFSK) / 3.3–2 Continuous-Phase Modulation (CPM)	
	3.4	Power Spectrum of Digitally Modulated Signals	131
		3.4–1 Power Spectral Density of a Digitally Modulated Signal	131
		with Memory / 3.4–2 Power Spectral Density of Linearly	
		Modulated Signals / 3.4–3 Power Spectral Density of	
		Digitally Modulated Signals with Finite Memory / 3.4-4	
		Power Spectral Density of Modulation Schemes with a Markov	
		Structure / 3.4-5 Power Spectral Densities of CPFSK and	
		CPM Signals	
		Bibliographical Notes and References	148
		Problems	148
Thanton 1	Onti	mum Dessivers for AWCN Channels	100
Chapter 4		mum Receivers for AWGN Channels	160
		Waveform and Vector Channel Models	160
		4.1-1 Optimal Detection for a General Vector Channel	
		Waveform and Vector AWGN Channels	167
		4.2–1 Optimal Detection for the Vector AWGN	
		Channel / 4.2–2 Implementation of the Optimal Receiver for	
		AWGN Channels / 4.2–3 A Union Bound on the Probability of	
		Error of Maximum Likelihood Detection	
		Optimal Detection and Error Probability for Band-Limited	100
		Signaling	188
		4.3–1 Optimal Detection and Error Probability for ASK or	
		PAM Signaling / 4.3–2 Optimal Detection and Error	
		Probability for PSK Signaling / 4.3–3 Optimal Detection and	
		Error Probability for QAM Signaling / 4.3-4 Demodulation	
		and Detection	
		Optimal Detection and Error Probability for Power-Limited	203
		Signaling	203
		4.4–1 Optimal Detection and Error Probability for Orthogonal	
		Signaling / 4.4–2 Optimal Detection and Error Probability	
		for Biorthogonal Signaling / 4.4–3 Optimal Detection and	
		Error Probability for Simplex Signaling	

	4.5	Optimal Detection in Presence of Uncertainty:	
		Noncoherent Detection	210
		4.5-1 Noncoherent Detection of Carrier Modulated	210
		Signals / 4.5–2 Optimal Noncoherent Detection of FSK	
		Modulated Signals / 4.5–3 Error Probability of Orthogonal	
		Signaling with Noncoherent Detection / 4.5-4 Probability of	
		Error for Envelope Detection of Correlated Binary Signals / 4.5–5 Differential PSK (DPSK)	
	4.6	A Comparison of Digital Signaling Methods	
	4.0	4.6–1 Bandwidth and Dimensionality	226
	4.7	Lattices and Constellations Based on Lattices	
	7./	4.7–1 An Introduction to Lattices / 4.7–2 Signal	230
		Constellations from Lattices	
	10	Detection of Signaling Schemes with Memory	242
	4.8	4.8–1 The Maximum Likelihood Sequence Detector	242
	4.0		246
	4.9	Optimum Receiver for CPM Signals	240
		4.9–1 Optimum Demodulation and Detection of CPM / 4.9–2 Performance of CPM Signals / 4.9–3 Suboptimum	
	410	Demodulation and Detection of CPM Signals Performance Analysis for Wireline and Radio	
	4.10		259
		Communication Systems	437
		4.10–1 Regenerative Repeaters / 4.10–2 Link Budget	
	411	Analysis in Radio Communication Systems Bibliographical Notes and Pafarances	265
	4.11	Bibliographical Notes and References Problems	266
		Problems	200
Chapter 5	Car	rier and Symbol Synchronization	290
Chapter 3		DESCRIPTION OF THE PROPERTY OF	
	5.1	0	290
		5.1–1 The Likelihood Function / 5.1–2 Carrier Recovery as	ıa
), YSVIDS	Symbol Synchronization in Signal Demodulation	205
	5.2	Carrier Phase Estimation	295
		5.2-1 Maximum-Likelihood Carrier Phase Estimation /	
		5.2–2 The Phase-Locked Loop / 5.2–3 Effect of Additive	
		Noise on the Phase Estimate / 5.2-4 Decision-Directed	
	39 653	Loops / 5.2–5 Non-Decision-Directed Loops	215
	5.3		315
		5.3-1 Maximum-Likelihood Timing Estimation /	
		5.3–2 Non-Decision-Directed Timing Estimation	221
	5.4	Joint Estimation of Carrier Phase and Symbol Timing	321
	5.5	Performance Characteristics of ML Estimators	323
	5.6	Bibliographical Notes and References	326
		Problems	327
Chapter 6	An	Introduction to Information Theory	330
		Mathematical Models for Information Sources	331

	6.2	A Logarithmic Measure of Information	332
	6.3	Lossless Coding of Information Sources	335
		6.3-1 The Lossless Source Coding Theorem / 6.3-2 Lossless	
		Coding Algorithms	
	6.4	Lossy Data Compression	348
		6.4-1 Entropy and Mutual Information for Continuous	
		Random Variables / 6.4-2 The Rate Distortion Function	
	6.5	Channel Models and Channel Capacity	354
		6.5-1 Channel Models / 6.5-2 Channel Capacity	
	6.6	Achieving Channel Capacity with Orthogonal Signals	367
	6.7	The Channel Reliability Function	369
	6.8	The Channel Cutoff Rate	371
		6.8-1 Bhattacharyya and Chernov Bounds / 6.8-2 Random	
		Coding	
	6.9	Bibliographical Notes and References	380
		Problems	381
	- T.	Disab Codes	400
Chapter	/ Lin	ear Block Codes	400
	7.1	Basic Definitions	401
		7.1-1 The Structure of Finite Fields / 7.1-2 Vector Spaces	
	7.2	General Properties of Linear Block Codes	411
		7.2-1 Generator and Parity Check Matrices / 7.2-2 Weight	
		and Distance for Linear Block Codes / 7.2-3 The Weight	
		Distribution Polynomial / 7.2-4 Error Probability of Linear	
		Block Codes	
	7.3	Some Specific Linear Block Codes	420
	7.5	7.3–1 Repetition Codes / 7.3–2 Hamming Codes /	720
		7.3–3 Maximum-Length Codes / 7.3–4 Reed-Muller	
	- 4	Codes / 7.3–5 Hadamard Codes / 7.3–6 Golay Codes	
	7.4	Optimum Soft Decision Decoding of Linear	101
		Block Codes	424
	7.5	Hard Decision Decoding of Linear Block Codes	428
		7.5-1 Error Detection and Error Correction Capability of	
		Block Codes / 7.5–2 Block and Bit Error Probability for Hard	
		Decision Decoding	
	7.6	Comparison of Performance between Hard Decision and	
		Soft Decision Decoding	436
	7.7	Bounds on Minimum Distance of Linear Block Codes	440
		7.7–1 Singleton Bound / 7.7–2 Hamming Bound /	
		7.7-3 Plotkin Bound / 7.7-4 Elias Bound / 7.7-5	
		McEliece-Rodemich-Rumsey-Welch (MRRW) Bound /	
		7.7–6 Varshamov-Gilbert Bound	
	7.8	Modified Linear Block Codes	445
	7.0		443
		7.8–1 Shortening and Lengthening / 7.8–2 Puncturing and	
		Extending / 7.8–3 Expurgation and Augmentation	

	7.9	Cyclic Codes	447
		7.9-1 Cyclic Codes — Definition and Basic Properties /	447
		7.9-2 Systematic Cyclic Codes / 7.9-3 Encoders for Cyclic	
		Codes / 7.9-4 Decoding Cyclic Codes / 7.9-5 Examples of	
		Cyclic Codes	
	7.10	Bose-Chaudhuri-Hocquenghem (BCH) Codes	160
		7.10-1 The Structure of BCH Codes / 7.10-2 Decoding	463
		BCH Codes	
	7.11	Reed-Solomon Codes	471
	7.12	Coding for Channels with Burst Errors	475
		Combining Codes	477
		7.13–1 Product Codes / 7.13–2 Concatenated Codes	4//
	7.14		482
		Problems	482
			402
Chapter 8	Trel	lis and Graph Based Codes	491
	8.1	The Structure of Convolutional Codes	491
	0.1	8.1–1 Tree, Trellis, and State Diagrams / 8.1–2 The Transfer	431
		Function of a Convolutional Code / 8.1–3 Systematic,	
		Nonrecursive, and Recursive Convolutional Codes /	
		8.1-4 The Inverse of a Convolutional Encoder and	
		Catastrophic Codes	510
	8.2	Decoding of Convolutional Codes	510
		8.2–1 Maximum-Likelihood Decoding of Convolutional	
		Codes — The Viterbi Algorithm / 8.2–2 Probability of	
		Error for Maximum-Likelihood Decoding of Convolutional	
		Codes	516
	8.3	Distance Properties of Binary Convolutional Codes	516
	8.4	Punctured Convolutional Codes	516
		8.4–1 Rate-Compatible Punctured Convolutional Codes	
	8.5	Other Decoding Algorithms for Convolutional Codes	525
	8.6	Practical Considerations in the Application of	
		Convolutional Codes	532
	8.7	Nonbinary Dual-k Codes and Concatenated Codes	537
	8.8	Maximum a Posteriori Decoding of Convolutional	
		Codes — The BCJR Algorithm	541
	8.9	Turbo Codes and Iterative Decoding	548
	0.7	8.9–1 Performance Bounds for Turbo Codes / 8.9–2 Iterative	
		Decoding for Turbo Codes / 8.9–3 EXIT Chart Study of	
		Iterative Decoding	558
	8.10		
		8.10-1 Tanner Graphs / 8.10-2 Factor Graphs / 8.10-3 The	
		Sum-Product Algorithm / 8.10-4 MAP Decoding Using the	
		Cum Product Algorithm	

	8.1	1 Low Density Parity Check Codes	568
		8.11–1 Decoding LDPC Codes	
	8.1	2 Coding for Bandwidth-Constrained Channels — Trellis	
		Coded Modulation	571
		8.12-1 Lattices and Trellis Coded Modulation /	
		8.12-2 Turbo-Coded Bandwidth Efficient Modulation	500
	8.13	Bibliographical Notes and References	589
		Problems	590
CI .	0 D!-	Lal Communication Through Rand Limited	
Chapt	_	gital Communication Through Band-Limited annels	597
	CII		
	9.1	Characterization of Band-Limited Channels	598
	9.2	Signal Design for Band-Limited Channels	602
		9.2-1 Design of Band-Limited Signals for No Intersymbol	
		Interference—The Nyquist Criterion / 9.2-2 Design of	
		Band-Limited Signals with Controlled ISI—Partial-Response	
		Signals / 9.2–3 Data Detection for Controlled ISI /	
		9.2-4 Signal Design for Channels with Distortion	
	9.3	Optimum Receiver for Channels with ISI and AWGN	623
		9.3-1 Optimum Maximum-Likelihood Receiver /	
		9.3-2 A Discrete-Time Model for a Channel with ISI /	
		9.3-3 Maximum-Likelihood Sequence Estimation (MLSE) for	
		the Discrete-Time White Noise Filter Model /	
		9.3-4 Performance of MLSE for Channels with ISI	
	9.4	Linear Equalization	640
		9.4-1 Peak Distortion Criterion / 9.4-2 Mean-Square-Error	
		(MSE) Criterion / 9.4–3 Performance Characteristics of the	
		MSE Equalizer / 9.4–4 Fractionally Spaced	
		Equalizers / 9.4–5 Baseband and Passband Linear Equalizers	
	9.5	Decision-Feedback Equalization	661
		9.5–1 Coefficient Optimization / 9.5–2 Performance	
		Characteristics of DFE / 9.5–3 Predictive Decision-Feedback	
		Equalizer / 9.5–4 Equalization at the	
		Transmitter—Tomlinson-Harashima Precoding	
	9.6	Reduced Complexity ML Detectors	669
	9.7	Iterative Equalization and Decoding—Turbo	007
	7.1	Equalization	671
	9.8		673
	7.0	Bibliographical Notes and References	
		Problems	674
hont	10 11	A. P. P. A. C.	
napter	TU Ada	ptive Equalization	689
	10.1	Adaptive Linear Equalizer	689
		10.1-1 The Zero-Forcing Algorithm / 10.1-2 The LMS	
		Algorithm / 10.1–3 Convergence Properties of the LMS	

		Algorithm / 10.1-4 Excess MSE due to Noisy Gradient	
		Estimates / 10.1–5 Accelerating the Initial Convergence Rate in the LMS Algorithm / 10.1–6 Adaptive Fractionally Spaced	
		Equalizer—The Tap Leakage Algorithm / 10.1–7 An Adaptive	
		Channel Estimator for ML Sequence Detection	
	10.2	Adaptive Decision-Feedback Equalizer	705
	10.3	Adaptive Equalization of Trellis-Coded Signals	706
	10.4	Recursive Least-Squares Algorithms for Adaptive	700
		Equalization	710
		10.4–1 Recursive Least-Squares (Kalman)	
		Algorithm / 10.4-2 Linear Prediction and the Lattice Filter	
	10.5	Self-Recovering (Blind) Equalization	721
		10.5-1 Blind Equalization Based on the Maximum-Likelihood	
		Criterion / 10.5–2 Stochastic Gradient Algorithms /	
		10.5-3 Blind Equalization Algorithms Based on Second- and	
		Higher-Order Signal Statistics	
	10.6	Bibliographical Notes and References	731
		Problems	732
Chapter 11	Mul	Itichannel and Multicarrier Systems	737
	11.1	Multichannel Digital Communications in AWGN	
		Channels	737
		11.1–1 Binary Signals / 11.1–2 M-ary Orthogonal Signals	
	11.2	Multicarrier Communications	743
		11.2–1 Single-Carrier Versus Multicarrier	
		Modulation / 11.2-2 Capacity of a Nonideal Linear Filter	
		Channel / 11.2–3 Orthogonal Frequency Division	
		Multiplexing (OFDM) / 11.2–4 Modulation and	
		Demodulation in an OFDM System / 11.2-5 An FFT	
		Algorithm Implementation of an OFDM System / 11.2-6	
		Spectral Characteristics of Multicarrier Signals / 11.2-7 Bit	
		and Power Allocation in Multicarrier Modulation / 11.2-8	
		Peak-to-Average Ratio in Multicarrier Modulation / 11.2-9	
	160	Channel Coding Considerations in Multicarrier Modulation	
	11.3		759
		Problems	760
Chapter 12		ead Spectrum Signals for Digital	
	Con	nmunications	762
	12.1	Model of Spread Spectrum Digital Communication	married 3
		System	763
	12.2	Direct Sequence Spread Spectrum Signals	765
		12.2-1 Error Rate Performance of the Decoder /	
		12.2-2 Some Applications of DS Spread Spectrum	
		Signals / 12 2 3 Effect of Pulsed Interference on DS Spread	

		Spectrum Systems / 12.2–4 Excision of Narrowband	
		Interference in DS Spread Spectrum Systems /	
		12.2–5 Generation of PN Sequences	
	12.3	Frequency-Hopped Spread Spectrum Signals	802
		12.3–1 Performance of FH Spread Spectrum Signals in an	
		AWGN Channel / 12.3-2 Performance of FH Spread	
		Spectrum Signals in Partial-Band Interference / 12.3–3 A	
		CDMA System Based on FH Spread Spectrum Signals	
	12.4	Other Types of Spread Spectrum Signals	814
	12.5	Synchronization of Spread Spectrum Systems	815
	12.6	Bibliographical Notes and References	823
		Problems	823
Chanter 13	Fad	ing Channels I: Characterization	
Chapter 15		Signaling	830
	13.1	Characterization of Fading Multipath Channels	831
	10.1	13.1–1 Channel Correlation Functions and Power	031
		Spectra / 13.1–2 Statistical Models for Fading Channels	
	13.2	The Effect of Signal Characteristics on the Choice of a	
	13.2	Channel Model	844
	122	Frequency-Nonselective, Slowly Fading Channel	
			846
	13.4	Diversity Techniques for Fading Multipath Channels	850
		13.4–1 Binary Signals / 13.4–2 Multiphase Signals / 13.4–3	
	125	M-ary Orthogonal Signals	
	13.5	Signaling over a Frequency-Selective, Slowly Fading	0.60
		Channel: The RAKE Demodulator	869
		13.5–1. A Tapped-Delay-Line Channel Model / 13.5–2 The	
		RAKE Demodulator / 13.5–3 Performance of RAKE	
		Demodulator / 13.5-4 Receiver Structures for Channels with	
		Intersymbol Interference	
	13.6	Multicarrier Modulation (OFDM)	884
		13.6-1 Performance Degradation of an OFDM System due to	
		Doppler Spreading / 13.6–2 Suppression of ICI in OFDM	
		Systems	
	13.7	Bibliographical Notes and References	890
		Problems	891
Chapter 14	Fadi	ng Channels II: Capacity and Coding	899
	14.1	Capacity of Fading Channels	900
		14.1–1 Capacity of Finite-State Channels	
	14.2	Ergodic and Outage Capacity	905
		14.2-1 The Ergodic Capacity of the Rayleigh Fading	
		Channel / 14.2-2 The Outage Capacity of Rayleigh Fading	
		Channels	
	14.3	Coding for Fading Channels	918

	14.4	Performance of Coded Systems In Fading Channels	919
		14.4-1 Coding for Fully Interleaved Channel Model	
	14.5	Trellis-Coded Modulation for Fading Channels	929
		14.5-1 TCM Systems for Fading Channels / 14.5-2 Multiple	
		Trellis-Coded Modulation (MTCM)	
	14.6	Bit-Interleaved Coded Modulation	936
	14.7	Coding in the Frequency Domain	942
		14.7-1 Probability of Error for Soft Decision Decoding of	
		Linear Binary Block Codes / 14.7-2 Probability of Error for	
		Hard-Decision Decoding of Linear Block Codes / 14.7-3	
		Upper Bounds on the Performance of Convolutional Codes for	
		a Rayleigh Fading Channel / 14.7-4 Use of Constant-Weight	
		Codes and Concatenated Codes for a Fading Channel	
	14.8	The Channel Cutoff Rate for Fading Channels	957
		14.8-1 Channel Cutoff Rate for Fully Interleaved Fading	The same of
		Channels with CSI at Receiver	
	14.9	Bibliographical Notes and References	960
		Problems	961
			701
hant	ton 15 Mul	tiple-Antenna Systems	064
парі	iei 13 Miui	upie-Antenna Systems	966
	15.1	Channel Models for Multiple-Antenna Systems	966
		15.1–1 Signal Transmission Through a Slow Fading	
		Frequency-Nonselective MIMO Channel / 15.1-2 Detection	
		of Data Symbols in a MIMO System / 15.1-3 Signal	
		Transmission Through a Slow Fading Frequency-Selective	
		MIMO Channel	
	15.2	Capacity of MIMO Channels	98
	2012	15.2–1 Mathematical Preliminaries / 15.2–2 Capacity of a	
		Frequency-Nonselective Deterministic MIMO	
		Channel / 15.2–3 Capacity of a Frequency-Nonselective	
		Ergodic Random MIMO Channel / 15.2-4 Outage	
		Capacity / 15.2–5 Capacity of MIMO Channel When the	
	MONG	Channel Is Known at the Transmitter	99
	15.3	Spread Spectrum Signals and Multicode Transmission	99.
		15.3–1 Orthogonal Spreading Sequences / 15.3–2	
		Multiplexing Gain Versus Diversity Gain / 15.3-3 Multicode	
		MIMO Systems	
	15.4	Coding for MIMO Channels	100
		15.4-1 Performance of Temporally Coded SISO Systems in	
		Rayleigh Fading Channels / 15.4-2 Bit-Interleaved Temporal	
		Coding for MIMO Channels / 15.4-3 Space-Time Block	
		Codes for MIMO Channels / 15.4-4 Pairwise Error	
		Probability for a Space-Time Code / 15.4–5 Space-Time	
		Trellis Codes for MIMO Channels / 15.4-6 Concatenated	
		Space-Time Codes and Turbo Codes	

	15.5	Bibliographical Notes and References	1021
		Problems	1021
Chapter 16	Mul	tiuser Communications	1028
	16.1	Introduction to Multiple Access Techniques	1028
	16.2	Capacity of Multiple Access Methods	1031
	16.3	Multiuser Detection in CDMA Systems	1036
		16.3-1 CDMA Signal and Channel Models / 16.3-2 The	
		Optimum Multiuser Receiver / 16.3–3 Suboptimum	
		Detectors / 16.3-4 Successive Interference	
		Cancellation / 16.3–5 Other Types of Multiuser	
		Detectors / 16.3-6 Performance Characteristics of Detectors	
	16.4	Multiuser MIMO Systems for Broadcast Channels	1053
		16.4–1 Linear Precoding of the Transmitted Signals / 16.4–2	
		Nonlinear Precoding of the Transmitted Signals—The QR	
		Decomposition / 16.4–3 Nonlinear Vector	
		Precoding / 16.4-4 Lattice Reduction Technique for	
		Precoding Random Access Methods	1060
	16.5		1068
		16.5–1 ALOHA Systems and Protocols / 16.5–2 Carrier Sense Systems and Protocols	
		Bibliographical Notes and References	1077
		Problems	1078
mehando esti			
Appendix A		trices	1085
	A.1	Eigenvalues and Eigenvectors of a Matrix	1086
	A.2	Singular-Value Decomposition	1087
	A.3	Matrix Norm and Condition Number	1088
	A.4	The Moore–Penrose Pseudoinverse	1088
Appendix B	Err	or Probability for Multichannel Binary Signals	1090
Appendix C	Eri	ror Probabilities for Adaptive Reception	
		M-Phase Signals	1096
	C.1	Mathematical Model for an M-Phase Signaling Communi-	
		cation System	1096
	C.2	Characteristic Function and Probability Density Function of	
		the Phase θ	1098
	C.3	Error Probabilities for Slowly Fading Rayleigh Channels	1100
	C.4	Error Probabilities for Time-Invariant and Ricean Fading	
		Channels	1104
Appendix D	Squ	uare Root Factorization	1107
References ar	nd Bi	bliography	1109
Index			1142