

Preface	xix
<b>1 Introduction</b>	<b>1</b>
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
<b>2 Probability and Stochastic Processes</b>	<b>17</b>
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
<b>3 Source Coding</b>	<b>80</b>
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
<b>4</b>	<b>Characterization of Communication Signals and Systems</b>	<b>148</b>
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
<b>5</b>	<b>Optimum Receivers for the Additive White Gaussian Noise Channel</b>	<b>231</b>
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>	

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

7.4	Bibliographical Notes and References	408
	Problems	409
<b>8</b>	<b>Block and Convolutional Channel Codes</b>	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
<b>9</b>	<b>Signal Design for Band-Limited Channels</b>	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

<b>10</b>	<b>Communication Through Band-Limited Linear Filter Channels</b>	598
10.1	Optimum Receiver for Channels with ISI and AWGN	599
	<i>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</i>	
10.2	Linear Equalization	616
	<i>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</i>	
10.3	Decision-Feedback Equalization	638
	<i>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</i>	
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
<b>11</b>	<b>Adaptive Equalization</b>	660
11.1	Adaptive Linear Equalizer	660
	<i>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</i>	
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
	<i>11.4.1 Recursive Least-Squares (Kalman) Algorithm   11.4.2 Linear Prediction and the Lattice Filter</i>	
11.5	Self-Recovering (Blind) Equalization	693
	<i>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</i>	
11.6	Bibliographical Notes and References	704
	Problems	705
<b>12</b>	<b>Multichannel and Multicarrier Systems</b>	709
12.1	Multichannel Digital Communications in AWGN Channels	709
	<i>12.1.1 Binary Signals   12.1.2 M-ary Orthogonal Signals</i>	

<b>12.2</b>	<b>Multicarrier Communications</b>	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>	
<b>12.3</b>	<b>Bibliographical Notes and References</b>	723
	Problems	724
<b>13</b>	<b>Spread Spectrum Signals for Digital Communications</b>	726
<b>13.1</b>	<b>Model of Spread Spectrum Digital Communication System</b>	728
<b>13.2</b>	<b>Direct Sequence Spread Spectrum Signals</b>	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>	
<b>13.3</b>	<b>Frequency-Hopped Spread Spectrum Signals</b>	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>	
<b>13.4</b>	<b>Other Types of Spread Spectrum Signals</b>	784
<b>13.5</b>	<b>Synchronization of Spread Spectrum Systems</b>	786
<b>13.6</b>	<b>Bibliographical Notes and References</b>	792
	Problems	794
<b>14</b>	<b>Digital Communications through Fading Multipath Channels</b>	800
<b>14.1</b>	<b>Characterization of Fading Multipath Channels</b>	801
	<i>14.1.1 Channel Correlation Functions and Power Spectra   14.1.2 Statistical Models for Fading Channels</i>	
<b>14.2</b>	<b>The Effect of Signal Characteristics on the Choice of a Channel Model</b>	814
<b>14.3</b>	<b>Frequency-Nonselective, Slowly Fading Channel</b>	816
<b>14.4</b>	<b>Diversity Techniques for Fading Multipath Channels</b>	821
	<i>14.4.1 Binary Signals   14.4.2 Multiphase Signals   14.4.3 M-ary Orthogonal Signals</i>	
<b>14.5</b>	<b>Digital Signaling over a Frequency-Selective, Slowly Fading Channel</b>	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>	
<b>14.6</b>	<b>Coded Waveforms for Fading Channels</b>	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>	

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