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EXHIBIT A

Wireless Communications

Andrea Goldsmith

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Wireless technology is a truly revolutionary paradigm shift, enabling multimedia communications between people and devices from any location. It also underpins exciting applications such as sensor networks, smart homes, telemedicine, and automated highways. This book provides a comprehensive introduction to the underlying theory, design techniques, and analytical tools of wireless communications, focusing primarily on the core principles of wireless system design.

The book begins with an overview of wireless systems and standards. The characteristics of the wireless channel are then described, including their fundamental capacity limits. Various modulation, coding, and signal processing schemes are then discussed in detail, including state-of-the-art adaptive modulation, multicarrier, spread-spectrum, and multiple-antenna techniques. The concluding chapters deal with multiuser communications, cellular system design, and ad hoc wireless network design.

Design insights and trade-offs are emphasized throughout the book. It contains many worked examples, more than 200 figures, almost 300 homework exercises, and more than 700 references. *Wireless Communications* is an ideal textbook for students as well as a valuable reference for engineers in the wireless industry.

Andrea Goldsmith received her Ph.D. from the University of California, Berkeley, and is an Associate Professor of Electrical Engineering at Stanford University. Prior to this she was an Assistant Professor at the California Institute of Technology, and she has also held positions in industry at Maxim Technologies and AT&T Bell Laboratories. She is a Fellow of the IEEE, has received numerous other awards and honors, and is the author of more than 150 technical papers in the field of wireless communications.

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Wireless Communications

Andrea Goldsmith

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Wireless Communications

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To Arturo, Daniel, and Nicole

The possession of knowledge does not kill the sense of wonder and mystery.

—*Anaïs Nin*

Brief Table of Contents

Preface		*page* xvii
Abbreviations		xxii
Notation		xxvii
1	**Overview of Wireless Communications**	1
2	**Path Loss and Shadowing**	27
3	**Statistical Multipath Channel Models**	64
4	**Capacity of Wireless Channels**	99
5	**Digital Modulation and Detection**	126
6	**Performance of Digital Modulation over Wireless Channels**	172
7	**Diversity**	204
8	**Coding for Wireless Channels**	228
9	**Adaptive Modulation and Coding**	283
10	**Multiple Antennas and Space-Time Communications**	321
11	**Equalization**	351
12	**Multicarrier Modulation**	374
13	**Spread Spectrum**	403
14	**Multiuser Systems**	452
15	**Cellular Systems and Infrastructure-Based Wireless Networks**	505
16	**Ad Hoc Wireless Networks**	535
Appendices		573
Bibliography		605
Index		633

Amazon
EX1035 Page 13

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

Amazon
EX1035 Page 14

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

Amazon
EX1035 Page 19

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

Amazon
EX1035 Page 21

Preface

Wireless communications is a broad and dynamic field that has spurred tremendous excitement and technological advances over the last few decades. The goal of this book is to provide readers with a comprehensive understanding of the fundamental principles underlying wireless communications. These principles include the characteristics and performance limits of wireless systems, the techniques and mathematical tools needed to analyze them, and the insights and trade-offs associated with their design. Current and envisioned wireless systems are used to motivate and exemplify these fundamental principles. The book can be used as a senior- or graduate-level textbook and as a reference for engineers, academic and industrial researchers, and students working in the wireless field.

ORGANIZATION OF THE BOOK

Chapter 1 begins with an overview of wireless communications, including its history, a vision for the future, and an overview of current systems and standards. Wireless channel characteristics, which drive many of the challenges in wireless system design, are described in Chapters 2 and 3. In particular, Chapter 2 covers path loss and shadowing in wireless channels, which vary over relatively large distances. Chapter 3 characterizes the flat and frequency-selective properties of multipath fading, which change over much smaller distances – on the order of the signal wavelength. Fundamental capacity limits of wireless channels along with the capacity-achieving transmission strategies are treated in Chapter 4. Although these techniques have unconstrained complexity and delay, they provide insight and motivation for many of the practical schemes discussed in later chapters. In Chapters 5 and 6 the focus shifts to digital modulation techniques and their performance in wireless channels. These chapters indicate that fading can significantly degrade performance. Thus, fading mitigation techniques are required for high-performance wireless systems.

The next several chapters cover the primary mitigation techniques for flat and frequency-selective fading. Specifically, Chapter 7 covers the underlying principles of diversity techniques, including a new mathematical tool that greatly simplifies performance analysis. These techniques can remove most of the detrimental effects of flat fading. Chapter 8 provides comprehensive coverage of coding techniques, including mature methods for block, convolutional, and trellis coding as well as recent developments in concatenated, turbo, and LDPC codes. This chapter illustrates that, though coding techniques for noisy channels have

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EX1035 Page 22

near-optimal performance, many open issues remain in the design and performance analysis of codes for wireless systems. Chapter 9 treats adaptive modulation in flat fading, which enables robust and spectrally efficient communication by leveraging the time-varying nature of the wireless channel. This chapter also ties the techniques and performance of adaptive modulation to the fundamental capacity limits of flat fading channels. Multiple-antenna techniques and space-time communication systems are covered in Chapter 10: the additional spatial dimension enables high data rates and robustness to fading. Equalization, which exploits signal processing in the receiver to compensate for frequency-selective fading, is covered in Chapter 11. Multicarrier modulation, described in Chapter 12, is simpler and more flexible than equalization for frequency-selective fading mitigation. Single-user and multiuser spread-spectrum techniques are described in Chapter 13. These techniques not only mitigate frequency-selective fading, they also allow multiple users to share the same wireless spectrum.

The last three chapters of the book focus on multiuser systems and networks. Chapter 14 treats multiple and random access techniques for sharing the wireless channel among many users with continuous or bursty data. Power control is also covered in this chapter as a mechanism to reduce interference between users while ensuring that all users meet their performance targets. The chapter closes by discussing the fundamental capacity limits of multiuser channels as well as the transmission and channel sharing techniques that achieve these limits. Chapter 15 covers the design, optimization, and performance analysis of cellular systems, along with advanced topics related to power control and fundamental limits in these systems. The last chapter, Chapter 16, discusses the fundamental principles and open research challenges associated with wireless ad hoc networks.

REQUIRED BACKGROUND

The only prerequisite knowledge for the book is a basic understanding of probability, random processes, and Fourier techniques for system and signal analysis. Background in digital communications is helpful but not required, as the underlying principles from this field are covered in the text. Three appendices summarize key background material used in different chapters of the text. Specifically, Appendix A discusses the equivalent lowpass representation of bandpass signals and systems, which simplifies bandpass system analysis. Appendix B provides a summary of the main concepts in probability and random processes that are used throughout the book. Appendix C provides definitions, results, and properties related to matrices, which are widely used in Chapters 10 and 12. The last appendix, Appendix D, summarizes the main characteristics of current wireless systems and standards.

BOOK FEATURES

The tremendous research activity in the wireless field – coupled with the complexity of wireless system design – make it impossible to provide comprehensive details on all topics discussed in the book. Thus, each chapter contains a broad list of references that build and expand on what is covered in the text. The book also contains nearly a hundred worked examples to illustrate and highlight key principles and trade-offs. In addition, the book includes about 300 homework exercises. These exercises, which fall into several broad categories, are designed to enhance and reinforce the material in the main text. Some exercises are targeted

Amazon
EX1035 Page 23

to exemplify or provide more depth to key concepts, as well as to derive or illustrate properties of wireless systems using these concepts. Exercises are also used to prove results stated but not derived in the text. Another category of exercises obtains numerical results that give insight into operating parameters and performance of wireless systems in typical environments. Exercises also introduce new concepts or system designs that are not discussed in the text. A solutions manual is available that covers all the exercises.

USING THIS BOOK IN COURSES

The book is designed to provide much flexibility as a textbook, depending on the desired length of the course, student background, and course focus. The core of the book is in Chapters 1 through 6. Thereafter, each chapter covers a different stand-alone topic that can be omitted or may be covered in other courses. Necessary prerequisites for a course using this text are an undergraduate course in signals and systems (both analog and digital) and one in probability theory and random processes. It is also helpful if students have a prerequisite or corequisite course in digital communications, in which case the material in Chapter 5 (along with overlapping material in other chapters) can be covered quickly as a review.

The book breaks down naturally into three segments: core material in Chapters 1–6, single-user wireless system design in Chapters 7–13, and multiuser wireless networks in Chapters 14–16. Most of the material in the book can be covered in two to three quarters or two semesters. A three-quarter sequence would follow the natural segmentation of the chapters, perhaps with an in-depth research project at the end. For a course sequence of two semesters or quarters, the first course could focus on Chapters 1–10 (single-user systems with flat fading) and the second course could focus on Chapters 11–16 (frequency-selective fading techniques, multiuser systems, and wireless networks). A one-quarter or semester course could focus on single-user wireless systems based on the core material in Chapters 1–6 and selected topics from Chapters 7–13. In this case a second optional quarter or semester could be offered covering multiuser systems and wireless networks (part of Chapter 13 and Chapters 14–16). I use this breakdown in a two-quarter sequence at Stanford, where the second quarter is offered every other year and includes additional reading material from the literature as well as an in-depth research project. Alternatively, a one-quarter or semester course could cover both single and multiuser systems based on Chapters 1–6 and Chapters 13–16, with some additional topics from Chapters 7–12 as time permits.

A companion Web site (http://www.cambridge.org/9780521837163) provides supplemental material for the book, including lecture slides, additional exercises, and errata.

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Amazon
EX1035 Page 25

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Abbreviations

3GPP	Third Generation Partnership Project
ACK	acknowledgment (packet)
ACL	Asynchronous Connection-Less
AFD	average fade duration
AFRD	average fade region duration
AGC	automatic gain control
AMPS	Advance Mobile Phone Service
AOA	angle of arrival
AODV	ad hoc on-demand distance vector
APP	a posteriori probability
ARQ	automatic repeat request (protocol)
ASE	area spectral efficiency
AWGN	additive white Gaussian noise
BC	broadcast channel
BCH	Bose–Chadhuri–Hocquenghem
BER	bit error rate
BICM	bit-interleaved coded modulation
BLAST	Bell Labs Layered Space Time
BPSK	binary phase-shift keying
BS	base station
CCK	complementary code keying
CD	code division
cdf	cumulative distribution function
CDI	channel distribution information
CDMA	code-division multiple access
CDPD	cellular digital packet data
CLT	central limit theorem
COVQ	channel-optimized vector quantizer
CPFSK	continuous-phase FSK
CSI	channel side information
CSIR	CSI at the receiver
CSIT	CSI at the transmitter

Amazon
EX1035 Page 27

CSMA	carrier-sense multiple access
CTS	clear to send (packet)
DARPA	Defense Advanced Research Projects Agency
D-BLAST	diagonal BLAST
DCA	dynamic channel assignment
DCS	Digital Cellular System
DECT	Digital Enhanced Cordless Telecommunications
DFE	decision-feedback equalization
DFT	discrete Fourier transform
D-MPSK	differential *M*-ary PSK
DPC	dirty paper coding
DPSK	differential binary PSK
D-QPSK	differential quadrature PSK
DS	direct sequence
DSDV	destination sequenced distance vector
DSL	digital subscriber line
DSR	dynamic source routing
DSSS	direct-sequence spread spectrum
EDGE	Enhanced Data rates for GSM Evolution
EGC	equal-gain combining
ETACS	European Total Access Communication System
ETSI	European Telecommunications Standards Institute
EURO-COST	European Cooperative for Scientific and Technical Research
FAF	floor attenuation factor
FCC	Federal Communications Commission
FD	frequency division
FDD	frequency-division duplexing
FDMA	frequency-division multiple access
FFH	fast frequency hopping
FFT	fast Fourier transform
FH	frequency hopping
FHSS	frequency-hopping spread spectrum
FIR	finite impulse response
FSK	frequency-shift keying
FSMC	finite-state Markov channel
GEO	geosynchronous orbit
GFSK	Gaussian frequency-shift keying
GMSK	Gaussian minimum-shift keying
GPRS	General Packet Radio Service
GRT	general ray tracing
GSM	Global Systems for Mobile Communications
GTD	geometrical theory of diffraction
HDD	hard decision decoding
HDR	high data rate

Amazon
EX1035 Page 28

HDSL	high–bit-rate digital subscriber line
HIPERLAN	high-performance radio local area network
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Data Packet Access
ICI	intercarrier interference
IDFT	inverse DFT
IEEE	Institute of Electrical and Electronics Engineers
IFFT	inverse FFT
i.i.d.	independent and identically distributed
IIR	infinite impulse response
IMT	International Mobile Telephone
IP	Internet protocol
ISI	intersymbol interference
ISM	Industrial, Scientific, and Medical (spectrum band)
ITU	International Telecommunications Union
JTACS	Japanese TACS
LAN	local area network
LDPC	low-density parity-check
LEO	low-earth orbit
LLR	log likelihood ratio
LMA	local mean attenuation
LMDS	local multipoint distribution service
LMS	least mean square
LOS	line of sight
MAC	multiple access channel
MAI	multiple access interference
MAN	metropolitan area network
MAP	maximum a posteriori
MC-CDMA	multicarrier CDMA
MDC	multiple description coding
MEO	medium-earth orbit
MFSK	M-ary FSK
MGF	moment generating function
MIMO	multiple-input multiple-output
MISO	multiple-input single-output
ML	maximum likelihood
MLSE	maximum likelihood sequence estimation
MMDS	multichannel multipoint distribution service
MMSE	minimum mean-square error
MPAM	M-ary PAM
MPSK	M-ary PSK
MQAM	M-ary QAM
MRC	maximal-ratio combining
MSE	mean-square error
MSK	minimum-shift keying

Amazon
EX1035 Page 29

MTSO	mobile telephone switching office
MUD	multiuser detector
N-AMPS	narrowband AMPS
NMT	Nordic Mobile Telephone
OFDM	orthogonal frequency-division multiplexing
OFDMA	OFDM with multiple access
O-QPSK	quadrature PSK with phase offset
OSI	open systems interconnect
OSM	Office of Spectral Management
PACS	Personal Access Communications System
PAF	partition attenuation factor
PAM	pulse amplitude modulation
PAR	peak-to-average power ratio
PBX	private branch exchange
PCS	Personal Communication Systems
PDA	personal digital assistant
PDC	Personal Digital Cellular
pdf	probability density function
PER	packet error rate
PHS	Personal Handyphone System
PLL	phase-locked loop
PN	pseudorandom
PRMA	packet-reservation multiple access
PSD	power spectral density
PSK	phase-shift keying
PSTN	public switched telephone network
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature PSK
RCPC	rate-compatible punctured convolutional
RCS	radar cross-section
RLS	root least squares
rms	root mean square
RS	Reed Solomon
RTS	request to send (packet)
RTT	radio transmission technology
SBS	symbol-by-symbol
SC	selection combining
SCO	Synchronous Connection Oriented
SDD	soft decision decoding
SDMA	space-division multiple access
SE	sequence estimator
SFH	slow frequency hopping

SHO	soft handoff
SICM	symbol-interleaved coded modulation
SIMO	single-input multiple-output
SINR	signal-to-interference-plus-noise power ratio
SIR	signal-to-interference power ratio
SISO	single-input single-output
SNR	signal-to-noise ratio
SOVA	soft output Viterbi algorithm
SSC	switch-and-stay combining
SSMA	spread-spectrum multiple access
STBC	space-time block code
STTC	space-time trellis code
SVD	singular value decomposition
TACS	Total Access Communication System
TCP	transport control protocol
TD	time division
TDD	time-division duplexing
TDMA	time-division multiple access
TIA	Telecommunications Industry Association
UEP	unequal error protection
UMTS	Universal Mobile Telecommunications System
U-NII	Unlicensed National Information Infrastructure
US	uncorrelated scattering
UWB	ultrawideband
V-BLAST	vertical BLAST
VC	vector coding
VCC	voltage-controlled clock
VCO	voltage-controlled oscillator
VQ	vector quantizer
WAN	wide area network
W-CDMA	wideband CDMA
WLAN	wireless LAN
WPAN	wireless personal area networks
WSS	wide-sense stationary
ZF	zero-forcing
ZMCSCQ	zero-mean circularly symmetric complex Gaussian
ZMSW	zero-mean spatially white
ZRP	zone routing protocol

Notation

$\approx$	approximately equal to
$\triangleq$	defined as equal to ($a \triangleq b$: a is defined as b)
$\gg$	much greater than
$\ll$	much less than
$\cdot$	multiplication operator
$*$	convolution operator
$\circledast$	circular convolution operator
$\otimes$	Kronecker product operator
$\sqrt[n]{x}$, $x^{1/n}$	nth root of x
$\arg\max[f(x)]$	value of x that maximizes the function $f(x)$
$\arg\min[f(x)]$	value of x that minimizes the function $f(x)$
$\mathrm{Co}(\mathcal{W})$	convex hull of region $\mathcal{W}$
$\delta(x)$	the delta function
$\mathrm{erfc}(x)$	the complementary error function
$\exp[x]$	e^x
$\mathrm{Im}\{x\}$	imaginary part of x
$I_0(x)$	modified Bessel function of the 0th order
$J_0(x)$	Bessel function of the 0th order
$\mathcal{L}(x)$	Laplace transform of x
$\ln(x)$	the natural log of x
$\log_x(y)$	the log, base x, of y
$\log_x \det[\mathbf{A}]$	the log, base x, of the determinant of matrix $\mathbf{A}$
$\max_x f(x)$	maximum value of $f(x)$ maximized over all x
$\mathrm{mod}_n(x)$	x modulo n
$N(\mu, \sigma^2)$	Gaussian (normal) distribution with mean μ and variance σ^2
$\bar{P}_r$	local mean received power
$Q(x)$	Gaussian Q-function
$\mathbb{R}$	field of all real numbers
$\mathrm{Re}\{x\}$	real part of x
$\mathrm{rect}(x)$	the rectangular function ($\mathrm{rect}(x) = 1$ for $\lvert x\rvert \leq .5$, 0 else)
$\mathrm{sinc}(x)$	the sinc function ($\sin(\pi x)/(\pi x)$)

Amazon
EX1035 Page 32

$\mathbf{E}[\cdot]$	expectation operator
$\mathbf{E}[\cdot \mid \cdot]$	conditional expectation operator
$\bar{X}$	expected (average) value of random variable X
$X \sim p_X(x)$	the random variable X has distribution $p_X(x)$
$\mathrm{Var}[X]$	variance of random variable X
$\mathrm{Cov}[X, Y]$	covariance of random variables X and Y
$H(X)$	entropy of random variable X
$H(Y \mid X)$	conditional entropy of random variable Y given random variable X
$I(X; Y)$	mutual information between random variables X and Y
$\mathcal{M}_X(s)$	moment generating function for random variable X
$\phi_X(s)$	characteristic function for random variable X
$\mathcal{F}[\cdot]$	Fourier transform operator ($\mathcal{F}_x[\cdot]$ is transform w.r.t. x)
$\mathcal{F}^{-1}[\cdot]$	inverse Fourier transform operator ($\mathcal{F}_x^{-1}[\cdot]$ is inverse transform w.r.t. x)
$\mathrm{DFT}\{\cdot\}$	discrete Fourier transform operator
$\mathrm{IDFT}\{\cdot\}$	inverse discrete Fourier transform operator
$\langle \cdot, \cdot \rangle$	inner product operator
x^*	complex conjugate of x
$\angle x$	phase of x
$\lvert x \rvert$	absolute value (amplitude) of x
$\lvert \mathcal{X} \rvert$	size of alphabet $\mathcal{X}$
$\lfloor x \rfloor$	largest integer less than or equal to x
$\lfloor x \rfloor_{\mathcal{S}}$	largest number in set $\mathcal{S}$ less than or equal to x
$\{x : \mathcal{C}\}$	set containing all x that satisfy condition $\mathcal{C}$
$\{x_i : i = 1, \ldots, n\}, \{x_i\}_{i=1}^n$	set containing $x_1, \ldots, x_n$
$(x_i : i = 1, \ldots, n)$	the vector $\mathbf{x} = (x_1, \ldots, x_n)$
$\lVert \mathbf{x} \rVert$	norm of vector $\mathbf{x}$
$\lVert \mathbf{A} \rVert_F$	Frobenius norm of matrix $\mathbf{A}$
$\mathbf{x}^*$	complex conjugate of vector $\mathbf{x}$
$\mathbf{x}^H$	Hermitian (conjugate transpose) of vector $\mathbf{x}$
$\mathbf{x}^T$	transpose of vector $\mathbf{x}$
$\mathbf{A}^{-1}$	inverse of matrix $\mathbf{A}$
$\mathbf{A}^H$	Hermitian (conjugate transpose) of matrix $\mathbf{A}$
$\mathbf{A}^T$	transpose of matrix $\mathbf{A}$
$\det[\mathbf{A}]$	determinant of matrix $\mathbf{A}$
$\mathrm{Tr}[\mathbf{A}]$	trace of matrix $\mathbf{A}$
$\mathrm{vec}(\mathbf{A})$	vector obtained by stacking columns of matrix $\mathbf{A}$
$N \times M$ matrix	a matrix with N rows and M columns
$\mathrm{diag}[x_1, \ldots, x_N]$	the $N \times N$ diagonal matrix with diagonal elements $x_1, \ldots, x_N$
$\mathbf{I}_N$	the $N \times N$ identity matrix (N omitted when size is clear from the context)

Amazon
EX1035 Page 33

1

Overview of Wireless Communications

Wireless communications is, by any measure, the fastest growing segment of the communications industry. As such, it has captured the attention of the media and the imagination of the public. Cellular systems have experienced exponential growth over the last decade and there are currently about two billion users worldwide. Indeed, cellular phones have become a critical business tool and part of everyday life in most developed countries, and they are rapidly supplanting antiquated wireline systems in many developing countries. In addition, wireless local area networks currently supplement or replace wired networks in many homes, businesses, and campuses. Many new applications – including wireless sensor networks, automated highways and factories, smart homes and appliances, and remote telemedicine – are emerging from research ideas to concrete systems. The explosive growth of wireless systems coupled with the proliferation of laptop and palmtop computers suggests a bright future for wireless networks, both as stand-alone systems and as part of the larger networking infrastructure. However, many technical challenges remain in designing robust wireless networks that deliver the performance necessary to support emerging applications. In this introductory chapter we will briefly review the history of wireless networks from the smoke signals of the pre-industrial age to the cellular, satellite, and other wireless networks of today. We then discuss the wireless vision in more detail, including the technical challenges that must still be overcome. We describe current wireless systems along with emerging systems and standards. The gap between current and emerging systems and the vision for future wireless applications indicates that much work remains to be done to make this vision a reality.

1.1 History of Wireless Communications

The first wireless networks were developed in the pre-industrial age. These systems transmitted information over line-of-sight distances (later extended by telescopes) using smoke signals, torch signaling, flashing mirrors, signal flares, or semaphore flags. An elaborate set of signal combinations was developed to convey complex messages with these rudimentary signals. Observation stations were built on hilltops and along roads to relay these messages over large distances. These early communication networks were replaced first by the telegraph network (invented by Samuel Morse in 1838) and later by the telephone. In 1895, a few decades after the telephone was invented, Marconi demonstrated the first radio transmission

Amazon
EX1035 Page 34

from the Isle of Wight to a tugboat 18 miles away, and radio communications was born. Radio technology advanced rapidly to enable transmissions over larger distances with better quality, less power, and smaller, cheaper devices, thereby enabling public and private radio communications, television, and wireless networking.

Early radio systems transmitted analog signals. Today most radio systems transmit digital signals composed of binary bits, where the bits are obtained directly from a data signal or by digitizing an analog signal. A digital radio can transmit a continuous bit stream or it can group the bits into packets. The latter type of radio is called a *packet radio* and is often characterized by bursty transmissions: the radio is idle except when it transmits a packet, although it may transmit packets continuously. The first network based on packet radio, ALOHANET, was developed at the University of Hawaii in 1971. This network enabled computer sites at seven campuses spread out over four islands to communicate with a central computer on Oahu via radio transmission. The network architecture used a star topology with the central computer at its hub. Any two computers could establish a bi-directional communications link between them by going through the central hub. ALOHANET incorporated the first set of protocols for channel access and routing in packet radio systems, and many of the underlying principles in these protocols are still in use today. The U.S. military was extremely interested in this combination of packet data and broadcast radio. Throughout the 1970s and early 1980s the Defense Advanced Research Projects Agency (DARPA) invested significant resources to develop networks using packet radios for tactical communications in the battlefield. The nodes in these ad hoc wireless networks had the ability to self-configure (or reconfigure) into a network without the aid of any established infrastructure. DARPA's investment in ad hoc networks peaked in the mid 1980s, but the resulting systems fell far short of expectations in terms of speed and performance. These networks continue to be developed for military use. Packet radio networks also found commercial application in supporting wide area wireless data services. These services, first introduced in the early 1990s, enabled wireless data access (including email, file transfer, and Web browsing) at fairly low speeds, on the order of 20 kbps. No strong market for these wide area wireless data services ever really materialized, due mainly to their low data rates, high cost, and lack of "killer applications". These services mostly disappeared in the 1990s, supplanted by the wireless data capabilities of cellular telephones and wireless local area networks (WLANs).

The introduction of wired Ethernet technology in the 1970s steered many commercial companies away from radio-based networking. Ethernet's 10-Mbps data rate far exceeded anything available using radio, and companies did not mind running cables within and between their facilities to take advantage of these high rates. In 1985 the Federal Communications Commission (FCC) enabled the commercial development of wireless LANs by authorizing the public use of the Industrial, Scientific, and Medical (ISM) frequency bands for wireless LAN products. The ISM band was attractive to wireless LAN vendors because they did not need to obtain an FCC license to operate in this band. However, the wireless LAN systems were not allowed to interfere with the primary ISM band users, which forced them to use a low power profile and an inefficient signaling scheme. Moreover, the interference from primary users within this frequency band was quite high. As a result, these initial wireless LANs had very poor performance in terms of data rates and coverage. This poor performance – coupled with concerns about security, lack of standardization, and high cost

Amazon
EX1035 Page 35

(the first wireless LAN access points listed for $1400 as compared to a few hundred dollars for a wired Ethernet card) – resulted in weak sales. Few of these systems were actually used for data networking: they were relegated to low-tech applications like inventory control. The current generation of wireless LANs, based on the family of IEEE 802.11 standards, have better performance, although the data rates are still relatively low (maximum collective data rates of tens of Mbps) and the coverage area is still small (around 100 m). Wired Ethernets today offer data rates of 1 Gbps, and the performance gap between wired and wireless LANs is likely to increase over time without additional spectrum allocation. Despite their lower data rates, wireless LANs are becoming the prefered Internet access method in many homes, offices, and campus environments owing to their convenience and freedom from wires. However, most wireless LANs support applications, such as email and Web browsing, that are not bandwidth intensive. The challenge for future wireless LANs will be to support many users simultaneously with bandwidth-intensive and delay-constrained applications such as video. Range extension is also a critical goal for future wireless LAN systems.

By far the most successful application of wireless networking has been the cellular telephone system. The roots of this system began in 1915, when wireless voice transmission between New York and San Francisco was first established. In 1946, public mobile telephone service was introduced in 25 cities across the United States. These initial systems used a central transmitter to cover an entire metropolitan area. This inefficient use of the radio spectrum – coupled with the state of radio technology at that time – severely limited the system capacity: thirty years after the introduction of mobile telephone service, the New York system could support only 543 users.

A solution to this capacity problem emerged during the 1950s and 1960s as researchers at AT&T Bell Laboratories developed the cellular concept [1]. Cellular systems exploit the fact that the power of a transmitted signal falls off with distance. Thus, two users can operate on the same frequency at spatially separate locations with minimal interference between them. This allows efficient use of cellular spectrum, so that a large number of users can be accommodated. The evolution of cellular systems from initial concept to implementation was glacial. In 1947, AT&T requested spectrum for cellular service from the FCC. The design was mostly completed by the end of the 1960s; but the first field test was not until 1978, and the FCC granted service authorization in 1982 – by which time much of the original technology was out of date. The first analog cellular system, deployed in Chicago in 1983, was already saturated by 1984, when the FCC increased the cellular spectral allocation from 40 MHz to 50 MHz. The explosive growth of the cellular industry took almost everyone by surprise. In fact, a marketing study commissioned by AT&T before the first system rollout predicted that demand for cellular phones would be limited to doctors and the very rich. AT&T basically abandoned the cellular business in the 1980s to focus on fiber optic networks, eventually returning to the business after its potential became apparent. Throughout the late 1980s – as more and more cities saturated with demand for cellular service – the development of digital cellular technology for increased capacity and better performance became essential.

The second generation of cellular systems, first deployed in the early 1990s, was based on digital communications. The shift from analog to digital was driven by its higher capacity and the improved cost, speed, and power efficiency of digital hardware. Although second-generation cellular systems initially provided mainly voice services, these systems

gradually evolved to support data services such as email, Internet access, and short messaging. Unfortunately, the great market potential for cellular phones led to a proliferation of second-generation cellular standards: three different standards in the United States alone, other standards in Europe and Japan, and all incompatible. The fact that different cities have different incompatible standards makes roaming throughout the United States and the world with only one cellular phone standard impossible. Moreover, some countries have initiated service for third-generation systems, for which there are also multiple incompatible standards. As a result of this proliferation of standards, many cellular phones today are multimode: they incorporate multiple digital standards to faciliate nationwide and worldwide roaming and possibly the first-generation analog standard as well, since only this standard provides universal coverage throughout the United States.

Satellite systems are typically characterized by the height of the satellite orbit: low-earth orbit (LEOs at roughly 2000 km altitude), medium-earth orbit (MEOs, 9000 km), or geosynchronous orbit (GEOs, 40,000 km). The geosynchronous orbits are seen as stationary from the earth, whereas satellites with other orbits have their coverage area change over time. The concept of using geosynchronous satellites for communications was first suggested by the science-fiction writer Arthur C. Clarke in 1945. However, the first deployed satellites – the Soviet Union's *Sputnik* in 1957 and the NASA/Bell Laboratories' *Echo-1* in 1960 – were not geosynchronous owing to the difficulty of lifting a satellite into such a high orbit. The first GEO satellite was launched by Hughes and NASA in 1963; GEOs then dominated both commercial and government satellite systems for several decades.

Geosynchronous satellites have large coverage areas, so fewer satellites (and dollars) are necessary to provide wide area or global coverage. However, it takes a great deal of power to reach the satellite, and the propagation delay is typically too large for delay-constrained applications like voice. These disadvantages caused a shift in the 1990s toward lower-orbit satellites [2; 3]. The goal was to provide voice and data service competitive with cellular systems. However, the satellite mobile terminals were much bigger, consumed much more power, and cost much more than contemporary cellular phones, which limited their appeal. The most compelling feature of these systems is their ubiquitous worldwide coverage, especially in remote areas or third-world countries with no landline or cellular system infrastructure. Unfortunately, such places do not typically have large demand or the resources to pay for satellite service either. As cellular systems became more widespread, they took away most revenue that LEO systems might have generated in populated areas. With no real market left, most LEO satellite systems went out of business.

A natural area for satellite systems is broadcast entertainment. Direct broadcast satellites operate in the 12-GHz frequency band. These systems offer hundreds of TV channels and are major competitors to cable. Satellite-delivered digital radio has also become popular. These systems, operating in both Europe and the United States, offer digital audio broadcasts at near-CD quality.

1.2 Wireless Vision

The vision of wireless communications supporting information exchange between people or devices is the communications frontier of the next few decades, and much of it already

exists in some form. This vision will allow multimedia communication from anywhere in the world using a small handheld device or laptop. Wireless networks will connect palmtop, laptop, and desktop computers anywhere within an office building or campus, as well as from the corner cafe. In the home these networks will enable a new class of intelligent electronic devices that can interact with each other and with the Internet in addition to providing connectivity between computers, phones, and security/monitoring systems. Such "smart" homes can also help the elderly and disabled with assisted living, patient monitoring, and emergency response. Wireless entertainment will permeate the home and any place that people congregate. Video teleconferencing will take place between buildings that are blocks or continents apart, and these conferences can include travelers as well – from the salesperson who missed his plane connection to the CEO off sailing in the Caribbean. Wireless video will enable remote classrooms, remote training facilities, and remote hospitals anywhere in the world. Wireless sensors have an enormous range of both commercial and military applications. Commercial applications include monitoring of fire hazards, toxic waste sites, stress and strain in buildings and bridges, carbon dioxide movement, and the spread of chemicals and gasses at a disaster site. These wireless sensors self-configure into a network to process and interpret sensor measurements and then convey this information to a centralized control location. Military applications include identification and tracking of enemy targets, detection of chemical and biological attacks, support of unmanned robotic vehicles, and counterterrorism. Finally, wireless networks enable distributed control systems with remote devices, sensors, and actuators linked together via wireless communication channels. Such systems in turn enable automated highways, mobile robots, and easily reconfigurable industrial automation.

The various applications described here are all components of the wireless vision. So then what, exactly, is wireless communications? There are many ways to segment this complex topic into different applications, systems, or coverage regions [4]. Wireless applications include voice, Internet access, Web browsing, paging and short messaging, subscriber information services, file transfer, video teleconferencing, entertainment, sensing, and distributed control. Systems include cellular telephone systems, wireless LANs, wide area wireless data systems, satellite systems, and ad hoc wireless networks. Coverage regions include in-building, campus, city, regional, and global. The question of how best to characterize wireless communications along these various segments has resulted in considerable fragmentation in the industry, as evidenced by the many different wireless products, standards, and services being offered or proposed. One reason for this fragmentation is that different wireless applications have different requirements. Voice systems have relatively low data-rate requirements (around 20 kbps) and can tolerate a fairly high probability of bit error (bit error rates, or BERs, of around 10^{-3}), but the total delay must be less than about 100 ms or else it becomes noticeable to the end user.[1] On the other hand, data systems typically require much higher data rates (1–100 Mbps) and very small BERs (a BER of 10^{-8} or less, and all bits received in error must be retransmitted) but do not have a fixed delay requirement. Real-time video systems have high data-rate requirements coupled with the same delay constraints as voice systems,

[1] Wired telephones have a delay constraint of ~30 ms. Cellular phones relax this constraint to ~100 ms, and voice over the Internet relaxes the constraint even further.

Amazon
EX1035 Page 38

while paging and short messaging have very low data-rate requirements and no hard delay constraints. These diverse requirements for different applications make it difficult to build one wireless system that can efficiently satisfy all these requirements simultaneously. Wired networks typically satisfy the diverse requirements of different applications using a single protocol, which means that the most stringent requirements for all applications must be met simultaneously. This may be possible on some wired networks – with data rates on the order of Gbps and BERs on the order of 10^{-12} – but it is not possible on wireless networks, which have much lower data rates and higher BERs. For these reasons, at least in the near future, wireless systems will continue to be fragmented, with different protocols tailored to support the requirements of different applications.

The exponential growth of cellular telephone use and wireless Internet access has led to great optimism about wireless technology in general. Obviously not all wireless applications will flourish. While many wireless systems and companies have enjoyed spectacular success, there have also been many failures along the way, including first-generation wireless LANs, the Iridium satellite system, wide area data services such as Metricom, and fixed wireless access (wireless "cable") to the home. Indeed, it is impossible to predict what wireless failures and triumphs lie on the horizon. Moreover, there must be sufficient flexibility and creativity among both engineers and regulators to allow for accidental successes. It is clear, however, that the current and emerging wireless systems of today – coupled with the vision of applications that wireless can enable – ensure a bright future for wireless technology.

1.3 Technical Issues

Many technical challenges must be addressed to enable the wireless applications of the future. These challenges extend across all aspects of the system design. As wireless terminals add more features, these small devices must incorporate multiple modes of operation in order to support the different applications and media. Computers process voice, image, text, and video data, but breakthroughs in circuit design are required to implement the same multimode operation in a cheap, lightweight, handheld device. Consumers don't want large batteries that frequently need recharging, so transmission and signal processing at the portable terminal must consume minimal power. The signal processing required to support multimedia applications and networking functions can be power intensive. Thus, wireless infrastructure-based networks, such as wireless LANs and cellular systems, place as much of the processing burden as possible on fixed sites with large power resources. The associated bottlenecks and single points of failure are clearly undesirable for the overall system. Ad hoc wireless networks without infrastructure are highly appealing for many applications because of their flexibility and robustness. For these networks, all processing and control must be performed by the network nodes in a distributed fashion, making energy efficiency challenging to achieve. Energy is a particularly critical resource in networks where nodes cannot recharge their batteries – for example, in sensing applications. Network design to meet application requirements under such hard energy constraints remains a big technological hurdle. The finite bandwidth and random variations of wireless channels also require robust applications that degrade gracefully as network performance degrades.

Amazon
EX1035 Page 39

Design of wireless networks differs fundamentally from wired network design owing to the nature of the wireless channel. This channel is an unpredictable and difficult communications medium. First of all, the radio spectrum is a scarce resource that must be allocated to many different applications and systems. For this reason, spectrum is controlled by regulatory bodies both regionally and globally. A regional or global system operating in a given frequency band must obey the restrictions for that band set forth by the corresponding regulatory body. Spectrum can also be very expensive: in many countries spectral licenses are often auctioned to the highest bidder. In the United States, companies spent over $9 billion for second-generation cellular licenses, and the auctions in Europe for third-generation cellular spectrum garnered around $100 billion (American). The spectrum obtained through these auctions must be used extremely efficiently to receive a reasonable return on the investment, and it must also be reused over and over in the same geographical area, thus requiring cellular system designs with high capacity and good performance. At frequencies around several gigahertz, wireless radio components with reasonable size, power consumption, and cost are available. However, the spectrum in this frequency range is extremely crowded. Thus, technological breakthroughs to enable higher-frequency systems with the same cost and performance would greatly reduce the spectrum shortage. However, path loss at these higher frequencies is larger with omnidirectional antennas, thereby limiting range.

As a signal propagates through a wireless channel, it experiences random fluctuations in time if the transmitter, receiver, or surrounding objects are moving because of changing reflections and attenuation. Hence the characteristics of the channel appear to change randomly with time, which makes it difficult to design reliable systems with guaranteed performance. Security is also more difficult to implement in wireless systems, since the airwaves are susceptible to snooping by anyone with an RF antenna. The analog cellular systems have no security, and one can easily listen in on conversations by scanning the analog cellular frequency band. All digital cellular systems implement some level of encryption. However, with enough knowledge, time, and determination, most of these encryption methods can be cracked; indeed, several have been compromised. To support applications like electronic commerce and credit-card transactions, the wireless network must be secure against such listeners.

Wireless networking is also a significant challenge. The network must be able to locate a given user wherever it is among billions of globally distributed mobile terminals. It must then route a call to that user as it moves at speeds of up to 100 km/hr. The finite resources of the network must be allocated in a fair and efficient manner relative to changing user demands and locations. Moreover, there currently exists a tremendous infrastructure of wired networks: the telephone system, the Internet, and fiber optic cables – which could be used to connect wireless systems together into a global network. However, wireless systems with mobile users will never be able to compete with wired systems in terms of data rates and reliability. Interfacing between wireless and wired networks with vastly different performance capabilities is a difficult problem.

Perhaps the most significant technical challenge in wireless network design is an overhaul of the design process itself. Wired networks are mostly designed according to a layered approach, whereby protocols associated with different layers of the system operation are designed in isolation, with baseline mechanisms to interface between layers. The layers in

Amazon
EX1035 Page 40

a wireless system include: the link or physical layer, which handles bit transmissions over the communications medium; the access layer, which handles shared access to the communications medium; the network and transport layers, which route data across the network and ensure end-to-end connectivity and data delivery; and the application layer, which dictates the end-to-end data rates and delay constraints associated with the application. While a layering methodology reduces complexity and facilitates modularity and standardization, it also leads to inefficiency and performance loss due to the lack of a global design optimization. The large capacity and good reliability of wired networks make these inefficiencies relatively benign for many wired network applications, although they do preclude good performance of delay-constrained applications such as voice and video. The situation is very different in a wireless network. Wireless links can exhibit very poor performance, and this performance, along with user connectivity and network topology, changes over time. In fact, the very notion of a wireless link is somewhat fuzzy owing to the nature of radio propagation and broadcasting. The dynamic nature and poor performance of the underlying wireless communication channel indicates that high-performance networks must be optimized for this channel and must be robust and adaptive to its variations, as well as to network dynamics. Thus, these networks require integrated and adaptive protocols at all layers, from the link layer to the application layer. This cross-layer protocol design requires interdisciplinary expertise in communications, signal processing, and network theory and design.

In the next section we give an overview of the wireless systems in operation today. It will be clear from this overview that the wireless vision remains a distant goal, with many technical challenges to overcome. These challenges will be examined in detail throughout the book.

1.4 Current Wireless Systems

This section provides a brief overview of current wireless systems in operation today. The design details of these system are constantly evolving, with new systems emerging and old ones going by the wayside. Thus, we will focus mainly on the high-level design aspects of the most common systems. More details on wireless system standards can be found in [5; 6; 7]. A summary of the main wireless system standards is given in Appendix D.

1.4.1 Cellular Telephone Systems

Cellular telephone systems are extremely popular and lucrative worldwide: these are the systems that ignited the wireless revolution. Cellular systems provide two-way voice and data communication with regional, national, or international coverage. Cellular systems were initially designed for mobile terminals inside vehicles with antennas mounted on the vehicle roof. Today these systems have evolved to support lightweight handheld mobile terminals operating inside and outside buildings at both pedestrian and vehicle speeds.

The basic premise behind cellular system design is frequency reuse, which exploits the fact that signal power falls off with distance to reuse the same frequency spectrum at spatially separated locations. Specifically, the coverage area of a cellular system is divided into nonoverlapping cells, where some set of channels is assigned to each cell. This same channel set is used in another cell some distance away, as shown in Figure 1.1, where C_i denotes the channel set used in a particular cell. Operation within a cell is controlled by a centralized

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EX1035 Page 41

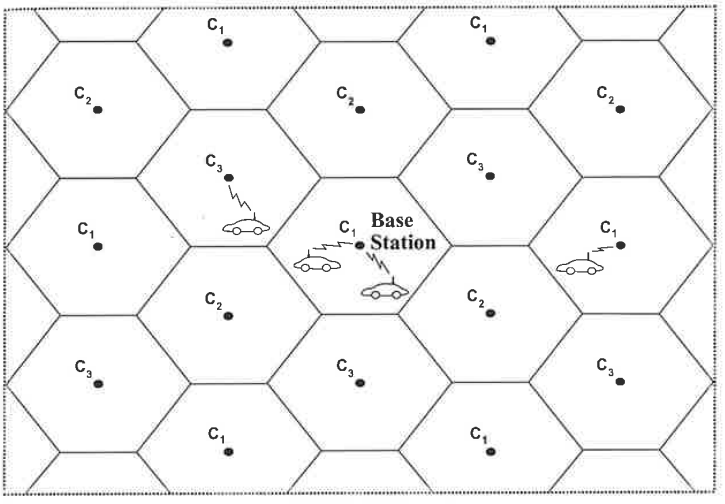

Figure 1.1: Cellular systems.

base station, as described in more detail below. The interference caused by users in different cells operating on the same channel set is called *intercell interference*. The spatial separation of cells that reuse the same channel set, the *reuse distance,* should be as small as possible so that frequencies are reused as often as possible, thereby maximizing spectral efficiency. However, as the reuse distance decreases, intercell interference increases owing to the smaller propagation distance between interfering cells. Since intercell interference must remain below a given threshold for acceptable system performance, reuse distance cannot be reduced below some minimum value. In practice it is quite difficult to determine this minimum value, since both the transmitting and interfering signals experience random power variations due to the characteristics of wireless signal propagation. In order to determine the best reuse distance and base station placement, an accurate characterization of signal propagation within the cells is needed.

Initial cellular system designs were mainly driven by the high cost of base stations, approximately $1 million each. For this reason, early cellular systems used a relatively small number of cells to cover an entire city or region. The cell base stations were placed on tall buildings or mountains and transmitted at very high power with cell coverage areas of several square miles. These large cells are called *macrocells.* Signal power radiated uniformly in all directions, so a mobile moving in a circle around the base station would have approximately constant received power unless the signal were blocked by an attenuating object. This circular contour of constant power yields a hexagonal cell shape for the system, since a hexagon is the closest shape to a circle that can cover a given area with multiple nonoverlapping cells.

Cellular systems in urban areas now mostly use smaller cells with base stations close to street level that are transmitting at much lower power. These smaller cells are called microcells or picocells, depending on their size. This evolution to smaller cells occured for two reasons: the need for higher capacity in areas with high user density and the reduced size and cost of base station electronics. A cell of any size can support roughly the same number

Amazon
EX1035 Page 42

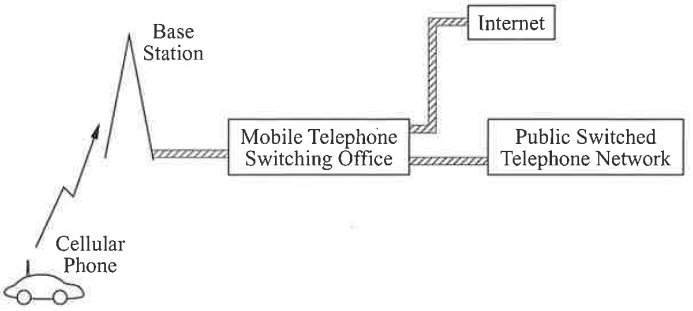

Figure 1.2: Current cellular network architecture.

of users if the system is scaled accordingly. Thus, for a given coverage area, a system with many microcells has a higher number of users per unit area than a system with just a few macrocells. In addition, less power is required at the mobile terminals in microcellular systems, since the terminals are closer to the base stations. However, the evolution to smaller cells has complicated network design. Mobiles traverse a small cell more quickly than a large cell, so handoffs must be processed more quickly. In addition, location management becomes more complicated, since there are more cells within a given area where a mobile may be located. It is also harder to develop general propagation models for small cells, since signal propagation in these cells is highly dependent on base station placement and the geometry of the surrounding reflectors. In particular, a hexagonal cell shape is generally not a good approximation to signal propagation in microcells. Microcellular systems are often designed using square or triangular cell shapes, but these shapes have a large margin of error in their approximation to microcell signal propagation [8].

All base stations in a given geographical area are connected via a high-speed communications link to a mobile telephone switching office (MTSO), as shown in Figure 1.2. The MTSO acts as a central controller for the network: allocating channels within each cell, coordinating handoffs between cells when a mobile traverses a cell boundary, and routing calls to and from mobile users. The MTSO can route voice calls through the public switched telephone network (PSTN) or provide Internet access. A new user located in a given cell requests a channel by sending a call request to the cell's base station over a separate control channel. The request is relayed to the MTSO, which accepts the call request if a channel is available in that cell. If no channels are available then the call request is rejected. A call handoff is initiated when the base station or the mobile in a given cell detects that the received signal power for that call is approaching a given minimum threshold. In this case the base station informs the MTSO that the mobile requires a handoff, and the MTSO then queries surrounding base stations to determine if one of these stations can detect that mobile's signal. If so then the MTSO coordinates a handoff between the original base station and the new base station. If no channels are available in the cell with the new base station then the handoff fails and the call is terminated. A call will also be dropped if the signal strength between a mobile and its base station falls below the minimum threshold needed for communication as a result of random signal variations.

The first generation of cellular systems used analog communications; these systems were primarily designed in the 1960s, before digital communications became prevalent. Second-generation systems moved from analog to digital because of the latter's many advantages. The components are cheaper, faster, and smaller, and they require less power. The degradation of voice quality caused by channel impairments can be mitigated with error correction coding and signal processing. Digital systems also have higher capacity than analog systems because they can use more spectrally efficient digital modulation and more efficient techniques to share the cellular spectrum. They can also take advantage of advanced compression techniques and voice activity factors. In addition, encryption techniques can be used to secure digital signals against eavesdropping. Digital systems can also offer data services in addition to voice, including short messaging, email, Internet access, and imaging capabilities (camera phones). Because of their lower cost and higher efficiency, service providers used aggressive pricing tactics to encourage user migration from analog to digital systems, and today analog systems are primarily used in areas with no digital service. However, digital systems do not always work as well as the analog ones. Users can experience poor voice quality, frequent call dropping, and spotty coverage in certain areas. System performance has certainly improved as the technology and networks mature. In some areas cellular phones provide almost the same quality as wireline service. Indeed, some people have replaced their wireline telephone service inside the home with cellular service.

Spectral sharing in communication systems, also called multiple access, is done by dividing the signaling dimensions along the time, frequency, and/or code space axes. In *frequency-division multiple access* (FDMA) the total system bandwidth is divided into orthogonal frequency channels. In *time-division multiple access* (TDMA), time is divided orthogonally and each channel occupies the entire frequency band over its assigned timeslot. TDMA is more difficult to implement than FDMA because the users must be time-synchronized. However, it is easier to accommodate multiple data rates with TDMA, since multiple timeslots can be assigned to a given user. *Code-division multiple access* (CDMA) is typically implemented using direct-sequence or frequency-hopping spread spectrum with either orthogonal or nonorthogonal codes. In direct sequence, each user modulates its data sequence by a different chip sequence that is much faster than the data sequence. In the frequency domain, the narrowband data signal is convolved with the wideband chip signal to yield a signal with a much wider bandwidth than the original data signal. In frequency hopping the carrier frequency used to modulate the narrowband data signal is varied by a chip sequence that may be faster or slower than the data sequence. This results in a modulated signal that hops over different carrier frequencies. Spread-spectrum signals are typically superimposed onto each other within the same signal bandwidth. A spread-spectrum receiver separates out each of the distinct signals by separately decoding each spreading sequence. However, for nonorthogonal codes, users within a cell interfere with each other (*intracell* interference) and codes that are reused in other cells cause intercell interference. Both the intracell and intercell interference power are reduced by the spreading gain of the code. Moreover, interference in spread-spectrum systems can be further reduced via multiuser detection or interference cancellation. More details on these different techniques for spectrum sharing and their performance analysis will be given in Chapters 13 and 14. The design trade-offs associated with

Amazon
EX1035 Page 44

spectrum sharing are very complex, and the decision of which technique is best for a given system and operating environment is never straightforward.

Efficient cellular system designs are *interference limited* – that is, the interference dominates the noise floor, since otherwise more users could be added to the system. As a result, any technique to reduce interference in cellular systems leads directly to an increase in system capacity and performance. Some methods for interference reduction in use today or proposed for future systems include cell sectorization, directional and smart antennas, multiuser detection, and dynamic resource allocation. Details of these techniques will be given in Chapter 15.

The first-generation (1G) cellular systems in the United States, called the Advance Mobile Phone Service (AMPS), used FDMA with 30-kHz FM-modulated voice channels. The FCC initially allocated 40 MHz of spectrum to this system, which was increased to 50 MHz shortly after service introduction to support more users. This total bandwidth was divided into two 25-MHz bands, one for mobile-to-base station channels and the other for base station-to-mobile channels. The FCC divided these channels into two sets that were assigned to two different service providers in each city to encourage competition. A similar system, the Total Access Communication System (TACS), emerged in Europe. AMPS was deployed worldwide in the 1980s and remains the only cellular service in some areas, including rural parts of the United States.

Many of the first-generation cellular systems in Europe were incompatible, and the Europeans quickly converged on a uniform standard for second-generation (2G) digital systems called GSM.[2] The GSM standard uses a combination of TDMA and slow frequency hopping with frequency-shift keying for the voice modulation. In contrast, the standards activities in the United States surrounding the second generation of digital cellular provoked a raging debate on spectrum-sharing techniques, resulting in several incompatible standards [9; 10; 11]. In particular, there are two standards in the 900-MHz cellular frequency band: IS-136,[3] which uses a combination of TDMA and FDMA and phase-shift keyed modulation; and IS-95, which uses direct-sequence CDMA with phase-shift keyed modulation and coding [12; 13]. The spectrum for digital cellular in the 2-GHz PCS (personal communication system) frequency band was auctioned off, so service providers could use any standard for their purchased spectrum. The end result has been three different digital cellular standards for this frequency band: IS-136, IS-95, and the European GSM standard. The digital cellular standard in Japan is similar to IS-136 but in a different frequency band, and the GSM system in Europe is at a different frequency than the GSM systems in the United States. This proliferation of incompatible standards in the United States and internationally makes it impossible to roam between systems nationwide or globally without a multimode phone and/or multiple phones (and phone numbers).

All of the second-generation digital cellular standards have been enhanced to support high-rate packet data services [14]. GSM systems provide data rates of up to 140 kbps by aggregating all timeslots together for a single user. This enhancement is called GPRS. A

[2] The acronym GSM originally stood for Groupe Spéciale Mobile, the name of the European charter establishing the GSM standard. As GSM systems proliferated around the world, the underlying acronym meaning was changed to Global Systems for Mobile Communications.

[3] IS-136 is the evolution of the older IS-54 standard and subsumes it.

Amazon
EX1035 Page 45

more fundamental enhancement, Enhanced Data rates for GSM Evolution (EDGE), further increases data rates up to 384 kbps by using a high-level modulation format combined with coding. This modulation is more sensitive to fading effects, and EDGE uses adaptive techniques to mitigate that problem. Specifically, EDGE defines nine different modulation and coding combinations, each optimized to a different value of received SNR (signal-to-noise ratio). The received SNR is measured at the receiver and fed back to the transmitter, and the best modulation and coding combination for this SNR value is used. The IS-136 systems also use GPRS and EDGE enhancements to support data rates up to 384 kbps. The IS-95 systems support data rates up to 115 kbps by aggregating spreading functions [15].

The third-generation (3G) cellular systems are based on a wideband CDMA standard developed under the auspices of the International Telecommunications Union (ITU) [14]. The standard, called International Mobile Telecommunications 2000 (IMT-2000), provides different data rates depending on mobility and location, from 384 kbps for pedestrian use to 144 kbps for vehicular use to 2 Mbps for indoor office use. The 3G standard is incompatible with 2G systems, so service providers must invest in a new infrastructure before they can provide 3G service. The first 3G systems were deployed in Japan. One reason that 3G services came out first in Japan was the Japanese allocation process for 3G spectrum, which was awarded without much up-front cost. The 3G spectrum in both Europe and the United States is allocated based on auctioning, thereby requiring a huge initial investment for any company wishing to provide 3G service. European companies collectively paid over $100 billion (American) in their 3G spectrum auctions. There has been much controversy over the 3G auction process in Europe, with companies charging that the nature of the auctions caused enormous overbidding and that it will thus be difficult if not impossible to reap a profit on this spectrum. A few of the companies decided to write off their investment in 3G spectrum and not pursue system buildout. In fact, 3G systems have not grown as anticipated in Europe, and it appears that data enhancements to 2G systems may suffice to satisfy user demands at least for some time. However, the 2G spectrum in Europe is severely overcrowded, so either users will eventually migrate to 3G or regulations will change so that 3G bandwidth can be used for 2G services (this is not currently allowed in Europe). Development of 3G in the United States has lagged far behind that in Europe. The available U.S. 3G spectrum is only about half that available in Europe. Due to wrangling about which parts of the spectrum will be used, 3G spectral auctions in the United States have not yet taken place. However, U.S. regulations do allow the 1G and 2G spectrum to be used for 3G, and this flexibility has facilitated a more gradual rollout and investment than the more restrictive 3G requirements in Europe. It appears that delaying the 3G spectral auctions in the United States has allowed the FCC and U.S. service providers to learn from the mistakes and successes in Europe and Japan.

1.4.2 Cordless Phones

Cordless telephones first appeared in the late 1970s and have experienced spectacular growth ever since. Many U.S. homes today have only cordless phones, which can be a safety risk because these phones – in contrast to their wired counterparts – don't work in a power outage. Cordless phones were originally designed to provide a low-cost, low-mobility wireless connection to the PSTN, that is, a short wireless link to replace the cord connecting a telephone

Amazon
EX1035 Page 46

base unit and its handset. Since cordless phones compete with wired handsets, their voice quality must be similar. Initial cordless phones had poor voice quality and were quickly discarded by users. The first cordless systems allowed only one phone handset to connect to each base unit, and coverage was limited to a few rooms of a house or office. This is still the main premise behind cordless telephones in the United States today, although some base units now support multiple handsets and coverage has improved. In Europe and Asia, digital cordless phone systems have evolved to provide coverage over much wider areas, both in and away from home, and are similar in many ways to cellular telephone systems.

The base units of cordless phones connect to the PSTN in the exact same manner as a landline phone, and thus they impose no added complexity on the telephone network. The movement of these cordless handsets is extremely limited: a handset must remain within transmission range of its base unit. There is no coordination with other cordless phone systems, so a high density of these systems in a small area (e.g., an apartment building) can result in significant interference between systems. For this reason cordless phones today have multiple voice channels and scan between these channels to find the one with minimal interference. Many cordless phones use spread-spectrum techniques to reduce interference from other cordless phone systems and from such other systems as baby monitors and wireless LANs.

In Europe and Asia, the second-generation digital cordless phone (CT-2, for "cordless telephone, second generation") has an extended range of use beyond a single residence or office. Within a home these systems operate as conventional cordless phones. To extend the range beyond the home, base stations (also called phone-points or telepoints) are mounted in places where people congregate: shopping malls, busy streets, train stations, and airports. Cordless phones registered with the telepoint provider can place calls whenever they are in range of a telepoint. Calls cannot be received from the telepoint because the network has no routing support for mobile users, although some CT-2 handsets have built-in pagers to compensate for this deficiency. These systems also do not hand off calls if a user moves between different telepoints, so a user must remain within range of the telepoint where his call was initiated for the duration of the call. Telepoint service was introduced twice in the United Kingdom and failed both times, but these systems grew rapidly in Hong Kong and Singapore through the mid 1990s. This rapid growth deteriorated quickly after the first few years as cellular phone operators cut prices to compete with telepoint service. The main complaint about telepoint service was the incomplete radio coverage and lack of handoff. Since cellular systems avoid these problems, as long as prices were competitive there was little reason for people to use telepoint services. Most of these services have now disappeared.

Another evolution of the cordless telephone designed primarily for office buildings is the European Digital Enhanced Cordless Telecommunications (DECT) system. The main function of DECT is to provide local mobility support for users in an in-building private branch exchange (PBX). In DECT systems, base units are mounted throughout a building, and each base station is attached through a controller to the PBX of the building. Handsets communicate with the nearest base station in the building, and calls are handed off as a user walks between base stations. DECT can also ring handsets from the closest base station. The DECT standard also supports telepoint services, although this application has not received much attention (due most likely to the failure of CT-2 services). There are currently about 7 million DECT users in Europe, but the standard has not yet spread to other countries.

Amazon
EX1035 Page 47

A more advanced cordless telephone system that emerged in Japan is the Personal Handyphone System (PHS). The PHS system is quite similar to a cellular system, with widespread base station deployment supporting handoff and call routing between base stations. With these capabilities PHS does not suffer from the main limitations of the CT-2 system. Initially PHS systems enjoyed one of the fastest growth rates ever for a new technology. In 1997, two years after its introduction, PHS subscribers peaked at about 7 million users, but its popularity then started to decline in response to sharp price cutting by cellular providers. In 2005 there were about 4 million subscribers, attracted by the flat-rate service and relatively high speeds (128 kbps) for data. PHS operators are trying to push data rates up to 1 Mbps, which cellular providers cannot yet compete with. The main difference between a PHS system and a cellular system is that PHS cannot support call handoff at vehicle speeds. This deficiency is mainly due to the dynamic channel allocation procedure used in PHS. Dynamic channel allocation greatly increases the number of handsets that can be serviced by a single base station and their corresponding data rates, thereby lowering the system cost, but it also complicates the handoff procedure. Given the sustained popularity of PHS, it is unlikely to go the same route as CT-2 any time soon, especially if much higher data rates become available. However, it is clear from the recent history of cordless phone systems that to extend the range of these systems beyond the home requires either matching or exceeding the functionality of cellular systems or a significantly reduced cost.

1.4.3 Wireless Local Area Networks

Wireless LANs support high-speed data transmissions within a small region (e.g., a campus or small building) as users move from place to place. Wireless devices that access these LANs are typically stationary or moving at pedestrian speeds. All wireless LAN standards in the United States operate in unlicensed frequency bands. The primary unlicensed bands are the ISM bands at 900 MHz, 2.4 GHz, and 5.8 GHz and the Unlicensed National Information Infrastructure (U-NII) band at 5 GHz. In the ISM bands, unlicensed users are secondary users and so must cope with interference from primary users when such users are active. There are no primary users in the U-NII band. An FCC license is not required to operate in either the ISM or U-NII bands. However, this advantage is a double-edged sword, since other unlicensed systems operate in these bands for the same reason, which can cause a great deal of interference between systems. The interference problem is mitigated by setting a limit on the power per unit bandwidth for unlicensed systems. Wireless LANs can have either a star architecture, with wireless access points or hubs placed throughout the coverage region, or a peer-to-peer architecture, where the wireless terminals self-configure into a network.

Dozens of wireless LAN companies and products appeared in the early 1990s to capitalize on the "pent-up demand" for high-speed wireless data. These first-generation wireless LANs were based on proprietary and incompatible protocols. Most operated within the 26-MHz spectrum of the 900-MHz ISM band using direct-sequence spread spectrum, with data rates on the order of 1–2 Mbps. Both star and peer-to-peer architectures were used. The lack of standardization for these products led to high development costs, low-volume production, and small markets for each individual product. Of these original products only a handful were even mildly successful. Only one of the first-generation wireless LANs, Motorola's Altair, operated outside the 900-MHz band. This system, operating in the licensed

Amazon
EX1035 Page 48

18-GHz band, had data rates on the order of 6 Mbps. However, performance of Altair was hampered by the high cost of components and the increased path loss at 18 GHz, and Altair was discontinued within a few years of its release.

The second-generation wireless LANs in the United States operate with 83.5 MHz of spectrum in the 2.4-GHz ISM band. A wireless LAN standard for this frequency band, the IEEE 802.11b standard, was developed to avoid some of the problems with the proprietary first-generation systems. The standard specifies direct-sequence spread spectrum with data rates of around 1.6 Mbps (raw data rates of 11 Mbps) and a range of approximately 100 m. The network architecture can be either star or peer-to-peer, although the peer-to-peer feature is rarely used. Many companies developed products based on the 802.11b standard, and after slow initial growth the popularity of 802.11b wireless LANs has expanded considerably. Many laptops come with integrated 802.11b wireless LAN cards. Companies and universities have installed 802.11b base stations throughout their locations, and many coffee houses, airports, and hotels offer wireless access, often for free, to increase their appeal.

Two additional standards in the 802.11 family were developed to provide higher data rates than 802.11b. The IEEE 802.11a wireless LAN standard operates with 300 MHz of spectrum in the 5-GHz U-NII band. The 802.11a standard is based on multicarrier modulation and provides 54-Mbps data rates at a range of about 30 m. Because 802.11a has much more bandwidth and consequently many more channels than 802.11b, it can support more users at higher data rates. There was some initial concern that 802.11a systems would be significantly more expensive than 802.11b systems, but in fact they quickly became quite competitive in price. The other standard, 802.11g, has the same design and data rates as 802.11a, but it operates in the the 2.4-GHz band with a range of about 50 m. Many wireless LAN cards and access points support all three standards to avoid incompatibilities.

In Europe, wireless LAN development revolves around the HIPERLAN (high-performance radio LAN) standards. The HIPERLAN/2 standard is similar to the IEEE 802.11a wireless LAN standard. In particular, it has a similar link layer design and also operates in a 5-GHz frequency band similar to the U-NII band. Hence it has the same maximum date rate of 54 Mbps and the same range of approximately 30 m as 802.11a. It differs from 802.11a in its access protocol and its built-in Quality-of-Service (QoS) support.

1.4.4 Wide Area Wireless Data Services

Wide area wireless data services provide wireless data to high-mobility users over a large coverage area. In these systems a given geographical region is serviced by base stations mounted on towers, rooftops, or mountains. The base stations can be connected to a backbone wired network or form a multihop ad hoc wireless network.

Initial wide area wireless data services had very low data rates, below 10 kbps, which gradually increased to 20 kbps. There were two main players providing this service: Motient and Bell South Mobile Data (formerly RAM Mobile Data). Metricom provided a similar service using architecture that consisted of a large network of small, inexpensive base stations with small coverage areas. The increased efficiency of the small coverage areas allowed for higher data rates in Metricom, 76 kbps, than in the other wide area wireless data systems. However, the high infrastructure cost for Metricom eventually forced it into bankruptcy, and the system was shut down. Some of the infrastructure was bought and is operating in a few areas as Ricochet.

Amazon
EX1035 Page 49

The cellular digital packet data (CDPD) system is a wide area wireless data service overlayed on the analog cellular telephone network. CDPD shares the FDMA voice channels of the analog systems, since many of these channels are idle owing to the growth of digital cellular. The CDPD service provides packet data transmission at rates of 19.2 kbps and is available throughout the United States. However, since newer generations of cellular systems also provide data services and at higher data rates, CDPD is mostly being replaced by these newer services. Thus, wide area wireless data services have not been very successful, although emerging systems that offer broadband access may have more appeal.

1.4.5 Broadband Wireless Access

Broadband wireless access provides high-rate wireless communications between a fixed access point and multiple terminals. These systems were initially proposed to support interactive video service to the home, but the application emphasis then shifted to providing both high-speed data access (tens of Mbps) to the Internet and the World Wide Web as well as high-speed data networks for homes and businesses. In the United States, two frequency bands were set aside for these systems: part of the 28-GHz spectrum for local distribution systems (local multipoint distribution service, LMDS) and a band in the 2-GHz spectrum for metropolitan distribution service (multichannel multipoint distribution services, MMDS). LMDS represents a quick means for new service providers to enter the already stiff competition among wireless and wireline broadband service providers [5, Chap. 2.3]. MMDS is a television and telecommunication delivery system with transmission ranges of 30–50 km [5, Chap. 11.11]. MMDS has the capability of delivering more than a hundred digital video TV channels along with telephony and access to the Internet. MMDS will compete mainly with existing cable and satellite systems. Europe is developing a standard similar to MMDS called Hiperaccess.

WiMax is an emerging broadband wireless technology based on the IEEE 802.16 standard [16; 17]. The core 802.16 specification is a standard for broadband wireless access systems operating at radio frequencies between 2 GHz and 11 GHz for non–line-of-sight operation, and between 10 GHz and 66 GHz for line-of-sight operation. Data rates of around 40 Mbps will be available for fixed users and 15 Mbps for mobile users, with a range of several kilometers. Many manufacturers of laptops and PDAs (personal digital assistants) are planning to incorporate WiMax once it becomes available to satisfy demand for constant Internet access and email exchange from any location. WiMax will compete with wireless LANs, 3G cellular services, and possibly wireline services like cable and DSL (digital subscriber line). The ability of WiMax to challenge or supplant these systems will depend on its relative performance and cost, which remain to be seen.

1.4.6 Paging Systems

Paging systems broadcast a short paging message simultaneously from many tall base stations or satellites transmitting at very high power (hundreds of watts to kilowatts). Systems with terrestrial transmitters are typically localized to a particular geographic area, such as a city or metropolitan region, while geosynchronous satellite transmitters provide national or international coverage. In both types of systems, no location management or routing functions are needed because the paging message is broadcast over the entire coverage area. The high complexity and power of the paging transmitters allows low-complexity, low-power,

Amazon
EX1035 Page 50

pocket paging receivers capable of long usage times from small and lightweight batteries. In addition, the high transmit power allows paging signals to easily penetrate building walls. Paging service also costs less than cellular service, both for the initial device and for the monthly usage charge, although this price advantage has declined considerably in recent years as cellular prices dropped. The low cost, small and lightweight handsets, long battery life, and ability of paging devices to work almost anywhere indoors or outdoors are the main reasons for their appeal.

Early radio paging systems were analog 1-bit messages signaling a user that someone was trying to reach him or her. These systems required callback over a landline telephone to obtain the phone number of the paging party. The system evolved to allow a short digital message, including a phone number and brief text, to be sent to the pagee as well. Radio paging systems were initially extremely successful, with a peak of 50 million subscribers in the United States alone. However, their popularity began to wane with the widespread penetration and competitive cost of cellular telephone systems. Eventually the competition from cellular phones forced paging systems to provide new capabilities. Some implemented "answer-back" capability (i.e., two-way communication). This required a major change in design of the pager because now it needed to transmit signals in addition to receiving them, and the transmission distance to a satellite or base station can be very large. Paging companies also teamed up with palmtop computer makers to incorporate paging functions into these devices [18]. Despite these developments, the market for paging devices has shrunk considerably, although there is still a niche market among doctors and other professionals who must be reachable anywhere.

1.4.7 Satellite Networks

Commercial satellite systems are another major component of the wireless communications infrastructure [2; 3]. Geosynchronous systems include Inmarsat and OmniTRACS. The former is geared mainly for analog voice transmission from remote locations. For example, it is commonly used by journalists to provide live reporting from war zones. The first-generation Inmarsat-A system was designed for large (1-m parabolic dish antenna) and rather expensive terminals. Newer generations of Inmarsats use digital techniques to enable smaller, less expensive terminals, about the size of a briefcase. Qualcomm's OmniTRACS provides two-way communications as well as location positioning. The system is used primarily for alphanumeric messaging and location tracking of trucking fleets. There are several major difficulties in providing voice and data services over geosynchronous satellites. It takes a great deal of power to reach these satellites, so handsets are typically large and bulky. In addition, there is a large round-trip propagation delay; this delay is quite noticeable in two-way voice communication. Geosynchronous satellites also have fairly low data rates of less than 10 kbps. For these reasons, lower-orbit LEO satellites were thought to be a better match for voice and data communications.

LEO systems require approximately 30–80 satellites to provide global coverage, and plans for deploying such constellations were widespread in the late 1990s. One of the most ambitious of these systems, the Iridium constellation, was launched at that time. However, the cost to build, launch, and maintain these satellites is much higher than costs for terrestrial base stations. Although these LEO systems can certainly complement terrestrial systems in low-population areas and are also appealing to travelers desiring just one handset and phone

Amazon
EX1035 Page 51

number for global roaming, the growth and diminished cost of cellular prevented many ambitious plans for widespread LEO voice and data systems from materializing. Iridium was eventually forced into bankruptcy and disbanded, and most of the other systems were never launched. An exception to these failures was the Globalstar LEO system, which currently provides voice and data services over a wide coverage area at data rates under 10 kbps. Some of the Iridium satellites are still operational as well.

The most appealing use for a satellite system is the broadcast of video and audio over large geographic regions. Approximately 1 in 8 U.S. homes have direct broadcast satellite service, and satellite radio is also emerging as a popular service. Similar audio and video satellite broadcasting services are widespread in Europe. Satellites are best tailored for broadcasting, since they cover a wide area and are not compromised by an initial propagation delay. Moreover, the cost of the system can be amortized over many years and many users, making the service quite competitive in cost with that of terrestrial entertainment broadcasting systems.

1.4.8 Low-Cost, Low-Power Radios: Bluetooth and ZigBee

As radios decrease their cost and power consumption, it becomes feasible to embed them into more types of electronic devices, which can be used to create smart homes, sensor networks, and other compelling applications. Two radios have emerged to support this trend: Bluetooth and ZigBee.

Bluetooth[4] radios provide short-range connections between wireless devices along with rudimentary networking capabilities. The Bluetooth standard is based on a tiny microchip incorporating a radio transceiver that is built into digital devices. The transceiver takes the place of a connecting cable for devices such as cell phones, laptop and palmtop computers, portable printers and projectors, and network access points. Bluetooth is mainly for short-range communications – for example, from a laptop to a nearby printer or from a cell phone to a wireless headset. Its normal range of operation is 10 m (at 1-mW transmit power), and this range can be increased to 100 m by increasing the transmit power to 100 mW. The system operates in the unlicensed 2.4-GHz frequency band, so it can be used worldwide without any licensing issues. The Bluetooth standard provides one asynchronous data channel at 723.2 kbps. In this mode, also known as Asynchronous Connection-Less (ACL), there is a reverse channel with a data rate of 57.6 kbps. The specification also allows up to three synchronous channels each at a rate of 64 kbps. This mode, also known as Synchronous Connection Oriented (SCO), is mainly used for voice applications such as headsets but can also be used for data. These different modes result in an aggregate bit rate of approximately 1 Mbps. Routing of the asynchronous data is done via a packet switching protocol based on frequency hopping at 1600 hops per second. There is also a circuit switching protocol for the synchronous data.

Bluetooth uses frequency hopping for multiple access with a carrier spacing of 1 MHz. Typically, up to eighty different frequencies are used for a total bandwidth of 80 MHz. At any given time, the bandwidth available is 1 MHz, with a maximum of eight devices sharing the bandwidth. Different logical channels (different hopping sequences) can simultaneously

[4] The Bluetooth standard is named after Harald I Bluetooth, the king of Denmark between 940 and 985 A.D. who united Denmark and Norway. Bluetooth proposes to unite devices via radio connections, hence the inspiration for its name.

Amazon
EX1035 Page 52

share the same 80-MHz bandwidth. Collisions will occur when devices in different piconets that are on different logical channels happen to use the same hop frequency at the same time. As the number of piconets in an area increases, the number of collisions increases and performance degrades.

The Bluetooth standard was developed jointly by 3 Com, Ericsson, Intel, IBM, Lucent, Microsoft, Motorola, Nokia, and Toshiba. The standard has now been adopted by over 1,300 manufacturers, and many consumer electronic products incorporate Bluetooth. These include wireless headsets for cell phones, wireless USB or RS232 connectors, wireless PCMCIA cards, and wireless settop boxes.

The ZigBee[5] radio specification is designed for lower cost and power consumption than Bluetooth [19]. Its specification is based on the IEEE 802.15.4 standard. The radio operates in the same ISM band as Bluetooth and is capable of connecting 255 devices per network. The specification supports data rates of up to 250 kbps at a range of up to 30 m. These data rates are slower than Bluetooth, but in exchange the radio consumes significantly less power with a larger transmission range. The goal of ZigBee is to provide radio operation for months or years without recharging, thereby targeting applications such as sensor networks and inventory tags.

1.4.9 Ultrawideband Radios

Ultrawideband (UWB) radios are extremely wideband radios with very high potential data rates [20; 21]. The concept of ultrawideband communications actually originated with Marconi's spark-gap transmitter, which occupied a very wide bandwidth. However, since only a single low-rate user could occupy the spectrum, wideband communications was abandoned in favor of more efficient communication techniques. Renewed interest in wideband communications was spurred by the FCC's decision in 2002 to allow operation of UWB devices underlayed beneath existing users in the 3.1–10.6-GHz range. The underlay in theory interferes with all systems in that frequency range, including critical safety and military systems, unlicensed systems such as 802.11 wireless LANs and Bluetooth, and cellular systems where operators paid billions of dollars for dedicated spectrum use. The FCC's ruling was quite controversial given the vested interest in interference-free spectrum of these users. To minimize the impact of UWB on primary band users, the FCC put in place severe transmit power restrictions. This requires UWB devices to be within close proximity of their intended receiver.

Ultrawideband radios come with unique advantages that have long been appreciated by the radar and communications communities. Their wideband nature provides precise ranging capabilities. Moreover, the available UWB bandwidth has the potential for extremely high data rates. Finally, power restrictions dictate that the devices be small and with low power consumption.

Initial UWB systems used ultrashort pulses with simple amplitude or position modulation. Multipath can significantly degrade performance of such systems, and proposals to mitigate the effects of multipath include equalization and multicarrier modulation. Precise

[5] ZigBee takes its name from the dance that honey bees use to communicate information about newly found food sources to other members of the colony.

Amazon
EX1035 Page 53

and rapid synchronization is also a big challenge for these systems. Although many technical challenges remain, the appeal of UWB technology has sparked great interest both commercially and in the research community to address these issues.

1.5 The Wireless Spectrum

1.5.1 Methods for Spectrum Allocation

Most countries have government agencies responsible for allocating and controlling use of the radio spectrum. In the United States, spectrum is allocated by the Federal Communications Commission (FCC) for commercial use and by the Office of Spectral Management (OSM) for military use. Commercial spectral allocation is governed in Europe by the European Telecommunications Standards Institute (ETSI) and globally by the International Telecommunications Union (ITU). Governments decide how much spectrum to allocate between commercial and military use, and this decision is dynamic depending on need. Historically the FCC allocated spectral blocks for specific uses and assigned licenses to use these blocks to specific groups or companies. For example, in the 1980s the FCC allocated frequencies in the 800-MHz band for analog cellular phone service and provided spectral licenses to two operators in each geographical area based on a number of criteria. The FCC and regulatory bodies in other countries still allocate spectral blocks for specific purposes, but these blocks are now commonly assigned through spectral auctions to the highest bidder. Some argue that this market-based method is the fairest and most efficient way for governments to allocate the limited spectral resource and that it provides significant revenue to the government besides; others believe that this mechanism stifles innovation, limits competition, and hurts technology adoption. Specifically, the high cost of spectrum dictates that only large companies or conglomerates can purchase it. Moreover, the large investment required to obtain spectrum can delay the ability to invest in infrastructure for system rollout and results in high initial prices for the end user. The 3G spectral auctions in Europe, in which several companies ultimately defaulted, have provided ammunition to the opponents of spectral auctions.

In addition to spectral auctions, spectrum can be set aside in specific frequency bands that are free to use without a license according to a specific set of etiquette rules. The rules may correspond to a specific communications standard, power levels, and so forth. The purpose of these *unlicensed bands* is to encourage innovation and low-cost implementation. Many extremely successful wireless systems operate in unlicensed bands, including wireless LANs, Bluetooth, and cordless phones. A major difficulty of unlicensed bands is that they can be killed by their own success. If many unlicensed devices in the same band are used in close proximity then they interfere with each other, which can make the band unusable.

Underlay systems are another alternative for allocating spectrum. An underlay system operates as a secondary user in a frequency band with other primary users. Operation of secondary users is typically restricted so that primary users experience minimal interference. This is usually accomplished by restricting the power per hertz of the secondary users. UWB is an example of an underlay system, as are unlicensed systems in the ISM frequency bands. Such underlay systems can be extremely controversial given the complexity of characterizing how interference affects the primary users. Yet the trend toward spectrum allocation for

Amazon
EX1035 Page 54

underlays appears to be accelerating, which is mainly due to the scarcity of available spectrum for new systems and applications.

Satellite systems cover large areas spanning many countries and sometimes the globe. For wireless systems that span multiple countries, spectrum is allocated by the International Telecommunications Union Radio Communications group (ITU-R). The standards arm of this body, ITU-T, adopts telecommunication standards for global systems that must interoperate across national boundaries.

There is some movement within regulatory bodies worldwide to change the way spectrum is allocated. Indeed, the basic mechanisms for spectral allocation have not changed much since the inception of regulatory bodies in the early to mid-1900s, although spectral auctions and underlay systems are relatively new. The goal of changing spectrum allocation policy is to take advantage of the technological advances in radios to make spectrum allocation more efficient and flexible. One compelling idea is the notion of a smart or cognitive radio. This type of radio could sense its spectral environment to determine dimensions in time, space, and frequency where it would not cause interference to other users even at moderate to high transmit powers. If such radios could operate over a wide frequency band, this would open up huge amounts of new bandwidth and tremendous opportunities for new wireless systems and applications. However, many technology and policy hurdles must be overcome to allow such a radical change in spectrum allocation.

1.5.2 Spectrum Allocations for Existing Systems

Most wireless applications reside in the radio spectrum between 30 MHz and 40 GHz. These frequencies are natural for wireless systems because they are not affected by the earth's curvature, require only moderately sized antennas, and can penetrate the ionosphere. Note that the required antenna size for good reception is inversely proportional to the signal frequency, so moving systems to a higher frequency allows for more compact antennas. However, received signal power with nondirectional antennas is proportional to the inverse of frequency squared, so it is harder to cover large distances with higher-frequency signals.

As discussed in the previous section, spectrum is allocated either in licensed bands (which regulatory bodies assign to specific operators) or in unlicensed bands (which can be used by any system subject to certain operational requirements). Table 1.1 shows the licensed spectrum allocated to major commercial wireless systems in the United States today; there are similar allocations in Europe and Asia.

Note that digital TV is slated for the same bands as broadcast TV, so all broadcasters must eventually switch from analog to digital transmission. Also, the 3G broadband wireless spectrum is currently allocated to UHF television stations 60–69 but is slated to be reallocated. Both 1G analog and 2G digital cellular services occupy the same cellular band at 800 MHz, and the cellular service providers decide how much of the band to allocate between digital and analog service.

Unlicensed spectrum is allocated by the governing body within a given country. Often different countries try to match their frequency allocation for unlicensed use so that technology developed for that spectrum is compatible worldwide. Table 1.2 shows the unlicensed spectrum allocations in the United States.

Amazon
EX1035 Page 55

Table 1.1: Licensed U.S. spectrum allocations

Service/system	Frequency span
AM radio	535–1605 kHz
FM radio	88–108 MHz
Broadcast TV (channels 2–6)	54–88 MHz
Broadcast TV (channels 7–13)	174–216 MHz
Broadcast TV (UHF)	470–806 MHz
Broadband wireless	746–764 MHz, 776–794 MHz
3G broadband wireless	1.7–1.85 MHz, 2.5–2.69 MHz
1G and 2G digital cellular phones	806–902 MHz
Personal communication systems (2G cell phones)	1.85–1.99 GHz
Wireless communications service	2.305–2.32 GHz, 2.345–2.36 GHz
Satellite digital radio	2.32–2.325 GHz
Multichannel multipoint distribution service (MMDS)	2.15–2.68 GHz
Digital broadcast satellite (satellite TV)	12.2–12.7 GHz
Local multipoint distribution service (LMDS)	27.5–29.5 GHz, 31–31.3 GHz
Fixed wireless services	38.6–40 GHz

Table 1.2: Unlicensed U.S. spectrum allocations

Band	Frequency
ISM band I (cordless phones, 1G WLANs)	902–928 MHz
ISM band II (Bluetooth, 802.11b and 802.11g WLANs)	2.4–2.4835 GHz
ISM band III (wireless PBX)	5.725–5.85 GHz
U-NII band I (indoor systems, 802.11a WLANs)	5.15–5.25 GHz
U-NII band II (short-range outdoor systems, 80211a WLANs)	5.25–5.35 GHz
U-NII band III (long-range outdoor systems, 80211a WLANs)	5.725–5.825 GHz

ISM Band I has licensed users transmitting at high power who interfere with the unlicensed users. Therefore, the requirements for unlicensed use of this band is highly restrictive and performance is somewhat poor. The U-NII bands have a total of 300 MHz of spectrum in three separate 100-MHz bands, with slightly different power restrictions on each band. Many unlicensed systems operate in these bands.

1.6 Standards

Communication systems that interact with each other require standardization. Standards are typically decided on by national or international committees; in the United States this role is played by the Telecommunications Industry Association (TIA). These committees adopt standards that are developed by other organizations. The IEEE is the major player for standards development in the United States, while ETSI plays this role in Europe. Both groups follow a lengthy process for standards development that entails input from companies and other interested parties as well as a long and detailed review process. The standards process

Amazon
EX1035 Page 56

is a large time investment, but companies participate because incorporating their ideas into the standard gives them an advantage in developing the resulting system. In general, standards do not include all the details on all aspects of the system design. This allows companies to innovate and differentiate their products from other standardized systems. The main goal of standardization is enabling systems to interoperate.

In addition to ensuring interoperability, standards also allow economies of scale and pressure prices lower. For example, wireless LANs typically operate in the unlicensed spectral bands, so they are not required to follow a specific standard. The first generation of wireless LANs were not standardized and so specialized components were needed for many systems, leading to excessively high cost that, when coupled with poor performance, led to limited adoption. This experience resulted in a strong push to standardize the next wireless LAN generation, which yielded the highly successful IEEE 802.11 family of standards.

There are, of course, disadvantages to standardization. The standards process is not perfect, as company participants often have their own agenda, which does not always coincide with the best technology or the best interests of consumers. In addition, the standards process must be completed at some point, after which it becomes more difficult to add new innovations and improvements to an existing standard. Finally, the standards process can become quite politicized. This happened with the second generation of cellular phones in the United States and ultimately led to the adoption of two different standards, a bit of an oxymoron. The resulting delays and technology split put the United States well behind Europe in the development of 2G cellular systems. Despite its flaws, standardization is clearly a necessary and often beneficial component of wireless system design and operation. However, it would benefit everyone in the wireless technology industry if some of the problems in the standardization process could be mitigated.

PROBLEMS

1-1. As storage capability increases, we can store larger and larger amounts of data on smaller and smaller storage devices. Indeed, we can envision microscopic computer chips storing terraflops of data. Suppose this data is to be transfered over some distance. Discuss the pros and cons of putting a large number of these storage devices in a truck and driving them to their destination rather than sending the data electronically.

1-2. Describe two technical advantages and disadvantages of wireless systems that use bursty data transmission rather than continuous data transmission.

1-3. Fiber optic cable typically exhibits a probability of bit error of $P_b = 10^{-12}$. A form of wireless modulation, DPSK, has $P_b = 1/2\bar{\gamma}$ in some wireless channels, where $\bar{\gamma}$ is the average SNR. Find the average SNR required to achieve the same P_b in the wireless channel as in the fiber optic cable. Because of this extremely high required SNR, wireless channels typically have P_b much larger than 10^{-12}.

1-4. Find the round-trip delay of data sent between a satellite and the earth for LEO, MEO, and GEO satellites assuming the speed of light is $3 \cdot 10^8$ m/s. If the maximum acceptable delay for a voice system is 30 ms, which of these satellite systems would be acceptable for two-way voice communication?

Amazon
EX1035 Page 57

1-5. What applications might significantly increase the demand for wireless data?

1-6. This problem illustrates some of the economic issues facing service providers as they migrate away from voice-only systems to mixed-media systems. Suppose you are a service provider with 120 kHz of bandwidth that you must allocate between voice and data users. The voice users require 20 kHz of bandwidth and the data users require 60 kHz of bandwidth. So, for example, you could allocate all of your bandwidth to voice users, resulting in six voice channels, or you could divide the bandwidth into one data channel and three voice channels, etc. Suppose further that this is a time-division system with timeslots of duration T. All voice and data call requests come in at the beginning of a timeslot, and both types of calls last T seconds. There are six independent voice users in the system: each of these users requests a voice channel with probability .8 and pays \$.20 if his call is processed. There are two independent data users in the system: each of these users requests a data channel with probability .5 and pays \$1 if his call is processed. How should you allocate your bandwidth to maximize your expected revenue?

1-7. Describe three disadvantages of using a wireless LAN instead of a wired LAN. For what applications will these disadvantages be outweighed by the benefits of wireless mobility? For what applications will the disadvantages override the advantages?

1-8. Cellular systems have migrated to smaller cells in order to increase system capacity. Name at least three design issues that are complicated by this trend.

1-9. Why does minimizing the reuse distance maximize the spectral efficiency of a cellular system?

1-10. This problem demonstrates the capacity increase associated with a decrease in cell size. Consider a square city of 100 square kilometers. Suppose you design a cellular system for this city with square cells, where every cell (regardless of cell size) has 100 channels and so can support 100 active users. (In practice, the number of users that can be supported per cell is mostly independent of cell size as long as the propagation model and power scale appropriately.)

(a) What is the total number of active users that your system can support for a cell size of 1 km^2?

(b) What cell size would you use if your system had to support 250,000 active users?

Now we consider some financial implications based on the fact that users do not talk continuously. Assume that Friday from 5–6 P.M. is the busiest hour for cell-phone users. During this time, the average user places a single call, and this call lasts two minutes. Your system should be designed so that subscribers need tolerate no greater than a 2% blocking probability during this peak hour. (Blocking probability is computed using the Erlang B model: $P_b = (A^C/C!)/\left(\sum_{k=0}^{C} A^k/k!\right)$, where C is the number of channels and $A = U\mu H$ for U the number of users, μ the average number of call requests per unit time per user, and H the average duration of a call [5, Chap. 3.6].

(c) How many total subscribers can be supported in the macrocell system (1-km^2 cells) and in the microcell system (with cell size from part (b))?

(d) If a base station costs \$500,000, what are the base station costs for each system?

(e) If the monthly user fee in each system is $50, what will be the monthly revenue in each case? How long will it take to recoup the infrastructure (base station) cost for each system?

1-11. How many CDPD data lines are needed to achieve the same data rate as the average rate of WiMax?

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Amazon
EX1035 Page 59

Appendix D: Summary of Wireless Standards

This chapter summarizes the technical details associated with the two most prevalent wireless systems in operation today: cellular phones and wireless LANs. It also summarizes the specifications for three short range wireless network standards that have emerged to support a broad range of applications. More details on wireless standards can be found in [1; 2; 3; 4; 5; 6].

D.1 Cellular Phone Standards

D.1.2 First-Generation Analog Systems

In this section we summarize cellular phone standards. We begin with the standards for first-generation (1G) analog cellular phones, whose main characteristics are summarized in Table D.1. Systems based on these standards were widely deployed in the 1980s. While many of these systems have been replaced by digital cellular systems, there are many places throughout the world where these analog systems are still in use. The best known standard is the Advanced Mobile Phone Service (AMPS), developed by Bell Labs in the 1970s and first used commercially in the United States in 1983. After its U.S. deployment, many other countries adopted AMPS as well. This system has a narrowband version, narrowband AMPS (N-AMPS), with voice channels that are one third the bandwidth of regular AMPS. Japan deployed the first commercial cellular phone system in 1979 with the NTT (MCS-L1) standard based on AMPS, but at a higher frequency and with voice channels of slightly lower bandwidth. Europe also developed a similar standard to AMPS called the Total Access Communication System (TACS), which operates at a higher frequency and with smaller bandwidth channels than AMPS. It was deployed in the United Kingdom and in other European countries as well as outside Europe. The frequency range for TACS was extended in the U.K. to obtain more channels, leading to a variation called ETACS. A variation of the TACS system called JTACS was deployed in metropolitan areas of Japan in 1989 to provide higher capacity than the NTT system. JTACS operates at a slightly higher frequency than TACS or ETACS, and it has a bandwidth-efficient version (called NTACS) where voice channels occupy half the bandwidth of the channnels in JTACS. In addition to TACS, countries in Europe had different incompatible standards at different frequencies for analog cellular, including the Nordic Mobile Telephone (NMT) standard in Scandanavia, the Radiocom 2000 (RC2000) standard in

Amazon
EX1035 Page 60

Table D.1: First-generation analog cellular phone standards

Parameter	AMPS	TACS	NMT (450/900)	NTT	C-450	RC2000
Uplink frequencies (MHz)	824–849	890–915	453–458/890–915	925–940[a]	450–455.74	414.8–418[b]
Downlink frequencies (MHz)	869–894	935–960	463–468/935–960	870–885	460–465.74	424.8–428
Modulation	FM	FM	FM	FM	FM	FM
Channel spacing (kHz)	30	25	25/12.5	25	10	12.5
Number of channels	832	1000	180/1999	600	573	256
Multiple access	FDMA	FDMA	FDMA	FDMA	FDMA	FDMA

[a] NTT also operated in several other frequency bands around 900 MHz.
[b] RC2000 also operated in several other frequency bands around 200 MHz.

France, and the C-450 standard in Germany and Portugal. The incompatibilities made it impossible to roam between European countries with a single analog phone, which motivated the need for one unified cellular standard and frequency allocation throughout Europe.

D.1.2 Second-Generation Digital Systems

Next we consider second-generation (2G) digital cellular phone standards, whose main characteristics are summarized in Table D.2. These systems were mostly deployed in the early 1990s. As a result of the incompatibilities in the first-generation analog systems, in 1982 the Groupe Spécial Mobile (GSM) was formed to develop a uniform digital cellular standard for all of Europe. The TACS spectrum in the 900-MHz band was allocated for GSM operation across Europe in order to facilitate roaming between countries. In 1989 the GSM specification was finalized and the system was launched in 1991, although availability was limited until 1992. The GSM standard uses TDMA combined with slow frequency hopping to combat out-of-cell interference. Convolutional coding and parity-check codes along with interleaving are used for error detection and correction. The standard also includes an equalizer to compensate for frequency-selective fading. The GSM standard is used in about 66% of the world's cell phones, with more than 470 GSM operators in 172 countries supporting over a billion users. As the GSM standard became more global, the meaning of the acronym was changed to the Global System for Mobile Communications.

Although Europe got an early jump on developing 2G digital systems, the United States was not far behind. In 1992 the IS-54 digital cellular standard was finalized, with commercial deployment beginning in 1994. This standard uses the same channel spacing (30 kHz) as AMPS to facilitate the analog-to-digital transition for wireless operators, along with a TDMA multiple access scheme to improve handoff and control signaling as compared with analog FDMA. The IS-54 standard (also called the North American Digital Cellular standard) was improved over time, and these improvements evolved into the IS-136 standard, which subsumed the original standard. Similar to the GSM standard, the IS-136 standard uses parity-check codes, convolutional codes, interleaving, and equalization.

A competing standard for 2G systems based on CDMA was proposed by Qualcomm in the early 1990s. The standard, called IS-95 or IS-95a, was finalized in 1993 and deployed

Table D.2: Second-generation digital cellular phone standards

Parameter	GSM	IS-136	IS-95 (cdmaOne)	PDC
Uplink frequencies (MHz)	890–915	824–849	824–849	940–956, 1429–1453
Downlink frequencies (MHz)	935–960	869–894	869–894	810–826, 1477–1501
Carrier separation (kHz)	200	30	1250	25
Number of channels	1000	832[a]	~2500	1600[a]
Modulation	GMSK	$\pi/4$-D-QPSK	BPSK/QPSK	$\pi/4$-D-QPSK
Compressed speech rate (Kbps)	13	7.95	1.2–9.6 (variable)	6.7
Channel data rate (Kbps)	270.833	48.6	(1.2288 Mchips/s)	42
Data code rate	1/2	1/2	1/2 (DL), 1/3 (UL)	1/2
ISI reduction/diversity	Equalizer	Equalizer	RAKE, SHO	Equalizer
Multiple access	TDMA/SFH	TDMA	CDMA	TDMA

[a] Three users per channel.

commercially under the name cdmaOne in 1995. Like IS-136, IS-95 was designed to be compatible with AMPS so that the two systems could coexist in the same frequency band. In CDMA all users are superimposed on top of each other with spreading codes that can separate out the users at the receiver. Thus, channel data rate does not apply to just one user, as in TDMA systems. The channel chip rate is 1.2288 Mchips per second for a total spreading factor of 128 for both the uplink and downlink. The spreading process in IS-95 is different for the downlink (DL) and the uplink (UL), with spreading on both links accomplished through a combination of spread-spectrum modulation and coding. On the downlink, data is first rate-1/2 convolutionally encoded and interleaved, then modulated by one of 64 orthogonal spreading sequences (Walsh functions). Next, a synchronized scrambling sequence unique to each cell is superimposed on top of the Walsh function to reduce interference between cells. The scrambling requires synchronization between base stations. Uplink spreading is accomplished using a combination of a rate-1/3 convolutional code with interleaving, modulation by an orthogonal Walsh function, and modulation by a nonorthogonal user/base station–specific code. The IS-95 standard includes a parity-check code for error detection, as well as power control for the reverse link to avoid the near–far problem. A three-finger RAKE receiver is also specified to provide diversity and to compensate for ISI. A form of base station diversity called soft handoff (SHO), whereby a mobile maintains a connection to both the new and old base stations during handoff and combines their signals, is also included in the standard. CDMA has some advantages over TDMA for cellular systems, including no need for frequency planning, SHO capabilities, the ability to exploit voice activity to increase capacity, and no hard limit on the number of users that can be accommodated in the system. There was much debate about the relative merits of the IS-136 and IS-95 standards throughout the early 1990s, with claims that IS-95 could achieve 20 times the capacity of AMPS whereas IS-136 could only achieve 3 times this capacity. In the end, both systems turned out to achieve approximately the same capacity increase over AMPS.

The 2G digital cellular standard in Japan, called the Personal Digital Cellular (PDC) standard, was established in 1991 and deployed in 1994. It is similar to the IS-136 standard but with 25-kHz voice channels for compatibility with the Japanese analog systems. This system operates in both the 800–900-MHz and 1400-MHz frequency bands. Each channel

Amazon
EX1035 Page 62

Table D.3: 2G enhancements to support 2.5G data capabilities

2G standard	2.5G enhancement	Technique	Data rates (kbps) maximum/realized
GSM	HSCSD	Aggregate timeslots	57.6/14.4–57.6
GSM/IS-136	GPRS	Aggregate timeslots with packet switching	140.8/56
	EDGE	GPRS with variable mod./cod.	384/200
IS-95	IS-95b	Aggregate Walsh functions	115/64

accommodates three users, and six users per channel can be accommodated with a higher compression rate.

D.1.3 Evolution of Second-Generation Systems

In the late 1990s, second-generation systems evolved in two directions: they were ported to higher frequencies as more cellular bandwidth became available in Europe and the United States, and they were modified to support data services in addition to voice. Specifically, in 1994 the FCC began auctioning spectrum in the Personal Communications Service (PCS) band at 1.9 GHz (1900 MHz) for cellular systems. Operators purchasing spectrum in this band could adopt any standard. Different operators chose different standards, so GSM, IS-136, and IS-95 were all deployed at 1.9 GHz in different parts of the country, making nationwide roaming with a single phone difficult. In fact, many of the initial digital cellphones included an analog AMPS mode in case the digital system was not available. GSM systems operating in the PCS band are sometimes referred to as PCS 1900 systems. The IS-136 and IS-95 (cdmaOne) standards translated to the PCS band go by the same names. Europe allocated additional cellular spectrum in the 1.8-GHz band. The standard for this frequency band, called GSM 1800 or DCS 1800 (for Digital Cellular System), uses GSM as the core standard with some modifications to allow overlays of macrocells and microcells. Note that second-generation cordless phones such as Digital Enhanced Cordless Telecommunications (DECT), the Personal Access Communications System (PACS), and the Personal Handyphone System (PHS) also operate in the 1.9-GHz frequency band, but these systems are mostly within buildings supporting private branch exchange (PBX) services.

Once digital cellular became available, operators began incorporating data services in addition to voice. The 2G systems with added data capabilities are sometimes referred to as 2.5G systems. The enhancements to 2G systems made to support data services are summarized in Table D.3. GSM systems followed several different upgrade paths to provide data services. The simplest, called High Speed Circuit Switched Data (HSCSD), allows up to four consecutive timeslots to be assigned to a single user, thereby providing a maximum transmission rate of up to 57.6 kbps. Circuit switching is quite inefficient for data, so a more complex enhancement provides for packet-switched data layered on top of the circuit-switched voice. This enhancement is referred to as General Packet Radio Service (GPRS). A maximum data rate of 171.2 kbps is possible with GPRS when all eight timeslots of a GSM frame are allocated to a single user. The data rates of GPRS are further enhanced through variable-rate modulation and coding, referred to as Enhanced Data rates for GSM Evolution (EDGE).

Table D.4: 3G digital cellular phone standards

	cdma2000				W-CDMA		
Parameter	1X	1XEV-DO	1XEV-DV	3X	UMTS	FOMA	J-phone
Channel bandwidth (MHz)	1.25	1.25	1.25	3.75	5	5	5
Chip rate (Mchips/s)	1.2288	1.2288	1.2288	3.6864	3.84	3.84	3.84
Peak data rate (Mbps)	.144	2.4	4.8	5–8	2.4[a]	2.4[a]	2.4[a]
Modulation	QPSK/MPSK (DL), BPSK/QPSK (UL)				QPSK (DL), BPSK (UL)		
Coding	Convolutional (low rate), Turbo (high rate)						
Power control (Hz)	800	800	800	800	1500	1500	1500

[a] 8–10 Mbps with HSDPA.

EDGE provides data rates up to 384 kbps with a bit rate of 48–69.2 kbps per timeslot. GPRS and EDGE are compatible with IS-136 as well as GSM, thus providing a convergent upgrade path for both of these systems.

The IS-95 standard was modified to provide data services by assigning multiple orthogonal Walsh functions to a single user. A maximum of eight functions can be assigned, leading to a maximum data rate of 115.2 kbps, although in practice only about 64 kbps is achieved. This evolution is referred to as the IS-95b standard.

D.1.4 Third-Generation Systems

The fragmentation of standards and frequency bands associated with 2G systems led the International Telecommunications Union (ITU) in the late 1990s to formulate a plan for a single global frequency band and standard for third-generation (3G) digital cellular systems. The standard was named the International Mobile Telephone 2000 (IMT-2000) standard with a desired system rollout in the 2000 timeframe. In addition to voice services, IMT-2000 was to provide Mbps data rates for demanding applications such as broadband Internet access, interactive gaming, and high-quality audio and video entertainment. Agreement on a single standard did not materialize, with most countries supporting one of two competing standards: cdma2000 (backward compatible with cdmaOne), supported by the Third Generation Partnership Project 2 (3GPP2); and wideband CDMA (W-CDMA, backward compatible with GSM and IS-136), supported by the Third Generation Partnership Project 1 (3GPP1). The main characteristics of these two 3G standards are summarized in Table D.4. Both standards use CDMA with power control and RAKE receivers, but the chip rates and other specification details are different. In particular, cdma2000 and W-CDMA are not compatible standards, so a phone must be dual-mode in order to operate with both systems. A third 3G standard, TD-SCDMA, is under consideration in China but is unlikely to be adopted elsewhere. The key difference between TD-SCDMA and the other 3G standards is its use of TDD instead of FDD for uplink/downlink signaling.

The cdma2000 standard builds on cdmaOne to provide an evolutionary path to 3G. The core of the cdma2000 standard is referred to cdma2000 1X or cdma2000 1XRTT, indicating that the radio transmission technology (RTT) operates in one pair of 1.25-MHz radio channels and is thus backward compatible with cdmaOne systems. The cdma2000 1X system doubles the voice capacity of cdmaOne systems and supports high-speed data with projected

Amazon
EX1035 Page 64

Table D.5: 802.11 wireless LAN link layer standards

Parameter	802.11	802.11a	802.11b	802.11g
Bandwidth (MHz)	83.5	300	83.5	83.5
Frequency range (GHz)	2.4–2.4835	5.15–5.25 (lower) 5.25–5.35 (middle) 5.725–5.825 (upper)	2.4–2.4835	2.4–2.4835
Number of channels	3	12 (4 per subband)	3	3
Modulation	BPSK, QPSK DSSS, FHSS	BPSK, QPSK, MQAM OFDM	BPSK, QPSK DSSS	BPSK, QPSK, MQAM OFDM
Coding	Undefined	Convolutional (rate 1/2, 2/3, 3/4)	Barker, CCK	Convolutional (rate 1/2, 2/3, 3/4)
Maximum data rate (Mbps)	2	54	11	54
Range (m)	Undefined	27–30 (lower band)	75–100	30
Random access	CSMA/CA	CSMA/CA	CSMA/CA	CSMA/CA

peak rates of about 300 kbps and actual rates of about 144 kbps. There are two evolutions of this core technology to provide high data rates (referred to as HDR service) above 1 Mbps; these evolutions are referred to as cdma2000 1XEV. The first phase of evolution, cdma2000 1XEV-DO (data only), enhances the cdmaOne system using a separate 1.25-MHz dedicated high-speed data channel that supports downlink data rates up to 3 Mbps and uplink data rates up to 1.8 Mbps for an average combined rate of 2.4 Mbps. The second phase of the evolution, cdma2000 1XEV-DV (data and voice), is projected to support up to 4.8-Mbps data rates as well as legacy 1X voice users, 1XRTT data users, and 1XEV-DO data users – and all within the same radio channel. Another proposed enhancement to cdma2000 is to aggregate three 1.25-MHz channels into one 3.75-MHz channel. This aggregation is referred to as cdma2000 3X, and its exact specifications are still under development.

W-CDMA is the primary competing 3G standard to cdma2000. It has been selected as the 3G successor to GSM and in this context is referred to as the Universal Mobile Telecommunications System (UMTS). W-CDMA is also used in the Japanese FOMA and J-Phone 3G systems. These different systems share the W-CDMA link layer protocol (air interface) but have different protocols for other aspects of the system such as routing and speech compression. W-CDMA supports peak rates of up to 2.4 Mbps, with typical rates anticipated in the 384-kbps range. W-CDMA uses 5-MHz channels, in contrast to the 1.25-MHz channels of cdma2000. An enhancement to W-CDMA called High Speed Data Packet Access (HSDPA) provides data rates of around 9 Mbps, and this may be the precursor to fourth-generation systems.

D.2 Wireless Local Area Networks

Wireless local area networks (WLANs) are built around the family of IEEE 802.11 standards. The main characteristics of this standards family are summarized in Table D.5. The baseline 802.11 standard, released in 1997, occupies 83.5 MHz of bandwidth in the unlicensed 2.4-GHz frequency band. It specifies PSK modulation with FHSS or DSSS. Data rates of up to 2 Mbps are supported, with CSMA/CA used for random access. The baseline standard

was expanded in 1999 to create the 802.11b standard, operating in the same 2.4-GHz band using only DSSS. This standard uses variable-rate modulation and coding, with BPSK or QPSK for modulation and channel coding via either Barker sequences or complementary code keying (CCK). This leads to a maximum channel rate of 11 Mbps and a maximum user data rate of about 1.6 Mbps. The transmission range is approximately 100 m. The network architecture in 802.11b is specified as either star or peer-to-peer, although the peer-to-peer feature is not typically used. This standard has been widely deployed, with manufacturers integrating 802.11b wireless LAN cards into many laptop computers.

The 802.11a standard was finalized in 1999 as an extension to 802.11 to improve on the 802.11b data rates. The 802.11a standard occupies 300 MHz of spectrum in the 5-GHz U-NII band. In fact, the 300 MHz of bandwidth is segmented into three 100-MHz subbands: a lower band (5.15–5.25 GHz), a middle band (5.25–5.35 GHz), and an upper band (5.725–5.825 GHz). Channels are spaced 20 MHz apart except on the outer edges of the lower and middle bands, where they are spaced 30 MHz apart. Three maximum transmit power levels are specified: 40 mW for the lower band, 200 mW for the middle band, and 800 mW for the upper band. These restrictions imply that the lower band is mostly suitable for indoor applications only, the middle band for indoor and outdoor, and the high band for outdoor. Variable-rate modulation and coding is used on each channel: the modulation varies over BPSK, QPSK, 16-QAM, and 64-QAM, and the convolutional code rate varies over 1/2, 2/3, and 3/4. This leads to a maximum data rate per channel of 54 Mbps. For indoor systems, the 5-GHz carrier coupled with the power restriction in the lower band reduces the range of 802.11a relative to 802.11b and also makes it more difficult for the signal to penetrate walls and other obstructions. The 802.11a standard uses orthogonal frequency division multiplexing (OFDM) multiple access instead of FHSS or DSSS, and in that sense it diverges from the original 802.11 standard.

The 802.11g standard, finalized in 2003, attempts to combine the best of 802.11a and 802.11b, with data rates of up to 54 Mbps in the 2.4-GHz band for greater range. The standard is backward compatible with 802.11b, so 802.11g access points will work with 802.11b wireless network adapters and vice versa. However, 802.11g uses the OFDM, modulation, and coding schemes of 802.11a. Access points and wireless LAN cards are available with all three standards to avoid incompatibilities. The 802.11a/b/g family of standards are collectively referred to as *Wi-Fi,* for wireless fidelity. Extending these standards to frequency allocations in countries other than the United States falls under the 802.11d standard. There are several other standards in the 802.11 family that are under development; these are summarized in Table D.6.

A potential competitor to the 802.11 standards as well as cellular systems is the emerging IEEE 802.16 standard called WiMAX. This standard promises broadband wireless access with data rates on the order of 40 Mbps for fixed users and 15 Mbps for mobile users, with a range of several kilometers. Details of the specification are still being worked out.

D.3 Wireless Short-Distance Networking Standards

This last section summarizes the main characteristics of ZigBee, Bluetooth, and UWB (ultra-wideband), which have emerged to support a wide range of short-distance wireless network

Amazon
EX1035 Page 66

Table D.6: IEEE 802.11 ongoing standards work

Standard	Scope
802.11e	Provides quality of service (QoS) at the MAC layer
802.11f	Roaming protocol across multivendor access points
802.11h	Adds frequency and power management features to 802.11a to make it more compatible with European operation
802.11i	Enhances security and authentication mechanisms
802.11j	Modifies 802.11a link layer to meet Japanese requirements
802.11k	Provides an interface to higher layers for radio and network measurements that can be used for radio resource management
802.11m	Maintenance of 802.11 standard (technical/editorial corrections)
802.11n	MIMO link enhancements to enable higher throughput

Table D.7: Short-range wireless network standards

Parameter	ZigBee (802.15.4)	Bluetooth (802.15.1)	UWB (802.15.3 proposal)
Frequency range (GHz)	2.4–2.4835	2.4–2.4835	3.1–10.6
Bandwidth (MHz)	83.5	83.5	7500
Modulation	BPSK, OQPSK DSSS	GFSK FHSS	BPSK, QPSK OFDM or DSSS
Maximum data rate (Mbps)	.25	1	100
Range (m)	30	10 (100)	10
Power consumption (mW)	5–20	1 (100)	80–150 mW
Access	CSMA/CA (optional TD)	TD	Undefined
Networking	Mesh/Star/Tree	Subnet clusters (8 nodes)	Undefined

applications. These specifications are designed to be compliant with the IEEE 802.15 standards, a family of IEEE standards for short-distance wireless networking called Wireless Personal Area Networks (WPANs). Bluetooth operates in the 2.4-GHz unlicensed band; ZigBee operates in the same band as well as in the 800-MHz and 900-MHz unlicensed bands; and UWB operates across a broad range of frequencies in an underlay to existing systems. ZigBee and Bluetooth include link, MAC, and higher-layer protocol specifications, whereas UWB specificies just the link layer protocol. Table D.7 summarizes the main characteristics of ZigBee (2.4-GHz band only), Bluetooth, and UWB.

ZigBee consists of link and MAC layer protocols that are compliant with the IEEE 802.15.4 standard, as well as higher-layer protocols for ad hoc networking (mesh, star, or tree topologies), power management, and security. ZigBee supports data rates of up to 250 kbps with PSK modulation and DSSS. ZigBee generally targets applications requiring relatively low data rates, low duty cycles, and large networks. Power efficiency is key, with the goal of nodes operating for months or years on a single battery charge.

In contrast to ZigBee, Bluetooth provides up to 1-Mbps data rate, including three guaranteed low-latency voice channels, using FHSS and FSK modulation with Gaussian pulse

shaping (Gaussian FSK or GFSK). Bluetooth normally transmits at a power of 1 mW with a transmission range of about 10 m, although this can be extended to 100 m by increasing the transmit power to 100 mW. Networks are formed in subnet clusters (piconets) of up to eight nodes, with one node acting as a master and the rest as slaves. Time division is used for channel access, with the master node coordinating the frequency-hopping sequence and synchronization with the slave nodes. Extended networks, or *scatternets,* can be formed when one node is part of multiple piconets. However, forming large networks through this approach is difficult owing to the synchronization requirements of FHSS. Portions of the Bluetooth standard were formally adopted by the IEEE as its 802.15.1 standard.

Ultrawideband has significantly higher data rates – up to 100 Mbps – than either ZigBee or Bluetooth. It also occupies significantly more bandwidth and has stringest power restrictions (to prevent it from interfering with primary band users). Thus, it is suitable only for short-range indoor applications. The UWB protocol defines only a link layer technology, so it requires a compatible MAC protocol as well as higher-layer protocols to become part of a wireless network standard. The modulation is BPSK or QPSK, with competing camps recommending either OFDM or DSSS overlayed on the data modulation. Ultrawideband is likely to become the link layer technology for the IEEE 802.15.3 standard, a family of standards for wireless networks supporting imaging and multimedia applications.

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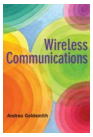
Amazon
EX1035 Page 68

EXHIBIT B



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	View all holdings
Barcode	89090293275
Item ID	23676325460002122
	View all items
Process type	Loan
MMS ID	9969783213602122
	Browse shelf listing
Status	Item not in place

General | ENUM/CHRON | Notes | History

General Information

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Item policy	**general (book)**
Provenance	-
Is magnetic	**No**
PO Line	
Issue date	-
Receiving date	**01/20/2006**
Expected receiving date	-
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Enumeration B	-
Chronology I	-
Chronology J	-
Description	-
Pages	-
Pieces	**1**
Replacement cost	-
Receiving operator	**import**

Physical condition	-
Process type	

Inventory Information

Inventory number	-
Inventory date	-
Inventory price	-

Location Information

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Item call number type	-
Item call number	-
Source (Subfield 2)	-
Storage location ID	-

Temporary Location Information

Item is in temporary location	**No**
Temporary location	-
Temporary call number type	-
Temporary call number	-
Temporary source (Subfield 2)	-
Temporary item policy	-
Due back date	-

Retention Information

Committed to Retain	-
Retention Reason	-
Retention Note	-