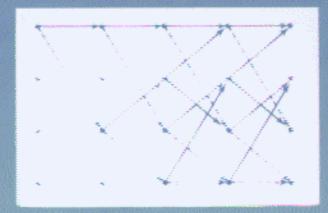
## COMMUNICATION SYSTEMS ENGINEERING

SECOND EDITION



John G. Proakis Masoud Salehi

## Contents

PRE	FACE	xi
INT	RODUCTION	1
1.1	Historical Review 1	
1.2	Elements of an Electrical Communication System 4 1.2.1 Digital Communication System, 7 1.2.2 Early Work in Digital Communications, 10	
1.3	Communication Channels and Their Characteristics 12	
1.4	Mathematical Models for Communication Channels 19	
1.5	Organization of the Book 22	
1.6	Further Reading 23	
	QUENCY DOMAIN ANALYSIS OF SIGNALS D SYSTEMS	24
2.1	Fourier Series 24 2.1.1 Fourier Series for Real Signals: the Trigonometric Fourier Series, 29	
2.2;	Fourier Transforms 31 2.2.1 Fourier Transform of Real, Even. and Odd Signals, 35	

	2.2.2 Basic Properties of the Fourier Transform, 36 2.2.3 Fourier Transform for Periodic Signals, 39	
2.3	Power and Energy 40 2.3.1 Energy-Type Signals, 41 2.3.2 Power-Type Signals, 42	
2.4	Sampling of Bandlimited Signals 45	
2.5	Bandpass Signals 49	
2.6	Further Reading 57	
	Problems 57	
ANA	LOG SIGNAL TRANSMISSION AND RECEPTION	7
3.1	Introduction to Modulation 70	
3.2	Amplitude Modulation (AM) 71 3.2.1 Double-Sideband Suppressed Carrier AM, 71 3.2.2 Conventional Amplitude Modulation, 78 3.2.3 Single-Sideband AM, 81 3.2.4 Vestigial-Sideband AM, 85 3.2.5 Implementation of AM Modulators and Demodulators, 88 3.2.6 Signal Multiplexing, 94	
3.3	Angle Modulation 96 3.3.1 Representation of FM and PM Signals, 97 3.3.2 Spectral Characteristics of Angle-Modulated Signals, 101 3.3.3 Implementation of Angle Modulators and Demodulators, 107	
3.4	Radio and Television Broadcasting 115 3.4.1 AM Radio Broadcasting, 115 3.4.2 FM Radio Broadcasting, 116 3.4.3 Television Broadcasting, 120	
3.5	Mobile Radio Systems 128	
3.6	Further Reading 131	
	Problems 131	
RAN	DOM PROCESSES	144
4.1	Probability and Random Variables 144	
4.2	Random Processes: Basic Concepts 159 4.2.1 Description of Random Processes, 162 4.2.2 Statistical Averages, 164 4.2.3 Stationary Processes, 166 4.2.4 Random Processes and Linear Systems, 174	

4.3	Random Processes in the Frequency Domain 177 4.3.1 Power Spectrum of Stochastic Processes, 177 4.3.2 Transmission over LTI Systems, 183	
4.4	Gaussian and White Processes 186 4.4.1 Gaussian Processes, 186 4.4.2 White Processes, 188	
4.5	Bandlimited Processes and Sampling 192	
4.6	Bandpass Processes 194	
4.7	Further Reading 201	
	Problems 202	
	CT OF NOISE ON ANALOG COMMUNICATION TEMS	217
5.1	Effect of Noise on Linear-Modulation Systems 217 5.1.1 Effect of Noise on a Baseband System, 218 5.1.2 Effect of Noise on DSB-SC AM, 218 5.1.3 Effect of Noise on SSB AM, 220 5.1.4 Effect of Noise on Conventional AM, 221	
5.2	Carrier-Phase Estimation with a Phase-Locked Loop (PLL) 225 5.2.1 The Phase-Locked Loop (PLL), 226 5.2.2 Effect of Additive Noise on Phase Estimation, 229	
5.3	Effect of Noise on Angle Modulation 234 5.3.1 Threshold Effect in Angle Modulation, 244 5.3.2 Pre-emphasis and De-emphasis Filtering, 248	
5.4	Comparison of Analog-Modulation Systems 251	
5.5	Effects of Transmission Losses and Noise in Analog Communication Systems 252 5.5.1 Characterization of Thermal Noise Sources, 253 5.5.2 Effective Noise Temperature and Noise Figure, 254 5.5.3 Transmission Losses, 257 5.5.4 Repeaters for Signal Transmission, 258	
5.6	Further Reading 261	
	Problems 261	
INFO	DRMATION SOURCES AND SOURCE CODING	267
6.1	Modeling of Information Sources 268 6.1.1 Measure of Information, 269 6.1.2 Joint and Conditional Entropy, 271	

6.2	Source-Coding Theorem 273	
6.3	Source-Coding Algorithms 276 6.3.1 The Huffman Source-Coding Algorithm, 276 6.3.2 The Lempel-Ziv Source-Coding Algorithm, 280	
6.4	Rate-Distortion Theory 282 6.4.1 Mutual Information, 283 6.4.2 Differential Entropy, 284 6.4.3 Rate-Distortion Function, 285	
6.5	Quantization 290 6.5.1 Scalar Quantization, 291 6.5.2 Vector Quantization, 300	
6.6	Waveform Coding 302 6.6.1 Pulse-Code Modulation (PCM), 302 6.6.2 Differential Pulse-Code Modulation (DPCM), 307 6.6.3 Delta Modulation ( $\Delta M$ ), 310	
6.7	Analysis-Synthesis Techniques 312	
6.8	Digital Audio Transmission and Digital Audio Recording 316 6.8.1 Digital Audio in Telephone Transmission Systems, 317 6.8.2 Digital Audio Recording, 319	
6.9	The JPEG Image-Coding Standard 323	
6.10	Further Reading 327	
	Problems 327	
	ITAL TRANSMISSION THROUGH THE ADDITIVE WHITE USSIAN NOISE CHANNEL	3
7.1	Geometric Representation of Signal Waveforms 341	
7.2	Pulse Amplitude Modulation 345	
7.3	<ul> <li>Two-dimensional Signal Waveforms 350</li> <li>7.3.1 Baseband Signals, 350</li> <li>7.3.2 Two-dimensional Bandpass Signals—Carrier-Phase Modulation, 354</li> <li>7.3.3 Two-dimensional Bandpass Signals—Quadrature Amplitude Modulation, 357</li> </ul>	
7.4	Multidimensional Signal Waveforms 360 7.4.1 Orthogonal Signal Waveforms, 360 7.4.2 Biorthogonal Signal Waveforms, 365 7.4.3 Simplex Signal Waveforms, 366 7.4.4 Binary-Coded Signal Waveforms, 367	

7.5	Optimum Receiver for Digitally Modulated Signals in Additive White
	Gaussian Noise 370
	7.5.1 Correlation-Type Demodulator, 370
	7.5.2 Matched-Filter-Type Demodulator, 375
	7.5.3 The Optimum Detector, 381
	7.5.4 Demodulation and Detection of Carrier-Amplitude Modulated Signals, 386
	7.5.5 Demodulation and Detection of Carrier-Phase Modulated Signals, 388
	7.5.6 Demodulation and Detection of Quadrature Amplitude Modulated Signals, 396
	7.5.7 Demodulation and Detection of Frequency-Modulated Signals, 398
7.6	Probability of Error for Signal Detection in Additive White
	Gaussian Noise 405
	7.6.1 Probability of Error for Binary Modulation, 405
	7.6.2 Probability of Error for M-ary PAM, 408
	7.6.3 Probability of Error for Phase-Coherent PSK Modulation, 413
	7.6.4 Probability of Error for DPSK, 417
	7.6.5 Probability of Error for QAM, 418
	7.6.6 Probability of Error for M-ary Orthogonal Signals, 423
	7.6.7 Probability of Error for M-ary Biorthogonal Signals, 428
	7.6.8 Probability of Error for M-ary Simplex Signals, 429
	7.6.9 Probability of Error for Noncoherent Detection of FSK, 430
	7.6.10 Comparison of Modulation Methods, 432
7.7	Performance Analysis for Wireline and Radio Communication
	Channels 436
	7.7.1 Regenerative Repeaters, 437
	7.7.2 Link Budget Analysis for Radio Channels, 438
7.8	Symbol Synchronization 442
	7.8.1 Early-Late Gate Synchronizers, 443
	7.8.2 Minimum Mean-Square-Error Method, 445
	7.8.3 Maximum-Likelihood Methods, 448
	7.8.4 Spectral Line Methods, 449
	7.8.5 Symbol Synchronization for Carrier-Modulated Signals, 451
7.9	Further Reading 452
	Problems 453
	TAL TRANSMISSION THROUGH BANDLIMITED GN CHANNELS
8.1	Digital Transmission through Bandlimited Channels 474 8.1.1 Digital PAM Transmission through Bandlimited Baseband

8.1.2 Digital Transmission through Bandlimited Bandpass Channels, 480

474

8

Channels, 478

8.2	The Power Spectrum of Digitally Modulated Signals 482 8.2.1 The Power Spectrum of the Baseband Signal, 483 8.2.2 The Power Spectrum of a Carrier-Modulated Signal, 488	
8.3	Signal Design for Bandlimited Channels 490 8.3.1 Design of Bandlimited Signals for Zero ISI—The Nyquist Criterion, 492 8.3.2 Design of Bandlimited Signals with Controlled ISI—Partial Response Signals, 497	
8.4	Probability of Error in Detection of Digital PAM 499 8.4.1 Probability of Error for Detection of Digital PAM with Zero ISI, 500 8.4.2 Symbol-by-Symbol Detection of Data with Controlled ISI, 501 8.4.3 Probability of Error for Detection of Partial Response Signals, 504	
8.5	Digitally Modulated Signals with Memory 507  8.5.1 Modulation Codes and Modulation Signals with Memory, 508  8.5.2 The Maximum-Likelihood Sequence Detector, 521  8.5.3 Maximum-Likelihood Sequence Detection of Partial Response Signals, 525  8.5.4 The Power Spectrum of Digital Signals with Memory, 530	
8.6	System Design in the Presence of Channel Distortion 534 8.6.1 Design of Transmitting and Receiving Filters for a Known Channel, 535 8.6.2 Channel Equalization, 538	
8.7	Multicarrier Modulation and OFDM 556 8.7.1 An OFDM System Implemented via the FFT Algorithm, 557	
8.8	Further Reading 560	
	Problems 561	
СНА	NNEL CAPACITY AND CODING	576
9.1	Modeling of Communication Channels 576	
9.2	Channel Capacity 579 9.2.1 Gaussian Channel Capacity, 583	
9.3	Bounds on Communication 586 9.3.1 Transmission of Analog Sources by PCM, 590	
9.4	Coding for Reliable Communication 591 9.4.1 A Tight Bound on Error Probability of Orthogonal Signals, 592 9.4.2 The Promise of Coding, 595	
9.5	Linear Block Codes 601 9.5.1 Decoding and Performance of Linear Block Codes, 606 9.5.2 Burst-Error-Correcting-Codes, 614	
9.6	Cyclic Codes 615 9.6.1 The Structure of Cyclic Codes, 615	

9.7	Convolutional Codes 623
	9.7.1 Basic Properties of Convolutional Codes, 624
	9.7.2 Optimum Decoding of Convolutional Codes—The Viterbi
	Algorithm, 629
	9.7.3 Other Decoding Algorithms for Convolutional Codes, 634
	9.7.4 Bounds on Error Probability of Convolutional Codes, 634
9.8	Complex Codes Based on Combination of Simple Codes 638
	9.8.1 Product Codes, 639
	9.8.2 Concatenated Codes, 640
	9.8.3 Turbo Codes, 640
	9.8.4 The BCJR Algorithm, 642
	9.8.5 Performance of Turbo Codes, 644
9.9	Coding for Bandwidth-Constrained Channels 646
	9.9.1 Combined Coding and Modulation, 647
	9.9.2 Trellis-Coded Modulation, 649
9.10	Practical Applications of Coding 655
	9.10.1 Coding for Deep-Space Communications, 656
	9.10.2 Coding for Telephone-Line Modems, 657
	9.10.3 Coding for Compact Discs, 658
9.11	Further Reading 661
	Problems 661
WIRE	LESS COMMUNICATIONS 674
10.1	Digital Transmission on Fading Multipath Channels 674
	10.1.1 Channel Models for Time-Variant Multipath Channels, 676
	10.1.2 Signal Design for Fading Multipath Channels, 684
	10.1.3 Performance of Binary Modulation in Frequency Nonselective Rayleigh
	Fading Channels, 686
	10.1.4 Performance Improvement Through Signal Diversity, 689
	10.1.5 Modulation and Demodulation on Frequency Selective Channels—
	The RAKE Demodulator, 694
	10.1.6 Multiple Antenna Systems and Space-Time Codes, 697
10.2	Continuous Carrier-Phase Modulation 702
	10.2.1 Continuous-Phase FSK (CPFSK), 702
	10.2.2 Continuous-Phase Modulation (CPM), 711
	10.2.3 Spectral Characteristics of CPFSK and CPM Signals, 715
	10.2.4 Demodulation and Detection of CPM Signals, 720
	10.2.5 Performance of CPM in AWGN and Rayleigh Fading Channels, 726
10.3	Spread-Spectrum Communication Systems 729
	10.3.1 Model of a Spread-Spectrum Digital Communication System, 730
	10.3.2 Direct-Sequence Spread-Spectrum Systems, 731
	10.3.3 Some Applications of DS Spread-Spectrum Signals, 742

	10.3.4 Effect of Pulsed Interference and Fading, 746	
	10.3.5 Generation of PN Sequences, 748	
	10.3.6 Frequency-Hopped Spread Spectrum, 752	
	10.3.7 Synchronization of Spread-Spectrum Systems, 758	
0.4	Digital Cellular Communication Systems 766	
	10.4.1 The GSM System, 766	
	10.4.2 CDMA System Based on IS-95, 768	
0.5	Further Reading 774	
	Problems 775	
ΔPPI	ENDIX A: THE PROBABILITY OF ERROR FOR	
	TICHANNEL RECEPTION OF BINARY SIGNALS	70
	HOWART SIGNALS	78.
REFE	RENCES	79

INDEX 794