

Digital Communications

Fourth Edition



John G. Proakis



McGRAW-HILL INTERNATIONAL EDITION
Electrical Engineering Series

Preface		xix
1 Introduction		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		13
1.5 Overview of the Book		15
1.6 Bibliographical Notes and References		16
2 Probability and Stochastic Processes		17
2.1 Probability		17
2.1.1 <i>Random Variables, Probability Distributions, and Probability Densities</i> 2.1.2 <i>Functions of Random Variables</i> 2.1.3 <i>Statistical Averages of Random Variables</i> 2.1.4 <i>Some Useful Probability Distributions</i> 2.1.5 <i>Upper Bounds on the Tail Probability</i> 2.1.6 <i>Sums of Random Variables and the Central Limit Theorem</i>		
2.2 Stochastic Processes		61
2.2.1 <i>Statistical Averages</i> 2.2.2 <i>Power Density Spectrum</i> 2.2.3 <i>Response of a Linear Time-Invariant System to a Random Input Signal</i> 2.2.4 <i>Sampling Theorem for Band-Limited Stochastic Processes</i> 2.2.5 <i>Discrete-Time Stochastic Signals and Systems</i> 2.2.6 <i>Cyclostationary Processes</i>		
2.3 Bibliographical Notes and References		75
Problems		75
3 Source Coding		80
3.1 Mathematical Models for Information Sources		80
3.2 A Logarithmic Measure of Information		82
3.2.1 <i>Average Mutual Information and Entropy</i> 3.2.2 <i>Information Measures for Continuous Random Variables</i>		
3.3 Coding for Discrete Sources		90
3.3.1 <i>Coding for Discrete Memoryless Sources</i> 3.3.2 <i>Discrete Stationary Sources</i> 3.3.3 <i>The Lempel–Ziv Algorithm</i>		

3.4	Coding for Analog Sources—Optimum Quantization	103
	3.4.1 <i>Rate-Distortion Function</i> 3.4.2 <i>Scalar Quantization</i> 3.4.3 <i>Vector Quantization</i>	
3.5	Coding Techniques for Analog Sources	121
	3.5.1 <i>Temporal Waveform Coding</i> 3.5.2 <i>Spectral Waveform Coding</i> 3.5.3 <i>Model-Based Source Coding</i>	
3.6	Bibliographical Notes and References	140
	Problems	141
4	Characterization of Communication Signals and Systems	148
4.1	Representation of Band-Pass Signals and Systems	148
	4.1.1 <i>Representation of Band-Pass Signals</i> 4.1.2 <i>Representation of Linear Band-Pass Systems</i> 4.1.3 <i>Response of a Band-Pass System to a Band-Pass Signal</i> 4.1.4 <i>Representation of Band-Pass Stationary Stochastic Processes</i>	
4.2	Signal Space Representations	158
	4.2.1 <i>Vector Space Concepts</i> 4.2.2 <i>Signal Space Concepts</i> 4.2.3 <i>Orthogonal Expansions of Signals</i>	
4.3	Representation of Digitally Modulated Signals	168
	4.3.1 <i>Memoryless Modulation Methods</i> 4.3.2 <i>Linear Modulation with Memory</i> 4.3.3 <i>Non-linear Modulation Methods with Memory—CPFSK and CPM</i>	
4.4	Spectral Characteristics of Digitally Modulated Signals	201
	4.4.1 <i>Power Spectra of Linearly Modulated Signals</i> 4.4.2 <i>Power Spectra of CPFSK and CPM Signals</i> 4.4.3 <i>Power Spectra of Modulated Signals with Memory</i>	
4.5	Bibliographical Notes and References	221
	Problems	222
5	Optimum Receivers for the Additive White Gaussian Noise Channel	231
5.1	Optimum Receiver for Signals Corrupted by Additive White Gaussian Noise	231
	5.1.1 <i>Correlation Demodulator</i> 5.1.2 <i>Matched-Filter Demodulator</i> 5.1.3 <i>The Optimum Detector</i> 5.1.4 <i>The Maximum-Likelihood Sequence Detector</i> 5.1.5 <i>A Symbol-by-Symbol MAP Detector for Signals with Memory</i>	
5.2	Performance of the Optimum Receiver for Memoryless Modulation	254
	5.2.1 <i>Probability of Error for Binary Modulation</i> 5.2.2 <i>Probability of Error for M-ary Orthogonal Signals</i> 5.2.3 <i>Probability of Error for M-ary Biorthogonal Signals</i> 5.2.4 <i>Probability of Error for Simplex Signals</i> 5.2.5 <i>Probability of Error for M-ary Binary-Coded Signals</i> 5.2.6 <i>Probability of Error for M-ary PAM</i> 5.2.7 <i>Probability of Error for M-ary PSK</i> 5.2.8 <i>Differential PSK (DPSK)</i>	

Contents

	<i>and Its Performance</i> 5.2.9 <i>Probability of Error for QAM</i> 5.2.10 <i>Comparison of Digital Modulation Methods</i>	
5.3	Optimum Receiver for CPM Signals	283
	5.3.1 <i>Optimum Demodulation and Detection of CPM</i> 5.3.2 <i>Performance of CPM Signals</i> 5.3.3 <i>Symbol-by-Symbol Detection of CPM Signals</i> 5.3.4 <i>Suboptimum Demodulation and Detection of CPM Signals</i>	
5.4	Optimum Receiver for Signals with Random Phase in AWGN Channel	300
	5.4.1 <i>Optimum Receiver for Binary Signals</i> 5.4.2 <i>Optimum Receiver for M-ary Orthogonal Signals</i> 5.4.3 <i>Probability of Error for Envelope Detection of M-ary Orthogonal Signals</i> 5.4.4 <i>Probability of Error for Envelope Detection of Correlated Binary Signals</i>	
5.5	Performance Analysis for Wireline and Radio Communication Systems	313
	5.5.1 <i>Regenerative Repeaters</i> 5.5.2 <i>Link Budget Analysis in Radio Communication Systems</i>	
5.6	Bibliographical Notes and References	318
	Problems	319
6	Carrier and Symbol Synchronziation	333
6.1	Signal Parameter Estimation	333
	6.1.1 <i>The Likelihood Function</i> 6.1.2 <i>Carrier Recovery and Symbol Synchronization in Signal Demodulation</i>	
6.2	Carrier Phase Estimation	338
	6.2.1 <i>Maximum-Likelihood Carrier Phase Estimation</i> 6.2.2 <i>The Phase-Locked Loop</i> 6.2.3 <i>Effect of Additive Noise on the Phase Estimate</i> 6.2.4 <i>Decision-Directed Loops</i> 6.2.5 <i>Non-Decision-Directed Loops</i>	
6.3	Symbol Timing Estimation	359
	6.3.1 <i>Maximum-Likelihood Timing Estimation</i> 6.3.2 <i>Non-Decision-Directed Timing Estimation</i>	
6.4	Joint Estimation of Carrier Phase and Symbol Timing	366
6.5	Performance Characteristics of ML Estimators	368
6.6	Bibliographical Notes and References	371
	Problems	372
7	Channel Capacity and Coding	376
7.1	Channel Models and Channel Capacity	376
	7.1.1 <i>Channel Models</i> 7.1.2 <i>Channel Capacity</i> 7.1.3 <i>Achieving Channel Capacity with Orthogonal Signals</i> 7.1.4 <i>Channel Reliability Functions</i>	
7.2	Random Selection of Codes	392
	7.2.1 <i>Random Coding Based on M-ary Binary-Coded Signals</i> 7.2.2 <i>Random Coding Based on M-ary Multiampitude Signals</i> 7.2.3 <i>Comparison of R_0^* with the Capacity of the AWGN Channel</i>	
7.3	Communication System Design Based on the Cutoff Rate	402

7.4	Bibliographical Notes and References	408
	Problems	409
8	Block and Convolutional Channel Codes	416
8.1	Linear Block Codes	416
	<i>8.1.1 The Generator Matrix and the Parity Check Matrix 8.1.2 Some Specific Linear Block Codes 8.1.3 Cyclic Codes 8.1.4 Optimum Soft-Decision Decoding of Linear Block Codes 8.1.5 Hard-Decision Decoding of Linear Block Codes 8.1.6 Comparison of Performance Between Hard-Decision and Soft-Decision Decoding 8.1.7 Bounds on Minimum Distance of Linear Block Codes 8.1.8 Nonbinary Block Codes and Concatenated Block Codes 8.1.9 Interleaving of Coded Data for Channels with Burst Errors 8.1.10 Serial and Parallel Concatenated Block Codes</i>	
8.2	Convolutional Codes	471
	<i>8.2.1 The Transfer Function of a Convolutional Code 8.2.2 Optimum Decoding of Convolutional Codes—The Viterbi Algorithm 8.2.3 Probability of Error for Soft-Decision Decoding 8.2.4 Probability of Error for Hard-Decision Decoding 8.2.5 Distance Properties of Binary Convolutional Codes 8.2.6 Punctured Convolutional Codes 8.2.7 Other Decoding Algorithms for Convolutional Codes 8.2.8 Practical Considerations in the Application of Convolutional Codes 8.2.9 Nonbinary Dual-k Codes and Concatenated Codes 8.2.10 Parallel and Serial Concatenated Convolutional Codes</i>	
8.3	Coded Modulation for Bandwidth-Constrained Channels—Trellis-Coded Modulation	522
8.4	Bibliographical Notes and References	539
	Problems	541
9	Signal Design for Band-Limited Channels	548
9.1	Characterization of Band-Limited Channels	548
9.2	Signal Design for Band-Limited Channels	554
	<i>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</i>	
9.3	Probability of Error in Detection of PAM	574
	<i>9.3.1 Probability of Error for Detection of PAM with Zero ISI 9.3.2 Probability of Error for Detection of Partial-Response Signals</i>	
9.4	Modulation Codes for Spectrum Shaping	578
9.5	Bibliographical Notes and References	588
	Problems	588

- 10 Communication Through Band-Limited Linear Filter Channels** 598
 - 10.1 Optimum Receiver for Channels with ISI and AWGN** 599
 - 10.1.1 Optimum Maximum-Likelihood Receiver | 10.1.2 A Discrete-Time Model for a Channel with ISI | 10.1.3 The Viterbi Algorithm for the Discrete-Time White Noise Filter Model | 10.1.4 Performance of MLSE for Channels with ISI*
 - 10.2 Linear Equalization** 616
 - 10.2.1 Peak Distortion Criterion | 10.2.2 Mean-Square-Error (MSE) Criterion | 10.2.3 Performance Characteristics of the MSE Equalizer | 10.2.4 Fractionally Spaced Equalizers | 10.2.5 Baseband and Passband Linear Equalizers*
 - 10.3 Decision-Feedback Equalization** 638
 - 10.3.1 Coefficient Optimization | 10.3.2 Performance Characteristics of DFE | 10.3.3 Predictive Decision-Feedback Equalizer | 10.3.4 Equalization at the Transmitter—Tomlinson—Harashima Precoding*
 - 10.4 Reduced Complexity ML Detectors** 647
 - 10.5 Iterative Equalization and Decoding—Turbo Equalization** 649
 - 10.6 Bibliographical Notes and References** 651
 - Problems 652

- 11 Adaptive Equalization** 660
 - 11.1 Adaptive Linear Equalizer** 660
 - 11.1.1 The Zero-Forcing Algorithm | 11.1.2 The LMS Algorithm | 11.1.3 Convergence Properties of the LMS Algorithm | 11.1.4 Excess MSE Due to Noisy Gradient Estimates | 11.1.5 Accelerating the Initial Convergence Rate in the LMS Algorithm | 11.1.6 Adaptive Fractionally Spaced Equalizer—The Tap Leakage Algorithm | 11.1.7 An Adaptive Channel Estimator for ML Sequence Detection*
 - 11.2 Adaptive Decision-Feedback Equalizer** 677
 - 11.3 Adaptive Equalization of Trellis-Coded Signals** 678
 - 11.4 Recursive Least-Squares Algorithms for Adaptive Equalization** 682
 - 11.4.1 Recursive Least-Squares (Kalman) Algorithm | 11.4.2 Linear Prediction and the Lattice Filter*
 - 11.5 Self-Recovering (Blind) Equalization** 693
 - 11.5.1 Blind Equalization Based on the Maximum-Likelihood Criterion | 11.5.2 Stochastic Gradient Algorithms | 11.5.3 Blind Equalization Algorithms Based on Second- and Higher-Order Signal Statistics*
 - 11.6 Bibliographical Notes and References** 704
 - Problems 705

- 12 Multichannel and Multicarrier Systems** 709
 - 12.1 Multichannel Digital Communications in AWGN Channels** 709
 - 12.1.1 Binary Signals | 12.1.2 M-ary Orthogonal Signals*

12.2	Multicarrier Communications	715
	<i>12.2.1 Capacity of a Nonideal Linear Filter Channel 12.2.2 An FFT-Based Multicarrier System 12.2.3 Minimizing Peak-to-Average Ratio in the Multicarrier Systems</i>	
12.3	Bibliographical Notes and References	723
	Problems	724
13	Spread Spectrum Signals for Digital Communications	726
13.1	Model of Spread Spectrum Digital Communication System	728
13.2	Direct Sequence Spread Spectrum Signals	729
	<i>13.2.1 Error Rate Performance of the Decoder 13.2.2 Some Applications of DS Spread Spectrum Signals 13.2.3 Effect of Pulsed Interference on DS Spread Spectrum Systems 13.2.4 Excision of Narrowband Interference in DS Spread Spectrum Systems 13.2.5 Generation of PN Sequences</i>	
13.3	Frequency-Hopped Spread Spectrum Signals	771
	<i>13.3.1 Performance of FH Spread Spectrum Signals in an AWGN Channel 13.3.2 Performance of FH Spread Spectrum Signals in Partial-Band Interference 13.3.3 A CDMA System Based on FH Spread Spectrum Signals</i>	
13.4	Other Types of Spread Spectrum Signals	784
13.5	Synchronization of Spread Spectrum Systems	786
13.6	Bibliographical Notes and References	792
	Problems	794
14	Digital Communications through Fading Multipath Channels	800
14.1	Characterization of Fading Multipath Channels	801
	<i>14.1.1 Channel Correlation Functions and Power Spectra 14.1.2 Statistical Models for Fading Channels</i>	
14.2	The Effect of Signal Characteristics on the Choice of a Channel Model	814
14.3	Frequency-Nonselective, Slowly Fading Channel	816
14.4	Diversity Techniques for Fading Multipath Channels	821
	<i>14.4.1 Binary Signals 14.4.2 Multiphase Signals 14.4.3 M-ary Orthogonal Signals</i>	
14.5	Digital Signaling over a Frequency-Selective, Slowly Fading Channel	840
	<i>14.5.1 A Tapped-Delay-Line Channel Model 14.5.2 The RAKE Demodulator 14.5.3 Performance of RAKE Demodulator 14.5.4 Receiver Structures for Channels with Intersymbol Interference</i>	
14.6	Coded Waveforms for Fading Channels	852
	<i>14.6.1 Probability of Error for Soft-Decision Decoding of Linear Binary Block Codes 14.6.2 Probability of Error for Hard-Decision Decoding of Linear Binary Block Codes 14.6.3 Upper Bounds on the Performance of Convolutional Codes for a Rayleigh Fading Channel 14.6.4 Use of Constant-Weight Codes and Concatenated Codes for a Fading Channel 14.6.5 System Design Based on the</i>	

Contents

<i>Cutoff Rate</i> 14.6.6 <i>Performance of Coded Phase-Coherent Communication Systems—Bit-Interleaved Coded Modulation</i> 14.6.7 <i>Trellis-Coded Modulation</i>	
14.7 Multiple-Antenna Systems	878
14.8 Bibliographical Notes and References Problems	885 887
15 Multiuser Communications	896
15.1 Introduction to Multiple Access Techniques	896
15.2 Capacity of Multiple Access Methods	899
15.3 Code-Division Multiple Access	905
<i>15.3.1 CDMA Signal and Channel Models</i> <i>15.3.2 The Optimum Receiver</i> <i>15.3.3 Suboptimum Detectors</i> <i>15.3.4 Successive Interference Cancellation</i> <i>15.3.5 Performance Characteristics of Detectors</i>	
15.4 Random Access Methods	922
<i>15.4.1 ALOHA Systems and Protocols</i> <i>15.4.2 Carrier Sense Systems and Protocols</i>	
15.5 Bibliographical Notes and References Problems	931 933
Appendix A The Levinson–Durbin Algorithm	939
Appendix B Error Probability for Multichannel Binary Signals	943
Appendix C Error Probabilities for Adaptive Reception of M-Phase Signals	949
C.1 Mathematical Model for M -Phase Signaling Communication System	949
C.2 Characteristic Function and Probability Density Function of the Phase θ	952
C.3 Error Probabilities for Slowly Rayleigh Fading Channels	953
C.4 Error Probabilities for Time-Invariant and Ricean Fading Channels	956
Appendix D Square-Root Factorization	961
References and Bibliography	963
Index	993