COMMUNICATION SYSTEMS

4TH EDITION

Simon Haykin
McMaster University

JOHN WILEY & SONS, INC.

CONTENTS

BACKGROUND AND PREVIEW 1

1. The Communication Process 1
2. Primary Communication Resources 3
3. Sources of Information 3
4. Communication Networks 10
5. Communication Channels 15
6. Modulation Process 19
7. Analog and Digital Types of Communication 21
8. Shannon's Information Capacity Theorem 23
9. A Digital Communication Problem 24
10. Historical Notes 26

Notes and References 29

CHAPTER 1 *Random Processes* 31

1.1 Introduction 31
1.2 Mathematical Definition of a Random Process 32
1.3 Stationary Processes 33
1.4 Mean, Correlation, and Covariance Functions 35
1.5 Ergodic Processes 41
1.6 Transmission of a Random Process Through a Linear Time-Invariant Filter 42
1.7 Power Spectral Density 44
1.8 Gaussian Process 54
1.9 Noise 58
1.10 Narrowband Noise 64
1.11 Representation of Narrowband Noise in Terms of In-phase and Quadrature Components 64
1.12 Representation of Narrowband Noise in Terms of Envelope and Phase Components 67
1.13 Sine Wave Plus Narrowband Noise 69
1.14 Computer Experiments: Flat-Fading Channel 71

1.15 Summary and Discussion 75
Notes and References 77
Problems 78

CHAPTER 2 *Continuous-Wave Modulation* **88**

2.1 Introduction 88
2.2 Amplitude Modulation 90
2.3 Linear Modulation Schemes 93
2.4 Frequency Translation 103
2.5 Frequency-Division Multiplexing 105
2.6 Angle Modulation 107
2.7 Frequency Modulation 109
2.8 Nonlinear Effects in FM Systems 126
2.9 Superheterodyne Receiver 128
2.10 Noise in CW Modulation Systems 130
2.11 Noise in Linear Receivers using Coherent Detection 132
2.12 Noise in AM Receivers using Envelope Detection 135
2.13 Noise in FM Receivers 142
2.14 Computer Experiments: Phase-locked Loop 157
2.15 Summary and Discussion 162
Notes and References 165
Problems 166

CHAPTER 3 *Pulse Modulation* **183**

3.1 Introduction 183
3.2 Sampling Process 184
3.3 Pulse-Amplitude Modulation 188
3.4 Other Forms of Pulse Modulation 191
3.5 Bandwidth–Noise Trade-off 193
3.6 Quantization Process 193
3.7 Pulse-Code Modulation 201
3.8 Noise Considerations in PCM Systems 209
3.9 Time-Division Multiplexing 211
3.10 Digital Multiplexers 214
3.11 Virtues, Limitations, and Modifications of PCM 217
3.12 Delta Modulation 218
3.13 Linear Prediction 223
3.14 Differential Pulse-Code Modulation 227
3.15 Adaptive Differential Pulse-Code Modulation 229

3.16 Computer Experiment: Adaptive Delta Modulation 232
3.17 MPEG Audio Coding Standard 234
3.18 Summary and Discussion 236
Notes and References 238
Problems 239

CHAPTER 4 *Baseband Pulse Transmission* 247

4.1 Introduction 247
4.2 Matched Filter 248
4.3 Error Rate Due to Noise 253
4.4 Intersymbol Interference 259
4.5 Nyquist's Criterion for Distortionless Baseband Binary Transmission 261
4.6 Correlative-Level Coding 267
4.7 Baseband *M*-ary PAM Transmission 275
4.8 Digital Subscriber Lines 277
4.9 Optimum Linear Receiver 282
4.10 Adaptive Equalization 287
4.11 Computer Experiments: Eye Patterns 293
4.12 Summary and Discussion 296
Notes and References 297
Problems 300

CHAPTER 5 *Signal-Space Analysis* 309

5.1 Introduction 309
5.2 Geometric Representation of Signals 311
5.3 Conversion of the Continuous AWGN Channel into a Vector Channel 318
5.4 Likelihood Functions 322
5.5 Coherent Detection of Signals in Noise: Maximum Likelihood Decoding 322
5.6 Correlation Receiver 326
5.7 Probability of Error 328
5.8 Summary and Discussion 337
Notes and References 337
Problems 338

CHAPTER 6 *Passband Digital Transmission* 344

6.1 Introduction 344
6.2 Passband Transmission Model 348
6.3 Coherent Phase-Shift Keying 349

6.4 Hybrid Amplitude/Phase Modulation Schemes 368
6.5 Coherent Frequency-Shift Keying 380
6.6 Detection of Signals with Unknown Phase 403
6.7 Noncoherent Orthogonal Modulation 407
6.8 Noncoherent Binary Frequency-Shift Keying 413
6.9 Differential Phase-Shift Keying 414
6.10 Comparison of Digital Modulation Schemes Using a Single Carrier 417
6.11 Voiceband Modems 420
6.12 Multichannel Modulation 431
6.13 Discrete Multitone 440
6.14 Synchronization 448
6.15 Computer Experiments: Carrier Recovery and Symbol Timing 458
6.16 Summary and Discussion 464
Notes and References 465
Problems 468

CHAPTER 7 *Spread-Spectrum Modulation* 479

7.1 Introduction 479
7.2 Pseudo-Noise Sequences 480
7.3 A Notion of Spread Spectrum 488
7.4 Direct-Sequence Spread Spectrum with Coherent Binary Phase-Shift Keying 490
7.5 Signal-Space Dimensionality and Processing Gain 493
7.6 Probability of Error 497
7.7 Frequency-Hop Spread Spectrum 499
7.8 Computer Experiments: Maximal-Length and Gold Codes 505
7.9 Summary and Discussion 508
Notes and References 509
Problems 509

CHAPTER 8 *Multiuser Radio Communications* 512

8.1 Introduction 512
8.2 Multiple-Access Techniques 513
8.3 Satellite Communications 514
8.4 Radio Link Analysis 517
8.5 Wireless Communications 529
8.6 Statistical Characterization of Multipath Channels 535
8.7 Binary Signaling over a Rayleigh Fading Channel 542
8.8 TDMA and CDMA Wireless Communication Systems 547
8.9 Source Coding of Speech for Wireless Communications 550

8.10 Adaptive Antenna Arrays for Wireless Communications 553
8.11 Summary and Discussion 559
Notes and References 560
Problems 562

CHAPTER 9 *Fundamental Limits in Information Theory* **567**

9.1 Introduction 567
9.2 Uncertainty, Information, and Entropy 568
9.3 Source-Coding Theorem 574
9.4 Data Compaction 575
9.5 Discrete Memoryless Channels 581
9.6 Mutual Information 584
9.7 Channel Capacity 587
9.8 Channel-Coding Theorem 589
9.9 Differential Entropy and Mutual Information for Continuous Ensembles 593
9.10 Information Capacity Theorem 597
9.11 Implications of the Information Capacity Theorem 601
9.12 Information Capacity of Colored Noise Channel 607
9.13 Rate Distortion Theory 611
9.14 Data Compression 614
9.15 Summary and Discussion 616
Notes and References 617
Problems 618

CHAPTER 10 *Error-Control Coding* **626**

10.1 Introduction 626
10.2 Discrete-Memoryless Channels 629
10.3 Linear Block Codes 632
10.4 Cyclic Codes 641
10.5 Convolutional Codes 654
10.6 Maximum Likelihood Decoding of Convolutional Codes 660
10.7 Trellis-Coded Modulation 668
10.8 Turbo Codes 674
10.9 Computer Experiment: Turbo Decoding 682
10.10 Low-Density Parity-Check Codes 683
10.11 Irregular Codes 691
10.12 Summary and Discussion 693
Notes and References 694
Problems 696

APPENDIX 1 Probability Theory 703
APPENDIX 2 Representation of Signals and Systems 715
APPENDIX 3 Bessel Functions 735
APPENDIX 4 Confluent Hypergeometric Functions 740
APPENDIX 5 Cryptography 742
APPENDIX 6 Tables 761

GLOSSARY 771
BIBLIOGRAPHY 777
INDEX 792