Contents

The numbers in parentheses after section titles identify previous sections that contain the minimum prerequisite material. The symbol \star identifies optional material.

Chapter 1

Introduction 1

- 1.1 Elements and Limitations of Communications Systems 2 Information, Messages, and Signals 2 Elements of a Communication System 3 Fundamental Limitations 5
- 1.2 Modulation and Coding 6 Modulation Methods 6 Modulation Benefits and Applications 8 Coding Methods and Benefits 11
- 1.3 Electromagnetic Wave Propagation Over Wireless Channels 12 RF Wave Deflection 14 Skywave Propagation 14
- 1.4 Emerging Developments 17
- 1.5 Societal Impact and Historical Perspective 20 Historical Perspective 21
- 1.6 Prospectus 24

Chapter 2

Signals and Spectra 27

2.1 Line Spectra and Fourier Series 29
Phasors and Line Spectra 29
Periodic Signals and Average Power 33
Fourier Series 35
Convergence Conditions and Gibbs
Phenomenon 39
Parseval's Power Theorem 42

2.2 Fourier Transforms and Continuous Spectra

(2.1) 43
Fourier Transforms 43

- Symmetric and Causal Signals 47 Rayleigh's Energy Theorem 50
- Duality Theorem 52
- Transform Calculations 54
- 2.3 Time and Frequency Relations (2.2) 54
 Superposition 55
 Time Delay and Scale Change 55

Frequency Translation and Modulation 58 Differentiation and Integration 60

- 2.4 Convolution (2.3) 62 Convolution Integral 63 Convolution Theorems 65
- 2.5 Impulses and Transforms in the Limit (2.4) 68
 Properties of the Unit Impulse 68
 Impulses in Frequency 71
 Step and Signum Functions 74
 Impulses in Time 76
- 2.6 Discrete Time Signals and the Discrete Fourier Transform 80 Convolution Using the DFT (2.4) 83

Chapter 3

Signal Transmission and Filtering 91

- 3.1 Response of LTI Systems (2.4) 92 Impulse Response and the Superposition Integral 93 Transfer Functions and Frequency Response 96 Block-Diagram Analysis 102
- 3.2 Signal Distortion in Transmission

 (3.1) 105
 Distortionless Transmission 105
 Linear Distortion 107
 Equalization 110
 Nonlinear Distortion and Companding 113
- 3.3 Transmission Loss and Decibels (3.2) 116
 Power Gain 116
 Transmission Loss and Repeaters 118
 Fiber Optics 119
 Radio Transmission 122
- 3.4 Filters and Filtering (3.3) 126 Ideal Filters 126 Bandlimiting and Timelimiting 128 Real Filters 129 Pulse Response and Risetime 134
- 3.5 Quadrature Filters and Hilbert Transforms (3.4) 138

3.6 Correlation and Spectral Density (3.4) 141
 Correlation of Power Signals 141
 Correlation of Energy Signals 145
 Spectral Density Functions 147

Chapter 4

Linear CW Modulation 161

- 4.1 Bandpass Signals and Systems (3.4) 162 Analog Message Conventions 162 Bandpass Signals 164 Bandpass Transmission 168 Bandwidth 172
 4.2 Double-Sideband Amplitude
- Modulation (4.1) 173 AM Signals and Spectra 173 DSB Signals and Spectra 176 Tone Modulation and Phasor Analysis 178 4.3 Modulators and Transmitters (4.2) 179
- 4.3 Modulators and Transmitters (4.2) 179
 Product Modulators 180
 Square-Law and Balanced Modulators 180
 Switching Modulators 184
- 4.4 Suppressed-Sideband Amplitude Modulation (3.5, 4.3) 185
 SSB Signals and Spectra 185
 SSB Generation 188
 VSB Signals and Spectra 191
- 4.5 Frequency Conversion and Demodulation (4.4) 193
 Frequency Conversion 194
 Synchronous Detection 195
 Envelope Detection 198

Chapter 5

Angle CW Modulation 207

5.1 Phase and Frequency Modulation

(4.3) 208
PM and FM signals 208
Narrowband PM and FM 212
Tone Modulation 213
Multitone and Periodic Modulation 220

5.2 Transmission Bandwidth and

Distortion (5.1) 223

Transmission Bandwidth Estimates 223 Linear Distortion 226 Nonlinear Distortion and Limiters 229

 5.3 Generation and Detection of FM and PM (4.5, 5.2) 232 Direct FM and VCOs 233 Phase Modulators and Indirect FM 234 Triangular-Wave FM 237 Frequency Detection 239

5.4 Interference (5.3) 243
 Interfering Sinusoids 243
 Deemphasis and Preemphasis Filtering 245
 FM Capture Effect 247

Chapter 6

Sampling and Pulse Modulation 257

- 6.1 Sampling Theory and Practice

 (2.6, 4.2)
 258
 Chopper Sampling
 258
 Ideal Sampling and Reconstruction
 263
 Practical Sampling and Aliasing
 266
- 6.2 Pulse-Amplitude Modulation (6.1) 272 Flat-Top Sampling and PAM 272
- 6.3 Pulse-Time Modulation (6.2) 275
 Pulse-Duration and Pulse-Position Modulation 275
 PPM Spectral Analysis 278

Chapter 7

Analog Communication Systems 287

- 7.1 Receivers for CW Modulation (2.6, 4.5, 5.3) 288
 Superheterodyne Receivers 288
 Direct Conversion Receivers 292
 Special-Purpose Receivers 293
 Receiver Specifications 294
 Scanning Spectrum Analyzers 295
- 7.2 Multiplexing Systems (4.5, 6.1) 297
 Frequency-Division Multiplexing 297
 Quadrature-Carrier Multiplexing 302
 Time-Division Multiplexing 303
 Crosstalk and Guard Times 307
 Comparison of TDM and FDM 309
- 7.3 Phase-Locked Loops (7.1) 311 PLL Operation and Lock-In 311 Synchronous Detection and Frequency Synthesizers 314 Linearized PLL Models and FM Detection 317
- 7.4 Television Systems (7.1) 319
 Video Signals, Resolution, and Bandwidth 319
 Monochrome Transmitters and Receivers 324
 Color Television 327
 HDTV 332

Chapter 8

Probability and Random Variables 345

- 8.1 Probability and Sample Space 346
 Probabilities and Events 346
 Sample Space and Probability Theory 347
 Conditional Probability and Statistical Independence 351
- 8.2 Random Variables and Probability Functions (8.1) 354
 Discrete Random Variables and CDFs 355
 Continuous Random Variables and PDFs 358
 Transformations of Random Variables 361
 Joint and Conditional PDFs 363
- 8.3 Statistical Averages (2.3, 8.2) 365 Means, Moments, and Expectation 365 Standard Deviation and Chebyshev's Inequality 366 Multivariate Expectations 368 Characteristic Functions 370
- 8.4 Probability Models (8.3) 371
 Binomial Distribution 371
 Poisson Distribution 373
 Gaussian PDF 374
 Rayleigh PDF 376
 Bivariate Gaussian Distribution 378
 Central Limit Theorem 379

Chapter 9

Random Signals and Noise 391

- 9.1 Random Processes (3.6, 8.4) 392 Ensemble Averages and Correlation Functions 393 Ergodic and Stationary Processes 397 Gaussian Processes 402
- 9.2 Random Signals (9.1) 403
 Power Spectrum 403
 Superposition and Modulation 408
 Filtered Random Signals 409
- 9.3 Noise (9.2) 412
 Thermal Noise and Available Power 413
 White Noise and Filtered Noise 416
 Noise Equivalent Bandwidth 419
 System Measurements Using White Noise 421
- 9.4 Baseband Signal Transmission With Noise (9.3) 422
 Additive Noise and Signal-to-Noise Ratios 422
 Analog Signal Transmission 424

9.5 Baseband Pulse Transmission With Noise (9.4) 427
Pulse Measurements in Noise 427
Pulse Detection and Matched Filters 429

Chapter 10

- Noise in Analog Modulation Systems 439
- 10.1 Bandpass Noise (4.4, 9.2) 440
 System Models 441
 Quadrature Components 443
 Envelope and Phase 445
 Correlation Functions 446
- 10.2 Linear CW Modulation With Noise (10.2) 448
 Synchronous Detection 449
 Envelope Detection and Threshold Effect 451
- 10.3 Angle CW Modulation With Noise (5.3, 10.2) 454
 Postdetection Noise 454
 Destination S/N 458
 FM Threshold Effect 460
 Threshold Extension by FM Feedback 463
- 10.4 Comparison of CW Modulation Systems (9.4, 10.3) 464
- 10.5 Phase-Locked Loop Noise Performance (7.3, 10.1) 467
- 10.6 Analog Pulse Modulation With Noise (6.3, 9.5) 468Signal-to-Noise Ratios 468False-Pulse Threshold Effect 471

Chapter 11

Baseband Digital Transmission 479

- 11.1 Digital Signals and Systems (9.1) 481 Digital PAM Signals 481 Transmission Limitations 484 Power Spectra of Digital PAM 487 Spectral Shaping by Precoding 490
- 11.2 Noise and Errors (9.4, 11.1) 491
 Binary Error Probabilities 492
 Regenerative Repeaters 496
 Matched Filtering 498
 Correlation Detector 501 *M*-ary Error Probabilities 502

Contents

- 11.3 Bandlimited Digital PAM Systems (11.2) 506 Nyquist Pulse Shaping 506 Optimum Terminal Filters 509 Equalization 513 Correlative Coding 517
- 11.4 Synchronization Techniques (11.2) 523
 Bit Synchronization 524
 Scramblers and PN Sequence Generators 526
 Frame Synchronization 531

Chapter 12

- Digitization Techniques for Analog Messages and Computer Networks 543
- 12.1 Pulse-Code Modulation (6.2, 11.1) 544
 PCM Generation and Reconstruction 545
 Quantization Noise 548
 Nonuniform Quantizing and Companding 550
- 12.2 PCM With Noise (11.2, 12.1) 554 Decoding Noise 555 Error Threshold 557 PCM Versus Analog Modulation 557
- 12.3 Delta Modulation and Predictive Coding (12.2) 559
 Delta Modulation 560
 Delta-Sigma Modulation 565
 Adaptive Delta Modulation 566
 Differential PCM 567
 LPC Speech Synthesis 569
- 12.4 Digital Audio Recording (12.3) 571 CD Recording 571 CD Playback 574
- 12.5 Digital Multiplexing (12.1, 9.2) 575 Multiplexers and Hierarchies 575 Digital Subscriber Lines 579 Synchronous Optical Network 580 Data Multiplexers 582

Chapter 13

Channel Coding 591

13.1 Error Detection and Correction (11.2) 592 Repetition and Parity-Check Codes 593 Interleaving 595 Code Vectors and Hamming Distance 595 Forward Error-Correction (FEC) Systems 597 ARQ Systems 600

- 13.2 Linear Block Codes (13.1) 604
 Matrix Representation of Block Codes 604
 Syndrome Decoding 608
 Cyclic Codes 611 *M*-ary Codes 616
- 13.3 Convolutional Codes (13.2) 617 Convolutional Encoding 617 Free Distance and Coding Gain 623 Decoding Methods 629 Turbo Codes 635

Chapter 14

Bandpass Digital Transmission 647 14.1 Digital CW Modulation (4.5, 5.1, 11.1) 648 Spectral Analysis of Bandpass Digital Signals 649 Amplitude Modulation Methods 650 Phase Modulation Methods 653 Frequency Modulation Methods 655 Minimum-Shift Keying (MSK) and Gaussian-Filtered MSK 658 14.2 Coherent Binary Systems (11.2, 14.1) 663 Optimum Binary Detection 663 Coherent OOK, BPSK, and FSK 668 Timing and Synchronization 670 Interference 671 14.3 Noncoherent Binary Systems (14.2) 673 Envelope of a Sinusoid Plus Bandpass Noise 673 Noncoherent OOK 674 Noncoherent FSK 677 Differentially Coherent PSK 679 14.4 Quadrature-Carrier and *M*-ary Systems (14.2) 682 Quadrature-Carrier Systems 682 M-ary PSK Systems 685 M-ary QAM Systems 689 M-ary FSK Systems 690 Comparison of Digital Modulation Systems 692 14.5 Orthogonal Frequency Division Multiplexing (OFDM) (14.4, 7.2, 2.6) 696 Generating OFDM Using the Inverse Discrete Fourier Transform 697 Channel Response and Cyclic Extensions 700

```
Contents
```

14.6 Trellis-Coded Modulation (13.3, 14.4) 703 TCM Basics 704 Hard Versus Soft Decisions 712 Modems 712

Chapter 15

Spread-Spectrum Systems 721 15.1 Direct-Sequence Spread-Spectrum (14.2) 723 DSSS Signals 723 DSSS Performance in the Presence of Interference 726 Multiple Access 728 Multipath and the Rake Receiver 729 15.2 Frequency Hopping Spread-Spectrum (15.1) 733 FHSS Signals 733 FHSS Performance in the Presence of Interference 735 Other SS Systems 737 15.3 Coding (15.1, 11.4) 738 15.4 Synchronization (7.3) 743 Acquisition 743 Tracking 745

- 15.5 Wireless Systems (15.2, 3.3, 14.5) 746
 Telephone Systems 746
 Wireless Networks 751
- 15.6 Ultra-Wideband Systems (6.3, 15.1) 754
 UWB Signals 754
 Coding Techniques 756
 Transmit Reference System 758
 Multiple Access 759
 Comparison With Direct-Sequence Spread-Spectrum 760

Chapter 16

Information and Detection

Theory 767 16.1 Information Measure and Source Coding (12.1) 769 Information Measure 769 Entropy and Information Rate 771 Coding for a Discrete Memoryless Channel 774 Predictive Coding for Sources With Memory 778 16.2 Information Transmission on Discrete Channels (16.1) 782 Mutual Information 782 Discrete Channel Capacity 786 Coding for the Binary Symmetric Channel 788 16.3 Continuous Channels and System Comparisons (16.2) 791 Continuous Information 791 Continuous Channel Capacity 794 Ideal Communication Systems 796 System Comparisons 799 16.4 Signal Space 803 Signals as Vectors 803 The Gram-Schmidt Procedure 806 16.5 Optimum Digital Detection (16.3, 16.4) 808 Optimum Detection and MAP Receivers 809 Error Probabilities 815 Signal Selection and Orthogonal Signaling 818

Appendix: Circuit and System Noise (9.4) 827 Circuit and Device Noise 828 Amplifier Noise 835 System Noise Calculations 840 Cable Repeater Systems 844

Tables 847

- T.1 Fourier Transforms 847
- T.2 Fourier Series 849
- T.3 Mathematical Relations 851
- T.4 The Sinc Function 854
- T.5 Probability Functions 855
- T.6 Gaussian Probabilities 857
- T.7 Glossary of Notation 859

Solutions to Exercises 861 Answers to Selected Problems 904 Index 000

viii