

Contents

1	Overview of Wireless Communications	1
1.1	History of Wireless Communications	1
1.2	Wireless Vision	4
1.3	Technical Issues	5
1.4	Current Wireless Systems	7
1.4.1	Cellular Telephone Systems	7
1.4.2	Cordless Phones	11
1.4.3	Wireless LANs	12
1.4.4	Wide Area Wireless Data Services	13
1.4.5	Broadband Wireless Access	14
1.4.6	Paging Systems	14
1.4.7	Satellite Networks	15
1.4.8	Low-Cost Low-Power Radios: Bluetooth and Zigbee	15
1.4.9	Ultrawideband Radios	16
1.5	The Wireless Spectrum	17
1.5.1	Methods for Spectrum Allocation	17
1.5.2	Spectrum Allocations for Existing Systems	18
1.6	Standards	19
2	Path Loss and Shadowing	24
2.1	Radio Wave Propagation	25
2.2	Transmit and Receive Signal Models	26
2.3	Free-Space Path Loss	28
2.4	Ray Tracing	29
2.4.1	Two-Ray Model	30
2.4.2	Ten-Ray Model (Dielectric Canyon)	33
2.4.3	General Ray Tracing	34
2.4.4	Local Mean Received Power	36
2.5	Empirical Path Loss Models	36
2.5.1	The Okumura Model	37
2.5.2	Hata Model	37
2.5.3	COST 231 Extension to Hata Model	38
2.5.4	Piecewise Linear (Multi-Slope) Model	38
2.5.5	Indoor Attenuation Factors	39
2.6	Simplified Path Loss Model	40
2.7	Shadow Fading	42

2.8	Combined Path Loss and Shadowing	45
2.9	Outage Probability under Path Loss and Shadowing	45
2.10	Cell Coverage Area	46
3	Statistical Multipath Channel Models	58
3.1	Time-Varying Channel Impulse Response	58
3.2	Narrowband Fading Models	63
3.2.1	Autocorrelation, Cross Correlation, and Power Spectral Density	64
3.2.2	Envelope and Power Distributions	69
3.2.3	Level Crossing Rate and Average Fade Duration	72
3.2.4	Finite State Markov Channels	74
3.3	Wideband Fading Models	75
3.3.1	Power Delay Profile	77
3.3.2	Coherence Bandwidth	79
3.3.3	Doppler Power Spectrum and Channel Coherence Time	81
3.3.4	Transforms for Autocorrelation and Scattering Functions	82
3.4	Discrete-Time Model	83
3.5	Space-Time Channel Models	84
4	Capacity of Wireless Channels	91
4.1	Capacity in AWGN	92
4.2	Capacity of Flat-Fading Channels	93
4.2.1	Channel and System Model	93
4.2.2	Channel Distribution Information (CDI) Known	94
4.2.3	Channel Side Information at Receiver	95
4.2.4	Channel Side Information at Transmitter and Receiver	98
4.2.5	Capacity with Receiver Diversity	103
4.2.6	Capacity Comparisons	104
4.3	Capacity of Frequency-Selective Fading Channels	106
4.3.1	Time-Invariant Channels	106
4.3.2	Time-Varying Channels	108
5	Digital Modulation and Detection	116
5.1	Signal Space Analysis	117
5.1.1	Signal and System Model	117
5.1.2	Geometric Representation of Signals	118
5.1.3	Receiver Structure and Sufficient Statistics	121
5.1.4	Decision Regions and the Maximum Likelihood Decision Criterion	124
5.1.5	Error Probability and the Union Bound	127
5.2	Passband Modulation Principles	131
5.3	Amplitude and Phase Modulation	131
5.3.1	Pulse Amplitude Modulation (MPAM)	132
5.3.2	Phase Shift Keying (MPSK)	135
5.3.3	Quadrature Amplitude Modulation (MQAM)	136
5.3.4	Differential Modulation	138
5.3.5	Constellation Shaping	140
5.3.6	Quadrature Offset	141

5.4	Frequency Modulation	141
5.4.1	Frequency Shift Keying (FSK) and Minimum Shift Keying (MSK)	142
5.4.2	Continuous-Phase FSK (CPFSK)	143
5.4.3	Noncoherent Detection of FSK	144
5.5	Pulse Shaping	145
5.6	Symbol Synchronization and Carrier Phase Recovery	148
5.6.1	Receiver Structure with Phase and Timing Recovery	148
5.6.2	Maximum Likelihood Phase Estimation	150
5.6.3	Maximum Likelihood Timing Estimation	152
6	Performance of Digital Modulation over Wireless Channels	159
6.1	AWGN Channels	159
6.1.1	Signal-to-Noise Power Ratio and Bit/Symbol Energy	159
6.1.2	Error Probability for BPSK and QPSK	160
6.1.3	Error Probability for MPSK	162
6.1.4	Error Probability for MPAM and MQAM	163
6.1.5	Error Probability for FSK and CPFSK	165
6.1.6	Error Probability Approximation for Coherent Modulations	166
6.1.7	Error Probability for Differential Modulation	166
6.2	Alternate Q Function Representation	168
6.3	Fading	168
6.3.1	Outage Probability	169
6.3.2	Average Probability of Error	170
6.3.3	Moment Generating Function Approach to Average Error Probability	171
6.3.4	Combined Outage and Average Error Probability	176
6.4	Doppler Spread	177
6.5	Intersymbol Interference	179
7	Diversity	190
7.1	Realization of Independent Fading Paths	190
7.2	Receiver Diversity	191
7.2.1	System Model	191
7.2.2	Selection Combining	193
7.2.3	Threshold Combining	196
7.2.4	Maximal Ratio Combining	199
7.2.5	Equal-Gain Combining	200
7.3	Transmitter Diversity	202
7.3.1	Channel Known at Transmitter	202
7.3.2	Channel Unknown at Transmitter - The Alamouti Scheme	203
7.4	Moment Generating Functions in Diversity Analysis	205
7.4.1	Diversity Analysis for MRC	205
7.4.2	Diversity Analysis for EGC and SC	208
7.4.3	Diversity Analysis for Noncoherent and Differentially Coherent Modulation	209

8	Coding for Wireless Channels	213
8.1	Overview of Code Design	214
8.2	Linear Block Codes	214
8.2.1	Binary Linear Block Codes	215
8.2.2	Generator Matrix	217
8.2.3	Parity Check Matrix and Syndrome Testing	219
8.2.4	Cyclic Codes	220
8.2.5	Hard Decision Decoding (HDD)	222
8.2.6	Probability of Error for HDD in AWGN	224
8.2.7	Probability of Error for SDD in AWGN	226
8.2.8	Common Linear Block Codes	227
8.2.9	Nonbinary Block Codes: the Reed Solomon Code	228
8.3	Convolutional Codes	229
8.3.1	Code Characterization: Trellis Diagrams	229
8.3.2	Maximum Likelihood Decoding	232
8.3.3	The Viterbi Algorithm	234
8.3.4	Distance Properties	235
8.3.5	State Diagrams and Transfer Functions	236
8.3.6	Error Probability for Convolutional Codes	238
8.4	Concatenated Codes	240
8.5	Turbo Codes	240
8.6	Low Density Parity Check Codes	243
8.7	Coded Modulation	244
8.8	Coding and Interleaving for Fading Channels	247
8.8.1	Block Coding with Interleaving	248
8.8.2	Convolutional Coding with Interleaving	250
8.8.3	Coded Modulation with Symbol/Bit Interleaving	251
8.9	Unequal Error Protection Codes	251
8.10	Joint Source and Channel Coding	253
9	Adaptive Modulation and Coding	263
9.1	Adaptive Transmission System	264
9.2	Adaptive Techniques	265
9.2.1	Variable-Rate Techniques	265
9.2.2	Variable-Power Techniques	266
9.2.3	Variable Error Probability	267
9.2.4	Variable-Coding Techniques	267
9.2.5	Hybrid Techniques	268
9.3	Variable-Rate Variable-Power MQAM	268
9.3.1	Error Probability Bounds	268
9.3.2	Adaptive Rate and Power Schemes	269
9.3.3	Channel Inversion with Fixed Rate	270
9.3.4	Discrete Rate Adaptation	271
9.3.5	Average Fade Region Duration	276
9.3.6	Exact versus Approximate P_b	277
9.3.7	Channel Estimation Error and Delay	279
9.3.8	Adaptive Coded Modulation	280

9.4	General M -ary Modulations	282
9.4.1	Continuous Rate Adaptation	282
9.4.2	Discrete Rate Adaptation	285
9.4.3	Average BER Target	286
9.5	Adaptive Techniques in Combined Fast and Slow Fading	289
10	Multiple Antennas and Space-Time Communications	299
10.1	Narrowband MIMO Model	299
10.2	Parallel Decomposition of the MIMO Channel	301
10.3	MIMO Channel Capacity	303
10.3.1	Static Channels	303
10.3.2	Fading Channels	306
10.4	MIMO Diversity Gain: Beamforming	309
10.5	Diversity/Multiplexing Tradeoffs	311
10.6	Space-Time Modulation and Coding	312
10.6.1	ML Detection and Pairwise Error Probability	313
10.6.2	Rank and Determinant Criterion	314
10.6.3	Space-Time Trellis and Block Codes	314
10.6.4	Spatial Multiplexing and BLAST Architectures	315
10.7	Frequency-Selective MIMO Channels	317
10.8	Smart Antennas	317
11	Equalization	327
11.1	Equalizer Noise Enhancement	328
11.2	Equalizer Types	329
11.3	Folded Spectrum and ISI-Free Transmission	329
11.4	Linear Equalizers	333
11.4.1	Zero Forcing (ZF) Equalizers	333
11.4.2	Minimum Mean Square Error (MMSE) Equalizer	334
11.5	Maximum Likelihood Sequence Estimation	337
11.6	Decision-Feedback Equalization	338
11.7	Other Equalization Methods	340
11.8	Adaptive Equalizers: Training and Tracking	340
12	Multicarrier Modulation	350
12.1	Data Transmission using Multiple Carriers	351
12.2	Multicarrier Modulation with Overlapping Subchannels	353
12.3	Mitigation of Subcarrier Fading	355
12.3.1	Coding with Interleaving over Time and Frequency	356
12.3.2	Frequency Equalization	356
12.3.3	Precoding	356
12.3.4	Adaptive Loading	357
12.4	Discrete Implementation of Multicarrier	358
12.4.1	The DFT and its Properties	358
12.4.2	The Cyclic Prefix	359
12.4.3	Orthogonal Frequency Division Multiplexing (OFDM)	360
12.4.4	Matrix Representation of OFDM	362

12.4.5	Vector Coding	364
12.5	Challenges in Multicarrier Systems	367
12.5.1	Peak to Average Power Ratio	367
12.5.2	Frequency and Timing Offset	369
12.6	Case Study: The IEEE 802.11a Wireless LAN Standard	370
13	Spread Spectrum	378
13.1	Spread Spectrum Principles	378
13.2	Direct Sequence Spread Spectrum (DSSS)	383
13.2.1	DSSS System Model	383
13.2.2	Spreading Codes for ISI Rejection: Random, Pseudorandom, and m -Sequences	387
13.2.3	Synchronization	390
13.2.4	RAKE receivers	392
13.3	Frequency-Hopping Spread Spectrum (FHSS)	393
13.4	Multiuser DSSS Systems	395
13.4.1	Spreading Codes for Multiuser DSSS	396
13.4.2	Downlink Channels	399
13.4.3	Uplink Channels	404
13.4.4	Multiuser Detection	408
13.4.5	Multicarrier CDMA	410
13.5	Multiuser FHSS Systems	411
14	Multiuser Systems	422
14.1	Multiuser Channels: The Uplink and Downlink	422
14.2	Multiple Access	424
14.2.1	Frequency-Division Multiple Access (FDMA)	424
14.2.2	Time-Division Multiple Access (TDMA)	426
14.2.3	Code-Division Multiple Access (CDMA)	427
14.2.4	Space-Division	429
14.2.5	Hybrid Techniques	429
14.3	Random Access	430
14.3.1	Pure ALOHA	431
14.3.2	Slotted ALOHA	432
14.3.3	Carrier Sense Multiple Access	433
14.3.4	Scheduling	434
14.4	Power Control	435
14.5	Downlink (Broadcast) Channel Capacity	437
14.5.1	Channel Model	437
14.5.2	Capacity in AWGN	438
14.5.3	Common Data	444
14.5.4	Capacity in Fading	444
14.5.5	Capacity with Multiple Antennas	448
14.6	Uplink (Multiple Access) Channel Capacity	450
14.6.1	Capacity in AWGN	450
14.6.2	Capacity in Fading	453
14.6.3	Capacity with Multiple Antennas	455
14.7	Uplink/Downlink Duality	455

14.8	Multiuser Diversity	458
14.9	MIMO Multiuser Systems	460
15	Cellular Systems and Infrastructure-Based Wireless Networks	470
15.1	Cellular System Fundamentals	470
15.2	Channel Reuse	473
15.3	SIR and User Capacity	477
15.3.1	Orthogonal Systems (TDMA/FDMA)	478
15.3.2	Non-Orthogonal Systems (CDMA)	480
15.4	Interference Reduction Techniques	482
15.5	Dynamic Resource Allocation	484
15.5.1	Scheduling	484
15.5.2	Dynamic Channel Assignment	484
15.5.3	Power Control	485
15.6	Fundamental Rate Limits	487
15.6.1	Shannon Capacity of Cellular Systems	487
15.6.2	Area Spectral Efficiency	488
16	Ad Hoc Wireless Networks	499
16.1	Applications	499
16.1.1	Data Networks	500
16.1.2	Home Networks	501
16.1.3	Device Networks	501
16.1.4	Sensor Networks	502
16.1.5	Distributed Control Systems	502
16.2	Design Principles and Challenges	503
16.3	Protocol Layers	504
16.3.1	Physical Layer Design	505
16.3.2	Access Layer Design	507
16.3.3	Network Layer Design	508
16.3.4	Transport Layer Design	513
16.3.5	Application Layer Design	513
16.4	Cross-Layer Design	514
16.5	Network Capacity Limits	516
16.6	Energy-Constrained Networks	517
16.6.1	Modulation and Coding	518
16.6.2	MIMO and Cooperative MIMO	519
16.6.3	Access, Routing, and Sleeping	519
16.6.4	Cross-Layer Design under Energy Constraints	520
16.6.5	Capacity per Unit Energy	521
A	Representation of Bandpass Signals and Channels	534
B	Probability Theory, Random Variables, and Random Processes	538
B.1	Probability Theory	538
B.2	Random Variables	539
B.3	Random Processes	542

B.4	Gaussian Processes	545
C	Matrix Definitions, Operations, and Properties	547
C.1	Matrices and Vectors	547
C.2	Matrix and Vector Operations	548
C.3	Matrix Decompositions	550
D	Summary of Wireless Standards	554
D.1	Cellular Phone Standards	554
D.1.1	First Generation Analog Systems	554
D.1.2	Second Generation Digital Systems	554
D.1.3	Evolution of 2G Systems	556
D.1.4	Third Generation Systems	557
D.2	Wireless Local Area Networks	558
D.3	Wireless Short-Distance Networking Standards	559