Contents

Preface *page* xvii
List of Abbreviations xxii
List of Notation xxvii

1 Overview of Wireless Communications 1

1.1 History of Wireless Communications 1
1.2 Wireless Vision 4
1.3 Technical Issues 6
1.4 Current Wireless Systems 8
1.4.1 Cellular Telephone Systems 8
1.4.2 Cordless Phones 13
1.4.3 Wireless Local Area Networks 15
1.4.4 Wide Area Wireless Data Services 16
1.4.5 Broadband Wireless Access 17
1.4.6 Paging Systems 17
1.4.7 Satellite Networks 18
1.4.8 Low-Cost, Low-Power Radios: Bluetooth and ZigBee 19
1.4.9 Ultrawideband Radios 20
1.5 The Wireless Spectrum 21
1.5.1 Methods for Spectrum Allocation 21
1.5.2 Spectrum Allocations for Existing Systems 22
1.6 Standards 23
Problems 24
References 26

2 Path Loss and Shadowing 27

2.1 Radio Wave Propagation 28
2.2 Transmit and Receive Signal Models 29
2.3 Free-Space Path Loss 31
2.4 Ray Tracing 33
2.4.1 Two-Ray Model 34
2.4.2 Ten-Ray Model (Dielectric Canyon) 37
2.4.3 General Ray Tracing 38
2.4.4 Local Mean Received Power 41

2.5 Empirical Path-Loss Models 42
2.5.1 Okumura Model 42
2.5.2 Hata Model 43
2.5.3 COST 231 Extension to Hata Model 44
2.5.4 Piecewise Linear (Multislope) Model 44
2.5.5 Indoor Attenuation Factors 45
2.6 Simplified Path-Loss Model 46
2.7 Shadow Fading 48
2.8 Combined Path Loss and Shadowing 51
2.9 Outage Probability under Path Loss and Shadowing 52
2.10 Cell Coverage Area 53
Problems 56
References 60

3 Statistical Multipath Channel Models 64

3.1 Time-Varying Channel Impulse Response 65
3.2 Narrowband Fading Models 70
3.2.1 Autocorrelation, Cross-Correlation, and Power Spectral Density 71
3.2.2 Envelope and Power Distributions 78
3.2.3 Level Crossing Rate and Average Fade Duration 79
3.2.4 Finite-State Markov Channels 82
3.3 Wideband Fading Models 82
3.3.1 Power Delay Profile 86
3.3.2 Coherence Bandwidth 88
3.3.3 Doppler Power Spectrum and Channel Coherence Time 90
3.3.4 Transforms for Autocorrelation and Scattering Functions 91
3.4 Discrete-Time Model 92
3.5 Space-Time Channel Models 93
Problems 94
References 97

4 Capacity of Wireless Channels 99

4.1 Capacity in AWGN 100
4.2 Capacity of Flat Fading Channels 102
4.2.1 Channel and System Model 102
4.2.2 Channel Distribution Information Known 102
4.2.3 Channel Side Information at Receiver 103
4.2.4 Channel Side Information at Transmitter and Receiver 107
4.2.5 Capacity with Receiver Diversity 113
4.2.6 Capacity Comparisons 114
4.3 Capacity of Frequency-Selective Fading Channels 116
4.3.1 Time-Invariant Channels 116
4.3.2 Time-Varying Channels 119
Problems 121
References 124

5 Digital Modulation and Detection 126

5.1 Signal Space Analysis 127
5.1.1 Signal and System Model 128
5.1.2 Geometric Representation of Signals 129

5.1.3 Receiver Structure and Sufficient Statistics 132
5.1.4 Decision Regions and the Maximum Likelihood Decision Criterion 134
5.1.5 Error Probability and the Union Bound 137
5.2 Passband Modulation Principles 142
5.3 Amplitude and Phase Modulation 142
5.3.1 Pulse Amplitude Modulation (MPAM) 144
5.3.2 Phase-Shift Keying (MPSK) 146
5.3.3 Quadrature Amplitude Modulation (MQAM) 148
5.3.4 Differential Modulation 149
5.3.5 Constellation Shaping 152
5.3.6 Quadrature Offset 152
5.4 Frequency Modulation 153
5.4.1 Frequency-Shift Keying (FSK) and Minimum-Shift Keying (MSK) 155
5.4.2 Continuous-Phase FSK (CPFSK) 156
5.4.3 Noncoherent Detection of FSK 156
5.5 Pulse Shaping 157
5.6 Symbol Synchronization and Carrier Phase Recovery 160
5.6.1 Receiver Structure with Phase and Timing Recovery 161
5.6.2 Maximum Likelihood Phase Estimation 163
5.6.3 Maximum Likelihood Timing Estimation 165
Problems 167
References 170

6 Performance of Digital Modulation over Wireless Channels 172

6.1 AWGN Channels 172
6.1.1 Signal-to-Noise Power Ratio and Bit/Symbol Energy 172
6.1.2 Error Probability for BPSK and QPSK 173
6.1.3 Error Probability for MPSK 175
6.1.4 Error Probability for MPAM and MQAM 176
6.1.5 Error Probability for FSK and CPFSK 179
6.1.6 Error Probability Approximation for Coherent Modulations 180
6.1.7 Error Probability for Differential Modulation 180
6.2 Alternate Q-Function Representation 182
6.3 Fading 182
6.3.1 Outage Probability 183
6.3.2 Average Probability of Error 184
6.3.3 Moment Generating Function Approach to Average Error Probability 187
6.3.4 Combined Outage and Average Error Probability 191
6.4 Doppler Spread 192
6.5 Intersymbol Interference 195
Problems 197
References 202

7 Diversity 204

7.1 Realization of Independent Fading Paths 204
7.2 Receiver Diversity 206
7.2.1 System Model 206

7.2.2 Selection Combining 208
7.2.3 Threshold Combining 211
7.2.4 Maximal-Ratio Combining 214
7.2.5 Equal-Gain Combining 216
7.3 Transmitter Diversity 217
7.3.1 Channel Known at Transmitter 217
7.3.2 Channel Unknown at Transmitter – The Alamouti Scheme 219
7.4 Moment Generating Functions in Diversity Analysis 220
7.4.1 Diversity Analysis for MRC 221
7.4.2 Diversity Analysis for EGC and SC 224
7.4.3 Diversity Analysis for Noncoherent and Differentially Coherent Modulation 224
Problems 225
References 227

8 Coding for Wireless Channels 228

8.1 Overview of Code Design 229
8.2 Linear Block Codes 230
8.2.1 Binary Linear Block Codes 231
8.2.2 Generator Matrix 232
8.2.3 Parity-Check Matrix and Syndrome Testing 234
8.2.4 Cyclic Codes 236
8.2.5 Hard Decision Decoding (HDD) 238
8.2.6 Probability of Error for HDD in AWGN 240
8.2.7 Probability of Error for SDD in AWGN 242
8.2.8 Common Linear Block Codes 244
8.2.9 Nonbinary Block Codes: The Reed Solomon Code 245
8.3 Convolutional Codes 246
8.3.1 Code Characterization: Trellis Diagrams 246
8.3.2 Maximum Likelihood Decoding 249
8.3.3 The Viterbi Algorithm 252
8.3.4 Distance Properties 253
8.3.5 State Diagrams and Transfer Functions 254
8.3.6 Error Probability for Convolutional Codes 257
8.4 Concatenated Codes 258
8.5 Turbo Codes 259
8.6 Low-Density Parity-Check Codes 262
8.7 Coded Modulation 263
8.8 Coding with Interleaving for Fading Channels 267
8.8.1 Block Coding with Interleaving 267
8.8.2 Convolutional Coding with Interleaving 270
8.8.3 Coded Modulation with Symbol/Bit Interleaving 271
8.9 Unequal Error Protection Codes 271
8.10 Joint Source and Channel Coding 274
Problems 275
References 279

9 Adaptive Modulation and Coding 283

9.1 Adaptive Transmission System 284
9.2 Adaptive Techniques 285
9.2.1 Variable-Rate Techniques 285

9.2.2 Variable-Power Techniques 286
9.2.3 Variable Error Probability 287
9.2.4 Variable-Coding Techniques 288
9.2.5 Hybrid Techniques 288
9.3 Variable-Rate Variable-Power MQAM 288
9.3.1 Error Probability Bounds 289
9.3.2 Adaptive Rate and Power Schemes 290
9.3.3 Channel Inversion with Fixed Rate 292
9.3.4 Discrete-Rate Adaptation 293
9.3.5 Average Fade Region Duration 298
9.3.6 Exact versus Approximate Bit Error Probability 300
9.3.7 Channel Estimation Error and Delay 300
9.3.8 Adaptive Coded Modulation 303
9.4 General *M*-ary Modulations 305
9.4.1 Continuous-Rate Adaptation 305
9.4.2 Discrete-Rate Adaptation 309
9.4.3 Average BER Target 310
9.5 Adaptive Techniques in Combined Fast and Slow Fading 314
Problems 315
References 319

10 Multiple Antennas and Space-Time Communications 321

10.1 Narrowband MIMO Model 321
10.2 Parallel Decomposition of the MIMO Channel 323
10.3 MIMO Channel Capacity 325
10.3.1 Static Channels 325
10.3.2 Fading Channels 329
10.4 MIMO Diversity Gain: Beamforming 334
10.5 Diversity–Multiplexing Trade-offs 335
10.6 Space-Time Modulation and Coding 337
10.6.1 ML Detection and Pairwise Error Probability 337
10.6.2 Rank and Determinant Criteria 339
10.6.3 Space-Time Trellis and Block Codes 339
10.6.4 Spatial Multiplexing and BLAST Architectures 340
10.7 Frequency-Selective MIMO Channels 342
10.8 Smart Antennas 343
Problems 344
References 347

11 Equalization 351

11.1 Equalizer Noise Enhancement 352
11.2 Equalizer Types 353
11.3 Folded Spectrum and ISI-Free Transmission 354
11.4 Linear Equalizers 357
11.4.1 Zero-Forcing (ZF) Equalizers 358
11.4.2 Minimum Mean-Square Error (MMSE) Equalizers 359
11.5 Maximum Likelihood Sequence Estimation 362
11.6 Decision-Feedback Equalization 364
11.7 Other Equalization Methods 365
11.8 Adaptive Equalizers: Training and Tracking 366

Problems 368
References 372

12 Multicarrier Modulation 374

12.1 Data Transmission Using Multiple Carriers 375
12.2 Multicarrier Modulation with Overlapping Subchannels 378
12.3 Mitigation of Subcarrier Fading 380
12.3.1 Coding with Interleaving over Time and Frequency 381
12.3.2 Frequency Equalization 381
12.3.3 Precoding 381
12.3.4 Adaptive Loading 382
12.4 Discrete Implementation of Multicarrier Modulation 383
12.4.1 The DFT and Its Properties 383
12.4.2 The Cyclic Prefix 384
12.4.3 Orthogonal Frequency-Division Multiplexing (OFDM) 386
12.4.4 Matrix Representation of OFDM 388
12.4.5 Vector Coding 390
12.5 Challenges in Multicarrier Systems 393
12.5.1 Peak-to-Average Power Ratio 393
12.5.2 Frequency and Timing Offset 395
12.6 Case Study: The IEEE 802.11a Wireless LAN Standard 396
Problems 398
References 401

13 Spread Spectrum 403

13.1 Spread-Spectrum Principles 403
13.2 Direct-Sequence Spread Spectrum (DSSS) 409
13.2.1 DSSS System Model 409
13.2.2 Spreading Codes for ISI Rejection: Random, Pseudorandom, and m-Sequences 413
13.2.3 Synchronization 417
13.2.4 RAKE Receivers 419
13.3 Frequency-Hopping Spread Spectrum (FHSS) 421
13.4 Multiuser DSSS Systems 424
13.4.1 Spreading Codes for Multiuser DSSS 425
13.4.2 Downlink Channels 428
13.4.3 Uplink Channels 433
13.4.4 Multiuser Detection 438
13.4.5 Multicarrier CDMA 441
13.5 Multiuser FHSS Systems 443
Problems 443
References 449

14 Multiuser Systems 452

14.1 Multiuser Channels: The Uplink and Downlink 452
14.2 Multiple Access 454
14.2.1 Frequency-Division Multiple Access (FDMA) 455
14.2.2 Time-Division Multiple Access (TDMA) 456
14.2.3 Code-Division Multiple Access (CDMA) 458

14.2.4 Space-Division Multiple Access (SDMA) 459
14.2.5 Hybrid Techniques 460
14.3 Random Access 461
14.3.1 Pure ALOHA 462
14.3.2 Slotted ALOHA 463
14.3.3 Carrier-Sense Multiple Access (CSMA) 464
14.3.4 Scheduling 466
14.4 Power Control 466
14.5 Downlink (Broadcast) Channel Capacity 469
14.5.1 Channel Model 470
14.5.2 Capacity in AWGN 470
14.5.3 Common Data 476
14.5.4 Capacity in Fading 477
14.5.5 Capacity with Multiple Antennas 483
14.6 Uplink (Multiple Access) Channel Capacity 484
14.6.1 Capacity in AWGN 484
14.6.2 Capacity in Fading 488
14.6.3 Capacity with Multiple Antennas 490
14.7 Uplink–Downlink Duality 490
14.8 Multiuser Diversity 494
14.9 MIMO Multiuser Systems 496
Problems 497
References 500

15 Cellular Systems and Infrastructure-Based Wireless Networks 505

15.1 Cellular System Fundamentals 505
15.2 Channel Reuse 508
15.3 SIR and User Capacity 514
15.3.1 Orthogonal Systems (TDMA/FDMA) 514
15.3.2 Nonorthogonal Systems (CDMA) 516
15.4 Interference Reduction Techniques 518
15.5 Dynamic Resource Allocation 520
15.5.1 Scheduling 520
15.5.2 Dynamic Channel Assignment 521
15.5.3 Power Control 522
15.6 Fundamental Rate Limits 524
15.6.1 Shannon Capacity of Cellular Systems 524
15.6.2 Area Spectral Efficiency 525
Problems 528
References 531

16 Ad Hoc Wireless Networks 535

16.1 Applications 535
16.1.1 Data Networks 537
16.1.2 Home Networks 537
16.1.3 Device Networks 538
16.1.4 Sensor Networks 538
16.1.5 Distributed Control Systems 539
16.2 Design Principles and Challenges 540

16.3 Protocol Layers 542
16.3.1 Physical Layer Design 543
16.3.2 Access Layer Design 544
16.3.3 Network Layer Design 547
16.3.4 Transport Layer Design 552
16.3.5 Application Layer Design 553
16.4 Cross-Layer Design 554
16.5 Network Capacity Limits 556
16.6 Energy-Constrained Networks 558
16.6.1 Modulation and Coding 559
16.6.2 MIMO and Cooperative MIMO 560
16.6.3 Access, Routing, and Sleeping 561
16.6.4 Cross-Layer Design under Energy Constraints 562
16.6.5 Capacity per Unit Energy 562
Problems 564
References 566

Appendix A
Representation of Bandpass Signals and Channels 573

Appendix B
Probability Theory, Random Variables, and Random Processes 577
B.1 Probability Theory 577
B.2 Random Variables 578
B.3 Random Processes 583
B.4 Gaussian Processes 586

Appendix C
Matrix Definitions, Operations, and Properties 588
C.1 Matrices and Vectors 588
C.2 Matrix and Vector Operations 589
C.3 Matrix Decompositions 592

Appendix D
Summary of Wireless Standards 595
D.1 Cellular Phone Standards 595
D.1.1 First-Generation Analog Systems 595
D.1.2 Second-Generation Digital Systems 596
D.1.3 Evolution of Second-Generation Systems 598
D.1.4 Third-Generation Systems 599
D.2 Wireless Local Area Networks 600
D.3 Wireless Short-Distance Networking Standards 601

Bibliography 605
Index 633