Wireless Communications

PRINCIPLES AND PRACTICE

Second Edition

THEODORE S. RAPPAPORT

Prentice Hall Communications Engineering and Emerging Technologies Series
Theodore S. Rappaport, Series Editor

MEDIATEK-1015
IPR2025-00030

WIRELESS COMMUNICATIONS

PRINCIPLES AND PRACTICE

SECOND EDITION

Theodore S. Rappaport

Prentice Hall PTR Communications Engineering and Emerging Technologies Series

Theodore S. Rappaport, *Series Editor*

DOSTERT *Powerline Communications*

DURGIN *Space–Time Wireless Channels*

GARG *Wireless Network Evolution: 2G to 3G*

GARG *IS-95 CDMA and cdma2000: Cellular/PCS Systems Implementation*

GARG & WILKES *Principles and Applications of GSM*

HAĆ *Multimedia Applications Support for Wireless ATM Networks*

KIM *Handbook of CDMA System Design, Engineering, and Optimization*

LIBERTI & RAPPAPORT *Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications*

PAHLAVAN & KRISHNAMURTHY *Principles of Wireless Networks: A Unified Approach*

RAPPAPORT *Wireless Communications: Principles and Practice, Second Edition*

RAZAVI *RF Microelectronics*

REED *Software Radio: A Modern Approach to Radio Engineering*

STARR, CIOFFI & SILVERMAN *Understanding Digital Subscriber Line Technology*

STARR, SORBARA, CIOFFI & SILVERMAN *DSL Advances*

TRANTER, SHANMUGAN, RAPPAPORT & KOSBAR *Principles of Communication Systems Simulation with Wireless Applications*

WIRELESS COMMUNICATIONS

PRINCIPLES AND PRACTICE

SECOND EDITION

Theodore S. Rappaport

Prentice Hall PTR
Upper Saddle River, NJ 07458
www.prenhall.com

Library of Congress Cataloging-in-Publication Data

CIP data available

Production Supervisor: Wil Mara
Publisher: Bernard M. Goodwin
Editorial Assistant: Michelle Vincenti
Marketing Manager: Dan DePasquale
Manufacturing Manager: Alexis R. Heydt
Cover Designer: Anthony Gemmellaro
Composition: Aurelia Scharnhorst

© 2002, 1996 Prentice Hall PTR
Prentice-Hall, Inc.
Upper Saddle River, NJ 07458

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the author and publisher.

The publisher offers discounts on this book when ordered in bulk quantities. For more information contact: Corporate Sales Department, Prentice Hall PTR, One Lake Street, Upper Saddle River, NJ 07458. Phone: 800-382-3419; FAX: 201-236-7141; E-mail: corpsales@prenhall.com.

Printed in the United States of America

10 9 8 7

ISBN 0-13-042232-0

Pearson Education LTD.
Pearson Education Australia PTY, Limited
Pearson Education Singapore, Pte. Ltd
Pearson Education North Asia Ltd
Pearson Education Canada, Ltd.
Pearson Educación de Mexico, S.A. de C.V.
Pearson Education—Japan
Pearson Education Malaysia, Pte. Ltd
Pearson Education, Upper Saddle River, New Jersey

The Lord has blessed me
with a wonderful family
to whom this book is dedicated.

To my wife Brenda Marie,
and to our children
Matthew, Natalie, and Jennifer

Contents

Preface xix

1 Introduction to Wireless Communication Systems 1

1.1 Evolution of Mobile Radio Communications 1
1.2 Mobile Radiotelephony in the U.S. 4
1.3 Mobile Radio Systems Around the World 6
1.4 Examples of Wireless Communication Systems 9
1.4.1 Paging Systems 11
1.4.2 Cordless Telephone Systems 12
1.4.3 Cellular Telephone Systems 13
1.4.3.1 How a Cellular Telephone Call is Made 15
1.4.4 Comparison of Common Wireless Communication Systems 18
1.5 Trends in Cellular Radio and Personal Communications 20
1.6 Problems 22

2 Modern Wireless Communication Systems 25

2.1 Second Generation (2G) Cellular Networks 26
2.1.1 Evolution to 2.5G Wireless Networks 29
2.1.2 Evolution for 2.5G TDMA Standards 30
2.1.2.1 HSCSD for 2.5G GSM 30
2.1.2.2 GPRS for 2.5G GSM and IS-136 31
2.1.2.3 EDGE for 2.5G GSM and IS-136 33
2.1.3 IS-95B for 2.5G CDMA 34
2.2 Third Generation (3G) Wireless Networks 34
2.2.1 3G W-CDMA (UMTS) 37
2.2.2 3G cdma2000 38
2.2.3 3G TD-SCDMA 39

2.3 Wireless Local Loop (WLL) and LMDS 40
2.4 Wireless Local Area Networks (WLANs) 46
2.5 Bluetooth and Personal Area Networks (PANs) 52
2.6 Summary 54
2.7 Problems 55

3 The Cellular Concept—System Design Fundamentals 57

3.1 Introduction 57
3.2 Frequency Reuse 58
3.3 Channel Assignment Strategies 62
3.4 Handoff Strategies 62
3.4.1 Prioritizing Handoffs 65
3.4.2 Practical Handoff Considerations 66
3.5 Interference and System Capacity 67
3.5.1 Co-channel Interference and System Capacity 68
3.5.2 Channel Planning for Wireless Systems 72
3.5.3 Adjacent Channel Interference 74
3.5.4 Power Control for Reducing Interference 76
3.6 Trunking and Grade of Service 77
3.7 Improving Coverage & Capacity in Cellular Systems 86
3.7.1 Cell Splitting 86
3.7.2 Sectoring 90
3.7.3 Repeaters for Range Extension 93
3.7.4 A Microcell Zone Concept 93
3.8 Summary 96
3.9 Problems 97

4 Mobile Radio Propagation: Large-Scale Path Loss 105

4.1 Introduction to Radio Wave Propagation 105
4.2 Free Space Propagation Model 107
4.3 Relating Power to Electric Field 110
4.4 The Three Basic Propagation Mechanisms 113
4.5 Reflection 114
4.5.1 Reflection from Dielectrics 114
4.5.2 Brewster Angle 119
4.5.3 Reflection from Perfect Conductors 120
4.6 Ground Reflection (Two-Ray) Model 120
4.7 Diffraction 126
4.7.1 Fresnel Zone Geometry 126
4.7.2 Knife-edge Diffraction Model 129
4.7.3 Multiple Knife-edge Diffraction 134
4.8 Scattering 135
4.8.1 Radar Cross Section Model 136

4.9 Practical Link Budget Design Using Path Loss Models 138
4.9.1 Log-distance Path Loss Model 138
4.9.2 Log-normal Shadowing 139
4.9.3 Determination of Percentage of Coverage Area 141
4.10 Outdoor Propagation Models 145
4.10.1 Longley–Rice Model 145
4.10.2 Durkin's Model—A Case Study 146
4.10.3 Okumura Model 150
4.10.4 Hata Model 153
4.10.5 PCS Extension to Hata Model 154
4.10.6 Walfisch and Bertoni Model 155
4.10.7 Wideband PCS Microcell Model 155
4.11 Indoor Propagation Models 157
4.11.1 Partition Losses (same floor) 157
4.11.2 Partition Losses between Floors 160
4.11.3 Log-distance Path Loss Model 161
4.11.4 Ericsson Multiple Breakpoint Model 161
4.11.5 Attenuation Factor Model 163
4.12 Signal Penetration into Buildings 166
4.13 Ray Tracing and Site Specific Modeling 167
4.14 Problems 168

5 Mobile Radio Propagation: Small-Scale Fading and Multipath 177

5.1 Small-Scale Multipath Propagation 177
5.1.1 Factors Influencing Small-Scale Fading 178
5.1.2 Doppler Shift 179
5.2 Impulse Response Model of a Multipath Channel 181
5.2.1 Relationship Between Bandwidth and Received Power 185
5.3 Small-Scale Multipath Measurements 192
5.3.1 Direct RF Pulse System 192
5.3.2 Spread Spectrum Sliding Correlator Channel Sounding 193
5.3.3 Frequency Domain Channel Sounding 196
5.4 Parameters of Mobile Multipath Channels 197
5.4.1 Time Dispersion Parameters 199
5.4.2 Coherence Bandwidth 202
5.4.3 Doppler Spread and Coherence Time 203
5.5 Types of Small-Scale Fading 205
5.5.1 Fading Effects Due to Multipath Time Delay Spread 205
5.5.1.1 Flat fading 205
5.5.1.2 Frequency Selective Fading 207
5.5.2 Fading Effects Due to Doppler Spread 208
5.5.2.1 Fast Fading 208
5.5.2.2 Slow Fading 209

5.6 Rayleigh and Ricean Distributions 210
5.6.1 Rayleigh Fading Distribution 210
5.6.2 Ricean Fading Distribution 212
5.7 Statistical Models for Multipath Fading Channels 214
5.7.1 Clarke's Model for Flat Fading 214
5.7.1.1 Spectral Shape Due to Doppler Spread in Clarke's Model 217
5.7.2 Simulation of Clarke and Gans Fading Model 220
5.7.3 Level Crossing and Fading Statistics 223
5.7.4 Two-ray Rayleigh Fading Model 226
5.7.5 Saleh and Valenzuela Indoor Statistical Model 227
5.7.6 SIRCIM and SMRCIM Indoor and Outdoor Statistical Models 227
5.8 Theory of Multipath Shape Factors for Small-Scale Fading Wireless Channels 229
5.8.1 Introduction to Shape Factors 230
5.8.1.1 Multipath Shape Factors 232
Angular Spread, Λ 232
Angular Constriction, γ 233
Azimuthal Direction of Maximum Fading, θ_{max} 233
5.8.1.2 Fading Rate Variance Relationships 233
Complex Received Voltage, $\tilde{V}(r)$ 233
Received Power, $P(r)$ 234
Received Envelope, $R(r)$ 234
5.8.1.3 Comparison to Omnidirectional Propagation 234
5.8.2 Examples of Fading Behavior 236
5.8.2.1 Sector Channel Model 236
5.8.2.2 Double Sector Channel Model 239
5.8.2.3 Ricean Channel Model 240
5.8.3 Second-Order Statistics Using Shape Factors 240
5.8.3.1 Level-Crossing Rates and Average Fade Duration 242
5.8.3.2 Spatial Autocovariance 242
5.8.3.3 Coherence Distance 243
5.8.4 Applying Shape Factors to Wideband Channels 243
5.8.5 Revisiting Classical Channel Models with Shape Factors 244
5.9 Summary 247
5.10 Problems 248

6 Modulation Techniques for Mobile Radio 255

6.1 Frequency Modulation vs. Amplitude Modulation 256
6.2 Amplitude Modulation 257
6.2.1 Single Sideband AM 260
6.2.2 Pilot Tone SSB 261
6.2.3 Demodulation of AM signals 262
6.3 Angle Modulation 264
6.3.1 Spectra and Bandwidth of FM Signals 266
6.3.2 FM Modulation Methods 267

6.3.3 FM Detection Techniques 268
6.3.4 Tradeoff Between SNR and Bandwidth in an FM Signal 276
6.4 Digital Modulation—an Overview 277
6.4.1 Factors That Influence the Choice of Digital Modulation 278
6.4.2 Bandwidth and Power Spectral Density of Digital Signals 281
6.5 Line Coding 282
6.6 Pulse Shaping Techniques 282
6.6.1 Nyquist Criterion for ISI Cancellation 282
6.6.2 Raised Cosine Rolloff Filter 287
6.6.3 Gaussian Pulse-Shaping Filter 290
6.7 Geometric Representation of Modulation Signals 291
6.8 Linear Modulation Techniques 294
6.8.1 Binary Phase Shift Keying (BPSK) 295
6.8.2 Differential Phase Shift Keying (DPSK) 298
6.8.3 Quadrature Phase Shift Keying (QPSK) 300
6.8.4 QPSK Transmission and Detection Techniques 301
6.8.5 Offset QPSK 303
6.8.6 $\pi/4$ QPSK 305
6.8.7 $\pi/4$ QPSK Transmission Techniques 305
6.8.8 $\pi/4$ QPSK Detection Techniques 308
6.9 Constant Envelope Modulation 311
6.9.1 Binary Frequency Shift Keying 312
6.9.2 Minimum Shift Keying (MSK) 314
6.9.3 Gaussian Minimum Shift Keying (GMSK) 318
6.10 Combined Linear and Constant Envelope Modulation Techniques 322
6.10.1 M-ary Phase Shift Keying (MPSK) 323
6.10.2 M-ary Quadrature Amplitude Modulation (QAM) 325
6.10.3 M-ary Frequency Shift Keying (MFSK) and OFDM 328
6.11 Spread Spectrum Modulation Techniques 329
6.11.1 Pseudo-Noise (PN) Sequences 330
6.11.2 Direct Sequence Spread Spectrum (DS–SS) 331
6.11.3 Frequency Hopped Spread Spectrum (FH–SS) 334
6.11.4 Performance of Direct Sequence Spread Spectrum 335
6.11.5 Performance of Frequency Hopping Spread Spectrum 338
6.12 Modulation Performance in Fading and Multipath Channels 339
6.12.1 Performance of Digital Modulation in Slow Flat-Fading Channels 340
6.12.2 Digital Modulation in Frequency Selective Mobile Channels 344
6.12.3 Performance of $\pi/4$ DQPSK in Fading and Interference 346
6.13 Problems 350

7 Equalization, Diversity, and Channel Coding 355

7.1 Introduction 355
7.2 Fundamentals of Equalization 356
7.3 Training A Generic Adaptive Equalizer 359

7.4 Equalizers in a Communications Receiver 363
7.5 Survey of Equalization Techniques 364
7.6 Linear Equalizers 366
7.7 Nonlinear Equalization 368
7.7.1 Decision Feedback Equalization (DFE) 369
7.7.2 Maximum Likelihood Sequence Estimation (MLSE) Equalizer 370
7.8 Algorithms for Adaptive Equalization 372
7.8.1 Zero Forcing Algorithm 374
7.8.2 Least Mean Square Algorithm 374
7.8.3 Recursive Least Squares Algorithm 376
7.8.4 Summary of Algorithms 379
7.9 Fractionally Spaced Equalizers 380
7.10 Diversity Techniques 380
7.10.1 Derivation of Selection Diversity Improvement 381
7.10.2 Derivation of Maximal Ratio Combining Improvement 384
7.10.3 Practical Space Diversity Considerations 385
7.10.3.1 Selection Diversity 386
7.10.3.2 Feedback or Scanning Diversity 386
7.10.3.3 Maximal Ratio Combining 387
7.10.3.4 Equal Gain Combining 387
7.10.4 Polarization Diversity 387
7.10.5 Frequency Diversity 390
7.10.6 Time Diversity 390
7.11 RAKE Receiver 391
7.12 Interleaving 393
7.13 Fundamentals of Channel Coding 394
7.14 Block Codes and Finite Fields 395
7.14.1 Examples of Block Codes 399
7.14.2 Case Study: Reed–Solomon Codes for CDPD 400
7.14.2.1 Reed–Solomon Encoding 401
7.14.2.2 Reed–Solomon Decoding 404
7.15 Convolutional Codes 407
7.15.1 Decoding of Convolutional Codes 409
7.15.1.1 The Viterbi Algorithm 409
7.15.1.2 Other Decoding Algorithms for Convolutional Codes 410
7.16 Coding Gain 411
7.17 Trellis Coded Modulation 412
7.18 Turbo Codes 412
7.19 Problems 412

8 Speech Coding 415

8.1 Introduction 415
8.2 Characteristics of Speech Signals 417

8.3 Quantization Techniques 418
8.3.1 Uniform Quantization 418
8.3.2 Nonuniform Quantization 419
8.3.3 Adaptive Quantization 421
8.3.4 Vector Quantization 422
8.4 Adaptive Differential Pulse Code Modulation (ADPCM) 423
8.5 Frequency Domain Coding of Speech 425
8.5.1 Sub-band Coding 425
8.5.2 Adaptive Transform Coding 428
8.6 Vocoders 429
8.6.1 Channel Vocoders 429
8.6.2 Formant Vocoders 430
8.6.3 Cepstrum Vocoders 430
8.6.4 Voice-Excited Vocoder 431
8.7 Linear Predictive Coders 431
8.7.1 LPC Vocoders 431
8.7.2 Multipulse Excited LPC 434
8.7.3 Code-Excited LPC 434
8.7.4 Residual Excited LPC 436
8.8 Choosing Speech Codecs for Mobile Communications 436
8.9 The GSM Codec 440
8.10 The USDC Codec 442
8.11 Performance Evaluation of Speech Coders 442
8.12 Problems 445

9 Multiple Access Techniques for Wireless Communications 447

9.1 Introduction 447
9.1.1 Introduction to Multiple Access 448
9.2 Frequency Division Multiple Access (FDMA) 449
9.3 Time Division Multiple Access (TDMA) 453
9.4 Spread Spectrum Multiple Access 456
9.4.1 Frequency Hopped Multiple Access (FHMA) 457
9.4.2 Code Division Multiple Access (CDMA) 458
9.4.3 Hybrid Spread Spectrum Techniques 459
9.5 Space Division Multiple Access (SDMA) 461
9.6 Packet Radio 462
9.6.1 Packet Radio Protocols 463
9.6.1.1 Pure ALOHA 464
9.6.1.2 Slotted ALOHA 465
9.6.2 Carrier Sense Multiple Access (CSMA) Protocols 466
9.6.3 Reservation Protocols 467
9.6.3.1 Reservation ALOHA 467
9.6.3.2 Packet Reservation Multiple Access (PRMA) 468
9.6.4 Capture Effect in Packet Radio 468

9.7 Capacity of Cellular Systems 469
9.7.1 Capacity of Cellular CDMA 474
9.7.2 Capacity of CDMA with Multiple Cells 477
9.7.3 Capacity of Space Division Multiple Access 484
9.8 Problems 488

10 Wireless Networking 491

10.1 Introduction to Wireless Networks 491
10.2 Differences Between Wireless and Fixed Telephone Networks 493
10.2.1 The Public Switched Telephone Network (PSTN) 493
10.2.2 Limitations in Wireless Networking 495
10.2.3 Merging Wireless Networks and the PSTN 496
10.3 Development of Wireless Networks 497
10.3.1 First Generation Wireless Networks 497
10.3.2 Second Generation Wireless Networks 499
10.3.3 Third Generation Wireless Networks 500
10.4 Fixed Network Transmission Hierarchy 501
10.5 Traffic Routing in Wireless Networks 502
10.5.1 Circuit Switching 503
10.5.2 Packet Switching 504
10.5.3 The X.25 Protocol 505
10.6 Wireless Data Services 506
10.6.1 Cellular Digital Packet Data (CDPD) 506
10.6.2 Advanced Radio Data Information Systems (ARDIS) 508
10.6.3 RAM Mobile Data (RMD) 508
10.7 Common Channel Signaling (CCS) 510
10.7.1 The Distributed Central Switching Office for CCS 510
10.8 Integrated Services Digital Network (ISDN) 512
10.8.1 Broadband ISDN and ATM 513
10.9 Signaling System No. 7 (SS7) 514
10.9.1 Network Services Part (NSP) of SS7 515
10.9.1.1 Message Transfer Part (MTP) of SS7 516
10.9.1.2 Signaling Connection Control Part (SCCP) of SS7 517
10.9.2 The SS7 User Part 517
10.9.2.1 Integrated Services Digital Network User Part (ISUP) 517
10.9.2.2 Transaction Capabilities Application Part (TCAP) 518
10.9.2.3 Operation Maintenance and Administration Part (OMAP) 518
10.9.3 Signaling Traffic in SS7 518
10.9.4 SS7 Services 519
10.9.5 Performance of SS7 519
10.10 An Example of SS7 — Global Cellular Network Interoperability 520

10.11 Personal Communication Services/Networks (PCS/PCNs) 522
10.11.1 Packet vs. Circuit Switching for PCN 523
10.11.2 Cellular Packet-Switched Architecture 523
10.11.2.1 Network Functionality in Cellular Packet-Switched Architecture 527
10.12 Protocols for Network Access 527
10.12.1 Packet Reservation Multiple Access (PRMA) 528
10.13 Network Databases 529
10.13.1 Distributed Database for Mobility Management 529
10.14 Universal Mobile Telecommunication System (UMTS) 530
10.15 Summary 531

11 Wireless Systems and Standards 533

11.1 AMPS and ETACS 533
11.1.1 AMPS and ETACS System Overview 534
11.1.2 Call Handling in AMPS and ETACS 535
11.1.3 AMPS and ETACS Air Interface 537
11.1.4 N-AMPS 540
11.2 United States Digital Cellular (IS-54 and IS-136) 541
11.2.1 USDC Radio Interface 542
11.2.2 United States Digital Cellular Derivatives (IS-94 and IS-136) 548
11.3 Global System for Mobile (GSM) 549
11.3.1 GSM Services and Features 550
11.3.2 GSM System Architecture 551
11.3.3 GSM Radio Subsystem 553
11.3.4 GSM Channel Types 555
11.3.4.1 GSM Traffic Channels (TCHs) 555
11.3.4.2 GSM Control Channels (CCH) 557
11.3.5 Example of a GSM Call 560
11.3.6 Frame Structure for GSM 561
11.3.7 Signal Processing in GSM 563
11.4 CDMA Digital Cellular Standard (IS-95) 567
11.4.1 Frequency and Channel Specifications 567
11.4.2 Forward CDMA Channel 569
11.4.2.1 Convolutional Encoder and Repetition Circuit 569
11.4.2.2 Block Interleaver 571
11.4.2.3 Long PN Sequence 571
11.4.2.4 Data Scrambler 572
11.4.2.5 Power Control Subchannel 572
11.4.2.6 Orthogonal Covering 573
11.4.2.7 Quadrature Modulation 574
11.4.3 Reverse CDMA Channel 575
11.4.3.1 Convolutional Encoder and Symbol Repetition 576
11.4.3.2 Block Interleaver 576
11.4.3.3 Orthogonal Modulation 576

11.4.3.4 Variable Data Rate Transmission 576
11.4.3.5 Direct Sequence Spreading 578
11.4.3.6 Quadrature Modulation 580
11.4.4 IS-95 with 14.4 kbps Speech Coder [ANS95] 580
11.5 CT2 Standard for Cordless Telephones 580
11.5.1 CT2 Services and Features 580
11.5.2 The CT2 Standard 581
11.6 Digital European Cordless Telephone (DECT) 582
11.6.1 Features and Characteristics 582
11.6.2 DECT Architecture 582
11.6.3 DECT Functional Concept 584
11.6.4 DECT Radio Link 584
11.7 PACS — Personal Access Communication Systems 587
11.7.1 PACS System Architecture 587
11.7.2 PACS Radio Interface 587
11.8 Pacific Digital Cellular (PDC) 590
11.9 Personal Handyphone System (PHS) 590
11.10 US PCS and ISM Bands 591
11.11 US Wireless Cable Television 593
11.12 Summary of Standards Throughout the World 594
11.13 Problems 597

APPENDICES

A Trunking Theory **601**

A.1 Erlang B 602
A.1.1 Derivation of Erlang B 602
A.2 Erlang C 607
A.2.1 Derivation of Erlang C 607

B Noise Figure Calculations for Link Budgets **611**

C Rate Variance Relationships for Shape Factor Theory **615**

C.1 Rate Variance for Complex Voltage 615
C.2 Rate Variance for Power 617
C.3 Rate Variance for Envelope 617

D Approximate Spatial Autocovariance Function for Shape Factor Theory **619**

E Gaussian Approximations for Spread Spectrum CDMA **621**

E.1 The Gaussian Approximation 629
E.2 The Improved Gaussian Approximation (IGA) 635
E.3 A Simplified Expression for the Improved Gaussian Approximation (SEIGA) 637

F ***Q*, *erf* & *erfc* Functions** **645**

F.1 The *Q*-Function 645
F.2 The *erf* and *erfc* Functions 648

G **Mathematical Tables, Functions, and Transforms** **651**

H **Abbreviations and Acronyms** **661**

I **References** **675**

INDEX **693**

CHAPTER 2

Modern Wireless Communication Systems

Since the mid 1990s, the cellular communications industry has witnessed explosive growth. Wireless communications networks have become much more pervasive than anyone could have imagined when the cellular concept was first developed in the 1960s and 1970s. As shown in Figure 2.1, the worldwide cellular and personal communication subscriber base surpassed 600 million users in late 2001, and the number of individual subscribers is projected to reach 2 billion (about 30% of the world's population) by the end of 2006! Indeed, most countries throughout the world continue to experience cellular subscription increases of 40% or more per year. The widespread adoption of wireless communications was accelerated in the mid 1990s, when governments throughout the world provided increased competition and new radio spectrum licenses for personal communications services (PCS) in the 1800–2000 MHz frequency bands.

The rapid worldwide growth in cellular telephone subscribers has demonstrated conclusively that wireless communications is a robust, viable voice and data transport mechanism. The widespread success of cellular has led to the development of newer wireless systems and standards for many other types of telecommunication traffic besides mobile voice telephone calls.

For example, next generation cellular networks are being designed to facilitate high speed data communications traffic in addition to voice calls. New standards and technologies are being implemented to allow wireless networks to replace fiber optic or copper lines between fixed points several kilometers apart (*fixed wireless access*). Similarly, wireless networks have been increasingly used as a replacement for wires within homes, buildings, and office settings through the deployment of *wireless local area networks* (WLANs). The evolving *Bluetooth* modem standard promises to replace troublesome appliance communication cords with invisible wireless connections within a person's personal workspace.

Used primarily within buildings, WLANs and Bluetooth use low power levels and generally do not require a license for spectrum use. These license-free networks provide an interesting

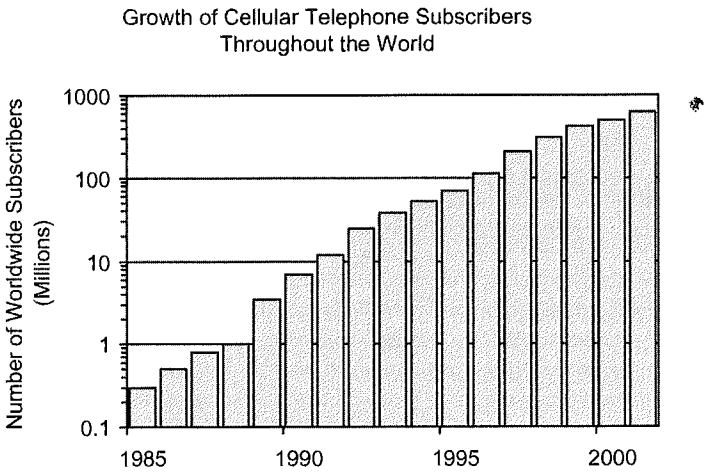


Figure 2.1 Growth of cellular and PCS telephone subscribers throughout the world.

dichotomy in the wireless market, since ad-hoc high data rate networks are being deployed by individuals within buildings without a license, whereas wireless carriers who own the spectrum licenses for mobile cellular telephone service have focused on providing outdoor voice coverage and have been slow to provide reliable in-building coverage and high data rate services to their cellular subscribers. While it is still too early to tell, it appears that the in-building wireless access market may become a huge battleground between licensed and unlicensed services, and this is prompting the architects of today's popular cellular standards to design for high data rate packet-based networking capabilities in the next generation of cellular technology.

This chapter highlights the key developments, technical details, and standards activities of the major modern wireless communications systems throughout the world. First, the state-of-the-art of the most popular cellular and PCS standards is presented, and the many competing evolutionary paths toward third generation (3G) mobile networks are described. Then, standards activities and recent developments in wireless fixed access techniques such as Local Multipoint Distribution Systems (LMDS) are presented. Finally, this chapter focuses on wireless systems and standards such as the worldwide wireless LAN (WLAN) movement and the Bluetooth standard that provide wireless connectivity across campuses to indoor users.

2.1 Second Generation (2G) Cellular Networks

Most of today's ubiquitous cellular networks use what is commonly called *second generation* or *2G* technologies which conform to the second generation cellular standards. Unlike first generation cellular systems that relied exclusively on FDMA/FDD and analog FM, second generation standards use digital modulation formats and TDMA/FDD and CDMA/FDD multiple access techniques.

The most popular second generation standards include three TDMA standards and one CDMA standard: (a) *Global System Mobile (GSM)*, which supports eight time slotted users for

each 200 kHz radio channel and has been deployed widely in the cellular and PCS bands by service providers in Europe, Asia, Australia, South America, and some parts of the US (in the PCS spectrum band only) [Gar99]; (b) *Interim Standard 136 (IS-136)*, also known as North American Digital Cellular (NADC) or US Digital Cellular (USDC), which supports three time slotted users for each 30 kHz radio channel and is a popular choice for carriers in North America, South America, and Australia (in both the cellular and PCS bands); (c) *Pacific Digital Cellular (PDC)*, a Japanese TDMA standard that is similar to IS-136 with more than 50 million users; and (d) the popular 2G CDMA standard *Interim Standard 95 Code Division Multiple Access (IS-95)*, also known as *cdmaOne*, which supports up to 64 users that are orthogonally coded and simultaneously transmitted on each 1.25 MHz channel. CDMA is widely deployed by carriers in North America (in both cellular and PCS bands), as well as in Korea, Japan, China, South America, and Australia [Lib99, ch. 1], [Kim00], [Gar00].

The 2G standards mentioned above represent the first set of wireless air interface standards to rely on digital modulation and sophisticated digital signal processing in the handset and the base station. As discussed in Chapter 11, second generation systems were first introduced in the early 1990s, and evolved from the first generation of analog mobile phone systems (e.g., AMPS, ETACS, and JTACS). Today, many wireless service providers use both first generation and second generation equipment in major markets and often provide customers with subscriber units that can support multiple frequency bands and multiple air interface standards. For example, in many countries it is possible to purchase a single tri-mode cellular handset phone that supports CDMA in the cellular and PCS bands in addition to analog first generation technology in the cellular band. Such tri-mode phones are able to automatically sense and adapt to whichever standard is being used in a particular market. Figure 2.2 illustrates how the world subscriber base was divided between the major 1G and 2G technologies as of late 2001. Table 2.1 highlights the key technical specifications of the dominant GSM, CDMA, and IS-136/PDC second generation standards.

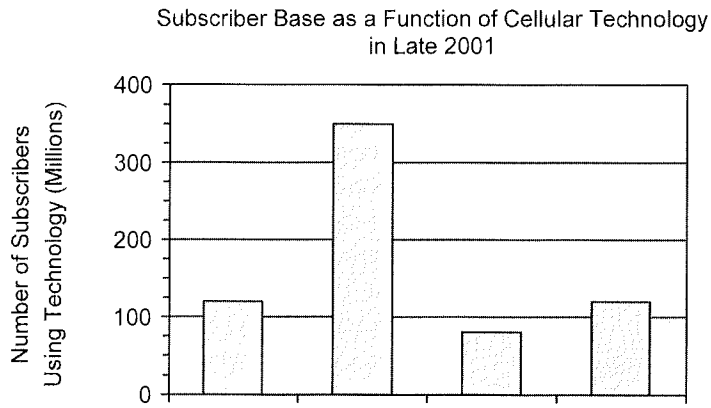


Figure 2.2 Worldwide subscriber base as a function of cellular technology in late 2001.

Table 2.1 Key Specifications of Leading 2G Technologies (adapted from [Lib99])

	cdmaOne, IS-95, ANSI J-STD-008	GSM, DCS-1900, ANSI J-STD-007	NADC, IS-54/IS-136, ANSI J-STD-011, PDC
Uplink Frequencies	824-849 MHz (US Cellular) 1850-1910 MHz (US PCS)	890-915 MHz (Europe) 1850-1910 MHz (US PCS)	800 MHz, 1500 MHz (Japan) 1850-1910 MHz (US PCS)
Downlink Frequencies	869-894 MHz (US Cellular) 1930-1990 MHz (US PCS)	935-960 MHz (Europe) 1930-1990 MHz (US PCS)	869-894 MHz (US Cellular) 1930-1990 MHz (US PCS) 800 MHz, 1500 MHz (Japan)
Duplexing	FDD	FDD	FDD
Multiple Access Technology	CDMA	TDMA	TDMA
Modulation	BPSK with Quadrature Spreading	GMSK with $BT = 0.3$	$\pi/4$ DQPSK
Carrier Separation	1.25 MHz	200 kHz	30 kHz (IS-136) (25 kHz for PDC)
Channel Data Rate	1.2288 Mchips/sec	270.833 kbps	48.6 kbps (IS-136) (42 kbps for PDC)
Voice channels per carrier	64	8	3
Speech Coding	Code Excited Linear Prediction (CELP) @ 13 kbps, Enhanced Variable Rate Codec (EVRC) @ 8 kbps	Residual Pulse Excited Long Term Prediction (RPE-LTP) @ 13 kbps	Vector Sum Excited Linear Predictive Coder (VSELP) @ 7.95 kbps

In many countries, 2G wireless networks are designed and deployed for conventional mobile telephone service, as a high capacity replacement for, or in competition with, existing older first generation cellular telephone systems. Modern cellular systems are also being installed to provide fixed (non-mobile) telephone service to residences and businesses in developing nations—this is particularly cost effective for providing *plain old telephone service (POTS)* in countries that have poor telecommunications infrastructure and are unable to afford the installation of copper wire to all homes. Since all 2G technologies offer at least a three-times increase in spectrum efficiency (and thus at least a 3X increase in overall system capacity) as compared to first generation analog technologies, the need to meet a rapidly growing customer base justifies the gradual, ongoing change out of analog to digital 2G technologies in any growing wireless network.

In mid-2001, several major carriers such as AT&T Wireless and Cingular in the US and NTT in Japan announced their decisions to eventually abandon the IS-136 and PDC standards as long term technology options in favor of emerging third generation standards based on the GSM

TDMA platform. Simultaneously, international wireless carrier Nextel announced its decision to upgrade its iDen air interface standard to support up to five times the number of current users based on a data compression methodology using Internet protocol (IP) packet data. Most other carriers throughout the world had already committed to adopting a 3G standard based on either GSM or CDMA prior to 2001. Decisions like these have set the stage for the inevitability of two universal and competing third generation (3G) cellular mobile radio technologies, one based on the philosophy and backward compatibility of GSM, and the other based on the philosophy and backward compatibility of CDMA.

2.1.1 Evolution to 2.5G Mobile Radio Networks

Since the mid 1990s, the 2G digital standards have been widely deployed by wireless carriers for cellular and PCS, even though these standards were designed before the widespread use of the Internet. Consequently, 2G technologies use circuit-switched data modems that limit data users to a single circuit-switched voice channel. Data transmissions in 2G are thus generally limited to the data throughput rate of an individual user, and this rate is of the same order of magnitude of the data rate of the designated speech coders given in Table 2.1. (As discussed in Chapter 11, each of the 2G standards specify different coding schemes and error protection algorithms for data transmissions versus voice transmissions, but the data throughput rate for computer data is approximately the same as the throughput rate for speech coded voice data in all 2G standards.) From inspection of Table 2.1, it can be seen that all 2G networks, as originally developed, only support single user data rates on the order of 10 kilobits per second, which is too slow for rapid email and Internet browsing applications. Chapter 11 presents the technical specifications of the original GSM, CDMA, and IS-136 standards which originally supported 9.6 kilobits per second transmission rates for data messages.

Even with relatively small user data rates, 2G standards are able to support limited Internet browsing and sophisticated short messaging capabilities using a circuit switched approach. *Short messaging service (SMS)* is a popular feature of GSM, and allows subscribers to send short, real-time messages to other subscribers in the same network by simply dialing a recipient's cell phone number. SMS first became popular in Europe through the dominant network of GSM service providers, and then became popular in Japan through the NTT DoCoMo PDC network. As of late 2001, SMS had not yet become widespread in the USA, since the wireless markets there are fragmented between many different types of technologies and network owners, and SMS presently only works between users of the same network.

In an effort to retrofit the 2G standards for compatibility with increased throughput data rates that are required to support modern Internet applications, new data-centric standards have been developed that can be overlaid upon existing 2G technologies. These new standards represent *2.5G* technology and allow existing 2G equipment to be modified and supplemented with new base station add-ons and subscriber unit software upgrades to support higher data rate transmissions for web browsing, e-mail traffic, mobile commerce (*m-commerce*), and location-based mobile services. The 2.5G technologies also support a popular new web browsing format language, called *Wireless*

Applications Protocol (WAP), that allows standard web pages to be viewed in a compressed format specifically designed for small, portable hand held wireless devices. Numerous other competing web page compression protocols have also been developed recently [Ald00].

It is interesting to note that Japan, one of the world's first countries to adopt commercial cellular telephony in the late 1970s, was the first country to enjoy a successful widespread mobile data service and web browser capability that preceded the introduction of WAP. NTT DoCoMo introduced its own proprietary wireless data service and Internet microbrowser technology, called *I-mode*, on its PDC network in 1998, and is currently distributing its I-mode technology to other wireless carriers throughout the world. I-mode supports games, color graphics, and interactive web page browsing using the modest 2G PDC data transmission rate of 9.6 kilobits per second. As of late 2001, DoCoMo's I-mode was supporting wireless web access for over 25 million Japanese subscribers.

The appropriate 2.5G upgrade path for a particular wireless carrier must match the original 2G technology choice made earlier by the same carrier. For example, a 2.5G upgrade solution designed for GSM must dovetail with the original GSM air interface standard [Gar99], since it would otherwise be incompatible and require wholesale equipment changes at each base station. For this reason, a wide range of 2.5G standards have been developed to allow each of the major 2G technologies (GSM, CDMA, and IS-136) to be upgraded incrementally for faster Internet data rates. Figure 2.3 illustrates the various 2.5G and 3G upgrade paths for the major 2G technologies [Tel01]. Table 2.2 describes the required changes to the network infrastructure (e.g., the base station and the switch) and the subscriber terminals (e.g., the handset) for the various upgrade options for 2.5G and 3G. The technical features of each 2.5G upgrade path are described below.

2.1.2 Evolution for 2.5G TDMA Standards

Three different upgrade paths have been developed for GSM carriers, and two of these solutions also support IS-136. The three TDMA upgrade options include: (a) High Speed Circuit Switched Data (HSCSD); (b) General Packet Radio Service (GPRS); and (c) Enhanced Data Rates for GSM Evolution (EDGE). These options provide significant improvements in Internet access speed over today's GSM and IS-136 technology and support the creation of new Internet-ready cell phones.

2.1.2.1 HSCSD for 2.5G GSM

As the name implies, High Speed Circuit Switched Data is a circuit switched technique that allows a single mobile subscriber to use consecutive user time slots in the GSM standard. That is, instead of limiting each user to only one specific time slot in the GSM TDMA standard, HSCSD allows individual data users to commandeer consecutive time slots in order to obtain higher speed data access on the GSM network. HSCSD relaxes the error control coding algorithms originally specified in the GSM standard for data transmissions and increases the available application data rate to 14,400 bps, as compared to the original 9,600 bps in the GSM specification. By using up to four consecutive time slots, HSCSD is able to provide a raw transmission rate of up to 57.6 kbps to

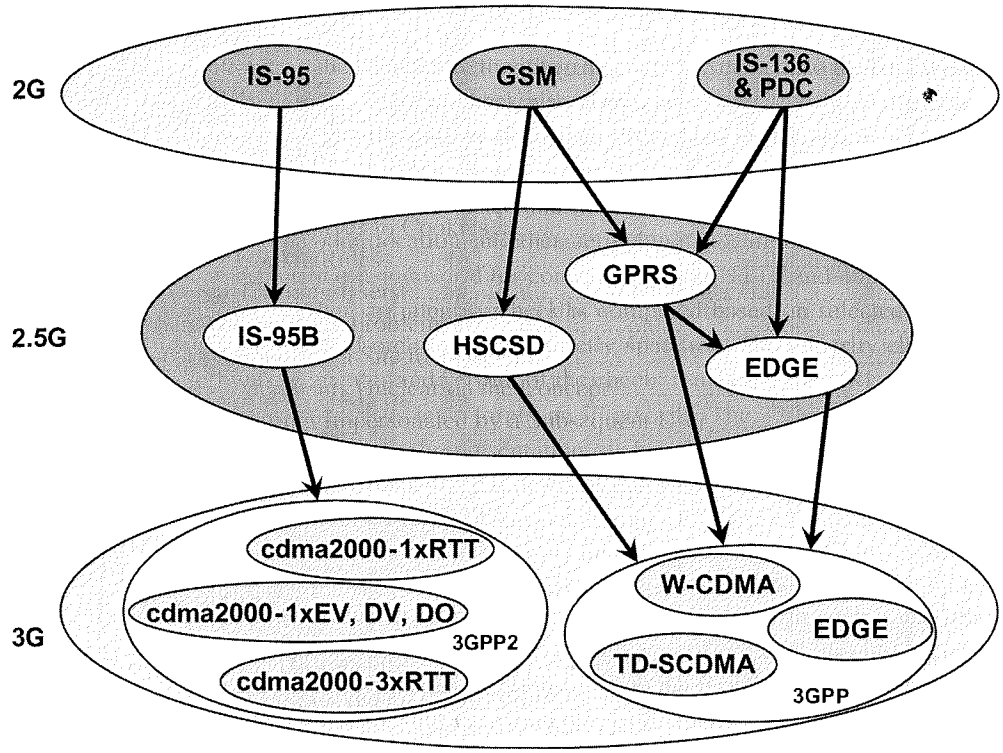


Figure 2.3 Various upgrade paths for 2G technologies.

individual users, and this enhanced data offering can be billed as a premium service by the carrier. HSCSD is ideal for dedicated streaming Internet access or real-time interactive web sessions and simply requires the service provider to implement a software change at existing GSM base stations.

2.1.2.2 GPRS for 2.5G GSM and IS-136

General Packet Radio Service is a packet-based data network, which is well suited for non-real time Internet usage, including the retrieval of email, faxes, and asymmetric web browsing, where the user downloads much more data than it uploads on the Internet. Unlike HSCSD, which dedicates circuit switched channels to specific users, GPRS supports multi-user network sharing of individual radio channels and time slots. Thus, GPRS can support many more users than HSCSD, but in a bursty manner. Similar to the Cellular Digital Packet Data (CDPD) standard developed for the North American AMPS systems in the early 1990s (see Chapter 10), the GPRS standard provides a packet network on dedicated GSM or IS-136 radio channels. GPRS retains the original modulation formats specified in the original 2G TDMA standards, but uses a completely redefined air interface in order to better handle packet data access. GPRS subscriber units are automatically instructed to tune to dedicated GPRS radio channels and particular time slots for "always on" access to the network.

Table 2.2 Current and Emerging 2.5G and 3G Data Communication Standards

Wireless Data Technologies	Channel BW	Duplex	Infrastructure change	Requires New Spectrum	Requires New Handsets
HSCSD	200 KHz	FDD	Requires software upgrade at base station.	No	Yes New HSCSD handsets provide 57.6 Kbps on HSCSD networks, and 9.6 Kbps on GSM networks with dual mode phones. GSM-only phones will not work in HSCSD networks.
GPRS	200 KHz	FDD	Requires new packet overlay including routers and gateways.	No	Yes New GPRS handsets work on GPRS networks at 171.2 Kbps, 9.6 Kbps on GSM networks with dual mode phones. GSM-only phones will not work in GPRS networks.
EDGE	200 KHz	FDD	Requires new transceiver at base station. Also, software upgrades to the base station controller and base station.	No	Yes New handsets work on EDGE networks at 384 Kbps, GPRS networks at 144 Kbps, and GSM networks at 9.6 Kbps with tri-mode phones. GSM and GPRS-only phones will not work in EDGE networks.
W-CDMA	5 MHz	FDD	Requires completely new base stations.	Yes	Yes New W-CDMA handsets will work on W-CDMA at 2 Mbps, EDGE networks at 384 Kbps, GPRS networks at 144 Kbps, GSM networks at 9.6 Kbps. Older handsets will not work in W-CDMA.
IS-95B	1.25 MHz	FDD	Requires new software in base station controller.	No	Yes New handsets will work on IS-95B at 64 Kbps and IS-95A at 14.4 Kbps. CdmaOne phones can work in IS-95B at 14.4 Kbps.
cdma2000 1xRTT	1.25 MHz	FDD	Requires new software in backbone and new channel cards at base station. Also need to build a new packet service node.	No	Yes New handsets will work on 1xRTT at 144 Kbps, IS-95B at 64 Kbps, IS-95A at 14.4 Kbps. Older handsets can work in 1xRTT but at lower speeds.
cdma2000 IxEV (DO and DV)	1.25 MHz	FDD	Requires software and digital card upgrade on 1xRTT networks.	No	Yes New handsets will work on 1xEV at 2.4 Mbps, 1xRTT at 144 Kbps, IS-95B at 64 Kbps, IS-95A at 14.4 Kbps. Older handsets can work in 1xEV but at lower speeds.
cdma2000 3xRTT	3.75 MHz	FDD	Requires backbone modifications and new channel cards at base station.	Maybe	Yes New handsets will work on 95A at 14.4 Kbps, 95B at 64 Kbps, 1xRTT at 144 Kbps, 3xRTT at 2 Mbps. Older handsets can work in 3X but at lower speeds.

When all eight time slots of a GSM radio channel are dedicated to GPRS, an individual user is able to achieve as much as 171.2 kbps (eight time slots multiplied by 21.4 kbps of raw uncoded data throughput). Applications are required to provide their own error correction schemes as part of the carried data payload in GPRS. As is the case for any packet network, the data throughput experienced by an individual GPRS user decreases substantially as more users attempt to use the network or as propagation conditions become poor for particular users. Just as in the case of CDPD, and as described in Table 2.2, implementation of GPRS merely requires the GSM operator to install new routers and Internet gateways at the base station, along with new software that redefines the base station air interface standard for GPRS channels and time slots—no new base station RF hardware is required.

It is worth noting that GPRS was originally designed to provide a packet data access overlay solely for GSM networks, but at the request of North American IS-136 operators (see UWC-136 Air Interface in Table 2.3), GPRS was extended to include both TDMA standards. As of late 2001, GPRS has been installed in markets serving over 100 million subscribers, and is poised to be the most popular near-term packet data solution for 2G TDMA-based technologies. The dedicated peak 21.4 kbps per channel data rate specified by GPRS works well with both GSM and IS-136 and has successfully been implemented.

2.1.2.3 EDGE for 2.5G GSM and IS-136

EDGE, which stands for Enhanced Data rates for GSM (or Global) Evolution is a more advanced upgrade to the GSM standard, and requires the addition of new hardware and software at existing base stations. Interestingly, EDGE was developed from the desire of both GSM and IS-136 operators to have a common technology path for eventual 3G high speed data access, but the initial impetus came from the GSM user community.

EDGE introduces a new digital modulation format, 8-PSK (octal phase shift keying), which is used in addition to GSM's standard GMSK modulation. EDGE allows for nine different (autonomously and rapidly selectable) air interface formats, known as *multiple modulation and coding schemes* (MCS), with varying degrees of error control protection. Each MCS state may use either GMSK (low data rate) or 8-PSK (high data rate) modulation for network access, depending on the instantaneous demands of the network and the operating conditions. Because of the higher data rates and relaxed error control covering in many of the selectable air interface formats, the coverage range is smaller in EDGE than in HSDRC or GPRS. EDGE is sometimes referred to as Enhanced GPRS, or EGPRS [Noe01].

EDGE uses the higher order 8-PSK modulation and a family of MCSs for each GSM radio channel time slot, so that each user connection may adaptively determine the best MCS setting for the particular radio propagation conditions and data access requirements of the user. This adaptive capability to select the "best" air interface is called *incremental redundancy*, whereby packets are transmitted first with maximum error protection and maximum data rate throughput, and then subsequent packets are transmitted with less error protection (usually using punctured convolutional codes) and less throughput, until the link has an unacceptable outage or delay. Rapid feedback between the base station and subscriber unit then restores the previous acceptable air interface

state, which is presumably at an acceptable level but with minimum required coding and minimum bandwidth and power drain. Incremental redundancy ensures that the radio link for each user will quickly reach a condition that uses the minimum amount of overhead, thereby providing acceptable link quality for each user while maximizing user capacity on the network.

When EDGE uses 8-PSK modulation without any error protection, and all eight times slots of a GSM radio channel are dedicated to a single user, a raw peak throughput data rate of 547.2 kbps can be provided. In practice, the slotting schemes used in EDGE, when combined with practical network contention issues and error control coding requirements, limits practical raw data rates to about 384 kilobits per second for a single dedicated user on a single GSM channel. By combining the capacity of different radio channels (e.g., using *multicarrier transmissions*), EDGE can provide up to several megabits per second of data throughput to individual data users.

2.1.3 IS-95B for 2.5G CDMA

Unlike the several GSM and IS-136 evolutionary paths to high speed data access, CDMA (often called *cdmaOne*) has a single upgrade path for eventual 3G operation. The interim data solution for CDMA is called IS-95B. Like GPRS, IS-95B is already being deployed worldwide, and provides high speed packet and circuit switched data access on a common CDMA radio channel by dedicating multiple orthogonal user channels (Walsh functions) for specific users and specific purposes. As seen in Chapter 11, each IS-95 CDMA radio channel supports up to 64 different user channels. The original IS-95 throughput rate specification of 9600 bps was not implemented in practice, but was improved to the current rate of 14,400 bps as specified in IS-95A. The 2.5G CDMA solution, IS-95B, supports *medium data rate* (MDR) service by allowing a dedicated user to command up to eight different user Walsh codes simultaneously and in parallel for an instantaneous throughput of 115.2 kbps per user (8 × 14.4 kbps). However, only about 64 kbps of practical throughput is available to a single user in IS-95B due to the slotting techniques of the air interface.

IS-95B also specifies hard handoff procedures that allow subscriber units to search different radio channels in the network without instruction from the switch so that subscriber units can rapidly tune to different base stations to maintain link quality. Prior to IS-95B, the link quality experienced by each subscriber had to be reported back to the switch through the serving base station several hundreds of times per second, and at the appropriate moment, the switch would initiate a soft-handoff between the subscriber and candidate base stations. The new hard handoff capability of IS-95B is more efficient for multiple channel systems now being used in today's more congested CDMA markets [Lib99], [Kim00], [Gar00], [Tie01].

2.2 Third Generation (3G) Wireless Networks

3G systems promise unparalleled wireless access in ways that have never been possible before. Multi-megabit Internet access, communications using Voice over Internet Protocol (VoIP), voice-activated calls, unparalleled network capacity, and ubiquitous "always-on" access are just some of the advantages being touted by 3G developers. Companies developing 3G equipment envision users having the ability to receive live music, conduct interactive web sessions, and

have simultaneous voice and data access with multiple parties at the same time using a single mobile handset, whether driving, walking, or standing still in an office setting.

As mentioned in Chapter 1, and described in detail in [Lib99], the International Telecommunications Union (ITU) formulated a plan to implement a global frequency band in the 2000 MHz range that would support a single, ubiquitous wireless communication standard for all countries throughout the world. This plan, called International Mobile Telephone 2000 (IMT-2000), has been successful in helping to cultivate active debate and technical analysis for new high speed mobile telephone solutions when compared to 2G. However, as can be seen in Figures 2.2 and 2.3, the hope for a single worldwide standard has not materialized, as the worldwide user community remains split between two camps: GSM/IS-136/PDC and CDMA.

The eventual 3G evolution for 2G CDMA systems leads to cdma2000. Several variants of CDMA 2000 are currently being developed, but they all are based on the fundamentals of IS-95 and IS-95B technologies. The eventual 3G evolution for GSM, IS-136, and PDC systems leads to Wideband CDMA (W-CDMA), also called Universal Mobile Telecommunications Service (UMTS). W-CDMA is based on the network fundamentals of GSM, as well as the merged versions of GSM and IS-136 through EDGE. It is fair to say that these two major 3G technology camps, cdma2000 and W-CDMA, will remain popular throughout the early part of the 21st century.

Table 2.3 illustrates the primary worldwide proposals that were submitted for IMT-2000 in 1998. Since 1998, many standards proposals have capitulated and joined with either the cdma2000 or UMTS (W-CDMA) camps. Commercial grade 3G equipment is expected to be available in the 2002-2003 time frame. Two good Internet sources for up-to-the-minute 3G developments can be found at GSM World (*www.gsmworld.com*) and the CDMA Developers Group (*www.cdg.org*). The ITU IMT-2000 standards organizations are currently separated into two major organizations reflecting the two 3G camps: 3GPP (3G Partnership Project for Wideband CDMA standards based on backward compatibility with GSM and IS-136/PDC) and 3GPP2 (3G Partnership Project for cdma2000 standards based on backward compatibility with IS-95).

Countries throughout the world are currently determining new radio spectrum bands to accommodate the 3G networks that will likely be deployed in the 2004-2005 time frame. ITU's 2000 World Radio Conference established the 2500–2690 MHz, 1710–1885 MHz, and 806–960 MHZ bands as candidates for 3G. In the US, additional spectrum in the upper UHF television bands near 700 MHz is also being considered for 3G. Given the economic downturn of the telecommunications industry during 2001, many governments throughout the world, including the US, had postponed their 3G auctions and spectrum decisions as of late 2001.

Some European governments, however, auctioned off radio spectrum for 3G well before the telecommunications industry depression of 2001. The sale price of the spectrum was astounding! England's first ever spectrum auction netted $35.5 Billion USD in April 2000 for five nationwide 3G licenses. Germany's 3G auction generated $46 Billion USD later the same year, for four competing nationwide licenses [Buc00, pp. 32-36.].

Table 2.3 Leading IMT-2000 Candidate Standards as of 1998 (adapted from [Lib99])

Air Interface	Mode of Operation	Duplexing Method	Key Features
cdma2000 US TIA TR45.5	Multi-Carrier and Direct Spreading DS-CDMA a $N = 1.2288$ Mcps with $N = 1, 3, 6, 9, 12$	FDD and TDD Modes	• Backward compatibility with IS-95A and IS-95B. Downlink can be implemented using either Multi-Carrier or Direct Spreading. Uplink can support a simultaneous combination of Multi-Carrier or Direct Spreading • Auxiliary carriers to help with downlink channel estimation in forward link beamforming.
UTRA (UMTS Terrestrial Radio Access) ETSI SMG2	DS_CDMA at Rates of $N \times 0.960$ Mcps with $N = 4, 8, 16$	FDD and TDD Modes	• Wideband DS_CDMA System. • Backward compatibility with GSM/DCS-1900. • Up to 2.048 Mbps on Downlink in FDD Mode. • Minimum forward channel bandwidth of 5 MHz. • The collection of proposed standards represented here each exhibit unique features, but support a common set of chip rates, 10 ms frame structure, with 16 slots per frame. • Connection-dedicated pilot bits assist in downlink beamforming.
W-CDMA/NA (Wideband CDMA) North America) USA T1P1-ATIS			
W-CDMA/Japan (Wideband CDMA) Japan ARIB			
CDMA II South Korea TTA			
WIMS/W-CDMA USA TIA TR46.1			
CDMA I South Korea TTA	DS-CDMA at $N \times 0.9216$ Mcps with $N = 1, 4, 16$	FDD and TDD Modes	• Up to 512 kbps per spreading code, code aggregation up to 2.048 Mbps.
UWC-136 (Universal Wireless Communications Consortium) USA TIA TR 45.3	TDMA - Up to 722.2 kbps (Outdoor/Vehicular), Up to 5.2 Mbps (Indoor Office)	FDD (Outdoor/Vehicular), TDD (Indoor Office)	• Backward compatibility and upgrade path for both IS-136 and GSM. • Fits into existing IS-136 and GSM. • Explicit plans to support adaptive antenna technology.
TD-SCDMA China Academy of Telecommunication Technology (CATT)	DS-CDMA 1.1136 Mcps	TDD	• RF channel bit rate up to 2.227 Mbps. • Use of smart antenna technology is fundamental (but not strictly required) in TD-SCMA.
DECT ETSI Project (EP) DECT	1150-3456 kbps TDMA	TDD	• Enhanced version of 2G DECT technology.

2.2.1 3G W-CDMA (UMTS)

The Universal Mobile Telecommunications System (UMTS) is a visionary air interface standard that has evolved since late 1996 under the auspices of the European Telecommunications Standards Institute (ETSI). European carriers, manufacturers, and government regulators collectively developed the early versions of UMTS as a competitive open air-interface standard for third generation wireless telecommunications.

UMTS was submitted by ETSI to ITU's IMT-2000 body in 1998 for consideration as a world standard. At that time, UMTS was known as UMTS Terrestrial Radio Access (UTRA), as shown in Table 2.3, and was designed to provide a high capacity upgrade path for GSM. Around the turn of the century, several other competing wideband CDMA (W-CDMA) proposals agreed to merge into a single W-CDMA standard, and this resulting W-CDMA standard is now called UMTS.

UMTS, or W-CDMA, assures backward compatibility with the second generation GSM, IS-136, and PDC TDMA technologies, as well as all 2.5G TDMA technologies. The network structure and bit level packaging of GSM data is retained by W-CDMA, with additional capacity and bandwidth provided by a new CDMA air interface. Figure 2.3 illustrates how the various 2G and 2.5G TDMA technologies will evolve into a unified W-CDMA standard. Today, W-CDMA is the primary focus of the 3GPP world standard body, and while ETSI remains the organizational body that coordinates the W-CDMA standards effort, W-CDMA development now involves leading manufacturers, carriers, engineers, and regulators from throughout the world within the 3GPP community. The 3GPP standards body is developing W-CDMA for both wide area mobile cellular coverage (using FDD) as well as indoor cordless type applications (using TDD).

The 3G W-CDMA air interface standard had been designed for "always-on" packet-based wireless service, so that computers, entertainment devices, and telephones may all share the same wireless network and be connected to the Internet, anytime, anywhere. W-CDMA will support packet data rates up to 2.048 Mbps per user (if the user is stationary), thereby allowing high quality data, multimedia, streaming audio, streaming video, and broadcast-type services to consumers. Future versions of W-CDMA will support stationary user data rates in excess of 8 Mbps. W-CDMA provides public and private network features, as well as videoconferencing and *virtual home entertainment* (VHE). W-CDMA designers contemplate that broadcasting, mobile commerce (m-commerce), games, interactive video, and virtual private networking will be possible throughout the world, all from a small portable wireless device.

W-CDMA requires a minimum spectrum allocation of 5 MHz, which is an important distinction from the other 3G standards. Although W-CDMA is designed to provide backward compatibility and interoperability for all GSM, IS-136/PDC, GPRS, and EDGE switching equipment and applications, it is clear that the wider air interface bandwidth of W-CDMA requires a complete change out of the RF equipment at each base station. With W-CDMA, data rates from as low as 8 kbps to as high as 2 Mbps will be carried simultaneously on a single W-CDMA 5 MHz radio channel, and each channel will be able to support between 100 and 350 simultaneous voice calls at once, depending on antenna sectoring, propagation conditions, user velocity, and antenna polarizations. As shown in Table 2.3, W-CDMA employs variable/selectable direct sequence

spread spectrum chip rates that can exceed 16 Megachips per second per user. A common rule of thumb is that W-CDMA will provide at least a six times increase in spectral efficiency over GSM when compared on a system wide basis [Buc00].

Because W-CDMA will require expensive new base station equipment, the installation of W-CDMA will likely be slow and gradual throughout the world. Thus, the evolutionary path to 3G will require dual mode or tri-mode cell phones that can automatically switch between the incumbent 2G TDMA technology, EDGE, or W-CDMA service where its available. By 2010, it is likely that W-CDMA will be fully installed, eliminating the need for backward compatibility with GSM/GPRS, IS-136, PDC, and EDGE.

2.2.2 3G cdma2000

The cdma2000 vision provides a seamless and evolutionary high data rate upgrade path for current users of 2G and 2.5G CDMA technology, using a building block approach that centers on the original 2G CDMA channel bandwidth of 1.25 MHz per radio channel. Based upon the original IS-95 and IS-95A (cdmaOne) CDMA standards, as well as the 2.5G IS-95B air interface, the cdma2000 3G standard allows wireless carriers to introduce a family of new high data rate Internet access capabilities in a gradual manner within existing systems, while assuring that such upgrades maintain backward compatibility with existing cdmaOne and IS-95B subscriber equipment. Thus, current CDMA operators may seamlessly and selectively introduce 3G capabilities at each cell without having to change out entire base stations or reallocate spectrum [Tie01], [Gar00], [Kim00].

The cdma2000 standard is being developed under the auspices of working group 45 of the Telecommunications Industry Association (TIA) of the US, and involves the participation of the international technical community through the 3GPP2 working group. The first 3G CDMA air interface, cdma2000 1xRTT, implies that a single 1.25 MHz radio channel is used (e.g. 1X simply implies one times the original cdmaOne channel bandwidth, or, put another way, a multicarrier mode with only one carrier). Within the ITU IMT-2000 body, cdma2000 1xRTT is also known as G3G-MC-CDMA-1X. The initials MC stand for multicarrier, and the initials RTT stand for *Radio Transmission Technology*, language suggested by the IMT-2000 body. For convenience, it is common to omit the MC and RTT designations, and simply refer to the standard as cdma2000 1X.

cdma2000 1X supports an instantaneous data rate of up to 307 kbps for a user in packet mode, and yields typical throughput rates of up to 144 kbps per user, depending on the number of users, the velocity of a user, and the propagation conditions. cdma2000 1X can also support up to twice as many voice users as the 2G CDMA standard, and provides the subscriber unit with up to two times the standby time for longer lasting battery life. As seen in Table 2.3, cdma2000 is being developed for both FDD (mobile radio) and TDD (in-building cordless) applications.

The improvements in cdma2000 1X over 2G and 2.5G CDMA systems are gained through the use of rapidly adaptable baseband signaling rates and chipping rates for each user (provided through incremental redundancy) and multi-level keying within the same gross

framework of the original cdmaOne standard. No additional RF equipment is needed to enhance performance—the changes are all made in software or in baseband hardware. As can be seen in Table 2.2, to upgrade from 2G CDMA to cdma2000 1X, a wireless carrier merely needs to purchase new backbone software and new channel cards at the base station, without having to change out RF system components at the base station.

cdma2000 1xEV is an evolutionary advancement for CDMA originally developed by Qualcomm, Inc. as a proprietary *high data rate* (HDR) packet standard to be overlaid upon existing IS-95, IS-95B, and cdma2000 networks. Qualcomm later modified its HDR standard to be compatible with W-CDMA as well, and in August 2001, ITU recognized cdma2000 1xEV as part of IMT-2000. cdma2000 1xEV provides CDMA carriers with the option of installing radio channels with *data only* (cdma2000 1xEV-DO) or with *data and voice* (cdma2000 1xEV-DV). Using cdma2000 1xEV technology, individual 1.25 MHz channels may be installed in CDMA base stations to provide specific high speed packet data access within selected cells. The cdma2000 1xEV-DO option dedicates the radio channel strictly to data users, and supports greater than 2.4 Mbps of instantaneous high-speed packet throughput per user on a particular CDMA channel, although actual user data rates are typically much lower and are highly dependent upon the number of users, the propagation conditions, and vehicle speed. Typical users may experience throughputs on the order of several hundred kilobits per second, which is sufficient to support web browsing, email access, and m-commerce applications. cdma2000 1xEV-DV supports both voice and data users, and can offer usable data rates up to 144 kilobits per second with about twice as many voice channels as IS-95B.

The ultimate 3G solution for CDMA relies upon multicarrier techniques that gang adjacent cdmaOne radio channels together for increased bandwidth. The cdma2000 3xRTT standard uses three adjacent 1.25 MHz radio channels that are used together to provide instantaneous packet data throughput speeds in excess of 2 Mbps per user, although actual throughput depends upon cell loading, vehicle speed, and propagation conditions. Three non-adjacent radio channels may be operated simultaneously and in parallel as individual 1.25 MHz channels (in which case no new RF hardware is required at the base station), or adjacent channels may be combined into a single 3.75 MHz super channel (in which case new RF hardware is required at the base station). With peak user data rates in excess of 2 Mbps, it is clear that cdma2000 3X has a very similar user data rate throughput goal when compared to W-CDMA (UMTS). Advocates of cdma2000 claim their standard gives a wireless service provider a much more seamless and less expensive upgrade path when compared to W-CDMA, since cdma2000 allows the same spectrum, bandwidth, RF equipment, and air interface framework to be used at each base station as the 3G upgrades are introduced over time.

2.2.3 3G TD-SCDMA

In China, GSM is the most popular wireless air interface standard, and the wireless subscriber growth in China is unmatched anywhere in the world. For example, in late 2001 more than eight million cell phone subscribers were added in just one month in China alone! Given the huge potential market for wireless services in China, and China's desire to craft its own wireless

vision, The China Academy of Telecommunications Technology (CATT) and Siemens Corporation jointly submitted an IMT-2000 3G standard proposal in 1998, based on Time Division-Synchronous Code Division Multiple Access (TD-SCDMA). This proposal was adopted by ITU as one of the 3G options in late 1999.

TD-SCDMA relies on the existing core GSM infrastructure and allows a 3G network to evolve through the addition of high data rate equipment at each GSM base station. TD-SCDMA combines TDMA and TDD techniques to provide a data-only overlay in an existing GSM network. Up to 384 kbps of packet data is provided to data users in TD-SCDMA [TD-SCDMA Forum]. The radio channels in TD-SCDMA are 1.6 MHz in bandwidth and rely on smart antennas, spatial filtering, and joint detection techniques to yield several times more spectrum efficiency than GSM. A 5 millisecond frame is used in TD-SCDMA, and this frame is subdivided into seven time slots which are flexibly assigned to either a single high data rate user or several slower users. By using TDD, different time slots within a single frame on a single carrier frequency are used to provide both forward channel and reverse channel transmissions. For the case of asynchronous traffic demand, such as when a user downloads a file, the forward link will require more bandwidth than the reverse link, and thus more time slots will be dedicated to providing forward link traffic than for providing reverse link traffic. TD-SCDMA proponents claim that the TDD feature allows this 3G standard to be very easily and inexpensively added to existing GSM systems.

2.3 Wireless Local Loop (WLL) and LMDS

The rapid growth of the Internet has created a concurrent demand for broadband Internet and computer access from businesses and homes throughout the world. Particularly in developing nations where there is inadequate telecommunications backbone infrastructure, there is a tremendous need for inexpensive, reliable, rapidly deployable broadband connectivity that can bring individuals and enterprises into the information age. In fact, as voice over Internet protocols (VoIP) become prevalent, it is quite conceivable that a single broadband Internet connection could someday provide all of the needed telecommunications services, including telephone service, television, radio, fax, and Internet, for a home or business customer.

Fixed wireless equipment is extremely well suited for rapidly deploying a broadband connection in many instances, and this approach is steadily becoming more popular for providing "last mile" broadband local loop access, as well as for emergency or redundant point-to-point or point-to-multipoint private networks.

Unlike mobile cellular telephone systems described earlier in this chapter, fixed wireless communication systems are able to take advantage of the very well-defined, time-invariant nature of the propagation channel between the fixed transmitter and fixed receiver. Furthermore, modern fixed wireless systems are usually assigned microwave or millimeter radio frequencies in the 28 GHz band and higher, which is greater than ten times the carrier frequency of 3G terrestrial cellular telephone networks. At these higher frequencies, the wavelengths are extremely small, which in turn allows very high gain directional antennas to be fabricated in small physical form factors. At higher

frequencies, too, more bandwidth can be easily used. As we see in later chapters, high gain antennas have spatial filter properties that can reject multipath signals that arrive from directions other than the desired line-of-sight (LOS), and this in turn supports the transmission of very wide bandwidth signals (on the order of tens or hundreds of megabits per second) without distortion. Also, since the carrier frequencies of these fixed wireless access terminals are so high, the radio channel behaves much like an optical channel—if you can see an antenna, you can successfully communicate to it! Conversely, if you cannot see the antenna, you will be unable to communicate with it. Thus, fixed wireless networks at very high microwave frequencies are only viable where there are no obstructions, such as in a relatively flat suburban or rural setting.

Microwave wireless links can be used to create a wireless local loop (WLL) such as the one shown in Figure 2.4. As we see in Chapter 10, the local loop can be thought of as the "last mile" of the telecommunication network that resides between the central office (CO) and the individual homes and businesses in close proximity to the CO. In most developed countries, copper or fiber optic cable already has been installed to residences and businesses. However, in many developing nations, cable is too expensive or can take months or years to install. Wireless equipment, on the other hand, can usually be deployed in just a couple of hours. An additional benefit of WLL technology is that once the wireless equipment is paid for, there are no additional costs for transport between the CO and the customer premises equipment (CPE), whereas buried cables often must be leased from a service provider or utility company on a monthly basis. It is possible that WLL systems could compete with copper-wire based Digital Subscriber Loop (DSL) technologies that are rapidly proliferating [Sta99].

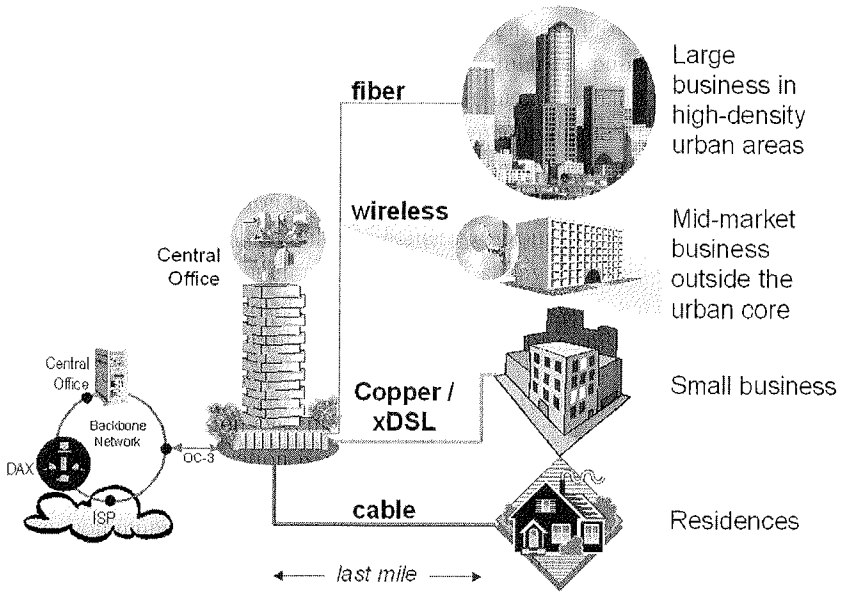


Figure 2.4 Example of the emerging applications and markets for broadband services. (Courtesy of Harris Corporation, ©1999, all rights reserved.)

Governments throughout the world have realized that WLL could greatly improve the efficiency of their citizens while stimulating competition that could lead to improved telecommunications services. A vast array of new services and applications have been proposed and are in the early stages of commercialization. These services include the concept of Local Multipoint Distribution Service (LMDS), which provides broadband telecommunications access in the local exchange [Cor97], [And98], [Xu00].

In 1998, 1300 MHz of unused spectrum in the 27–31 GHz band was auctioned by the US government to support LMDS. Similar auctions have been held in other countries around the world. Figure 2.5 illustrates various spectrum allocations made by countries throughout the world. Note that most LMDS allocations share frequencies with the Teledesic band which was approved by the ITU World Radio Conference for broadband satellite systems. The Teledesic band was originally established for the Motorola Iridium System, whose spectrum was later merged into the Teledesic system. Ironically, as of late 2001, broadband low earth orbit (LEO) satellite services were not yet commercially viable.

To gain a perspective of the enormous amount of bandwidth that is available for fixed wireless services such as LMDS, and how such licenses represent an unprecedented opportunity for wireless carriers, consider Figure 2.6. The figure compares the total spectrum bandwidths of various spectrum offerings for different wireless communication services in the United States from 1983 through 1998. Figure 2.6 also shows the tremendous amount of spectrum in the 59–64 GHz range that is earmarked for unlicensed WLAN use.

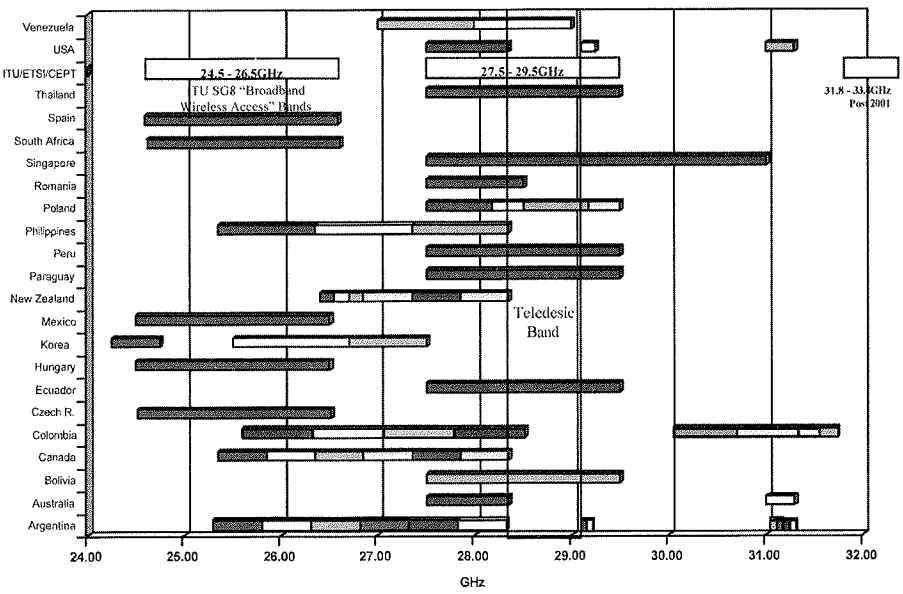
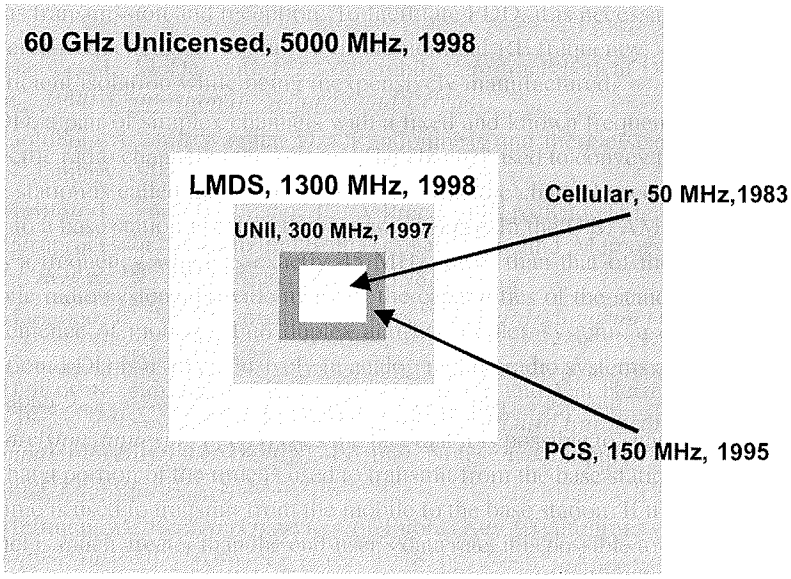


Figure 2.5 Allocation of broadband wireless spectrum throughout the world. (Courtesy of Ray W. Nettleton and reproduced by permission of Formus Communications.)



- A voice channel occupies ≈ 10 kHz of spectrum.
- A TV channel occupies ≈ 5 MHz of spectrum.

Figure 2.6 Comparison of spectrum allocations for various US wireless communications services. The areas of the rectangles are proportional to the amount of bandwidth allocated for each service.

The US LMDS band is 27.5–28.35 GHz, 29.1–29.25 GHz, and 31.075–31.225 GHz. The IEEE 802.16 Standards Committee is developing interoperability standards for fixed broadband wireless access. In Europe, a similar standard, HIPERACCESS, is being developed by a standardization committee for Broadband Radio Access Networks (BRAN) for operation in the 40.5–43.5 GHz band; it will use TDMA. Also, HIPERLINK is a very high speed short range interconnection for HIPERLANs and HIPERACCESS, up to 155 Mbps within 150 meters, and is planned to operate in the 17 GHz band in Europe.

In Figure 2.6, each rectangle has an area proportional to the amount of radio spectrum allocated to the specified service. For example, the US cellular service was first issued spectrum in 1983 and currently occupies 50 MHz of total bandwidth. The PCS service occupies 150 MHz of bandwidth, and the unlicensed National Information Infrastructure (UNII) band, discussed in Section 2.4, occupies 300 MHz. LMDS, on the other hand, was allocated a whopping 1300 MHz of bandwidth—enough spectrum to provide over 200 broadcast quality television channels or 65,000 full duplex voice channels! Yet, the revenues generated from the auction of all the US LMDS licenses was a paltry $500 million, compared to the more than $30 billion generated from the PCS auctions held three years earlier! This market difference is due to the fact that LMDS is a brand new type of service, vastly unproven, and dependent upon millimeter wave equipment that is still expensive. Nevertheless, the vast bandwidth capabilities of LMDS for WLL applications

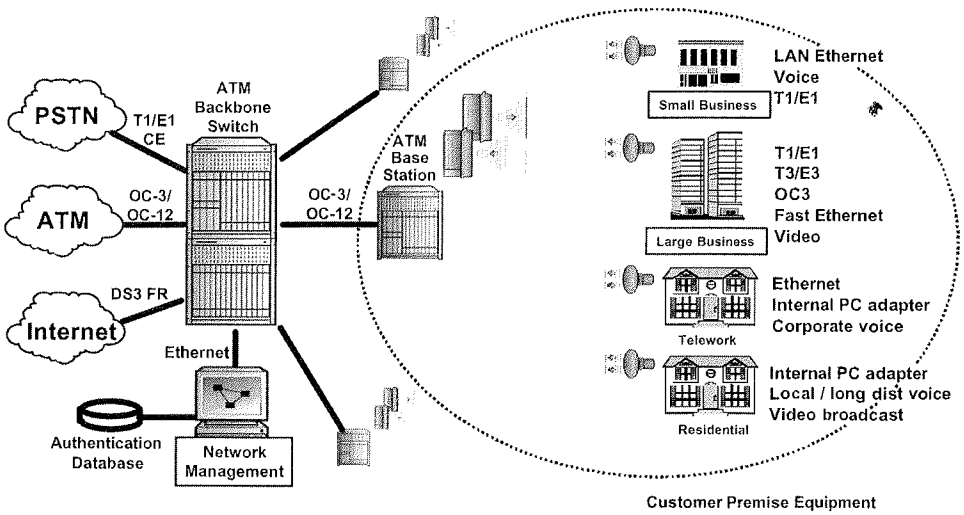


Figure 2.7 A wireless Competitive Local Exchange Carrier (CLEC) using Asynchronous Transfer Mode (ATM) distribution.

will someday prove valuable. The free spectrum available at 60 GHz provides an enormous incentive to reduce the cost of millimeter wave electronics for consumer use.

One of the most promising applications for LMDS is in a local exchange carrier (LEC) network. Figure 2.7 shows a typical network configuration, where the LEC owns a very wide bandwidth asynchronous transfer mode (ATM) or Synchronous Optical Network (SONET) backbone switch, capable of connecting hundreds of megabits per second of traffic with the Internet, the PSTN, or to its own private network. As long as a LOS path exists, LMDS will allow LECs to install wireless equipment on the premises of customers for rapid broadband connectivity without having to lease or install its own cables to the customers.

Unfortunately, finding a line-of-sight path is not the only requirement for maintaining a suitable fixed wireless connection for millimeter wave fixed wireless links. Rain, snow, and hail can create large changes in the channel gain between transmitter and receiver. In [Xu00], an extensive experimental study was conducted on various short-hop fixed wireless links in various weather conditions to determine signal loss and multipath effects due to weather impairments. In [Xu00], a novel design method was found to accurately predict received power and multipath delay for any fixed wireless link in the vicinity of surrounding buildings and in weather. Figure 2.8 from [Xu00] illustrates actual measured received power levels, as a function of precipitation, for a fixed 605 meter wireless hop operating at 38 GHz over several different days. Note that on a clear day, the received signal level is –47 dBm, and during a relatively light 40 mm/hr rain rate, the received signal level drops 4.8 dB to –51.8 dBm. However, when measured during a hail storm, the received signal level drops to –72.7 dBm, a full 25.7 dB loss from clear sky conditions!

Figure 2.9 shows how the instantaneous received power is directly a function of the instantaneous rain rate. Note that over a 41 minute period, the received signal level fluctuates by about

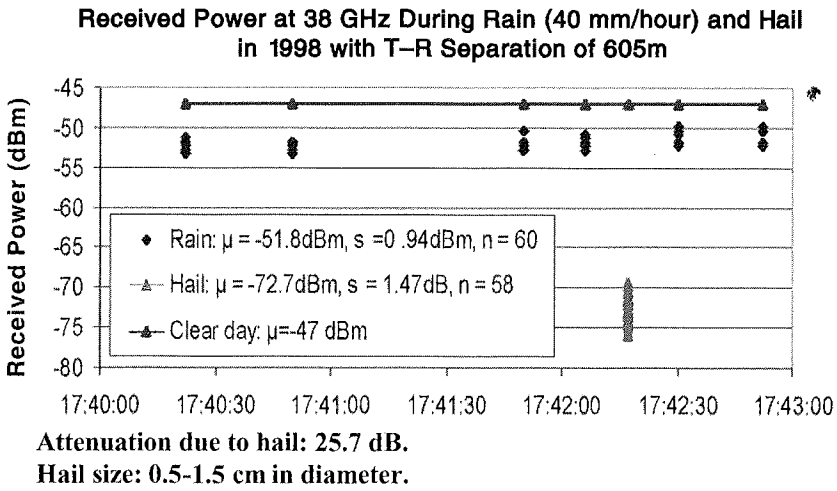


Figure 2.8 Measured received power levels over a 605 m 38 GHz fixed wireless link in clear sky, rain, and hail [from [Xu00], ©IEEE].

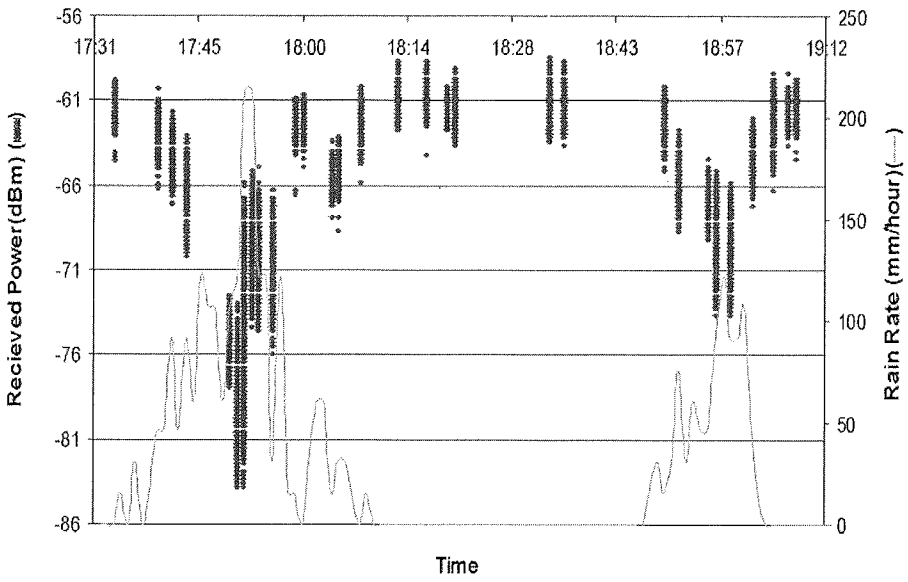


Figure 2.9 Measured received power during rain storm at 38 GHz [from [Xu00], ©IEEE].

27 dB. As shown in Chapters 4 and 5, the attenuation caused by weather effects must be statistically accounted for in the proper design of a fixed wireless network so that an outage probability can be computed based on local rain patterns and rain statistics.

2.4 Wireless Local Area Networks (WLANs)

As shown in Figure 2.6, in 1997 the FCC allocated 300 MHz of unlicensed spectrum in the Industrial Scientific and Medical (ISM) bands of 5.150–5.350 GHz and 5.725–5.825 GHz for the express purpose of supporting low-power license-free spread spectrum data communication. This allocation is called the *Unlicensed National Information Infrastructure (UNII)* band.

The FCC's generous spectrum allotment followed a much earlier allocation of unlicensed spread spectrum bands by the FCC in the mid 1980s. Specifically, in the late 1980s the FCC first provided license free bands under Part 15 of the FCC regulations for low power spread spectrum devices in the 902–928 MHz, 2400–2483.5 MHz, and 5.725–5.825 MHz ISM bands.

By providing a license-free spectrum allocation, the FCC hoped to encourage competitive development of spread spectrum knowledge, spread spectrum equipment, and ownership of individual WLANs and other low-power short range devices that could facilitate private computer communications in the workplace. The IEEE 802.11 Wireless LAN working group was founded in 1987 to begin standardization of spread spectrum WLANs for use in the ISM bands. Despite the unrestricted spectrum allocation and intense industry interest, the WLAN movement did not gain momentum until the late 1990s, when the phenomenal popularity of the Internet combined with widescale acceptance of portable, laptop computers finally caused WLAN to become an important and rapidly growing segment of the modern wireless communications marketplace. IEEE 802.11 was finally standardized in 1997 and provided interoperability standards for WLAN manufacturers using 11 Mcps DS-SS spreading and 2 Mbps user data rates (with fallback to 1 Mbps in noisy conditions). With an international standard now approved, numerous manufacturers began to comply for interoperability, and the market began to accelerate rapidly. In 1999, the 802.11 High Rate standard (called IEEE 802.11b) was approved, thereby providing new user data rate capabilities of 11 Mbps, 5.5 Mbps in addition to the original 2 Mbps and 1 Mbps user rates of IEEE 802.11, which were retained.

Figure 2.10 illustrates the evolution of IEEE 802.11 Wireless LAN standards, which also include infrared communications. Figure 2.10 shows how both frequency hopping and direct sequence approaches were used in the original IEEE 802.11 standard (2 Mbps user throughput), but as of late 2001 only direct sequence spread spectrum (DS-SS) modems had thus far been standardized for high rate (11 Mbps) user data rates within IEEE 802.11. Not shown in Figure 2.10 is the IEEE 802.11a standard, which will provide up to 54 Mbps throughput in the 5 GHz band. The DS-SS IEEE 802.11b standard has been named *Wi-Fi* by the *Wireless Ethernet Compatibility Alliance (WECA)*, a group that promotes adoption of 802.11b DS-SS WLAN equipment and interoperability between vendors. IEEE 802.11g is developing *Complimentary Code Keying Orthogonal Frequency Division Multiplexing (CCK-OFDM)* standards in both the 2.4 GHz (802.11b) and 5 GHz (802.11a) bands, and will support roaming capabilities and dual-band use for public WLAN networks, while supporting backward compatibility with 802.11b technology.

The frequency-hopping spread spectrum (FH-SS) proponents of IEEE 802.11 have formed the HomeRF standard that supports frequency hopping equipment. In 2001, HomeRF developed a 10 Mbps FH-SS standard called HomeRF 2.0. It is worth noting that both DS and FH types of

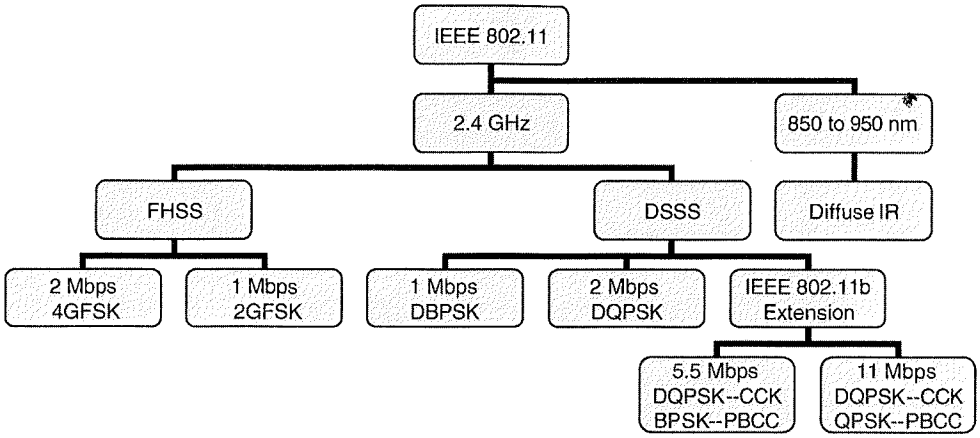


Figure 2.10 Overview of the IEEE 802.11 Wireless LAN standard.

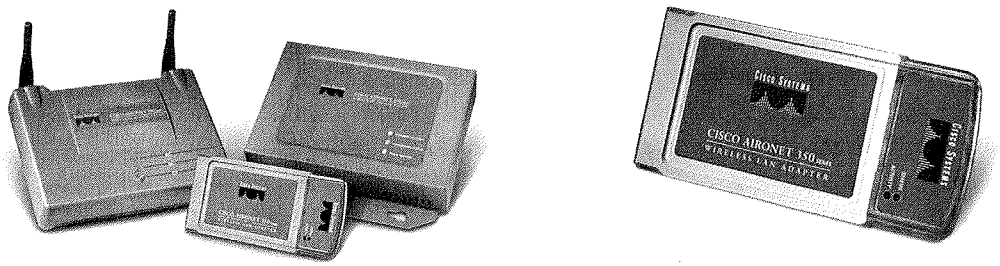


Figure 2.11 Photographs of popular 802.11b WLAN equipment. Access points and a client card are shown on left, and PCMCIA Client card is shown on right. (Courtesy of Cisco Systems, Inc.)

WLANs must operate in the same unlicensed bands that contain cordless phones, baby monitors, Bluetooth devices, and other WLAN users. Both DS and FH vendors claim to have advantages over the other for operation in such radio environments [Are01]. Figure 2.11 shows the popular CISCO Aironet WLAN products in various form factors. Table 2.4 lists international channel allocations for DS and FH WLANs in the 2.4 GHz band.

Figure 2.12 illustrates the unique WLAN channels that are specified in the IEEE 802.11b standard for the 2400–2483.5 MHz band. All WLANs are manufactured to operate on any one of the specified channels and are assigned to a particular channel by the network operator when the WLAN system is first installed. The channelization scheme used by the network installer becomes very important for a high density WLAN installation, since neighboring access points must be separated from one another in frequency to avoid interference and significantly degraded performance. As we show in Chapter 3, *all* wireless systems must be designed with knowledge of

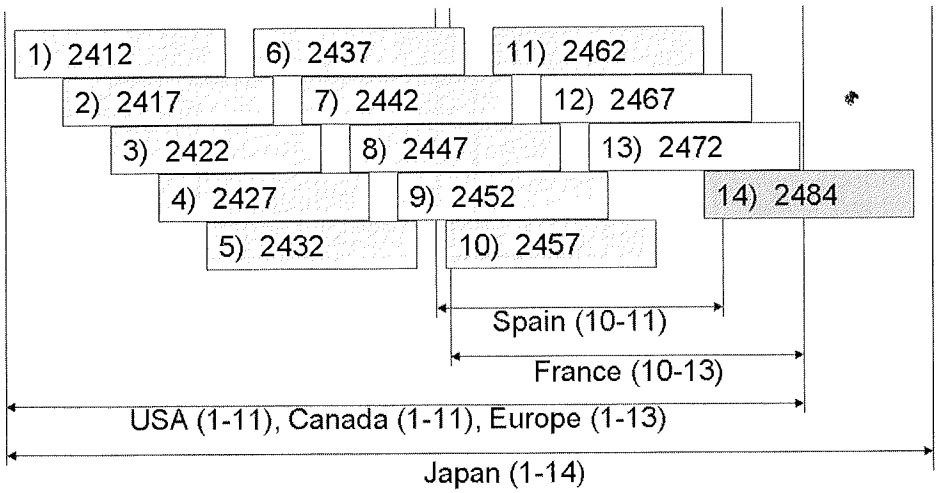


Figure 2.12 2400 MHz channelization scheme for IEEE 802.11b throughout the world.

the interference and propagation environment—prudent WLAN deployment dictates that the placement of transmitters and their frequency assignments be done systematically to minimize impact. Even though WLAN networks are designed to work in an interference-rich environment, and manufacturers may downplay the importance of planning, the fact is that the ability to measure or predict the coverage and interference effects caused by specific placements of access points can provide *orders of magnitude* of improvement in cost and end user data throughputs in a heavily loaded system. Research conducted in [Hen01] showed that the user throughput performance changes radically when access points or clients are located near an interfering transmitter or when frequency planning is not carefully conducted.

Using new computer-aided design (CAD) measurement and prediction software such as *SitePlanner* by Wireless Valley [Wir01], WLAN deployments can be done very rapidly without any trial and error. By loading the blueprint of the building or campus within a computer, propagation modeling techniques can now predict user data throughput based on radio signal strength and interference prediction algorithms [Hen01]. Figure 2.13 illustrates how the proper placements for WLAN access points can be rapidly found before ever setting foot in the building. By using an interactive computer program, the network operator can rapidly provision and plan the channelization scheme, as well as the locations of the access points, before doing an actual network deployment. In fact, email and Internet correspondence can be done to rapidly provision any physical environment. When the deployment is complete, the same CAD environment is able to archive the exact physical locations, cost and maintenance records of the network, and the specific channelization schemes for future use and modification as network growth occurs.

Figure 2.13 shows the result of coverage for an actual WLAN installation made in a large modern lecture hall on a university campus. The design was first conducted blind in less than ten minutes, over the Internet, using a CAD design product. Then, the student used his complete

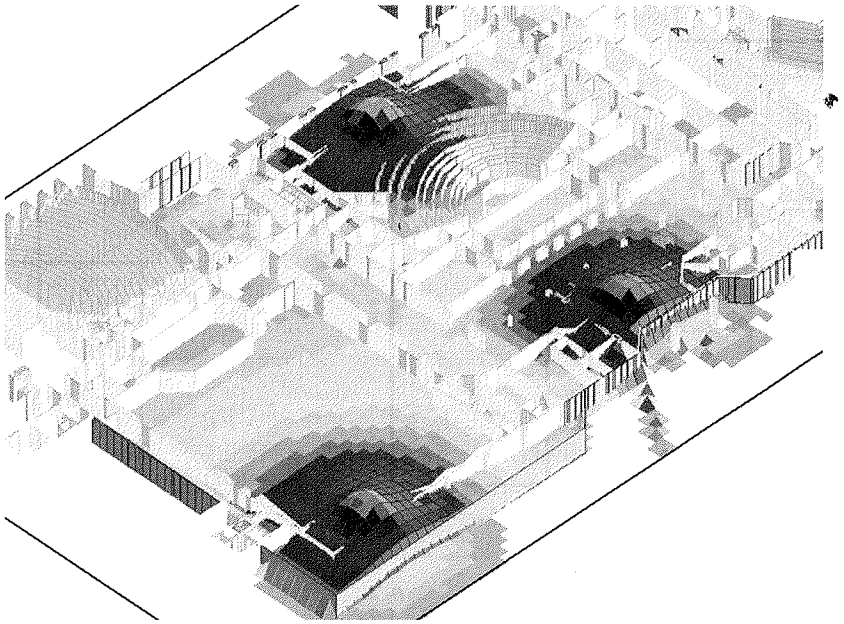


Figure 2.13 A predicted coverage plot for three access points in a modern large lecture hall. (Courtesy of Wireless Valley Communications, Inc., ©2000, all rights reserved.)

strawman design of the WLAN system and visited the building to place the access points, and verified the design by measuring network performance with the CAD product as he walked throughout the building. In under 30 minutes, the student was able to verify his strawman design and had completely measured and archived the true user throughput and delays experienced at specific locations throughout the building (due to both propagation loss and interference) with all access points in operation. During the validation field test, the student was able to keep track of actual field measurements directly on an electronic blueprint while storing all measurements, all predictions, and all system parameters (such as the channelization scheme used and physical location of access points). In [Hen01], the *SitePlanner* design environment was used with WLAN measurement products (*LANFielder* and *SiteSpy*) to enable new and efficient methods for collecting and using in-the-field network measurements for rapid network validation and tuning for optimal WLAN design. As WLANs proliferate and interference levels rise, having a design and archiving environment that can be tuned to measurements will be increasingly important. Figure 2.14 illustrates one of the measurement experiments conducted in [Hen01] in order to model the end user's throughput data as a function of signal strength and interference.

In Europe in the mid 1990s, the *High Performance Radio Local Area Network* (HIPERLAN) standard was developed to provide a similar capability to IEEE 802.11. HIPERLAN was intended to provide individual wireless LANs for computer communications and used the 5.2 GHz and the 17.1 GHz frequency bands. HIPERLAN provides asynchronous user data rates

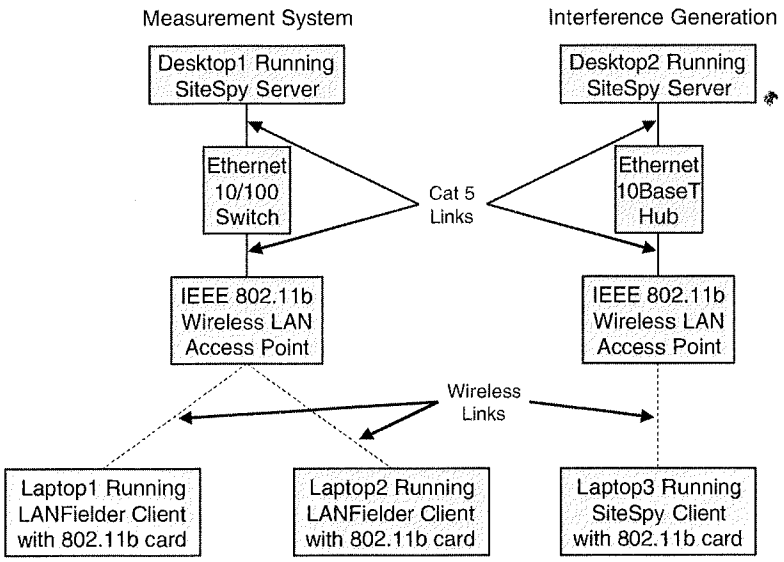


Figure 2.14 Schematic of an experiment to determine how received interference impacts end user performance on a WLAN network [Hen01]. Work in [Hen01] demonstrated that a CAD prediction and measurement environment can be used to accurately and rapidly predict true end user throughput in a multi-node network using blind prediction. Such capabilities will be vital as user densities increase in WLAN networks within buildings or campuses.

of between 1 to 20 Mbps, as well as time bounded messaging at rates of 64 kbps to 2.048 Mbps. HIPERLAN was designed to operate up to vehicle speeds of 35 km/hr, and typically provided 20 Mbps throughput at 50 m range.

Convergence in the WLAN industry appears to be on the horizon, as standard organizations in Europe, North America, and Japan begin to coordinate spectrum allocations and end user data rates. In 1997, Europe's ETSI established a standardization committee for Broadband Radio Access Networks (BRANs). The goal of BRAN is to develop a family of broadband WLAN-type protocols that allow user interoperability, covering both short range (e.g., WLAN) and long range (e.g., fixed wireless) networking. HIPERLAN/2 has emerged as the next generation European WLAN standard and will provide up to 54 Mbps of user data to a variety of networks, including the ATM backbone, IP based networks, and the UMTS core. HIPERLAN/2 is anticipated to operate in the 5 GHz band. Meanwhile, IEEE 802.11a is emerging as North America's next generation WLAN. Like HIPERLAN/2, IEEE 802.11a supports up to 54 Mbps user data rate for integration into backbone ATM, UMTS, and IP networks and will operate in the 5.15–5.35 GHz ISM band. Meanwhile, Japan's Multimedia Mobile Access Communication System (MMAC) has been developing high data rate (25 Mbps) WLAN standards for use in the 5.15–5.35 GHz band.

As wireless data rates increase and worldwide standards begin to converge, new applications for WLANs become evident. Numerous companies have been exploring a public LAN

(publan) concept whereby a nationwide Wireless Internet Service Provider (WISP) builds a nationwide infrastructure of WLAN access points in selected hotels, restaurants, airports, or coffee shops, and then charges a monthly subscription fee to users who wish to have always-on Internet access in those select locations. Other recent ideas suggest that WLANs could be used to provide access for the last 100 meters into homes and businesses, in competition with fixed wireless access, and in competition with IMT-2000. Certainly, the price point for WLAN hardware is far below 3G base stations and fixed wireless millimeter wave equipment. However, the WLAN spectrum is unlicensed, and unless judicious frequency planning and radio engineering is employed, careless WLAN deployments in buildings or neighborhoods could become saturated. This again points to the need for WLAN deployment strategies that use knowledge of the interference and propagation conditions, such as shown in Figure 2.13.

It is instructive to investigate how a futuristic WLAN system might work in a typical neighborhood if WLAN access points were mounted on lamp poles along the street. Consider the neighborhood shown in Figure 2.15, where three homes are located in a heavily wooded area. In [Dur98], measurements were conducted in several homes and in different types of foliage using street-mounted lamp-post transmitters in the 5.8 GHz band. Houses were measured for WLAN signal strength, both outside the house (for an externally mounted Customer Premises Equipment (CPE) antenna at roof height and at head height) and inside the house (at head height to represent a cordless phone or portable antenna). Figure 2.16 shows actual measured path loss values for various antenna heights within the house. Note that the street-mounted transmitter is

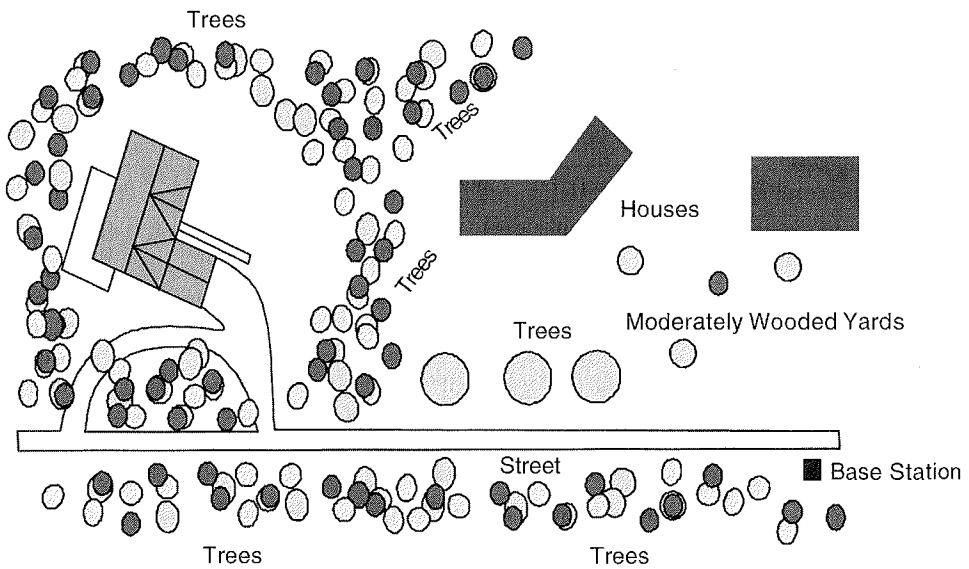


Figure 2.15 A typical neighborhood where high speed license free WLAN service from the street might be contemplated [Dur98b].

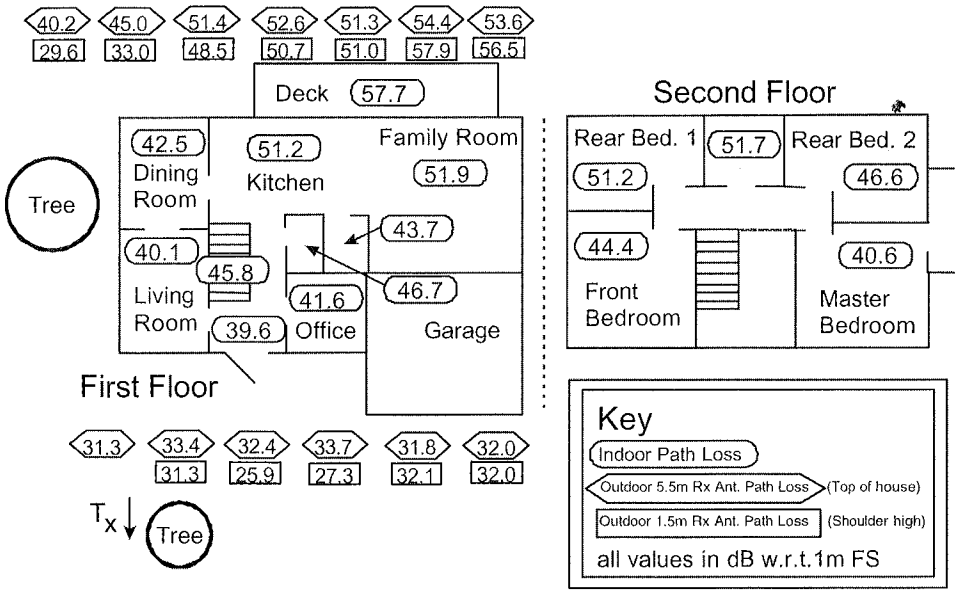


Figure 2.16 Measured values of path loss using a street-mounted lamp-post transmitter at 5.8 GHz, for various types of customer premise antenna [from [Dur98], ©IEEE].

located on the bottom left of Figure 2.16. It can be seen that the signal level in the kitchen (51.2 dB loss) is 11.5 dB weaker than the signal level at the front door (39.6 dB), and the signal on the back deck is 18.1 dB weaker than the signal level at the front door.

Knowing the specific signal loss values throughout a home or neighborhood is vital for determining the coverage, capacity, and cost of a contemplated system. Work in [Dur98], [Mor00], [Hen01], and [Rap00] shows definitively that extremely accurate predictions of coverage, WLAN end-user performance, infrastructure cost, and overall network capacity can be found easily and directly by using just a small amount of site-specific blue print information [Dur98].

2.5 Bluetooth and Personal Area Networks (PANs)

Given the revolutionary strides that wireless technology has made during the past two decades, electronics manufacturers recently realized there is huge consumer appreciation for "removing the wire." The ability to replace the cumbersome cords that connect devices to one another (such as printer cables, headphone cables, wires that run from a personal computer to a mouse) with an invisible, low power short-range wireless connection, would provide convenience and flexibility. Furthermore, wireless connectivity would allow the ability to move equipment throughout an office, and would allow collaborative communication between individuals, their appliances, and their environment.

Table 2.4 IEEE 802.11b Channels for Both DS-SS and FH-SS WLAN Standards

Country	Frequency Range Available	DSSS Channels Available	FHSS Channels Available
United States	2.4 to 2.4835 GHz	1 through 11	2 through 80
Canada	2.4 to 2.4835 GHz	1 through 11	2 through 80
Japan	2.4 to 2.497 GHz	1 through 14	2 through 95
France	2.4465 to 2.4835 GHz	10 through 13	48 through 82
Spain	2.445 to 2.4835 GHz	10 through 11	47 through 73
Remainder of Europe	2.4 to 2.4835	1 through 13	2 through 80

Bluetooth is an open standard that has been embraced by over 1,000 manufacturers of electronic appliances. It provides an ad-hoc approach for enabling various devices to communicate with one another within a nominal 10 meter range. Named after King Harald Bluetooth, the 10^{th} century Viking who united Denmark and Norway, the Bluetooth standard aims to unify the connectivity chores of appliances within the personal workspace of an individual [Rob01].

Bluetooth operates in the 2.4 GHz ISM Band (2400–2483.5 MHz) and uses a frequency hopping TDD scheme for each radio channel. Each Bluetooth radio channel has a 1 MHz bandwidth and hops at a rate of approximately 1600 hops per second. Transmissions are performed in 625 microsecond slots with a single packet transmitted over a single slot. For long data transmissions, particular users may occupy multiple slots using the same transmission frequency, thus slowing the instantaneous hopping rate to below 1600 hops/second. The frequency hopping scheme of each Bluetooth user is determined from a cyclic code of length $2^{27} - 1$, and each user has a channel symbol rate of 1 Mbps using GFSK modulation. The standard has been designed to support operation in very high interference levels and relies on a number of forward error control (FEC) coding and automatic repeat request (ARQ) schemes to support a raw channel bit error rate (BER) of about 10^{-3}.

Different countries have allocated various channels for Bluetooth operation. In the US and most of Europe, the FHSS 2.4 GHz ISM band is available for Bluetooth use (see Table 2.4). A detailed list of states are defined in the Bluetooth standard to support a wide range of applications, appliances, and potential uses of the Personal Area Network. Audio, text, data, and even video is contemplated in the Bluetooth standard [Tra01]. Figure 2.17 provides a depiction of the Bluetooth concept where a gateway to the Internet via IEEE 802.11b is shown as a conceptual possibility.

The IEEE 802.15 standards committee has been formed to provide an international forum for developing Bluetooth and other PANs that interconnect pocket PCs, personal digital assistants (PDAs), cellphones, light projectors, and other appliances [Bra00]. With the rapid proliferation of

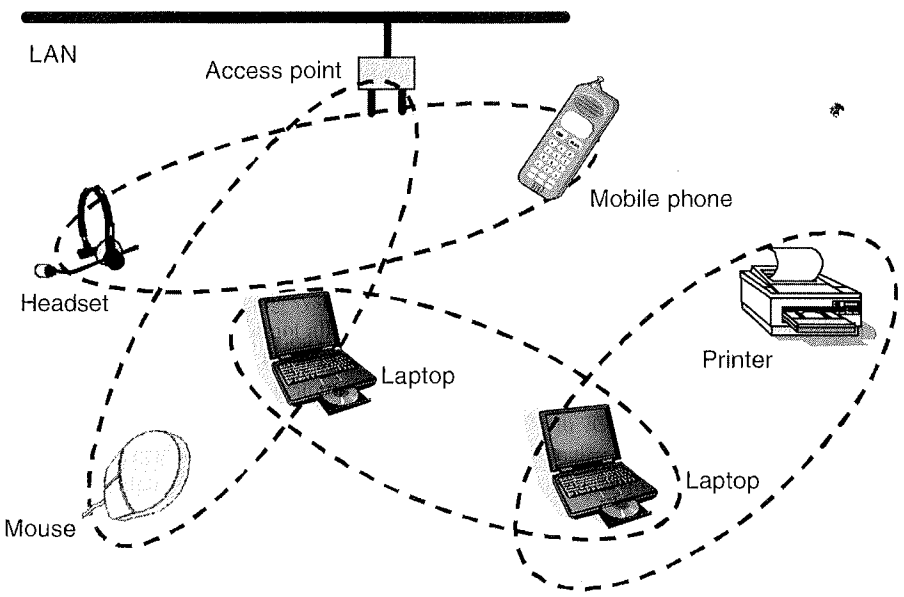


Figure 2.17 Example of a Personal Area Network (PAN) as provided by the Bluetooth standard.

wearable computers, such as PDAs, cellphones, smart cards, and position location devices, PANs may provide the connection to an entire new era of remote retrieval and monitoring of the world around us.

2.6 Summary

This chapter has provided an overview of the modern wireless communication networks that are currently being developed throughout the world. From mobile telephone, to broadband wireless access, to inside buildings and across campuses, it is clear that wireless communications will become a ubiquitous means of transport for information in the 21st century. In this chapter, the convergence of second generation mobile telephone standards into third generation standards was described, and the interim 2.5G data solutions were explained for all major mobile technologies. The current state-of-the-art of broadband millimeter wave systems were presented, along with the vision for wireless LMDS broadband networks as a complement to the existing fiber backbone. Current WLAN developments, and the evolution of WLANs from incompatible low data rate devices to powerful multi-megabit standardized networks were highlighted. Current WLAN standard activities were also presented. Finally, the emergence of Bluetooth, and the concept of a personal area network (PAN) were described. Armed with a high level understanding of the various emerging markets and competing technology choices facing the wireless telecommunication industry, the reader is now ready to study the fundamental technical issues that impact all wireless systems. The remaining chapters of this book provide such fundamental treatment.

2.7 Problems

2.1 In your place of work, how many modern wireless communications networks are available to you? Identify the types of services, the types of technologies, the commercial names of the service providers, and the commercial names of the equipment manufacturers that offer these wireless access capabilities.

2.2 In your home, how many modern wireless communications networks are available to you? Identify the types of services, the types of technologies, the commercial names of the service providers, and the commercial names of the equipment manufacturers that offer these wireless access capabilities.

2.3 Create a table that lists all 2G, 2.5G, and 3G mobile telephone standards. Carefully research the latest sources to determine the following parameters for each standard: a) RF channel BW; b) peak data rate; c) typical data rate; d) responsible standards body; e) maximum number of concurrent users; f) modulation type.

2.4 Conduct research to find out all of the accepted air interface standards for IMT-2000. Briefly describe the technical features and discuss the political and business motivations of each of the groups that proposed the winning standards. What is your favorite IMT-2000 standard? Justify your answer.

2.5 Specify the unlicensed frequency bands and the channel assignment plans that European, Japanese, and North American wireless local area network (WLAN) equipments are allowed to use within the 2 to 6 GHz range. How does international frequency compatibility help the growth of air interface standards in an unlicensed frequency band?

2.6 Why would an entrenched US wireless carrier announce that its long term plan is to abandon its IS-136 North American Digital Cellular standard in favor of a W-CDMA 3rd generation standard with foundations in GSM? Consider the decision in the face of the following business, political, and technical considerations: a) availability of low price equipment from manufacturers; b) compatibility with competing US wireless carriers; c) compatibility with carriers it considers its business allies; d) compatibility with wireless carriers outside of the US; d) access to field-proven equipment that provides off-the-shelf 3G capabilities; e) domain experience by its current engineering staff; f) cost and maintainability of the infrastructure; g) other factors not mentioned above.

2.7 If an IS-136 operator desires to provide competitive high speed Internet access to customers, it must choose to either adopt GPRS, or alternatively it may wish to change out its existing infrastructure to GSM and then use the various options available to GSM operators. Conduct a literature search to determine the current state of GPRS for IS-136 carriers. Given your findings, what is the most sensible option for the IS-136 carrier based on price, availability, and user experience?

2.8 Compare and contrast the various 2.5G technology paths that each of the major 2G standards provide. Which path has the highest Internet access speed? Is this speed true user speed, or peak instantaneous throughput speed? Which technology path is easiest to implement in existing subscriber handsets? Which path would be best suited for real-time network access?

2.9 How would multicarrier transmissions impact an operator's approach to allocating resources to accommodate a growing subscriber database that increasingly desires data connectivity over voice? How would heavy HSCSD usage impact a cellular carrier's strategy in allocating channels in the base stations of a cellular network? How would the rapid adoption of Voice over Internet Protocol (VoIP) impact cellular congestion? Explain.

2.10 Determine the maximum raw instantaneous data rate that can be provided to a single user in EDGE, assuming that a single time slot on a single GSM channel is available.

2.11 Find the maximum raw instantaneous data rate that can be provided using IS-95B if four user channels are dedicated to a single user.

channels in a cell is about 57. The channels listed in the upper half of the chart belong to block A and those in the lower half belong to block B. The shaded set of numbers correspond to the control channels which are standard to all cellular systems in North America.

Table 3.2 AMPS Channel Allocation for A and B Side Carriers

1A	2A	3A	4A	5A	6A	7A	1B	2B	3B	4B	5B	6B	7B	1C	2C	3C	4C	5C	6C	7C	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	
43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	
64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	
85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	
106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	
127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	
148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	
169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	
190	191	192	193	194	195	196	197	198	199	20	201	202	203	204	205	206	207	208	209	210	A
211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	SIDE
232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	
253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	
274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	
295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	-	-	-	
313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	667	668	669	
670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	
691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	
712	713	714	715	716	-	-	-	-	991	992	993	994	995	996	997	998	999	1000	1001	1002	
1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	
334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	
355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	
376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	
397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	
418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	
439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	
460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	
481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	
502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	
523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	B
544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	SIDE
565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	
586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	
607	608	609	610	611	6612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	
628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	
649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	-	-	-	
-	-	-	-	-	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	
733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	
754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	
775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	
796	797	798	799																		

3.5.4 Power Control for Reducing Interference

In practical cellular radio and personal communication systems, the power levels transmitted by every subscriber unit are under constant control by the serving base stations. This is done to ensure that each mobile transmits the smallest power necessary to maintain a good quality link

on the reverse channel. Power control not only helps prolong battery life for the subscriber unit, but also dramatically reduces the reverse channel *S/I* in the system. As shown in Chapters 9 and 11, power control is especially important for emerging CDMA spread spectrum systems that allow every user in every cell to share the same radio channel.

3.6 Trunking and Grade of Service

Cellular radio systems rely on *trunking* to accommodate a large number of users in a limited radio spectrum. The concept of trunking allows a large number of users to share the relatively small number of channels in a cell by providing access to each user, on demand, from a pool of available channels. In a trunked radio system, each user is allocated a channel on a per call basis, and upon termination of the call, the previously occupied channel is immediately returned to the pool of available channels.

Trunking exploits the statistical behavior of users so that a fixed number of channels or circuits may accommodate a large, random user community. The telephone company uses trunking theory to determine the number of telephone circuits that need to be allocated for office buildings with hundreds of telephones, and this same principle is used in designing cellular radio systems. There is a trade-off between the number of available telephone circuits and the likelihood of a particular user finding that no circuits are available during the peak calling time. As the number of phone lines decreases, it becomes more likely that all circuits will be busy for a particular user. In a trunked mobile radio system, when a particular user requests service and all of the radio channels are already in use, the user is blocked, or denied access to the system. In some systems, a queue may be used to hold the requesting users until a channel becomes available.

To design trunked radio systems that can handle a specific capacity at a specific "grade of service," it is essential to understand trunking theory and queuing theory. The fundamentals of trunking theory were developed by Erlang, a Danish mathematician who, in the late 19th century, embarked on the study of how a large population could be accommodated by a limited number of servers [Bou88]. Today, the measure of traffic intensity bears his name. One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied (i.e. one call-hour per hour or one call-minute per minute). For example, a radio channel that is occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic.

The *grade of service (GOS)* is a measure of the ability of a user to access a trunked system during the busiest hour. The busy hour is based upon customer demand at the busiest hour during a week, month, or year. The busy hours for cellular radio systems typically occur during rush hours, between 4 p.m. and 6 p.m. on a Thursday or Friday evening. The grade of service is a benchmark used to define the desired performance of a particular trunked system by specifying a desired likelihood of a user obtaining channel access given a specific number of channels available in the system. It is the wireless designer's job to estimate the maximum required capacity and to allocate the proper number of channels in order to meet the *GOS*. *GOS* is typically given as the likelihood that a call is blocked, or the likelihood of a call experiencing a delay greater than a certain queuing time.

6.1 Frequency Modulation vs. Amplitude Modulation

Frequency modulation (FM) is the most popular analog modulation technique used in mobile radio systems. In FM, the amplitude of the modulated carrier signal is kept constant while its frequency is varied by the modulating message signal. Thus, FM signals have all their information in the *phase* or *frequency* of the carrier. As shown subsequently, this provides a nonlinear and very rapid improvement in reception quality once a certain minimum received signal level, called the FM threshold, is achieved. In amplitude modulation (AM) schemes, there is a linear relationship between the quality of the received signal and the power of the received signal since AM signals superimpose the exact relative amplitudes of the modulating signal onto the carrier. Thus, AM signals have all their information in the *amplitude* of the carrier. FM offers many advantages over amplitude modulation (AM), which makes it a better choice for many mobile radio applications.

Frequency modulation has better noise immunity when compared to amplitude modulation. Since signals are represented as frequency variations rather than amplitude variations, FM signals are less susceptible to atmospheric and impulse noise, which tend to cause rapid fluctuations in the amplitude of the received radio signal. Also, message amplitude variations do not carry information in FM, so burst noise does not affect FM system performance as much as AM systems, provided that the FM received signal is above the FM threshold. Chapter 5 illustrated how small-scale fading can cause rapid fluctuations in the received signal, thus FM offers superior qualitative performance in fading when compared to AM. Also, in an FM system, it is possible to tradeoff bandwidth occupancy for improved noise performance. Unlike AM, in an FM system, the *modulation index*, and hence bandwidth occupancy, can be varied to obtain greater signal-to-noise performance. It can be shown that, under certain conditions, the FM signal-to-noise ratio improves 6 dB for each doubling of bandwidth occupancy. This ability of an FM system to trade bandwidth for SNR is perhaps the most important reason for its superiority over AM. However, AM signals are able to occupy less bandwidth as compared to FM signals, since the transmission system is linear. In modern AM systems, susceptibility to fading has been dramatically improved through the use of in-band pilot tones which are transmitted along with the standard AM signal. The modern AM receiver is able to monitor the pilot tone and rapidly adjust the receiver gain to compensate for the amplitude fluctuations.

An FM signal is a *constant envelope* signal, due to the fact that the envelope of the carrier does not change with changes in the modulating signal. Hence the transmitted power of an FM signal is constant regardless of the amplitude of the message signal. The constant envelope of the transmitted signal allows efficient Class C power amplifiers to be used for RF power amplification of FM. In AM, however, it is critical to maintain linearity between the applied message and the amplitude of the transmitted signal, thus linear Class A or AB amplifiers, which are not as power efficient, must be used.

The issue of amplifier efficiency is extremely important when designing portable subscriber terminals since the battery life of the portable is tied to the power amplifier efficiency. Typical efficiencies for Class C amplifiers are 70%, meaning that 70% of the applied DC power

to the final amplifier circuit is converted into radiated RF power. Class A or AB amplifiers have efficiencies on the order of 30-40%. This implies that for the same battery, constant envelope FM modulation may provide twice as much talk time as AM.

Frequency modulation exhibits a so-called *capture effect* characteristic. The capture effect is a direct result of the rapid nonlinear improvement in received quality for an increase in received power. If two signals in the same frequency band are available at an FM receiver, the one appearing at the higher received signal level is accepted and demodulated, while the weaker one is rejected. This inherent ability to pick up the strongest signal and reject the rest makes FM systems very resistant to co-channel interference and provides excellent subjective received quality. In AM systems, on the other hand, all of the interferers are received at once and must be discriminated after the demodulation process.

While FM systems have many advantages over AM systems, they also have certain disadvantages. FM systems require a wider frequency band in the transmitting media (generally several times as large as that needed for AM) in order to obtain the advantages of reduced noise and capture effect. FM transmitter and receiver equipment is also more complex than that used by amplitude modulation systems. Although frequency modulation systems are tolerant to certain types of signal and circuit nonlinearities, special attention must be given to phase characteristics. Both AM and FM may be demodulated using inexpensive noncoherent detectors. AM is easily demodulated using an envelope detector whereas FM is demodulated using a discriminator or slope detector. AM may be detected coherently with a product detector, and in such cases AM can outperform FM in weak signal conditions since FM must be received above threshold.

6.2 Amplitude Modulation

In amplitude modulation, the amplitude of a high frequency carrier signal is varied in accordance to the instantaneous amplitude of the modulating message signal. If $A_c\cos(2\pi f_c t)$ is the carrier signal and $m(t)$ is the modulating message signal, the AM signal can be represented as

$$s_{\text{AM}}(t) = A_c[1 + m(t)]\cos(2\pi f_c t) \tag{6.1}$$

The *modulation index* k of an AM signal is defined as the ratio of the peak message signal amplitude to the peak carrier amplitude. For a sinusoidal modulating signal $m(t) = (A_m/A_c)\cos(2\pi f_m t)$, the modulation index is given by

$$k = \frac{A_m}{A_c} \tag{6.2}$$

The modulation index is often expressed as a percentage, and is called *percentage modulation.* Figure 6.1 shows a sinusoidal modulating signal and the corresponding AM signal. For the case shown in Figure 6.1, $A_m = 0.5A_c$, and the signal is said to be 50% modulated. A percentage of

CHAPTER 9

Multiple Access Techniques for Wireless Communications

Multiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing of spectrum is required to achieve high capacity by simultaneously allocating the available bandwidth (or the available amount of channels) to multiple users. For high quality communications, this must be done without severe degradation in the performance of the system.

9.1 Introduction

In wireless communications systems, it is often desirable to allow the subscriber to send simultaneously information to the base station while receiving information from the base station. For example, in conventional telephone systems, it is possible to talk and listen simultaneously, and this effect, called *duplexing*, is generally required in wireless telephone systems.

Duplexing may be done using frequency or time domain techniques. *Frequency division duplexing* (FDD) provides two distinct bands of frequencies for every user. The *forward band* provides traffic from the base station to the mobile, and the *reverse band* provides traffic from the mobile to the base station. In FDD, any *duplex channel* actually consists of two simplex channels (a forward and reverse), and a device called a *duplexer* is used inside each subscriber unit and base station to allow simultaneous bidirectional radio transmission and reception for both the subscriber unit and the base station on the duplex channel pair. The frequency separation between each forward and reverse channel is constant throughout the system, regardless of the particular channel being used.

Time division duplexing (TDD) uses time instead of frequency to provide both a forward and reverse link. In TDD, multiple users share a single radio channel by taking turns in the time domain. Individual users are allowed to access the channel in assigned *time slots*, and each

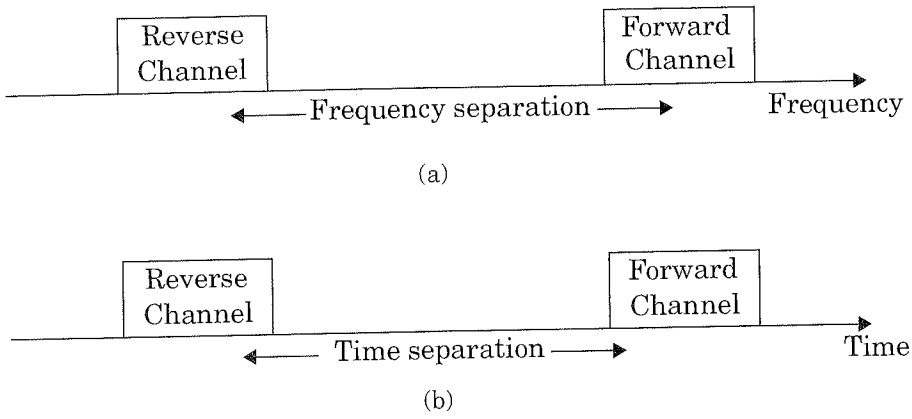


Figure 9.1 (a) FDD provides two simplex channels at the same time; (b) TDD provides two simplex time slots on the same frequency.

duplex channel has both a forward time slot and a reverse time slot to facilitate bidirectional communication. If the time separation between the forward and reverse time slot is small, then the transmission and reception of data appears simultaneous to the users at both the subscriber unit and on the base station side. Figure 9.1 illustrates FDD and TDD techniques. TDD allows communication on a single channel (as opposed to requiring two separate simplex or dedicated channels) and simplifies the subscriber equipment since a duplexer is not required.

There are several tradeoffs between FDD and TDD approaches. FDD is geared toward radio communications systems that allocate individual radio frequencies for each user. Because each transceiver simultaneously transmits and receives radio signals which can vary by more than 100 dB, the frequency allocation used for the forward and reverse channels must be carefully coordinated within its own system and with out-of-band users that occupy spectrum between these two bands. Furthermore, the frequency separation must be coordinated to permit the use of inexpensive RF and oscillator technology. TDD enables each transceiver to operate as either a transmitter or receiver on the same frequency, and eliminates the need for separate forward and reverse frequency bands. However, there is a time latency created by TDD due to the fact that communications is not full duplex in the truest sense, and this latency creates inherent sensitivities to propagation delays of individual users. Because of the rigid timing required for time slotting, TDD generally is limited to cordless phone or short range portable access. TDD is effective for fixed wireless access when all users are stationary so that propagation delays do not vary in time among the users.

9.1.1 Introduction to Multiple Access

Frequency division multiple access (FDMA), *time division multiple access* (TDMA), and *code division multiple access* (CDMA) are the three major access techniques used to share the available bandwidth in a wireless communication system. These techniques can be grouped as *narrowband* and *wideband* systems, depending upon how the available bandwidth is allocated to the users. The duplexing technique of a multiple access system is usually described along with the particular multiple access scheme, as shown in the examples that follow.

Narrowband Systems — The term *narrowband* is used to relate the bandwidth of a single channel to the expected coherence bandwidth of the channel. In a narrowband multiple access system, the available radio spectrum is divided into a large number of narrowband channels. The channels are usually operated using FDD. To minimize interference between forward and reverse links on each channel, the frequency separation is made as great as possible within the frequency spectrum, while still allowing inexpensive duplexers and a common transceiver antenna to be used in each subscriber unit. In narrowband FDMA, a user is assigned a particular channel which is not shared by other users in the vicinity, and if FDD is used (that is, each duplex channel has a forward and reverse simplex channel), then the system is called FDMA/FDD. Narrowband TDMA, on the other hand, allows users to share the same radio channel but allocates a unique time slot to each user in a cyclical fashion on the channel, thus separating a small number of users in time on a single channel. For narrowband TDMA systems, there generally are a large number of radio channels allocated using either FDD or TDD, and each channel is shared using TDMA. Such systems are called TDMA/FDD or TDMA/TDD access systems.

Wideband systems — In wideband systems, the transmission bandwidth of a single channel is much larger than the coherence bandwidth of the channel. Thus, multipath fading does not greatly vary the received signal power within a wideband channel, and frequency selective fades occur in only a small fraction of the signal bandwidth at any instance of time. In wideband multiple access systems a large number of transmitters are allowed to transmit on the same channel. TDMA allocates time slots to the many transmitters on the same channel and allows only one transmitter to access the channel at any instant of time, whereas spread spectrum CDMA allows all of the transmitters to access the channel at the same time. TDMA and CDMA systems may use either FDD or TDD multiplexing techniques.

In addition to FDMA, TDMA, and CDMA, two other multiple access schemes will soon be used for wireless communications. These are *packet radio* (PR) and *space division multiple access* (SDMA). In this chapter, the above mentioned multiple access techniques, their performance, and their capacity in digital wireless systems are discussed. Table 9.1 shows the different multiple access techniques being used in various wireless communications systems.

9.2 Frequency Division Multiple Access (FDMA)

Frequency division multiple access (FDMA) assigns individual channels to individual users. It can be seen from Figure 9.2 that each user is allocated a unique frequency band or channel. These channels are assigned on demand to users who request service. During the period of the call, no other user can share the same channel. In FDD systems, the users are assigned a channel as a pair of frequencies; one frequency is used for the forward channel, while the other frequency is used for the reverse channel. The features of FDMA are as follows:

- The FDMA channel carries only one phone circuit at a time.
- If an FDMA channel is not in use, then it sits idle and cannot be used by other users to increase or share capacity. It is essentially a wasted resource.

Table 9.1 Multiple Access Techniques Used in Different Wireless Communication Systems

Cellular System	Multiple Access Technique
Advanced Mobile Phone System (AMPS)	FDMA/FDD
Global System for Mobile (GSM)	TDMA/FDD
US Digital Cellular (USDC)	TDMA/FDD
Pacific Digital Cellular (PDC)	TDMA/FDD
CT2 (Cordless Telephone)	FDMA/TDD
Digital European Cordless Telephone (DECT)	FDMA/TDD
US Narrowband Spread Spectrum (IS-95)	CDMA/FDD
W-CDMA (3GPP)	CDMA/FDD CDMA/TDD
cdma2000 (3GPP2)	CDMA/FDD CDMA/TDD

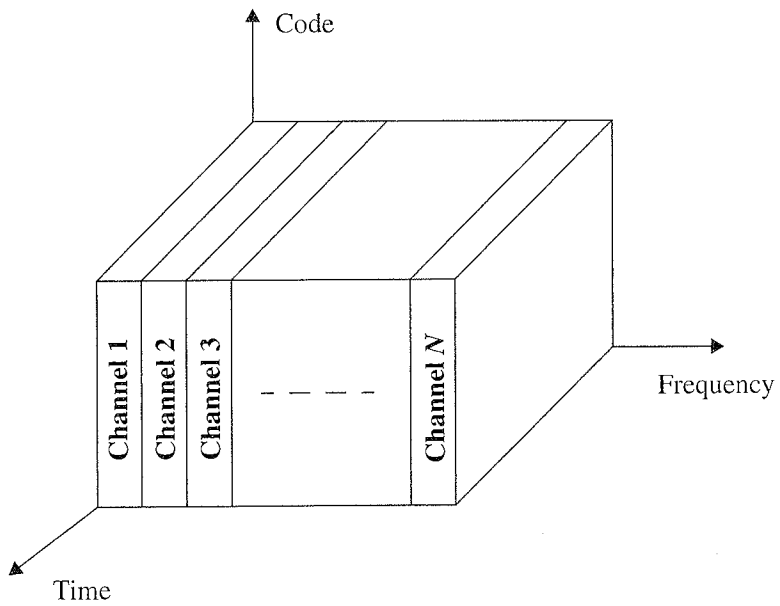


Figure 9.2 FDMA where different channels are assigned different frequency bands.

- After the assignment of a voice channel, the base station and the mobile transmit simultaneously and continuously.
- The bandwidths of FDMA channels are relatively narrow (30 kHz in AMPS) as each channel supports only one circuit per carrier. That is, FDMA is usually implemented in narrowband systems.
- The symbol time of a narrowband signal is large as compared to the average delay spread. This implies that the amount of intersymbol interference is low and, thus, little or no equalization is required in FDMA narrowband systems.
- The complexity of FDMA mobile systems is lower when compared to TDMA systems, though this is changing as digital signal processing methods improve for TDMA.
- Since FDMA is a continuous transmission scheme, fewer bits are needed for overhead purposes (such as synchronization and framing bits) as compared to TDMA.
- FDMA systems have higher cell site system costs as compared to TDMA systems, because of the single channel per carrier design, and the need to use costly bandpass filters to eliminate spurious radiation at the base station.
- The FDMA mobile unit uses duplexers since both the transmitter and receiver operate at the same time. This results in an increase in the cost of FDMA subscriber units and base stations.
- FDMA requires tight RF filtering to minimize adjacent channel interference.

Nonlinear Effects in FDMA — In a FDMA system, many channels share the same antenna at the base station. The power amplifiers or the power combiners, when operated at or near saturation for maximum power efficiency, are nonlinear. The nonlinearities cause signal spreading in the frequency domain and generate *intermodulation* (IM) frequencies. IM is undesired RF radiation which can interfere with other channels in the FDMA systems. Spreading of the spectrum results in adjacent-channel interference. Intermodulation is the generation of undesirable harmonics. Harmonics generated outside the mobile radio band cause interference to adjacent services, while those present inside the band cause interference to other users in the wireless system [Yac93].

Example 9.1

Find the intermodulation frequencies generated if a base station transmits two carrier frequencies at 1930 MHz and 1932 MHz that are amplified by a saturated clipping amplifier. If the mobile radio band is allocated from 1920 MHz to 1940 MHz, designate the IM frequencies that lie inside and outside the band.

Solution

Intermodulation distortion products occur at frequencies $mf_1 + nf_2$ for all integer values of m and n, i.e., $-\infty < m,n < \infty$. Some of the possible intermodulation frequencies that are produced by a nonlinear device are

$$(2n + 1)f_1 - 2nf_2,\ (2n + 2)f_1 - (2n + 1)f_2,\ (2n + 1)f_1 - 2nf_2,$$
$$(2n + 2)f_2 - (2n + 1)f_1, \text{ etc.} \qquad \text{for } n = 0, 1, 2, \ldots\ldots$$

Table E8.1 lists several intermodulation product terms.

Table E8.1 Intermodulation Products

$n = 0$	$n = 1$	$n = 2$	$n = 3$
1930	1926	1922	1918
1928	1924	1920	1916
1932	1936	1940	1944*
1934	1938	1942*	1946*

The frequencies in the table marked with an asterisk (*) are the frequencies that lie outside the allocated mobile radio band.

The first US analog cellular system, the *Advanced Mobile Phone System* (AMPS), is based on FDMA/FDD. A single user occupies a single channel while the call is in progress, and the single channel is actually two simplex channels which are frequency duplexed with a 45 MHz split. When a call is completed, or when a handoff occurs, the channel is vacated so that another mobile subscriber may use it. Multiple or simultaneous users are accommodated in AMPS by giving each user a unique channel. Voice signals are sent on the forward channel from the base station to mobile unit, and on the reverse channel from the mobile unit to the base station. In AMPS, analog narrowband frequency modulation (NBFM) is used to modulate the carrier. The number of channels that can be simultaneously supported in a FDMA system is given by

$$N = \frac{B_t - 2B_{guard}}{B_c} \tag{9.1}$$

where B_t is the total spectrum allocation, B_{guard} is the guard band allocated at the edge of the allocated spectrum band, and B_c is the channel bandwidth. Note that B_t and B_c may be specified in terms of simplex bandwidths where it is understood that there are symmetric frequency allocations for the forward band and reverse band.

Example 9.2

If a US AMPS cellular operator is allocated 12.5 MHz for each simplex band, and if B_t is 12.5 MHz, B_{guard} is 10 kHz, and B_c is 30 kHz, find the number of channels available in an FDMA system.

Solution

The number of channels available in the FDMA system is given as

$$N = \frac{12.5 \times 10^6 - 2(10 \times 10^3)}{30 \times 10^3} = 416$$

In the US, each cellular carrier is allocated 416 channels.

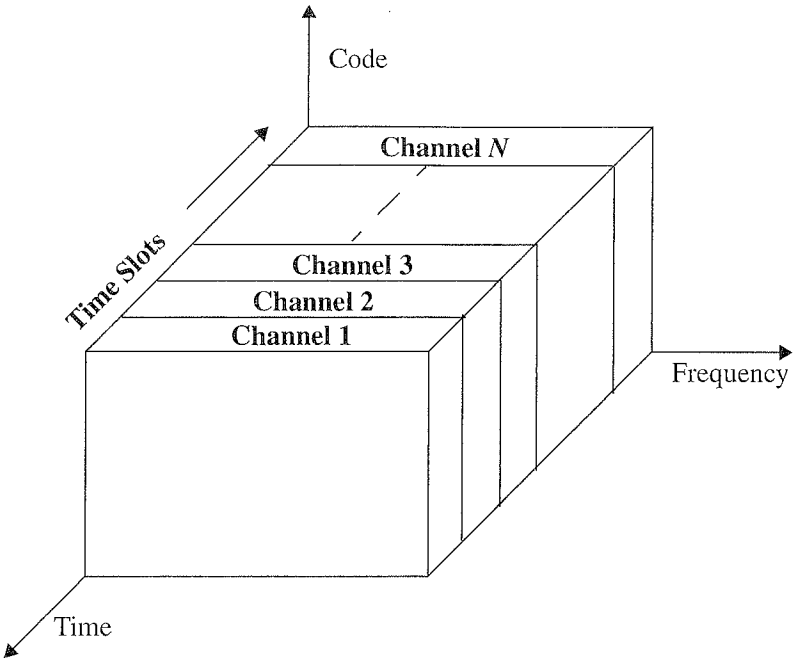


Figure 9.3 TDMA scheme where each channel occupies a cyclically repeating time slot.

9.3 Time Division Multiple Access (TDMA)

Time division multiple access (TDMA) systems divide the radio spectrum into time slots, and in each slot only one user is allowed to either transmit or receive. It can be seen from Figure 9.3 that each user occupies a cyclically repeating time slot, so a channel may be thought of as a particular time slot that reoccurs every frame, where N time slots comprise a frame. TDMA systems transmit data in a *buffer-and-burst* method, thus the transmission for any user is noncontinuous. This implies that, unlike in FDMA systems which accommodate analog FM, digital data and digital modulation must be used with TDMA. The transmission from various users is interlaced into a repeating frame structure as shown in Figure 9.4. It can be seen that a frame consists of a number of slots. Each frame is made up of a preamble, an information message, and tail bits. In TDMA/TDD, half of the time slots in the frame information message would be used for the forward link channels and half would be used for reverse link channels. In TDMA/FDD systems, an identical or similar frame structure would be used solely for either forward or reverse transmission, but the carrier frequencies would be different for the forward and reverse links. In general, TDMA/FDD systems intentionally induce several time slots of delay between the forward and reverse time slots for a particular user, so that duplexers are not required in the subscriber unit.

In a TDMA frame, the preamble contains the address and synchronization information that both the base station and the subscribers use to identify each other. Guard times are utilized to allow synchronization of the receivers between different slots and frames. Different TDMA wireless

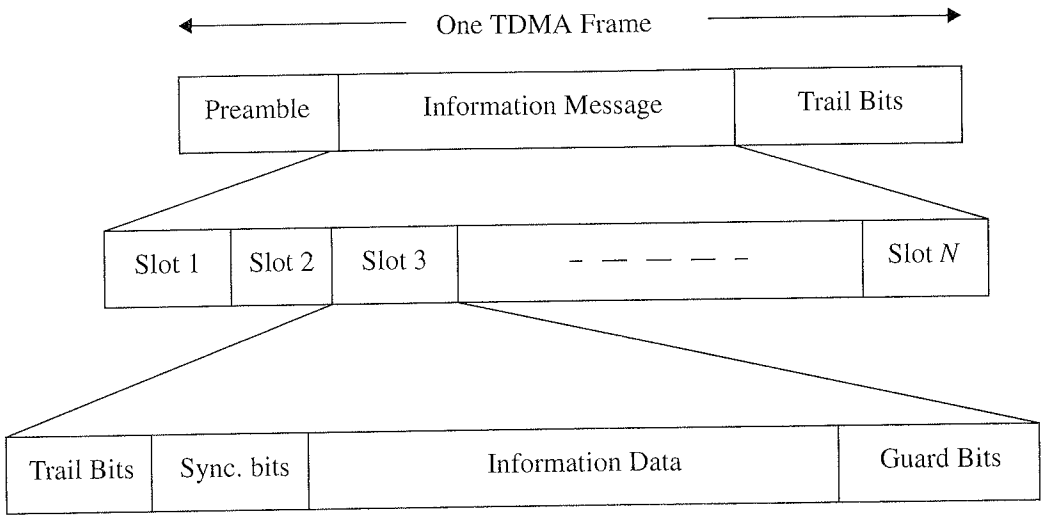


Figure 9.4 TDMA frame structure. The frame is cyclically repeated over time.

standards have different TDMA frame structures, and some are described in Chapter 11. The features of TDMA include the following:

- TDMA shares a single carrier frequency with several users, where each user makes use of nonoverlapping time slots. The number of time slots per frame depends on several factors, such as modulation technique, available bandwidth, etc.
- Data transmission for users of a TDMA system is not continuous, but occurs in bursts. This results in low battery consumption, since the subscriber transmitter can be turned off when not in use (which is most of the time).
- Because of discontinuous transmissions in TDMA, the handoff process is much simpler for a subscriber unit, since it is able to listen for other base stations during idle time slots. An enhanced link control, such as that provided by *mobile assisted handoff* (MAHO) can be carried out by a subscriber by listening on an idle slot in the TDMA frame.
- TDMA uses different time slots for transmission and reception, thus duplexers are not required. Even if FDD is used, a switch rather than a duplexer inside the subscriber unit is all that is required to switch between transmitter and receiver using TDMA.
- Adaptive equalization is usually necessary in TDMA systems, since the transmission rates are generally very high as compared to FDMA channels.
- In TDMA, the guard time should be minimized. If the transmitted signal at the edges of a time slot are suppressed sharply in order to shorten the guard time, the transmitted spectrum will expand and cause interference to adjacent channels.
- High synchronization overhead is required in TDMA systems because of burst transmissions. TDMA transmissions are slotted, and this requires the receivers to be synchronized for each data burst. In addition, guard slots are necessary to separate users, and this results in the TDMA systems having larger overheads as compared to FDMA.

- TDMA has an advantage in that it is possible to allocate different numbers of time slots per frame to different users. Thus, bandwidth can be supplied on demand to different users by concatenating or reassigning time slots based on priority.

Efficiency of TDMA — The efficiency of a TDMA system is a measure of the percentage of transmitted data that contains information as opposed to providing overhead for the access scheme. The frame efficiency, η_f, is the percentage of bits per frame which contain transmitted data. Note that the transmitted data may include source and channel coding bits, so the raw end-user efficiency of a system is generally less than η_f. The frame efficiency can be found as follows.

The number of overhead bits per frame is [Zie92],

$$b_{OH} = N_r b_r + N_t b_p + N_t b_g + N_r b_g \tag{9.2}$$

where N_r is the number of reference bursts per frame, N_t is the number of traffic bursts per frame, b_r is the number of overhead bits per reference burst, b_p is the number of overhead bits per preamble in each slot, and b_g is the number of equivalent bits in each guard time interval. The total number of bits per frame, b_T, is

$$b_T = T_f R \tag{9.3}$$

where T_f is the frame duration, and R is the channel bit rate. The frame efficiency η_f is thus given as

$$\eta_f = \left(1 - \frac{b_{OH}}{b_T}\right) \times 100\% \tag{9.4}$$

Number of channels in TDMA system — The number of TDMA channel slots that can be provided in a TDMA system is found by multiplying the number of TDMA slots per channel by the number of channels available and is given by

$$N = \frac{m(B_{tot} - 2B_{guard})}{B_c} \tag{9.5}$$

where m is the maximum number of TDMA users supported on each radio channel. Note that two guard bands, one at the low end of the allocated frequency band and one at the high end, are required to ensure that users at the edge of the band do not "bleed over" into an adjacent radio service.

Example 9.3

Consider Global System for Mobile, which is a TDMA/FDD system that uses 25 MHz for the forward link, which is broken into radio channels of 200 kHz. If 8 speech channels are supported on a single radio channel, and if no guard band is assumed, find the number of simultaneous users that can be accommodated in GSM.

Solution
The number of simultaneous users that can be accommodated in GSM is given as

$$N = \frac{25 \text{ MHz}}{(200 \text{ kHz})/8} = 1000$$

Thus, GSM can accommodate 1000 simultaneous users.

Example 9.4
If GSM uses a frame structure where each frame consists of eight time slots, and each time slot contains 156.25 bits, and data is transmitted at 270.833 kbps in the channel, find (a) the time duration of a bit, (b) the time duration of a slot, (c) the time duration of a frame, and (d) how long must a user occupying a single time slot wait between two successive transmissions.

Solution
(a) The time duration of a bit, $T_b = \frac{1}{270.833 \text{ kbps}} = 3.692 \ \mu\text{s}$.
(b) The time duration of a slot, $T_{slot} = 156.25 \times T_b = 0.577$ ms.
(c) The time duration of a frame, $T_f = 8 \times T_{slot} = 4.615$ ms.
(d) A user has to wait 4.615 ms, the arrival time of a new frame, for its next transmission.

Example 9.5
If a normal GSM time slot consists of six trailing bits, 8.25 guard bits, 26 training bits, and two traffic bursts of 58 bits of data, find the frame efficiency.

Solution
A time slot has 6 + 8.25 + 26 + 2(58) = 156.25 bits.
A frame has $8 \times 156.25 = 1250$ bits/frame.
The number of overhead bits per frame is given by

$$b_{OH} = 8(6) + 8(8.25) + 8(26) = 322 \text{ bits}$$

Thus, the frame efficiency

$$\eta_f = \left[1 - \frac{322}{1250}\right] \times 100 = 74.24\%$$

9.4 Spread Spectrum Multiple Access

Spread spectrum multiple access (SSMA) uses signals which have a transmission bandwidth that is several orders of magnitude greater than the minimum required RF bandwidth. A pseudo-noise (PN) sequence (discussed in Chapter 6) converts a narrowband signal to a wideband noise-like signal before transmission. SSMA also provides immunity to multipath interference and robust

multiple access capability. SSMA is not very bandwidth efficient when used by a single user. However, since many users can share the same spread spectrum bandwidth without interfering with one another, spread spectrum systems become bandwidth efficient in a multiple user environment. It is exactly this situation that is of interest to wireless system designers. There are two main types of spread spectrum multiple access techniques; *frequency hopped multiple access* (FH) and *direct sequence multiple access* (DS). Direct sequence multiple access is also called *code division multiple access* (CDMA).

9.4.1 Frequency Hopped Multiple Access (FHMA)

Frequency hopped multiple access (FHMA) is a digital multiple access system in which the carrier frequencies of the individual users are varied in a pseudorandom fashion within a wideband channel. Figure 9.5 illustrates how FHMA allows multiple users to simultaneously occupy the same spectrum at the same time, where each user dwells at a specific narrowband channel at a particular instance of time, based on the particular PN code of the user. The digital data of each user is broken into uniform sized bursts which are transmitted on different channels within the allocated spectrum band. The instantaneous bandwidth of any one transmission burst is much smaller than the total spread bandwidth. The pseudorandom change of the channel frequencies of the user randomizes the occupancy of a specific channel at any given time, thereby allowing for multiple access over a wide range of frequencies. In the FH receiver, a locally generated PN code is used to synchronize the receiver's instantaneous frequency with that of the transmitter. At any given point in time, a frequency hopped signal only occupies a single, relatively narrow channel since narrowband FM or FSK is used. The difference between FHMA and a traditional FDMA system is that the frequency hopped signal changes channels at rapid intervals. If the rate of change of the carrier frequency is greater than the symbol rate, then the system is referred to as a *fast frequency hopping system*. If the channel changes at a rate less than or equal to the symbol rate, it is called *slow frequency hopping*. A fast frequency hopper may thus be thought of as an FDMA system which employs frequency diversity. FHMA systems often employ energy efficient constant envelope modulation. Inexpensive receivers may be built to provide noncoherent detection of FHMA. This implies that linearity is not an issue, and the power of multiple users at the receiver does not degrade FHMA performance.

A frequency hopped system provides a level of security, especially when a large number of channels are used, since an unintended (or an intercepting) receiver that does not know the pseudorandom sequence of frequency slots must retune rapidly to search for the signal it wishes to intercept. In addition, the FH signal is somewhat immune to fading, since error control coding and interleaving can be used to protect the frequency hopped signal against deep fades which may occasionally occur during the hopping sequence. Error control coding and interleaving can also be combined to guard against *erasures* which can occur when two or more users transmit on the same channel at the same time. Bluetooth and HomeRF wireless technologies have adopted FHMA for power efficiency and low cost implementation.

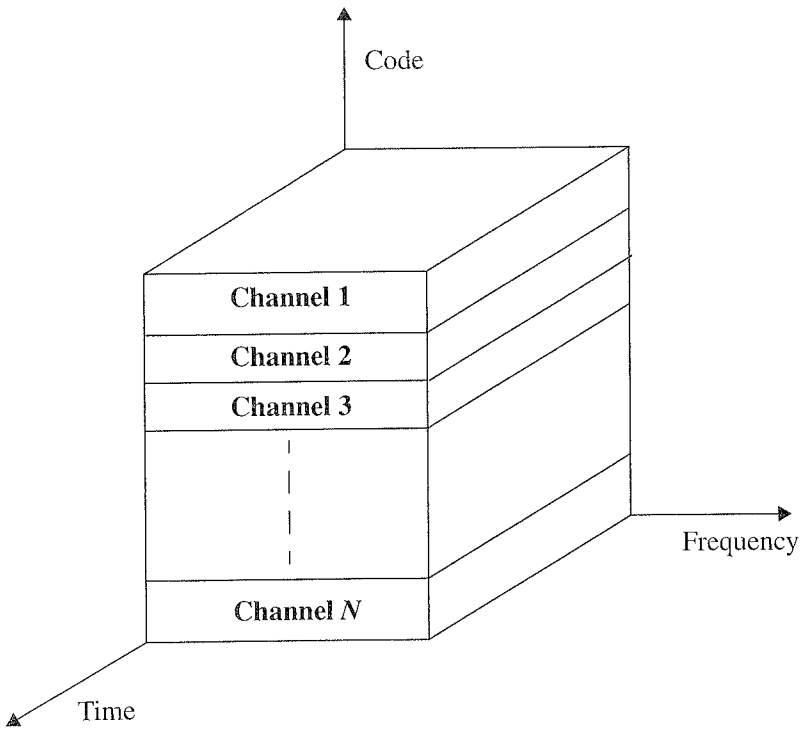


Figure 9.5 Spread spectrum multiple access in which each channel is assigned a unique PN code which is orthogonal or approximately orthogonal to PN codes used by other users.

9.4.2 Code Division Multiple Access (CDMA)

In *code division multiple access* (CDMA) systems, the narrowband message signal is multiplied by a very large bandwidth signal called the *spreading signal*. The spreading signal is a pseudo-noise code sequence that has a chip rate which is orders of magnitudes greater than the data rate of the message. All users in a CDMA system, as seen from Figure 9.5, use the same carrier frequency and may transmit simultaneously. Each user has its own pseudorandom codeword which is approximately orthogonal to all other codewords. The receiver performs a time correlation operation to detect only the specific desired codeword. All other codewords appear as noise due to decorrelation. For detection of the message signal, the receiver needs to know the codeword used by the transmitter. Each user operates independently with no knowledge of the other users.

In CDMA, the power of multiple users at a receiver determines the noise floor after decorrelation. If the power of each user within a cell is not controlled such that they do not appear equal at the base station receiver, then the *near–far problem* occurs.

The near–far problem occurs when many mobile users share the same channel. In general, the strongest received mobile signal will *capture* the demodulator at a base station. In CDMA, stronger received signal levels raise the noise floor at the base station demodulators for the weaker signals, thereby decreasing the probability that weaker signals will be received. To combat the near–far problem, *power control* is used in most CDMA implementations. Power control is pro-

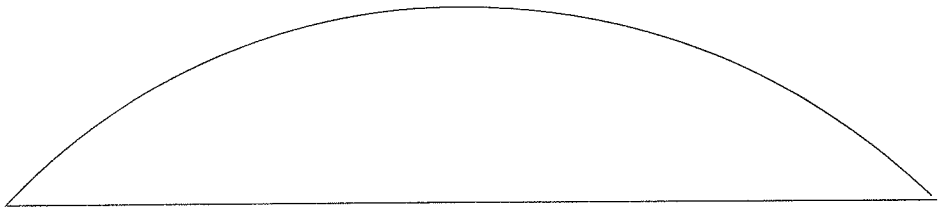
vided by each base station in a cellular system and assures that each mobile within the base station coverage area provides the same signal level to the base station receiver. This solves the problem of a nearby subscriber overpowering the base station receiver and drowning out the signals of far away subscribers. Power control is implemented at the base station by rapidly sampling the radio signal strength indicator (RSSI) levels of each mobile and then sending a power change command over the forward radio link. Despite the use of power control within each cell, out-of-cell mobiles provide interference which is not under the control of the receiving base station. The features of CDMA including the following:

- Many users of a CDMA system share the same frequency. Either TDD or FDD may be used.
- Unlike TDMA or FDMA, CDMA has a soft capacity limit. Increasing the number of users in a CDMA system raises the noise floor in a linear manner. Thus, there is no absolute limit on the number of users in CDMA. Rather, the system performance gradually degrades for all users as the number of users is increased, and improves as the number of users is decreased.
- Multipath fading may be substantially reduced because the signal is spread over a large spectrum. If the spread spectrum bandwidth is greater than the coherence bandwidth of the channel, the inherent frequency diversity will mitigate the effects of small-scale fading.
- Channel data rates are very high in CDMA systems. Consequently, the symbol (chip) duration is very short and usually much less than the channel delay spread. Since PN sequences have low autocorrelation, multipath which is delayed by more than a chip will appear as noise. A RAKE receiver can be used to improve reception by collecting time delayed versions of the required signal.
- Since CDMA uses co-channel cells, it can use macroscopic spatial diversity to provide soft handoff. Soft handoff is performed by the MSC, which can simultaneously monitor a particular user from two or more base stations. The MSC may chose the best version of the signal at any time without switching frequencies.
- Self-jamming is a problem in CDMA system. Self-jamming arises from the fact that the spreading sequences of different users are not exactly orthogonal, hence in the despreading of a particular PN code, non-zero contributions to the receiver decision statistic for a desired user arise from the transmissions of other users in the system.
- The near–far problem occurs at a CDMA receiver if an undesired user has a high detected power as compared to the desired user.

9.4.3 Hybrid Spread Spectrum Techniques

In addition to the frequency hopped and direct sequence, spread spectrum multiple access techniques, there are certain other hybrid combinations that provide certain advantages. These hybrid techniques are described below.

Hybrid FDMA/CDMA (FCDMA) — This technique can be used as an alternative to the DS-CDMA techniques discussed above. Figure 9.6 shows the spectrum of this hybrid scheme. The available wideband spectrum is divided into a number of subspectras with smaller bandwidths.



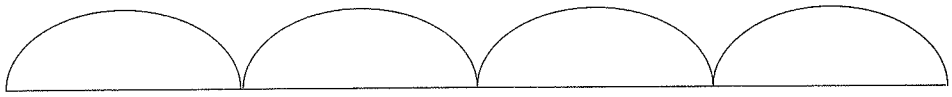


Figure 9.6 Spectrum of wideband CDMA compared to the spectrum of a hybrid, frequency division, direct sequence multiple access.

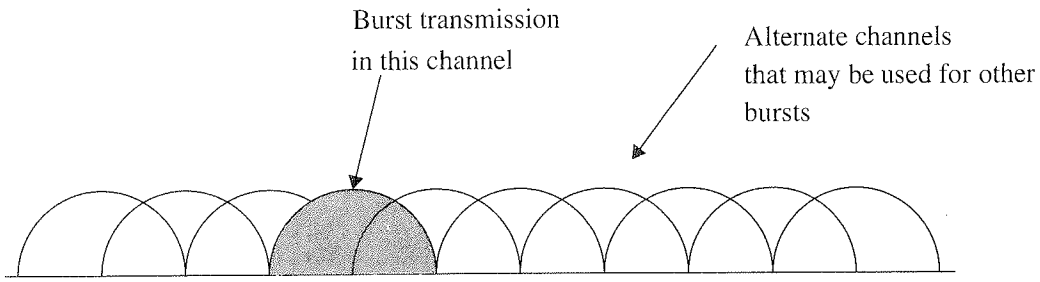


Figure 9.7 Frequency spectrum of a hybrid FH/DS system.

Each of these smaller subchannels becomes a narrowband CDMA system having processing gain lower than the original CDMA system. This hybrid system has an advantage in that the required bandwidth need not be contiguous and different users can be allotted different subspectrum bandwidths depending on their requirements. The capacity of this FDMA/CDMA technique is calculated as the sum of the capacities of a system operating in the subspectra [Eng93].

Hybrid Direct Sequence/Frequency Hopped Multiple Access (DS/FHMA) — This technique consists of a direct sequence modulated signal whose center frequency is made to hop periodically in a pseudorandom fashion. Figure 9.7 shows the frequency spectrum of such a signal [Dix94]. Direct sequence, frequency hopped systems have an advantage in that they avoid the near–far effect. However, frequency hopped CDMA systems are not adaptable to the soft handoff process since it is difficult to synchronize the frequency hopped base station receiver to the multiple hopped signals.

Time Division CDMA (TCDMA) — In a TCDMA (also called TDMA/CDMA) system, different spreading codes are assigned to different cells. Within each cell, only one user per cell is allotted a particular time slot. Thus at any time, only one CDMA user is transmitting in each cell.

When a handoff takes place, the spreading code of the user is changed to that of the new cell. Using TCDMA has an advantage in that it avoids the near–far effect since only one user transmits at a time within a cell.

Time Division Frequency Hopping (TDFH) — This multiple access technique has an advantage in severe multipath or when severe co-channel interference occurs. The subscriber can hop to a new frequency at the start of a new TDMA frame, thus avoiding a severe fade or erasure event on a particular channel. This technique has been adopted for the GSM standard, where the hopping sequence is predefined and the subscriber is allowed to hop only on certain frequencies which are assigned to a cell. This scheme also avoids co-channel interference problems between neighboring cells if two interfering base station transmitters are made to transmit on different frequencies at different times. The use of TDFH can increase the capacity of GSM by several fold [Gud92]. Chapter 11 describes the GSM standard in more detail.

9.5 Space Division Multiple Access (SDMA)

Space division multiple access (SDMA) controls the radiated energy for each user in space. It can be seen from Figure 9.8 that SDMA serves different users by using spot beam antennas. These different areas covered by the antenna beam may be served by the same frequency (in a TDMA or CDMA system) or different frequencies (in an FDMA system). Sectorized antennas may be thought of as a primitive application of SDMA. In the future, adaptive antennas will likely be used to simultaneously steer energy in the direction of many users at once and appear to be best suited for TDMA and CDMA base station architectures.

The reverse link presents the most difficulty in cellular systems for several reasons [Lib94b]. First, the base station has complete control over the power of all the transmitted signals on the forward link. However, because of different radio propagation paths between each

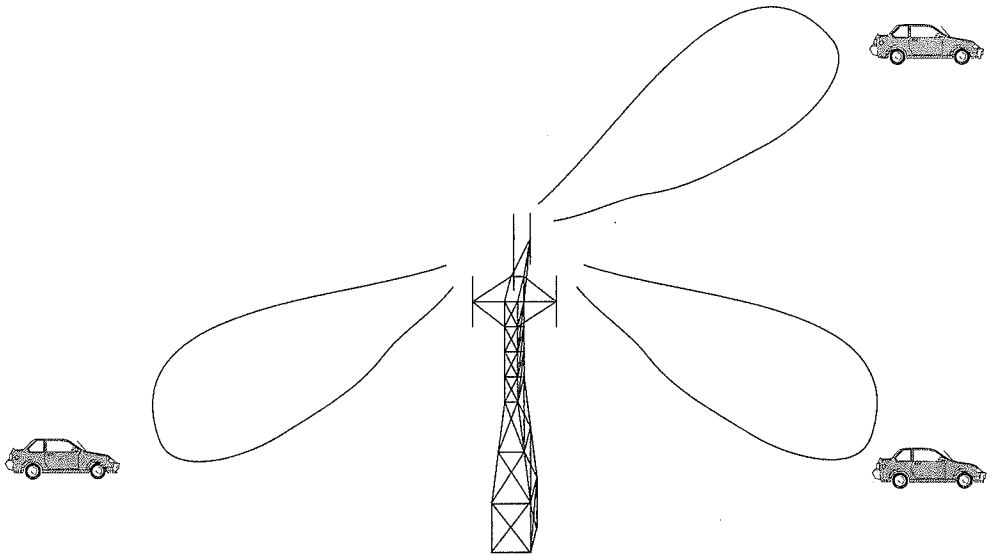


Figure 9.8 A spatially filtered base station antenna serving different users by using spot beams.

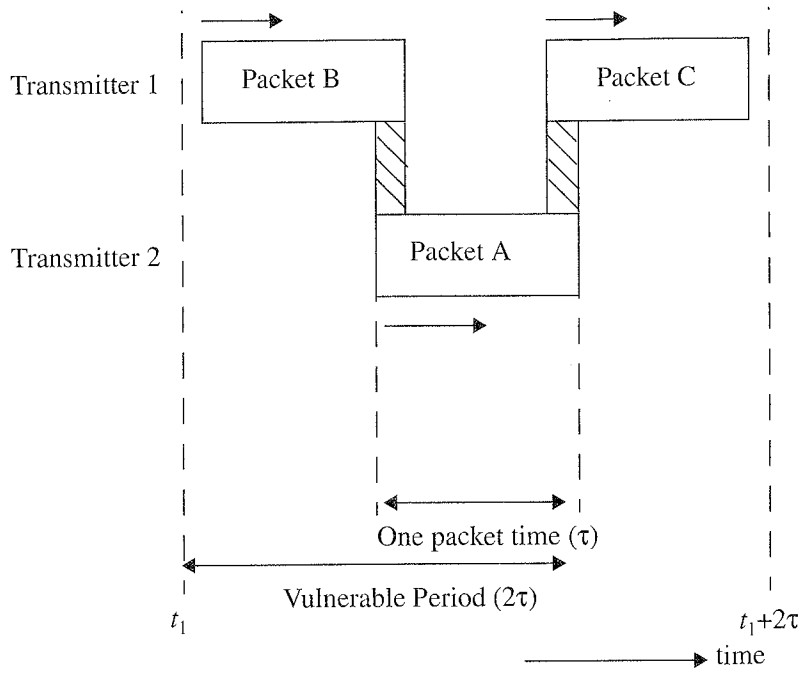
user and the base station, the transmitted power from each subscriber unit must be dynamically controlled to prevent any single user from driving up the interference level for all other users. Second, transmit power is limited by battery consumption at the subscriber unit, therefore there are limits on the degree to which power may be controlled on the reverse link. If the base station antenna is made to spatially filter each desired user so that more energy is detected from each subscriber, then the reverse link for each user is improved and less power is required.

Adaptive antennas used at the base station (and eventually at the subscriber units) promise to mitigate some of the problems on the reverse link. In the limiting case of infinitesimal beamwidth and infinitely fast tracking ability, adaptive antennas implement optimal SDMA, thereby providing a unique channel that is free from the interference of all other users in the cell. With SDMA, all users within the system would be able to communicate at the same time using the same channel. In addition, a perfect adaptive antenna system would be able to track individual multipath components for each user and combine them in an optimal manner to collect all of the available signal energy from each user. The perfect adaptive antenna system is not feasible since it requires infinitely large antennas. However, Section 9.7.2 illustrates what gains might be achieved using reasonably sized arrays with moderate directivities.

9.6 Packet Radio

In *packet radio* (PR) access techniques, many subscribers attempt to access a single channel in an uncoordinated (or minimally coordinated) manner. Transmission is done by using bursts of data. Collisions from the simultaneous transmissions of multiple transmitters are detected at the base station receiver, in which case an *ACK* or *NACK* signal is broadcast by the base station to alert the desired user (and all other users) of received transmission. The ACK signal indicates an acknowledgment of a received burst from a particular user by the base station, and a NACK (negative acknowledgment) indicates that the previous burst was not received correctly by the base station. By using ACK and NACK signals, a PR system employs perfect feedback, even though traffic delay due to collisions may be high.

Packet radio multiple access is very easy to implement, but has low spectral efficiency and may induce delays. The subscribers use a contention technique to transmit on a common channel. ALOHA protocols, developed for early satellite systems, are the best examples of contention techniques. ALOHA allows each subscriber to transmit whenever they have data to send. The transmitting subscribers listen to the acknowledgment feedback to determine if transmission has been successful or not. If a collision occurs, the subscriber waits a random amount of time, and then retransmits the packet. The advantage of packet contention techniques is the ability to serve a large number of subscribers with virtually no overhead. The performance of contention techniques can be evaluated by the *throughput* (T), which is defined as the average number of messages successfully transmitted per unit time, and the average *delay* (D) experienced by a typical message burst.



Packet A will collide with packets B and C because of overlap in transmission time.

Figure 9.9 Vulnerable period for a packet using the ALOHA protocol.

9.6.1 Packet Radio Protocols

In order to determine the throughput, it is important to determine the *vulnerable period,* V_p, which is defined as the time interval during which the packets are susceptible to collisions with transmissions from other users. Figure 9.9 shows the vulnerable period for a packet using ALOHA [Tan81]. The Packet A will suffer a collision if other terminals transmit packets during the period t_1 to $t_1 + 2\tau$. Even if only a small portion of packet A sustains a collision, the interference may render the message useless.

To study packet radio protocols, it is assumed that all packets sent by all users have a constant packet length and fixed, channel data rate, and all other users may generate new packets at random time intervals. Furthermore, it is assumed that packet transmissions occur with a Poisson distribution having a mean arrival rate of λ packets per second. If τ is the packet duration in seconds, then the *traffic occupancy* or *throughput* R of a packet radio network is given by

$$R = \lambda\tau \tag{9.6}$$

In Equation (9.6), R is the normalized channel traffic (measured in Erlangs) due to arriving and buffered packets, and is a relative measure of the channel utilization. If $R > 1$, then the packets generated by the users exceed the maximum transmission rate of the channel [Tan81]. Thus, to obtain a reasonable throughput, the rate at which new packets are generated must lie within $0 < R < 1$. Under conditions of normal loading, the throughput T is the same as the total offered load, L. The load L is the sum of the newly generated packets and the retransmitted

packets that suffered collisions in previous transmissions. The normalized throughput is always less than or equal to unity and may be thought of as the fraction of time (fraction of an Erlang) a channel is utilized. The normalized throughput is given as the total offered load times the probability of successful transmission, i.e.,

$$T = R \cdot \Pr[no\ collision] = \lambda\tau \cdot \Pr[no\ collision] \tag{9.7}$$

where $\Pr[no\ collision]$ is the probability of a user making a successful packet transmission. The probability that n packets are generated by the user population during a given packet duration interval is assumed to be Poisson distributed and is given as

$$Pr(n) = \frac{R^n e^{-R}}{n!} \tag{9.8}$$

A packet is assumed successfully transmitted if there are no other packets transmitted during the given packet time interval. The probability that zero packets are generated (i.e., no collision) during this interval is given by

$$Pr(0) = e^{-R} \tag{9.9}$$

Based on the type of access, contention protocols are categorized as *random access*, *scheduled access*, and *hybrid access*. In random access, there is no coordination among the users and the messages are transmitted from the users as they arrive at the transmitter. Scheduled access is based on a coordinated access of users on the channel, and the users transmit messages within allotted slots or time intervals. Hybrid access is a combination of random access and scheduled access.

9.6.1.1 Pure ALOHA

The pure ALOHA protocol is a random access protocol used for data transfer. A user accesses a channel as soon as a message is ready to be transmitted. After a transmission, the user waits for an acknowledgment on either the same channel or a separate feedback channel. In case of collisions, (i.e., when a NACK is received), the terminal waits for a random period of time and retransmits the message. As the number of users increase, a greater delay occurs because the probability of collision increases.

For the ALOHA protocol, the vulnerable period is double the packet duration (see Figure 9.9). Thus, the probability of no collision during the interval of 2τ is found by evaluating $Pr(n)$ given as

$$Pr(n) = \frac{(2R)^n e^{-2R}}{n!} \quad \text{at } n = 0 \tag{9.10}$$

One may evaluate the mean of Equation (9.10) to determine the average number of packets sent during 2τ. (This is useful in determining the average offered traffic.) The probability of no collision is $Pr(0) = e^{-2R}$. The throughput of the ALOHA protocol is found by using Equation (9.7) as

$$T = Re^{-2R} \tag{9.11}$$

9.6.1.2 Slotted ALOHA

In slotted ALOHA, time is divided into equal time slots of length greater than the packet duration τ. The subscribers each have synchronized clocks and transmit a message only at the beginning of a new time slot, thus resulting in a discrete distribution of packets. This prevents partial collisions, where one packet collides with a portion of another. As the number of users increase, a greater delay will occur due to complete collisions and the resulting repeated transmissions of those packets originally lost. The number of slots which a transmitter waits prior to retransmitting also determines the delay characteristics of the traffic. The vulnerable period for slotted ALOHA is only one packet duration, since partial collisions are prevented through synchronization. The probability that no other packets will be generated during the vulnerable period is e^{-R}. The throughput for the case of slotted ALOHA is thus given by

$$T = Re^{-R} \tag{9.12}$$

Figure 9.10 illustrates how ALOHA and slotted ALOHA systems tradeoff throughput for delay.

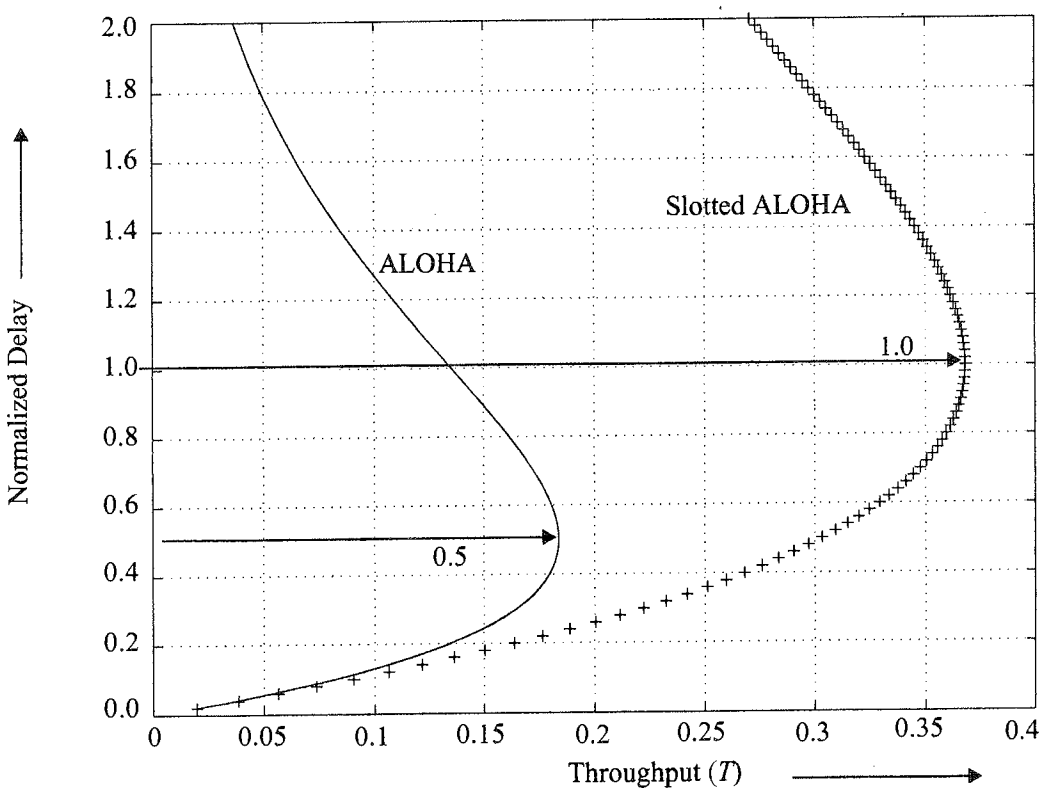


Figure 9.10 Tradeoff between throughput and delay for ALOHA and slotted ALOHA packet radio protocols.

Example 9.6
Determine the maximum throughput that can be achieved using ALOHA and slotted ALOHA protocols.

Solution The rate of arrival which maximizes the throughput for ALOHA is found by taking the derivative of Equation (9.11) and equating it to zero

$$\frac{dT}{dR} = e^{-2R} - 2Re^{-2R} = 0$$

$$R_{max} = 1/2$$

Maximum throughput achieved by using the ALOHA protocol is found by substituting R_{max} in Equation (9.11), and this value can be seen as the maximum throughput in Figure 9.10

$$T = \frac{1}{2}e^{-1} = 0.1839$$

Thus the best traffic utilization one can hope for using ALOHA is 0.184 Erlangs.
The maximum throughput for slotted ALOHA is found by taking the derivative of Equation (9.12) and equating it to zero

$$\frac{dT}{dR} = e^{-R} - Re^{-R} = 0$$

$$R_{max} = 1$$

Maximum throughput is found by substituting R_{max} in Equation (9.12), and this value can be seen as the maximum throughput in Figure 9.10

$$T = e^{-1} = 0.3679$$

Notice that slotted ALOHA provides a maximum channel utilization of 0.368 Erlangs, double that of ALOHA.

9.6.2 Carrier Sense Multiple Access (CSMA) Protocols

ALOHA protocols do not listen to the channel before transmission, and therefore do not exploit information about the other users. By listening to the channel before engaging in transmission, greater efficiencies may be achieved. CSMA protocols are based on the fact that each terminal on the network is able to monitor the status of the channel before transmitting information. If the channel is idle (i.e., no carrier is detected), then the user is allowed to transmit a packet based on a particular algorithm which is common to all transmitters on the network.

In CSMA protocols, *detection delay* and *propagation delay* are two important parameters. Detection delay is a function of the receiver hardware and is the time required for a terminal to sense whether or not the channel is idle. Propagation delay is a relative measure of how fast it takes for a packet to travel from a base station to a mobile terminal. With a small detection time, a terminal detects a free channel quite rapidly, and small propagation delay means that a packet is transmitted through the channel in a small interval of time relative to the packet duration.

Propagation delay is important, since just after a user begins sending a packet, another user may be ready to send and may be sensing the channel at the same time. If the transmitting packet has not reached the user who is poised to send, the latter user will sense an idle channel and will also send its packet, resulting in a collision between the two packets. Propagation delay impacts the performance of CSMA protocols. If t_p is the propagation time in seconds, R_b is the channel bit rate, and m is the expected number of bits in a data packet [Tan81], [Ber92], then the propagation delay t_d (in packet transmission units) can be expressed as

$$t_d = \frac{t_p R_b}{m} \tag{9.13}$$

There exist several variations of the CSMA strategy [Kle75], [Tob75]:

- ***1-persistent CSMA*** — The terminal listens to the channel and waits for transmission until it finds the channel idle. As soon as the channel is idle, the terminal transmits its message with probability one.
- ***non-persistent CSMA*** — In this type of CSMA strategy, after receiving a negative acknowledgment the terminal waits a random time before retransmission of the packet. This is popular for wireless LAN applications, where the packet transmission interval is much greater than the propagation delay to the farthermost user.
- ***p-persistent CSMA*** — p-persistent CSMA is applied to slotted channels. When a channel is found to be idle, the packet is transmitted in the first available slot with probability p or in the next slot with probability 1-p.
- ***CSMA/CD*** — In CSMA with collision detection (CD), a user monitors its transmission for collisions. If two or more terminals start a transmission at the same time, collision is detected, and the transmission is immediately aborted in midstream. This is handled by a user having both a transmitter and receiver which is able to support *listen-while-talk* operation. For a single radio channel, this is done by interrupting the transmission in order to sense the channel. For duplex systems, a full duplex transceiver is used [Lam80].
- ***Data sense multiple access*** (DSMA) — DSMA is a special type of CSMA that relies on successfully demodulating a forward control channel before broadcasting data back on a reverse channel. Each user attempts to detect a *busy-idle* message which is interspersed on the forward control channel. When the busy-idle message indicates that no users are transmitting on the reverse channel, a user is free to send a packet. This technique is used in the cellular digital packet data (CDPD) cellular network described in Chapter 10.

9.6.3 Reservation Protocols

9.6.3.1 Reservation ALOHA

Reservation ALOHA is a packet access scheme based on time division multiplexing. In this protocol, certain packet slots are assigned with priority, and it is possible for users to reserve slots for the transmission of packets. Slots can be permanently reserved or can be reserved on request.

For high traffic conditions, reservations on request offers better throughput. In one type of reservation ALOHA, the terminal making a successful transmission reserves a slot permanently until its transmission is complete, although very large duration transmissions may be interrupted. Another scheme allows a user to transmit a request on a subslot which is reserved in each frame. If the transmission is successful (i.e., no collisions are detected), the terminal is allocated the next regular slot in the frame for data transmission [Tan81].

9.6.3.2 Packet Reservation Multiple Access (PRMA)

PRMA uses a discrete packet time technique similar to reservation ALOHA and combines the cyclical frame structure of TDMA in a manner that allows each TDMA time slot to carry either voice or data, where voice is given priority. PRMA was proposed in [Goo89] as a means of integrating bursty data and human speech. PRMA defines a frame structure, much like is used in TDMA systems. Within each frame, there are a fixed number of time slots which may be designated as either "reserved" or "available", depending on the traffic as determined by the controlling base station. PRMA is discussed in Chapter 10.

9.6.4 Capture Effect in Packet Radio

Packet radio multiple access techniques are based on contention within a channel. When used with FM or spread spectrum modulation, it is possible for the strongest user to successfully *capture* the intended receiver, even when many other users are also transmitting. Often, the closest transmitter is able to capture a receiver because of the small propagation path loss. This is called the *near–far effect*. The capture effect offers both advantages and disadvantages in practical systems. Because a particular transmitter may capture an intended receiver, many packets may survive despite collision on the channel. However, a strong transmitter may make it impossible for the receiver to detect a much weaker transmitter which is attempting to communicate to the same receiver. This problem is known as the *hidden transmitter* problem.

A useful parameter in analyzing the capture effects in packet radio protocols is the minimum power ratio of an arriving packet, relative to the other colliding packets, such that it is received. This ratio is called the *capture ratio*, and is dependent upon the receiver and the modulation used.

In summary, packet radio techniques support mobile transmitters sending bursty traffic in the form of data packets using random access. Ideal channel throughput can be increased if terminals synchronize their packet transmissions into common time slots, such that the risk of partial packet overlap is avoided. With high traffic loads, both unslotted and slotted ALOHA protocols become inefficient, since the contention between all transmitted packets exposes most of the offered traffic to collisions, and thus results in multiple retransmissions and increased delays. To reduce this situation, CSMA can be used where the transmitter first listens either to the common radio channel or to a separate dedicated acknowledgment control channel from the base station. In a real world mobile system, the CSMA protocols may fail to detect ongoing radio transmissions of packets subject to deep fading on the reverse channel path. Utilization of an ALOHA channel can be improved by

Table 9.2 Multiple Access Techniques for Different Traffic Types

Type of Traffic	Multiple Access Technique
Bursty, short messages	Contention protocols
Bursty, long messages, large number of users	Reservation protocols
Bursty, long messages, small number of users	Reservation protocols with fixed TDMA reservation channel
Stream or deterministic (voice)	FDMA, TDMA, CDMA

deliberately introducing differences between the transmit powers of multiple users competing for the base station receiver. Table 9.2 shows the multiple access techniques which should be used for different types of traffic conditions.

9.7 Capacity of Cellular Systems

Channel capacity for a radio system can be defined as the maximum number of channels or users that can be provided in a fixed frequency band. Radio capacity is a parameter which measures spectrum efficiency of a wireless system. This parameter is determined by the required carrier-to-interference ratio (C/I) and the channel bandwidth B_c.

In a cellular system, the interference at a base station receiver will come from the subscriber units in the surrounding cells. This is called *reverse channel interference*. For a particular subscriber unit, the desired base station will provide the desired forward channel while the surrounding co-channel base stations will provide the *forward channel interference.* Considering the forward channel interference problem, let D be the distance between two co-channel cells and R be the cell radius. Then the minimum ratio of D/R that is required to provide a tolerable level of co-channel interference is called the co-channel reuse ratio and is given by [Lee89a]

$$Q = \frac{D}{R} \tag{9.14}$$

The radio propagation characteristics determine the *carrier-to-interference ratio (C/I)* at a given location, and models presented in Chapter 4 and Appendix B are used to find sensible C/I values. As shown in Figure 9.11, the M closest co-channel cells may be considered as first order interference, in which case C/I is given by

$$\frac{C}{I} = \frac{D_0^{-n_o}}{\sum_{k=1}^{M} D_k^{-n_k}} \tag{9.15}$$

where n_0 is the path loss exponent in the desired cell, D_0 is the distance from the desired base station to the mobile, D_k is the distance of the kth cell from the mobile, and n_k is the path loss

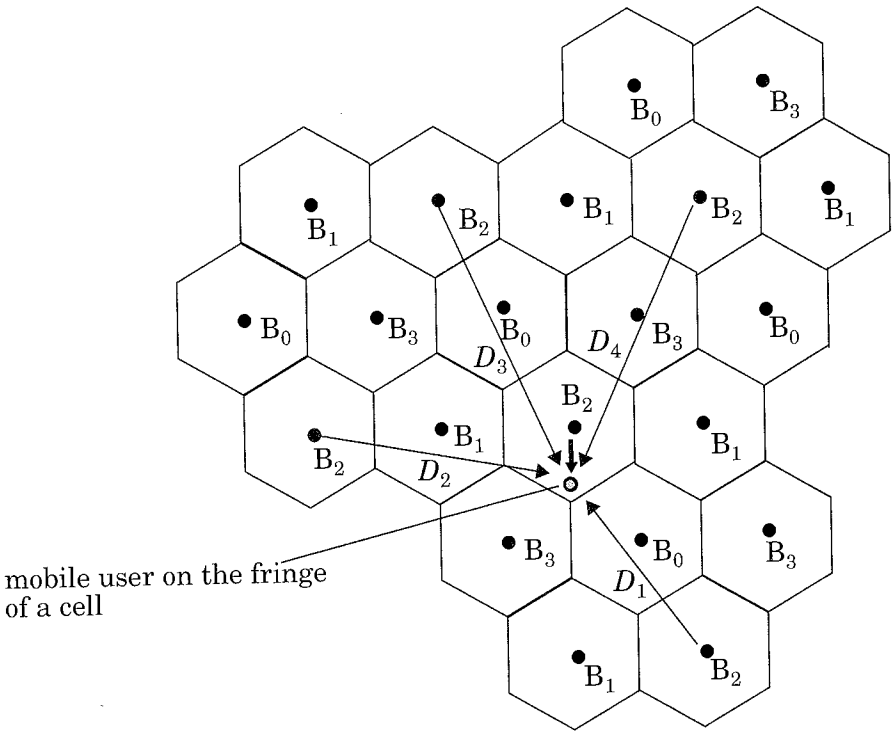


Figure 9.11 Illustration of forward channel interference for a cluster size of $N = 4$. Shown here are four co-channel base stations which interfere with the serving base station. The distance from the serving base station to the user is D_0, and interferers are a distance D_k from the user.

exponent to the kth interfering base station. If only the six closest interfering cells are considered, and all are approximately at the same distance D and have similar path loss exponents equal to that in the desired cell, then C/I is given by

$$\frac{C}{I} = \frac{D_0^{-n}}{6D^{-n}} \tag{9.16}$$

Now, if it is assumed that maximum interference occurs when the mobile is at the cell edge $D_0 = R$, and if the C/I for each user is required to be greater than some minimum $(C/I)_{min}$, which is the minimum carrier-to-interference ratio that still provides acceptable signal quality at the receiver, then the following equation must hold for acceptable performance:

$$\frac{1}{6}\left(\frac{R}{D}\right)^{-n} \geq \left(\frac{C}{I}\right)_{min} \tag{9.17}$$

Thus, from Equation (9.14), the co-channel reuse factor is

$$Q = \left(6\left(\frac{C}{I}\right)_{min}\right)^{1/n} \tag{9.18}$$

The radio capacity of a cellular system is defined as

$$m = \frac{B_t}{B_c N} \text{ radio channels/cell} \tag{9.19}$$

where m is the radio capacity metric, B_t is the total allocated spectrum for the system, B_c is the channel bandwidth, and N is the number of cells in a complete frequency reuse cluster. As shown in Chapter 3, N is related to the co-channel reuse factor Q by

$$Q = \sqrt{3N} \tag{9.20}$$

From Equations (9.18), (9.19), and (9.20), the radio capacity is given as

$$m = \frac{B_t}{B_c \frac{Q^2}{3}} = \frac{B_t}{B_c \left(\frac{6}{3^{n/2}} \left(\frac{C}{I} \right)_{min} \right)^{2/n}} \tag{9.21}$$

As shown by Lee [Lee89a], when $n = 4$, the radio capacity is given by

$$m = \frac{B_t}{B_c \sqrt{\frac{2}{3} \left(\frac{C}{I} \right)_{min}}} \text{ radio channels/cell} \tag{9.22}$$

In order to provide the same voice quality, $(C/I)_{min}$ may be lower in a digital systems when compared to an analog system. Typically, the minimum required C/I is about 12 dB for narrowband digital systems and 18 dB for narrowband analog FM systems, although exact values are determined by subjective listening tests in real-world propagation conditions. Each digital wireless standard has a different $(C/I)_{min}$, and in order to compare different systems, an equivalent C/I must be used. Lower $(C/I)_{min}$ values imply more capacity. If B_t and m are kept constant in Equation (9.22), then it is clear that B_c and $(C/I)_{min}$ are related by

$$\left(\frac{C}{I} \right)_{eq} = \left(\frac{C}{I} \right)_{min} \left(\frac{B_c}{B_c'} \right)^2 \tag{9.23}$$

where B_c is the bandwidth of a particular system, $(C/I)_{min}$ is the tolerable value for the same system, B_c' is the channel bandwidth for a different system, and $(C/I)_{eq}$ is the minimum C/I value for the different system when compared to the $(C/I)_{min}$ for a particular system. Notice that for a constant number of users per radio channel, the same voice quality will be maintained in a different system if $(C/I)_{min}$ increases by a factor of four when the bandwidth is halved. Equation (9.22) indicates that maximum radio capacity occurs when $(C/I)_{min}$ and B_c are minimized, yet Equation (9.23) shows that $(C/I)_{min}$ and B_c are inversely related.

Example 9.7

Evaluate four different cellular radio standards, and choose the one with the maximum radio capacity. Assume $n = 4$ propagation path loss.

System A: B_c = 30 kHz, $(C/I)_{min}$ = 18 dB
System B: B_c = 25 kHz, $(C/I)_{min}$ = 14 dB
System C: B_c = 12.5 kHz, $(C/I)_{min}$ = 2 dB
System D: B_c = 6.25 kHz, $(C/I)_{min}$ = 9 dB

Solution

Consider each system for 6.25 kHz bandwidth, and use Equation (9.23)

System A; B_c = 6.25 kHz, $(C/I)_{eq}$ = 18 – 20 log (6.25/30) = 31.680 dB
System B; B_c = 6.25 kHz, $(C/I)_{eq}$ = 14 – 20 log (6.25/25) = 26.00 dB
System C; B_c = 6.25 kHz, $(C/I)_{eq}$ = 2 – 20 log (6.25/12.5) = –4 dB
System D; B_c = 6.25 kHz, $(C/I)_{eq}$ = 9 – 20 log (6.25/6.25) = 9 dB

Based on comparison, the smallest value of $(C/I)_{eq}$ should be selected for maximum capacity in Equation (9.22). System C offers the best capacity.

In a digital cellular system, C/I can be expressed as

$$\frac{C}{I} = \frac{E_b R_b}{I} = \frac{E_c R_c}{I} \tag{9.24}$$

where R_b is channel bit rate, E_b is the energy per bit, R_c is the rate of the channel code, and E_c is the energy per code symbol. From Equations (9.23) and (9.24) $n = 4$, the ratio of C/I to $(C/I)_{eq}$ of a different system is given as

$$\frac{\left(\frac{C}{I}\right)}{\left(\frac{C}{I}\right)_{eq}} = \frac{\frac{E_c R_c}{I}}{\frac{E_c' R_c'}{I'}} = \left(\frac{B_c'}{B_c}\right)^2 \tag{9.25}$$

The relationship between R_c and B_c is always linear, and if the interference level I is the same in the mobile environment for two different digital systems, then Equation (9.25) can be rewritten as

$$\frac{E_c}{E_c'} = \left(\frac{B_c'}{B_c}\right)^3 \tag{9.26}$$

Equation (9.26) shows that if B_c is reduced by half, then the energy code symbol increases eight times. This gives the relationship between E_b/N_0 and B_c in a digital cellular system.

A comparison can now be made between the spectrum efficiency for FDMA and TDMA. In FDMA, B_t is divided into M channels, each with bandwidth B_c. Therefore, the radio capacity for FDMA in $n = 4$ propagation path loss conditions is given by

$$m = \frac{B_t}{\frac{B_t}{M}\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)}} \tag{9.27}$$

Consider the case where a multichannel FDMA system occupies the same spectrum as a single channel TDMA system with multiple time slots. The carrier and interference terms for the first access technique (in this case FDMA) can be written as, $C = E_b R_b$, $I = I_0 B_c$, whereas the second access technique (in this case TDMA) has carrier and interference terms represented by $C' = E_b R_b'$, $I' = I_0 B_c'$, where R_b and R_b' are the radio transmission rates of two digital systems, E_b is the energy per bit, and I_0 represents the interference power per Hertz. The terms C' and I' are the parameters for the TDMA channels, and the terms C and I apply to the FDMA channels.

Example 9.8

Consider an FDMA system with three channels, each having a bandwidth of 10 kHz and a transmission rate of 10 kbps. A TDMA system has three time slots, channel bandwidth of 30 kHz, and a transmission rate of 30 kbps.

For the TDMA scheme, the received carrier-to-interference ratio for a single user is measured for 1/3 of the time the channel is in use. For example, C'/I' can be measured in 333.3 ms in one second. Thus, C'/I' is given by

$$C' = E_b R_b' = \frac{E_b 10^4 \text{ bits}}{0.333 \text{ s}} = 3R_b E_b = 3C \tag{E.8.8.1}$$

$$I' = I_0 B_c' = I_0 30 \text{ kHz} = 3I$$

It can be seen that the received carrier-to-interference ratio for a user in this TDMA system C'/I' is the same as C/I for a user in the FDMA system. Therefore, for this example, FDMA and TDMA have the same radio capacity and consequently the same spectrum efficiency. However, the required peak power for TDMA is $10\log k$ higher than FDMA, where k is the number of time slots in a TDMA system of equal bandwidth.

Capacity of Digital Cellular TDMA — In practice, TDMA systems improve capacity by a factor of three to six times as compared to analog cellular radio systems. Powerful error control and speech coding enable better link performance in high interference environments. By exploiting speech activity, some TDMA systems are able to better utilize each radio channel. Mobile assisted handoff (MAHO) allows subscribers to monitor the neighboring base stations, and the best base station choice may be made by each subscriber. MAHO allows the deployment of densely packed microcells, thus giving substantial capacity gains in a system. TDMA also makes it possible to introduce *adaptive channel allocation* (ACA). ACA eliminates system planning since it is not

Table 9.3 Comparison of AMPS with Digital TDMA Based Cellular Systems [Rai91]

Parameter	AMPS	GSM	USDC	PDC
Bandwidth (MHz)	25	25	25	25
Voice Channels	833	1000	2500	3000
Frequency Reuse (Cluster sizes)	7	4 or 3	7 or 4	7 or 4
Channels/Site	119	250 or 333	357 or 625	429 or 750
Traffic (Erlangs/sq. km)	11.9	27.7 or 40	41 or 74.8	50 or 90.8
Capacity Gain	1.0	2.3 or 3.4	3.5 or 6.3	4.2 or 7.6

required to plan frequencies for cells. Various proposed standards such as the GSM, US digital cellular (USDC), and Pacific Digital Cellular (PDC) have adopted digital TDMA for high capacity. Table 9.3 compares analog FM based AMPS to other digital TDMA based cellular systems.

9.7.1 Capacity of Cellular CDMA

The capacity of CDMA systems is interference limited, while it is bandwidth limited in FDMA and TDMA. Therefore, any reduction in the interference will cause a linear increase in the capacity of CDMA. Put another way, in a CDMA system, the link performance for each user increases as the number of users decreases. A straightforward way to reduce interference is to use multisectorized antennas, which results in spatial isolation of users. The directional antennas receive signals from only a fraction of the current users, thus leading to the reduction of interference. Another way of increasing CDMA capacity is to operate in a *discontinuous transmission mode* (DTX), where advantage is taken of the intermittent nature of speech. In DTX, the transmitter is turned off during the periods of silence in speech. It has been observed that voice signals have a duty factor of about 3/8 in landline networks [Bra68], and 1/2 for mobile systems, where background noise and vibration can trigger voice activity detectors. Thus, the average capacity of a CDMA system can be increased by a factor inversely proportional to the duty factor. While TDMA and FDMA reuse frequencies depending on the isolation between cells provided by the path loss in terrestrial radio propagation, CDMA can reuse the entire spectrum for all cells, and this results in an increase of capacity by a large percentage over the normal frequency reuse factor. A number of recent texts provide details on CDMA capacity and system design [Lib99], [Kim00], [Gar00}, [Mol01].

For evaluating the capacity of a CDMA system, first consider a single cell system [Gil91]. The cellular network consists of a large number of mobile users communicating with a base station. (In a multiple cell system, all the base stations are interconnected by the mobile switching center.) The cell-site transmitter consists of a linear combiner which adds the spread signals of the individual users and also uses a weighting factor for each signal for forward link power control purposes. For a single cell system under consideration, these weighting factors can be assumed to

be equal. A pilot signal is also included in the cell-site transmitter and is used by each mobile to set its own power control for the reverse link. For a single-cell system with power control, all the signals on the reverse channel are received at the same power level at the base station.

Let the number of users be N. Then, each demodulator at the cell site receives a composite waveform containing the desired signal of power S and $(N-1)$ interfering users, each of which has power, S. Thus, the signal-to-noise ratio is [Gil91],

$$SNR = \frac{S}{(N-1)S} = \frac{1}{(N-1)} \tag{9.28}$$

In addition to SNR, bit energy-to-noise ratio is an important parameter in communication systems. It is obtained by dividing the signal power by the baseband information bit rate, R, and the interference power by the total RF bandwidth, W. The SNR at the base station receiver can be represented in terms of E_b/N_0 given by

$$\frac{E_b}{N_0} = \frac{S/R}{(N-1)(S/W)} = \frac{W/R}{N-1} \tag{9.29}$$

Equation (9.29) does not take into account the background thermal noise, η, in the spread bandwidth. To take this noise into consideration, E_b/N_0 can be represented as

$$\frac{E_b}{N_0} = \frac{W/R}{(N-1)+(\eta/S)} \tag{9.30}$$

The number of users that can access the system is thus given as

$$N = 1 + \frac{W/R}{E_b/N_0} - (\eta/S) \tag{9.31}$$

where W/R is called the processing gain. The background noise determines the cell radius for a given transmitter power.

In order to achieve an increase in capacity, the interference due to other users should be reduced. This can be done by decreasing the denominator of Equations (9.28) or (9.29). The first technique for reducing interference is antenna sectorization. As an example, a cell site with three antennas, each having a beam width of 120°, has interference N_0' which is one-third of the interference received by an omnidirectional antenna. This increases the capacity by a factor of three, since three times as many users may now be served within a sector while matching the performance of the omnidirectional antenna system. Looking at it another way, the same number of users in an omnidirectional cell may now be served in 1/3rd the area. The second technique involves the monitoring of voice activity such that each transmitter is switched off during periods of no *voice activity.* Voice activity is denoted by a factor α, and the interference term in

Equation (9.29) becomes $(N_s - 1)\alpha$, where N_s is the number of users per sector. With the use of these two techniques, the new average value of E_b/N_0' *within a sector* is given as

$$\frac{E_b}{N_0'} = \frac{W/R}{(N_s - 1)\alpha + (\eta/S)} \tag{9.32}$$

When the number of users is large and the system is interference limited rather than noise limited, the number of users can be shown to be

$$N_s = 1 + \frac{1}{\alpha}\left[\frac{W/R}{\frac{E_b}{N_0'}}\right] \tag{9.33}$$

If the voice activity factor is assumed to have a value of 3/8, and three sectors per cell site are used, Equation (9.33) demonstrates that the SNR increases by a factor of eight, which leads to an eight-fold increase in the number of users compared to an omnidirectional antenna system with no voice activity detection.

CDMA Power Control — In CDMA, the system capacity is maximized if each mobile transmitter power level is controlled so that its signal arrives at the cell site with the minimum required signal-to-interference ratio [Sal91]. If the signal powers of all mobile transmitters within an area covered by a cell site are controlled, then the total signal power received at the cell site from all mobiles will be equal to the average received power times the number of mobiles operating in the region of coverage. A tradeoff must be made if a mobile signal arrives at the cell site with a signal that is too weak, and often the weak user will be dropped. If the received power from a mobile user is too great, the performance of this mobile unit will be acceptable, but it will add undesired interference to all other users in the cell.

Example 9.9

If $W = 1.25$ MHz, $R = 9600$ bps, and a minimum acceptable E_b/N_0 is found to be 10 dB, determine the maximum number of users that can be supported in a single-cell CDMA system using (a) omnidirectional base station antennas and no voice activity detection, and (b) three-sectors at the base station and activity detection with $\alpha = 3/8$. Assume the system is interference limited.

Solution

(a) Using Equation (9.31)

$$N = 1 + \frac{1.25 \times 10^6/9600}{10} = 1 + 13.02 = 14$$

(b) Using Equation (9.33) for each sector, we can find N_s.

$$N_s = 1 + \frac{1}{0.375}\left[\frac{1.25 \times 10^6/9600}{10}\right] = 35.7$$

The total number of users is given by $3N_s$, since three sectors exist within a cell; therefore $N = 3 \times 35.7 = 107$ users/ cell.

9.7.2 Capacity of CDMA with Multiple Cells

In actual CDMA cellular systems that employ separate forward and reverse links, neighboring cells share the same frequency, and each base station controls the transmit power of each of its own in-cell users. However, a particular base station is unable to control the power of users in neighboring cells, and these users add to the noise floor and decrease capacity on the reverse link of the particular cell of interest. Figure 9.12 illustrates an example of how users in adjacent cells may be distributed over the coverage area. The transmit powers of each out-of-cell user will add to the in-cell interference (where users are under power control) at the base station receiver. The amount of out-of-cell interference determines the *frequency reuse factor*, f, of a CDMA cellular system. Ideally, each cell shares the same frequency and the maximum possible value of f ($f = 1$) is achieved. In practice, however, the out-of-cell interference reduces f significantly. In contrast to CDMA systems which use the same frequency for each cell, narrowband FDMA/ FDD systems typically reuse channels every seven cells, in which case f is simply 1/7 (see Chapter 3).

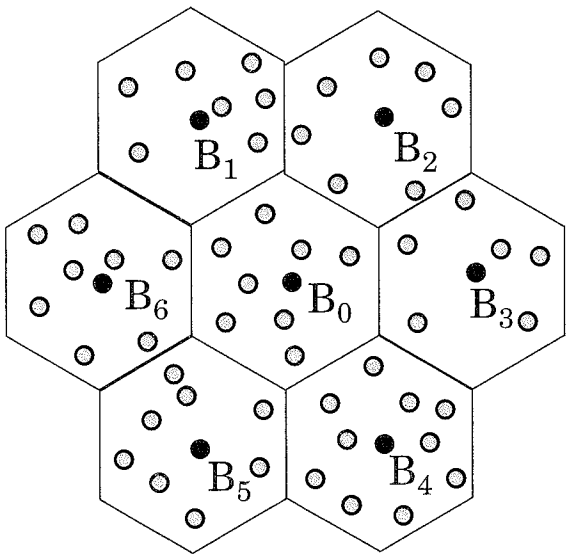


Figure 9.12 Illustration of users within a CDMA cellular radio system. Each base station reuses the same frequency. The small circles represent users within the system, which have their transmit power controlled by their own base station.

The frequency reuse factor for a CDMA system on the reverse link can be defined as [Rap92b]

$$f = \frac{N_0}{N_0 + \sum_i U_i N_{ai}} \tag{9.34}$$

and the frequency reuse efficiency, F, is defined as

$$F = f \times 100\,\% \tag{9.35}$$

In Equation (9.34), N_0 is the total interference power received from the $N-1$ in-cell users, U_i is the number of users in the ith adjacent cell, and N_{ai} is the average interference power for a user located in the ith adjacent cell. Within the cell of interest, the desired user will have the same received power as the $N-1$ undesired in-cell users when power control is employed, and the average received power from users in an adjacent cell can be found by

$$N_{ai} = \sum_j N_{ij}/U_i \tag{9.36}$$

where N_{ij} is the power received at the base station of interest from the jth user in the ith cell. Each adjacent cell may have a different number of users, and each out-of-cell user will offer a different level of interference depending on its exact transmitted power and location relative to the base station of interest. The variance of N_{ai} can be computed using standard statistical techniques for a particular cell.

An analysis described by Liberti and Rappaport and Milstein [Lib94b] [Rap92b] [Lib99] uses a recursive geometric technique to determine how the propagation path loss impacts the frequency reuse of a CDMA system by considering the interference from both in-cell and out-of-cell users. The geometric technique, called the *concentric circle cellular geometry*, considers all cells to have equal geographic area and specifies the cell of interest to be a circular cell, which is located in the center of all surrounding cells. Interfering cells are wedge-shaped and are arranged in layers around the center cell of interest. Figure 9.13 illustrates the concentric circle geometry for a single layer of adjacent cells.

Let the center cell of interest have radius R, and assume that there is some close-in distance d_o such that all users in the center cell are located no closer than d_o meters to the center base station and that all users in the cell of interest are located a distance d from the base station of interest such that $d_o \le d \le R$. Then, a first layer of adjacent interfering cells is found on $R \le d \le 3R$, a second layer is located on $3R \le d \le 5R$, and the ith interfering layer is located on $(2i-1)R \le d \le (2i+1)R$. In each surrounding layer, there are M_i adjacent cells, where i denotes the layer number. If d_o is assumed to be much less than R, then the area A of the center cell of interest is

$$A = \pi R^2 - \pi d_0^2 \approx \pi R^2 \tag{9.37}$$

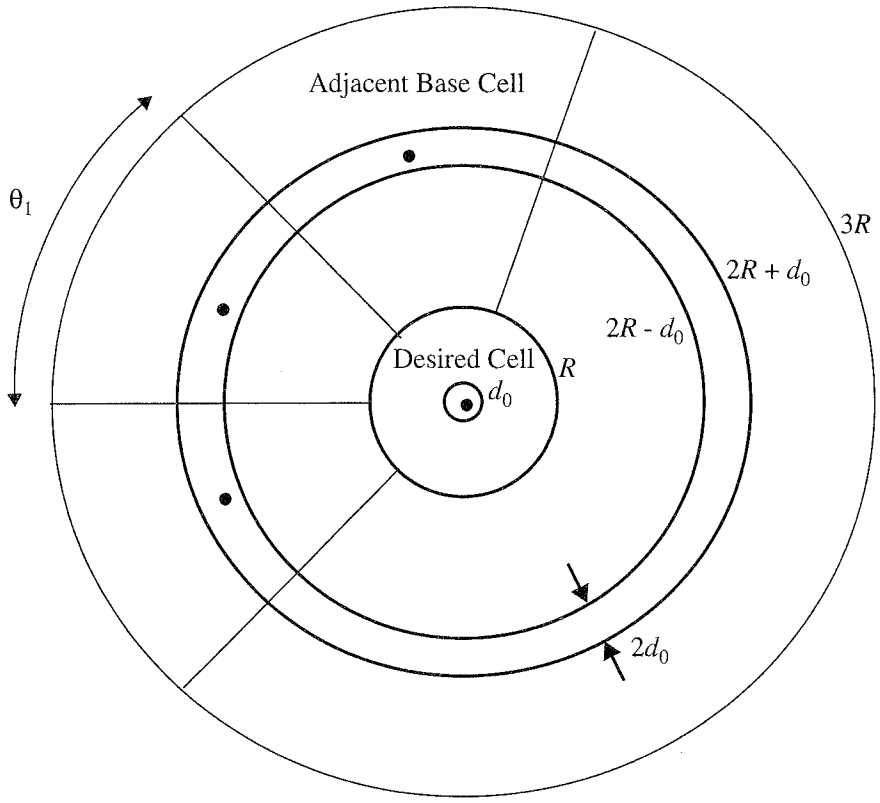


Figure 9.13 The concentric circle cellular geometry proposed by Rappaport and Milstein [Rap92b]. Notice that the center cell is circular, and that the surrounding cells are wedge-shaped. Each cell, however, covers the same area.

Within the first surrounding layer of cells, let A_1 denote the entire area of the region. If each cell in the first surrounding layer is to have the same area A, then there should be M_1 wedge-shaped cells that each span a particular angle θ_1. Neglecting d_o, it is clear that for the first surrounding layer

$$A_1 = \pi(3R)^2 - \pi R^2 = M_1 A \tag{9.38}$$

$$\theta_1 = 2\pi / M_1 \tag{9.39}$$

Solving Equations (9.38) and (9.39), $M_1 = 8$ and $\theta_1 = 45°$. In other words, there are eight wedge-shaped cells in the first surrounding layer, each cell covering a span of 45°. By recursion, it can be shown that for the second, and all subsequent surrounding layers, the area of the ith surrounding layer is related to the number of cells within the layer by

$$A_i = M_i A = iM_1 A = i8A \quad i \geq 1 \tag{9.40}$$

$$\theta_i = \theta_1 / i = \pi / 4i \tag{9.41}$$

The concentric circle geometry is appealing because, once the area of a cell of interest is specified, it becomes easy to specify an entire system of surrounding cells that each occupy the same coverage area. Furthermore, since each adjacent cell has the same geometry and angular span as any other cell within the surrounding layer, and since each cell within a particular layer has the same radial geometry to the center cell of interest, it becomes possible to consider the interference effects of just a single cell within the surrounding layer. One can simply multiply the effects of a single cell by the number of cells within the surrounding layer.

Weighting Factors

It is often useful to consider the adjacent cell interference effects for various distributions of users within the interfering cells. This allows one to determine worst case frequency reuse and provides flexibility for determining a range of possible values of f for various user distributions. The concentric circle geometry allows the interfering layers to be broken into two sublayers, an inner sublayer which is on $(2i-1)R \le d \le 2iR - d_0$, and the outer sublayer which is on $2iR + d_0 \le d \le (2i+1)R$. This partitioning is shown in Figure 9.13 (as described subsequently, there is a small forbidden zone around the base station of the adjacent cells). The partitioning of layers provides two sectors within each wedge-shaped cell in a given layer: the inner sector (which contains a smaller fraction of the area of the cell) and the outer sector (which contains a greater fraction of the area of the cell). Since each cell contains the same area as the center cell, it is clear that for a uniform distribution of users over an adjacent cell, the inner sector will contain fewer users than the outer sector, and this will certainly impact the interference power received at the center cell base station. To account for a wide range of user distributions in the interfering layers, weighting factors are used to redistribute users in the inner and outer sectors of an adjacent cell.

If K is the user density (i.e., the number of users per unit area), then the total number of users within the center cell is given by $U = KA$. If it is assumed that all cells have the same number of users, then in the first surrounding layer there will also be KA users. Weighting factors can be used to break up the distribution of adjacent cell users between the inner and outer sectors. In the first surrounding layer, the inner and outer sectors of each cell have areas given by

$$A_{1in}/M_1 = (\pi(2R)^2 - \pi R^2)/8 = 3A/8 \tag{9.42}$$

and

$$A_{1out}/M_1 = (\pi(3R)^2 - \pi(2R)^2)/8 = 5A/8 \tag{9.43}$$

For each first layer cell to possess $U = KA$ users, weighting factors for the user density within the inner (W_{1in}) and outer (W_{1out}) sectors may be applied such that

$$U = KA = (KW_{1in}A_{1in})/M_1 + (KW_{1out}A_{1out})/M_1 \tag{9.44}$$

and

$$U = KA = KA[3/8W_{1in} + 5/8W_{1out}] \tag{9.45}$$

Using Equation (9.45), it can be seen that if $W_{1in} = 1$ and $W_{1out} = 1$, then 3/8 of the users will be in the inner sector and 5/8 of the users will be in the outer sector. This can be thought of as an optimistic condition (or upper bound) for frequency reuse, since not even half of the interferers are less than $2R$ away from the base station, and 5/8 of the users are farther than $2R$ away and will offer smaller levels of interference to the center cell. However, if $W_{1in} = 4/3$ and $W_{1out} = 4/5$, then half of the users in the first layer cells will be closer than $2R$ and half will be farther than $2R$ from the center base station (this corresponds to the case of hexagonal cells, where half of the users would be closer to the base station of interest, and half would be farther away from the base station of interest). For a worst case interference scenario, all of the U users in each of the first layer cells would be located in the inner sector (thereby providing more interference to the center cell due to smaller distance and smaller path loss). The weighting factors account for this worst case by setting $W_{1in} = 8/3$ and $W_{1out} = 0$. It is left as an exercise to determine appropriate weighting factors for the second and subsequent layer cells.

The area of the center and wedge-shaped cells in the concentric circle geometry exceeds the area of a traditional hexagonal cell described in Chapter 3. Whereas a hexagonal cell occupies an area of $A_{hex} = (3\sqrt{3}R^2)/2 = 2.598R^2$, the cells in the concentric circle geometry each possess and area of πR^2. Thus, the center cell occupies an area which is 1.21 times as large as a traditional hexagonal cell and the first layer of eight wedge-shaped cells shown in Figure 9.13 occupies the area of 9.666 hexagonal cells. Since frequency reuse is based on the relative amount of interference from neighboring cells, as long as the number of users and the coverage area can be accurately represented and scaled, the particular geometry does not dramatically impact capacity predictions [Lib99], [Lib94b], [Rap92b]. Thus, the concentric circle geometry offers analytical advantages for analyzing the effects of co-channel cells.

Using Concentric Circle Geometry to Find CDMA Capacity

To find the capacity of a multicell CDMA system, the concentric circle geometry can be used in conjunction with a propagation path loss model to determine interference from adjacent cell users. Then, using Equation (9.34), the frequency reuse factor can be found. Note that the in-cell interference power N_0 is simply given by

$$N_0 = P_0(U-1) \approx P_0 U = P_0 KA \tag{9.46}$$

where P_0 is the power received from any one of the U users in the center cell (since all users are assumed to be under power control and thus provide the same received power at the base station receiver). In general, it is practical to assume that any adjacent cells will also contain U users and will receive power P_0 from each of its own in-cell users. In the adjacent cells, each subscriber is under power control within its own cell, and is a distance d' from its own base station. Since propagation path loss laws are based on all distances greater than d_0, a small forbidden zone having width $2d_0$ is assumed to exist in all surrounding rings (see Figure 9.14). The forbidden zone is a small annulus in each layer which is assumed not to contain users, so that any propagation path loss model may be used in analysis without having $d' < d_0$. It is easy to

show that when $d_0 < R$, the small forbidden zone occupies negligible area and provides virtually the same interference results as for the case when the forbidden zone is a circle of radius d_0 around each adjacent cell.

A slight approximation for d' is made when computing the power of the adjacent cell user to its own base station. Figure 9.14 illustrates how the distances are computed for inner and outer sector users within a first layer interfering cell. Using the law of cosines, it can be shown that within any cell in the ith layer

$$d' = \sqrt{d^2 \sin^2\theta + (2Ri - d_0 - d\cos\theta)^2} \quad \text{for} \quad (2i-1)R \le d \le (2i)R - d_0 \tag{9.47}$$

$$d' = \sqrt{d^2 \sin^2\theta + (d\cos\theta - 2Ri - d_0)^2} \quad \text{for} \quad (2i)R + d_0 \le d \le (2i+1)R \tag{9.48}$$

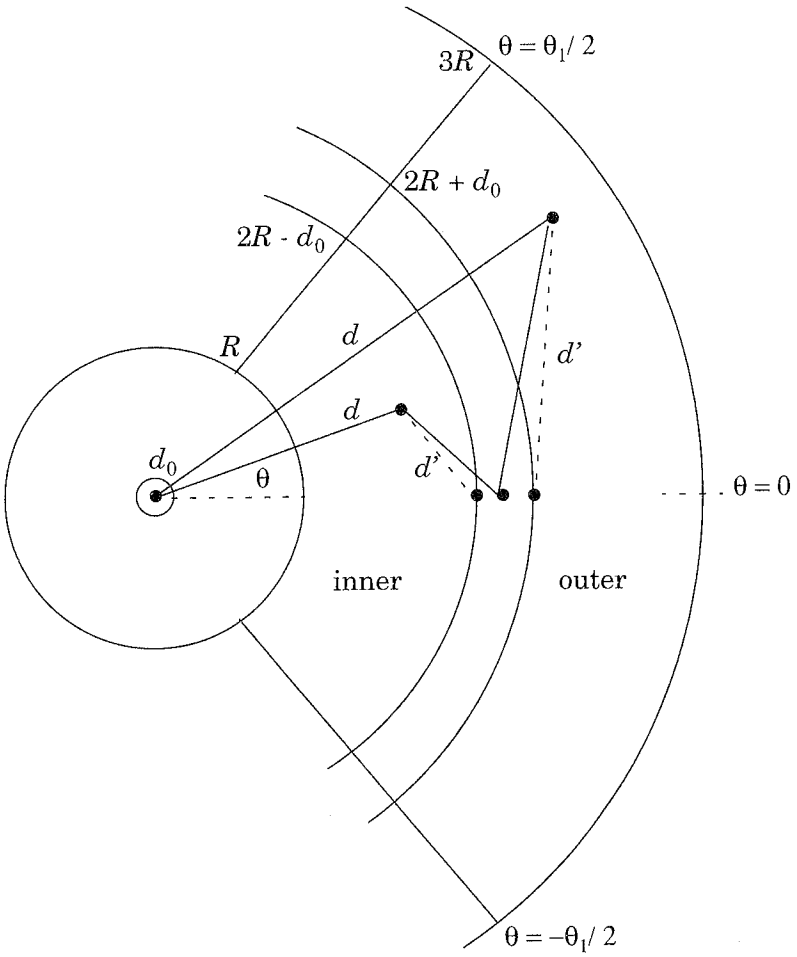


Figure 9.14 Geometry for computing distance between adjacent users and the center base station of interest. By breaking the adjacent cells into inner and outer sectors, the distribution of users within neighboring cells may be varied.

Then, using d' and d, the interference power $P_{0,i,j}$ at the center cell from the jth user in the ith interfering cell can be given by

$$P_{0,i,j}(r, \theta, d_0) = N_{i,j} = P_0(d'/d_0)^n(d_0/d)^n \tag{9.49}$$

where n is the propagation path loss exponent described in Chapters 3 and 4, and d' is a function of θ as given by Equations (9.47) and (9.48). The two factors on the right side of Equation (9.49) represent the actual transmitter power radiated by the jth subscriber in the ith cell, multiplied by the propagation path loss from that subscriber to the center base station receiver. By evaluating Equation (9.49) for each user in an adjacent cell, it is possible to compute N_{ai} using Equation (9.36) and then apply Equation (9.34) to determine f.

Simulations which considered various user weighting factors, as well as path loss exponents of $n = 2$, 3, and 4, and varying cell sizes were carried out by Rappaport and Milstein [Rap92b]. Table 9.4 indicates typical results, which show that f can range between 0.316 and 0.707, depending on the path loss exponent and the distribution of users. Thus, while a single cell CDMA system offers ideal frequency reuse ($f = 1$), the actual frequency reuse is a strong function of user distribution and path loss.

Table 9.4 Frequency Reuse Factor for Reverse Channel of CDMA Cellular System, as a Function of n for Two System Implementations [from [Rap92b] © IEEE]

		Frequency reuse efficiency		
d (km)	n	lower bound $W_1 = 3.0$ $W_2 = 0.0$	hex $W_1 = 1.38$ $W_2 = 0.78$	upper bound $W_1 = 1.0$ $W_2 = 1.0$
2	2	0.316	0.425	0.462
2	3	0.408	0.558	0.613
2	4	0.479	0.646	0.707
10	2	0.308	0.419	0.455
10	3	0.396	0.550	0.603
10	4	0.462	0.634	0.695

9.7.3 Capacity of Space Division Multiple Access

For interference limited CDMA operating in an AWGN channel, with perfect power control with no interference from adjacent cells and with omnidirectional antennas used at the base stations, the average bit error rate, P_b, for a user can be found from the Gaussian approximation in Chapter 6 and Appendix E as

$$P_b = Q\left(\sqrt{\frac{3N}{K-1}}\right) \tag{9.50}$$

where K is the number of users in a cell and N is the spreading factor. $Q(x)$ is the standard Q-function. Equation (9.35) assumes that the signature sequences are random and that K is sufficiently large to allow the Gaussian approximation to be valid.

To illustrate how directive antennas can improve the reverse link in a single-cell CDMA system, consider Figure 9.15, which illustrates three possible base station antenna configurations. The omnidirectional receiver antenna will detect signals from all users in the system, and thus will receive the greatest amount of noise. The sectored antenna will divide the received noise into a smaller value and will increase the number of users in the CDMA system (as illustrated in Example 9.9). The adaptive antenna shown in Figure 9.15(c) provides a spot beam for each user, and it is this implementation which is the most powerful form of SDMA. An ideal adaptive antenna is able to form a beam for each user in the cell of interest, and the base station tracks each user in the cell as it moves. Assume that a beam pattern, $G(\phi)$, is formed such that the pattern has maximum gain in the direction of the desired user. Such a directive pattern can be formed at the base station using an N-element adaptive array antenna. Assume that a beam pattern, $G(\phi)$, with no variation in the elevation plane, such as shown in Figure 9.16, can be formed by an array. The pattern, $G(\phi)$, can be steered through 360° in the horizontal (ϕ) plane such that the desired user is always in the main beam of the pattern. It is assumed that K users in the single-cell CDMA system are uniformly distributed throughout a two-dimensional cell (in the horizontal plane, $\theta = \pi/2$), and the base station antenna is capable of simultaneously providing such a pattern for all users in the cell. On the reverse link, the power received from the desired mobile signals is $P_{r;0}$. The powers of the signal incident at the base station antenna from $K-1$ interfering users are given by $P_{r;i}$ for $i = 1, ...k-1$. The average total interference power, I, seen by a single desired user, (measured in the received signal at the array port of the base station antenna array, which is steered to the User 0), is given by

$$I = E\left\{\sum_{i=1}^{K-1} G(\phi_i)P_{r;i}\right\} \tag{9.51}$$

where ϕ_i is the direction of the ith user in the horizontal plane, measured in the x-axis, and E is the expectation operator. No interference from adjacent cells contributes to total received inter-

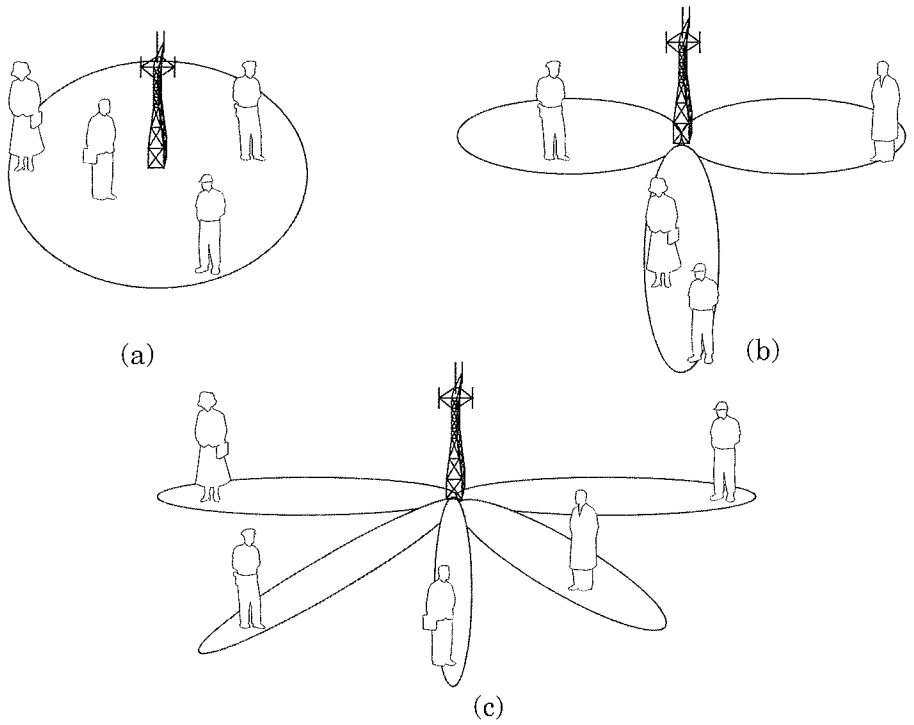


Figure 9.15 Illustration showing different antenna patterns. (a) An omni-directional base station antenna pattern; (b) sectorized base station antenna pattern; (c) adaptive antenna pattern which provides individual spot beams for each user in the cell.

ference in Equation (9.51). If perfect power control is applied such that the power incident at the base station antenna from each user is the same, then $P_{r;i} = P_c$ for each of the K users, and the average interference power seen by User 0 is given by

$$I = P_c E\left\{\sum_{i=1}^{K-1} G(\phi_i)\right\} \tag{9.52}$$

Assuming that users are independently and identically distributed throughout the cell, the average total interference seen by a user in the central cell is given by

$$I = \frac{P_c(K-1)}{D} \tag{9.53}$$

where D is the directivity of the antenna, given by $max(G(\phi))$. In typical cellular installations, D ranges between 3 dB to 10 dB. As the antenna beam pattern is made more narrow, D increases,

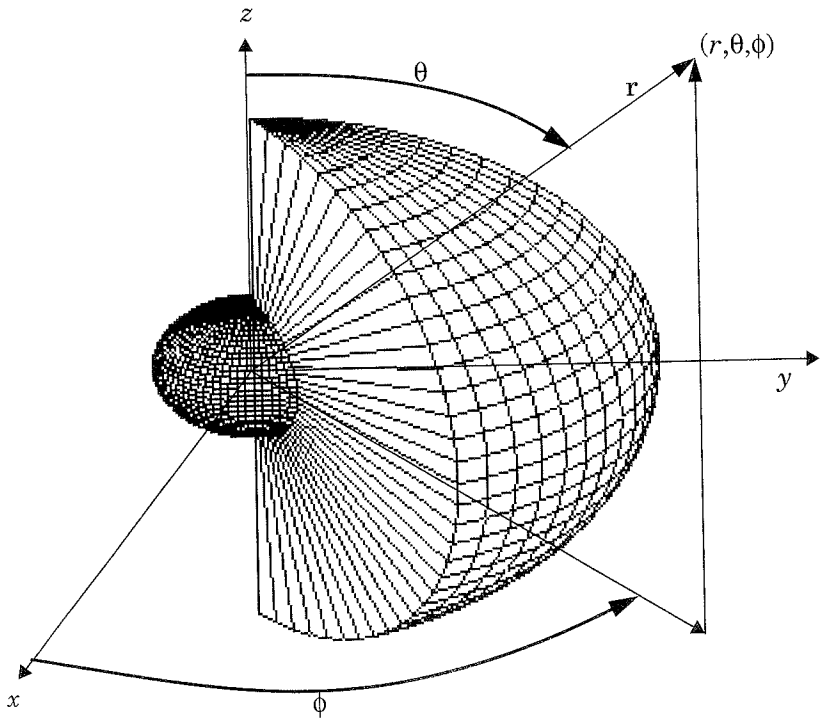


Figure 9.16 An idealized flat-topped pattern with a 60 degree beamwidth and a –6dB sidelobe level. The pattern has no variation in the elevation axis to account for users which are close to, and far from, the base station [from [Lib94b] © IEEE].

and the received interference I decreases proportionally. The average bit error rate for User 0 can thus be given by

$$P_b = Q\left(\sqrt{\frac{3DN}{K-1}}\right) \tag{9.54}$$

Thus, it can be seen that the probability of bit error is dependent on the beam pattern of a receiver, and there is considerable improvement that is achieved using high gain adaptive antennas at the base station.

Using the fact that the additional interference from adjacent cells simply adds to the interference level, the average probability of error for a particular user using directive antennas in a multiple-cell environment is given by

$$P_b = Q\left(\sqrt{\frac{3fDN}{K-1}}\right) \tag{9.55}$$

where f is the frequency reuse factor described by Equation (9.34) and Table 9.4. Figure 9.17 illustrates the average probability of error for different propagation path loss exponents, where two different types of base station antennas are compared using simulations which considered a single layer of interfering cells using the geometry described in Section 9.7.2 [Lib94b]. In the

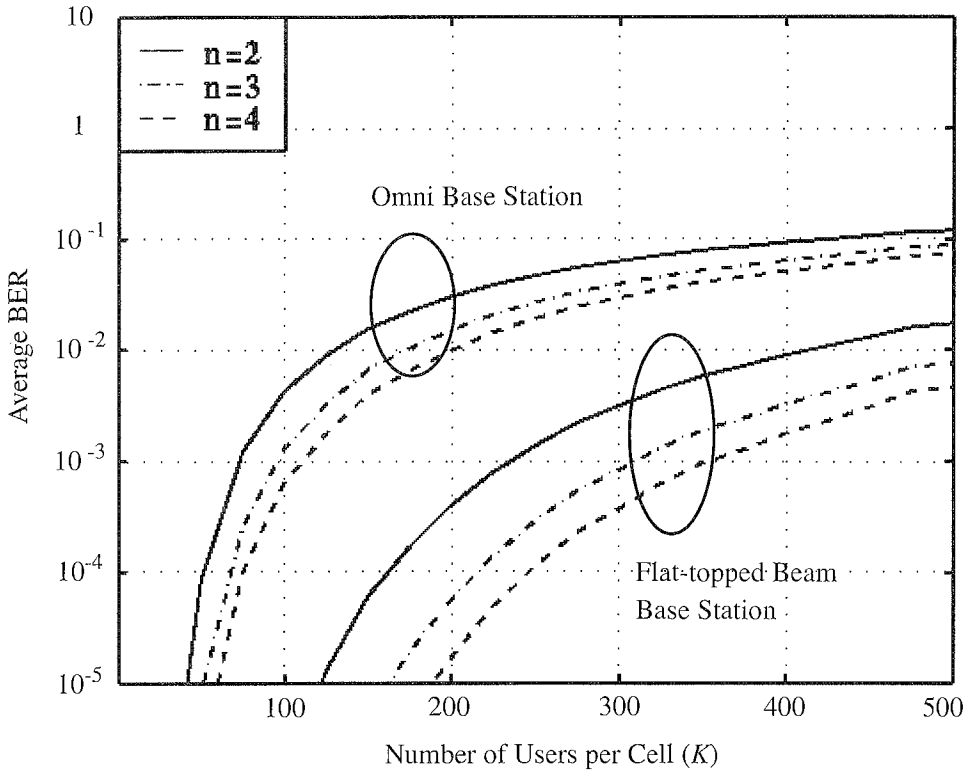


Figure 9.17 Average probability of error for a user in a CDMA system with one interfering layer of co-channel cells. Base station of interest using (a) an omnidirectional base station antenna and (b) SDMA with a flat top beam having $D = 5.1$ dB and pointed at each of the K users within the cell of interest. Notice that SDMA offers significant capacity gains for a given average probability of error.

figure, one set of average probability of error curves is found for a standard omnidirectional base station antenna, and another set of curves is found for a flat top beam (a beam with constant gain over a specific angular region) having a directivity of about 5.1 dB. The flat top beam is assumed to have a constant maximum gain lobe spanning an azimuth of 30 degrees, and a constant side lobe level which is 6 dB down from the maximum gain. Furthermore, it is assumed that K separate flat top beams can be formed by the base station and pointed at each of the K users within the cell of interest. Notice that for an average probability of error of 0.001 in a propagation path loss environment of $n = 4$, the flat top beam system will support 350 users, whereas the omni-directional antenna will support only 100 users [Lib94b]. This increase in the number of users is roughly equal to the directivity offered by the flat top beam system, and illustrates the promise SDMA offers for improving capacity in wireless systems. Note that multipath is not considered. The impact of scattering and diffuse multipath on the performance of SDMA is currently a topic of research and is certain to impact performance and implementation strategies for emerging SDMA techniques.

11.4 CDMA Digital Cellular Standard (IS-95)

As discussed in Chapter 9, Code Division Multiple Access (CDMA) offers many advantages over TDMA and FDMA. A US digital cellular system based on CDMA which promised increased capacity [Gil91] was standardized as Interim Standard 95 (IS-95) by the US Telecommunications Industry Association (TIA) [TIA93]. Like IS-136, the IS-95 system was designed to be compatible with the existing US analog cellular system (AMPS) frequency band, hence mobiles and base stations can be economically produced for dual mode operation. Pilot production, CDMA/AMPS, dual mode phones were made available by Qualcomm in 1994, and as of 2001, there are over 80 million CDMA subscribers worldwide.

IS-95 allows each user within a cell to use the same radio channel, and users in adjacent cells also use the same radio channel, since this is a direct sequence spread spectrum CDMA system. CDMA completely eliminates the need for frequency planning within a market. To facilitate graceful transition from AMPS to CDMA, each IS-95 channel occupies 1.25 MHz of spectrum on each one-way link, or 10% of the available cellular spectrum for a US cellular provider (recall, the US cellular system is allocated 25 MHz and each service provider receives half the spectrum or 12.5 MHz). In practice, AMPS carriers must provide a 270 kHz guard band (typically 9 AMPS channels) on each side of the spectrum dedicated for IS-95. IS-95 is fully compatible with the IS-41 networking standard described in Chapter 10.

Unlike other cellular standards, the user data rate (but not the channel chip rate) changes in real-time, depending on the voice activity and requirements in the network. Also, IS-95 uses a different modulation and spreading technique for the forward and reverse links. On the forward link, the base station simultaneously transmits the user data for all mobiles in the cell by using a different spreading sequence for each mobile. A pilot code is also transmitted simultaneously and at a higher power level, thereby allowing all mobiles to use coherent carrier detection while estimating the channel conditions. On the reverse link, all mobiles respond in an asynchronous fashion and have ideally a constant signal level due to power control applied by the base station.

The speech coder used in the IS-95 system is the Qualcomm 9600 bps Code Excited Linear Predictive (QCELP) coder. The original implementation of this vocoder detects voice activity, and reduces the data rate to 1200 bps during silent periods. Intermediate user data rates of 2400, 4800, and 9600 bps are also used for special purposes. As discussed in Chapter 8 and Section 11.4.4, a 14,400 bps coder which uses 13.4 kbps of speech data (QCELP13) was introduced by Qualcomm in 1995.

11.4.1 Frequency and Channel Specifications

IS-95 is specified for reverse link operation in the 824–849 MHz band and 869–894 MHz for the forward link. A PCS version of IS-95 has also been designed for international use in the 1800–2000 MHz bands. A forward and reverse channel pair is separated by 45 MHz for cellular band operation. Many users share a common channel for transmission. The maximum user data rate is 9.6 kb/s. User data in IS-95 is spread to a channel chip rate of 1.2288 Mchip/s (a total spreading factor of 128) using a combination of techniques. The spreading process is different for the

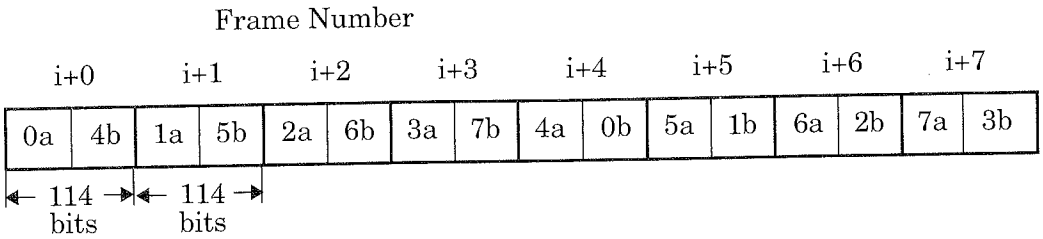


Figure 11.13 Diagonal interleaving used for TCH/SACCH/FACCH data. Eight speech sub-blocks are spread over eight successive TCH time slots for a specific time slot number.

call to call. Two types of ciphering algorithms, called A3 and A5, are used in GSM to prevent unauthorized network access and privacy for the radio transmission respectively. The A3 algorithm is used to authenticate each mobile by verifying the users passcode within the SIM with the cryptographic key at the MSC. The A5 algorithm provides the scrambling for the 114 coded data bits sent in each TS.

Burst Formatting — Burst formatting adds binary data to the ciphered blocks, in order to help synchronization and equalization of the received signal.

Modulation — The modulation scheme used by GSM is 0.3 GMSK, where 0.3 describes the 3 dB bandwidth of the Gaussian pulse shaping filter with relation to the bit rate (e.g., $BT = 0.3$). As described in Chapter 6, GMSK is a special type of digital FM modulation. Binary ones and zeros are represented in GSM by shifting the RF carrier by ±67.708 kHz. The channel data rate of GSM is 270.833333 kbps, which is exactly four times the RF frequency shift. This minimizes the bandwidth occupied by the modulation spectrum and hence improves channel capacity. The MSK modulated signal is passed through a Gaussian filter to smooth the rapid frequency transitions which would otherwise spread energy into adjacent channels.

Frequency Hopping — Under normal conditions, each data burst belonging to a particular physical channel is transmitted using the same carrier frequency. However, if users in a particular cell have severe multipath problems, the cell may be defined as a *hopping cell* by the network operator, in which case *slow frequency hopping* may be implemented to combat the multipath or interference effects in that cell. Frequency hopping is carried out on a frame-by-frame basis, thus hopping occurs at a maximum rate of 217.6 hops per second. As many as 64 different channels may be used before a hopping sequence is repeated. Frequency hopping is completely specified by the service provider.

Equalization — Equalization is performed at the receiver with the help of the training sequences transmitted in the midamble of every time slot. The type of equalizer for GSM is not specified and is left up to the manufacturer.

Demodulation — The portion of the transmitted forward channel signal which is of interest to a particular user is determined by the assigned TS and ARFCN. The appropriate TS is demodulated with the aid of synchronization data provided by the burst formatting. After demodulation, the binary information is deciphered, de-interleaved, channel decoded, and speech decoded.

forward and reverse links in the original CDMA specification. On the forward link, the user data stream is encoded using a rate 1/2 convolutional code, interleaved, and spread by one of sixty-four orthogonal spreading sequences (Walsh functions). Each mobile in a given cell is assigned a different spreading sequence, providing perfect separation among the signals from different users, at least for the case where multipath does not exist. To reduce interference between mobiles that use the same spreading sequence in different cells, and to provide the desired wideband spectral characteristics (not all of the Walsh functions yield a wideband power spectrum), all signals in a particular cell are scrambled using a pseudorandom sequence of length 2^{15} chips.

Orthogonality among all forward channel users within a cell is preserved because their signals are scrambled synchronously. A pilot channel (code) is provided on the forward link so that each subscriber within the cell can determine and react to the channel characteristics while employing coherent detection. The pilot channel is transmitted at higher power than the user channels.

On the reverse link, a different spreading strategy is used since each received signal arrives at the base station via a different propagation path. The reverse channel user data stream is first convolutionally encoded with a rate 1/3 code. After interleaving, each block of six encoded symbols is mapped to one of the 64 orthogonal Walsh functions, providing sixty-four-ary orthogonal signaling. A final fourfold spreading, giving a rate of 1.2288 Mchip/s, is achieved by spreading the resulting 307.2 kchip/s stream by user-specific and base-station specific codes having periods of $2^{42} - 1$ chips and 2^{15} chips, respectively. The rate 1/3 coding and the mapping onto Walsh functions result in a greater tolerance for interference than would be realized from traditional repetition spreading codes. This added robustness is important on the reverse link, due to the noncoherent detection and the in-cell interference received at the base station.

Another essential element of the reverse link is tight control of each subscriber's transmitter power, to avoid the "near–far" problem that arises from varying received powers of the users. A combination of open-loop and fast, closed-loop power control is used to adjust the transmit power of each in-cell subscriber so that the base station receives each user with the same received power. The commands for the closed-loop power control are sent at a rate of 800 b/s, and these bits are stolen from the speech frames. Without fast power control, the rapid power changes due to fading would degrade the performance of all users in the system.

At both the base station and the subscriber, RAKE receivers are used to resolve and combine multipath components, thereby reducing the degree of fading. As described in Chapter 7, a RAKE receiver exploits the multipath time delays in a channel and combines the delayed replicas of the transmitted signal in order to improve link quality. In IS-95, a three finger RAKE is used at the base station. The IS-95 architecture also provides base station diversity during "soft" handoffs, whereby a mobile making the transition between cells maintains links with both base stations during the transition. The mobile receiver combines the signals from the two base stations in the same manner as it would combine signals associated with different multipath components.

Table 11.4 IS-95 Forward Traffic Channel Modulation Parameters Summary (does not reflect new 13.4 kbps coder)

Parameter	Data Rate (bps)			
User data rate	**9600**	**4800**	**2400**	**1200**
Coding Rate	1/2	1/2	1/2	1/2
User Data Repetition Period	1	2	4	8
Baseband Coded Data Rate	19,200	19,200	19,200	19,200
PN Chips/Coded Data Bit	64	64	64	64
PN Chip Rate (Mcps)	1.2288	1.2288	1.2288	1.2288
PN Chips/Bit	128	256	512	1024

11.4.2 Forward CDMA Channel

The forward CDMA channel consists of a pilot channel, a synchronization channel, up to seven paging channels, and up to sixty-three forward traffic channels [Li93]. The pilot channel allows a mobile station to acquire timing for the Forward CDMA channel, provides a phase reference for coherent demodulation, and provides each mobile with a means for signal strength comparisons between base stations for determining when to handoff. The synchronization channel broadcasts synchronization messages to the mobile stations and operates at 1200 bps. The paging channel is used to send control information and paging messages from the base station to the mobiles and operates at 9600, 4800, and 2400 bps. The forward traffic channel (FTC) supports variable user data rates at 9600, 4800, 2400, or 1200 bps.

The forward traffic channel modulation process is described in Figure 11.14 [EIA90]. Data on the forward traffic channel is grouped into 20 ms frames. The user data is first convolutionally coded and then formatted and interleaved to adjust for the actual user data rate, which may vary. Then the signal is spread with a Walsh code and a long PN sequence at a rate of 1.2288 Mcps. Table 11.4 lists the coding and repetition parameters for the forward traffic channel.

The speech data rate applied to the transmitter is variable over the range of 1200 bps to 9600 bps.

11.4.2.1 Convolutional Encoder and Repetition Circuit

Speech coded voice or user data are encoded using a half-rate convolutional encoder with constraint length 9. The encoding process is described by generator vectors G_0 and G_1 which are 753 (octal) and 561 (octal), respectively.

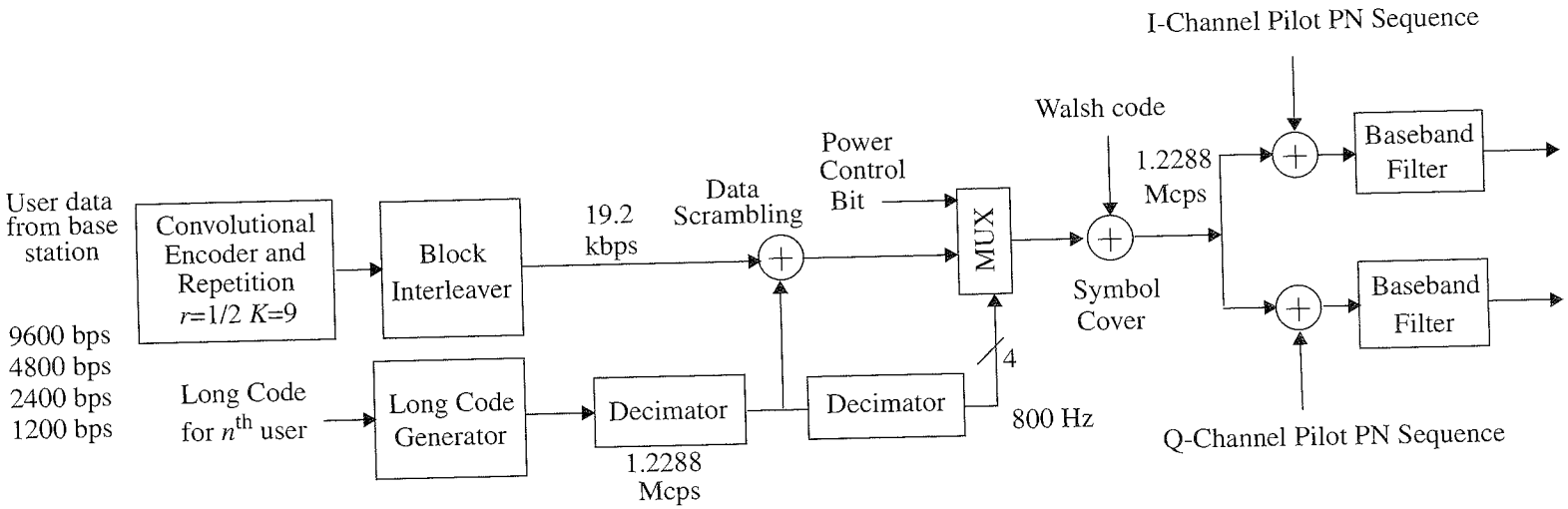


Figure 11.14 Forward CDMA channel modulation process.

The speech encoder exploits pauses and gaps in speech, and reduces its output from 9600 bps to 1200 bps during silent periods. In order to keep a constant baseband symbol rate of 19.2 kbps, whenever the user rate is less than 9600 bps, each symbol from the convolution encoder is repeated before block interleaving. If the information rate is 4800 bps, each code symbol is repeated one time. If the information rate is 2400 bps or 1200 bps, each code symbol is repeated three or seven times, respectively. The repetition results in a constant coded rate of 19,200 symbols per second for all possible information data rates.

11.4.2.2 Block Interleaver

After convolution coding and repetition, symbols are sent to a 20 ms block interleaver, which is a 24 by 16 array.

11.4.2.3 Long PN Sequence

In the forward channel, direct sequence is used for data scrambling. The long PN sequence is uniquely assigned to each user is a periodic long code with period 2^{42}-1 chips. (This corresponds to repeating approximately once per century.) The long code is specified by the following characteristic polynomial [TIA93]

$$p(x) = x^{42} + x^{35} + x^{33} + x^{31} + x^{27} + x^{26} + x^{25} + x^{22} + x^{21} + x^{19} + x^{18} + x^{17} + x^{16} + x^{10} + x^{7} + x^{6} + x^{5} + x^{3} + x^{2} + x^{1} + 1$$

Each PN chip of the long code is generated by the modulo-2 inner product of a 42 bit mask and the 42 bit state vector of the sequence generator. The initial state of the generator is defined to be when the output of the generator becomes '1' after following 41 consecutive '0' outputs, with the binary mask consisting of '1' in the most significant bit (MSB) followed by 41 '0's.

Two types of masks are used in the long code generator: a public mask for the mobile station's electronic serial number (ESN) and a private mask for the mobile station identification number (MIN). All CDMA calls are initiated using the public mask. Transition to the private mask is carried out after authentication is performed. The public long code is specified as follows: M_{41} through M_{32} is set to 1100011000, and M_{31} through M_0 is set to a permutation of the mobile station's ESN bits. The permutation is specified as follows [TIA93]:

$$\text{ESN} = (E_{31},E_{30},E_{29},E_{28},E_{27},.....E_3,E_2,E_1,E_0)$$

$$\begin{aligned}\text{Permuted ESN} =(&E_0, E_{31}, E_{22}, E_{13}, E_4, E_{26}, E_{17}, E_8,E_{30},E_{21},E_{12},E_3,\\ &E_{25},E_{16},E_7, E_{29}, E_{20}, E_{11}, E_2, E_{24},E_{15}, E_6, E_{28}, E_{19},\\ &E_{10}, E_1, E_{23}, E_{14},E_5, E_{27}, E_{18}, E_9)\end{aligned}$$

The private long code mask is specified so M_{41} and M_{40} are set to '01', and M_{39} through M_0 are set by a private procedure. Figure 11.15 illustrates the long code mask format.

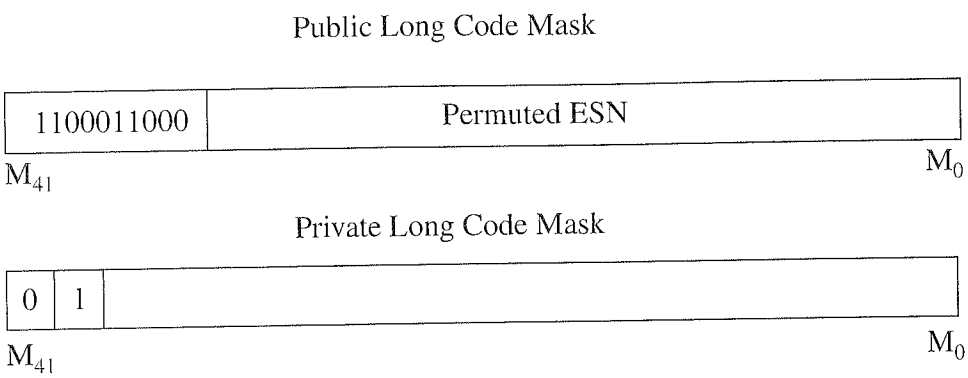


Figure 11.15 Long code mask format for IS-95.

11.4.2.4 Data Scrambler

Data scrambling is performed after the block interleaver. The 1.2288 MHz PN sequence is applied to a decimator, which keeps only the first chip out of every sixty-four consecutive PN chips. The symbol rate from the decimator is 19.2 ksps. The data scrambling is performed by modulo-2 addition of the interleaver output with the decimator output symbol as shown in Figure 11.14.

11.4.2.5 Power Control Subchannel

To minimize the average BER for each user, IS-95 strives to force each user to provide the same power level at the base station receiver. The base station reverse traffic channel receiver estimates and responds to the signal strength (actually, the signal strength and the interference) for a particular mobile station. Since both the signal and interference are continually varying, power control updates are sent by the base station every 1.25 ms. Power control commands are sent to each subscriber unit on the forward control subchannel which instruct the mobile to raise or lower its transmitted power in 1 dB steps. If the received signal is low, a '0' is transmitted over the power control subchannel, thereby instructing the mobile station to increase its mean output power level. If the mobile's power is high, a '1' is transmitted to indicate that the mobile station should decrease its power level. The power control bit corresponds to two modulation symbols on the forward traffic channel. Power control bits are inserted after data scrambling as shown in Figure 11.16.

Power control bits are transmitted by using puncturing techniques [TIA93]. During a 1.25 ms period, twenty-four data symbols are transmitted, and IS-95 specifies sixteen possible power control group positions for the power control bit. Each position corresponds to one of the first sixteen modulation symbols. Twenty-four bits from the long code decimator are used for data scrambling in a period of 1.25 ms. Only the last 4 bits of the 24 bits are used to determine the position of the power control bit. In the example shown in Figure 11.16, the last 4 bits (23, 22, 21, and 20) are '1011' (11 decimal), and the power control bit consequently starts in position eleven.

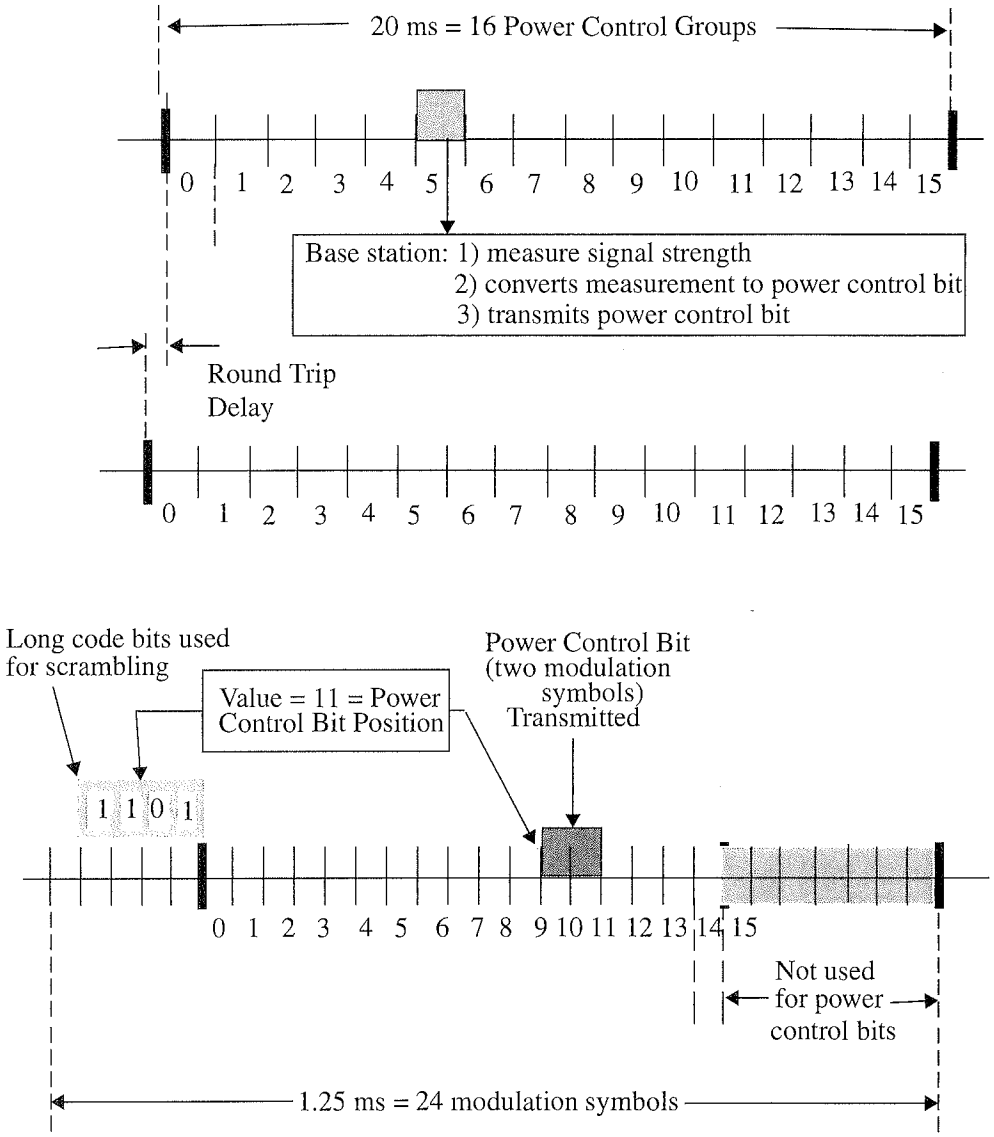


Figure 11.16 Randomization of power control bit positions in a IS-95 forward traffic channel.

11.4.2.6 Orthogonal Covering

Orthogonal covering is performed following the data scrambling on the forward link. Each traffic channel transmitted on the forward CDMA channel is spread with a Walsh function at a fixed chip rate of 1.2288 Mcps. The Walsh functions comprise of sixty-four binary sequences, each of length 64, which are completely orthogonal to each other and provide orthogonal channelization for all users on the forward link. A user that is spread using Walsh function n is assigned channel number n (n = 0 to 63). The Walsh sequence repeats every 52.083 μs, which is equal to one coded data symbol. In other words, each data symbol is spread by 64 Walsh chips.

References

[Abe70] Abend, K. and Fritchman, B. D., "Statistical Detection for Communication Channels with Intersymbol Interference," *Proceedings of IEEE*, pp. 779–785, May 1970.

[Ald00] Aldridge, I., Analysis of Existing Wireless Communication Protocols, COMS E6998-5 Course Project taught by Prof. M. Lerner, Summer 2000, Columbia University, NY, USA, *http://www.columbia.edu/~ir94/wireless.html.*

[Aka87] Akaiwa, Y., and Nagata, Y., "Highly Efficient Digital Mobile Communications with a Linear Modulation Method," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 5, pp. 890–895, June 1987.

[Ake88] Akerberg, D., "Properties of a TDMA Picocellular Office Communication System," *IEEE Globecom*, pp. 1343–1349, December 1988.

[Ale82] Alexander, S. E., "Radio Propagation Within Buildings at 900 MHz," *Electronics Letters*, Vol. 18, No. 21, pp. 913–914, 1982.

[Ale86] Alexander, S. T., *Adaptive Signal Processing,* Springer-Verlag, 1986.

[Ame53] Ament, W. S., "Toward a Theory of Reflection by a Rough Surface," *Proceedings of the IRE*, Vol. 41, No. 1, pp. 142–146, January 1953.

[Amo80] Amoroso, F., "The Bandwidth of Digital Data Signals," *IEEE Communications Magazine*, pp. 13–24, November 1980.

[And94] Anderson, J. B., Rappaport, T. S., and Yoshida, S., "Propagation Measurements and Models for Wireless Communications Channels," *IEEE Communications Magazine*, November 1994.

[And98] Andrisano, O., Tralli, V., and Verdone, R., "Millimeter Waves for Short-range Multimedia Communication Systems," *Proceedings IEEE*, Vol. 86, pp. 1383–1401, July 1998.

[Anv91] Anvari, K., and Woo, D., "Susceptibility of p/4 DQPSK TDMA Channel to Receiver Impairments," *RF Design*, pp. 49–55, February 1991.

[ANS95] ANSI J-STD-008 - Personal Station-Base Compatibility Requirements for 1.8-2.0 GHz Code Division Multiple Access (CDMA) Personal Communication Systems, March 1995.

[Are01] Arensman, R., "Cutting the Cord," *Electronics Business Magazine*, pp 51–60, June 2001.

[Ash93] Ashitey, D., Sheikh, A., and Murthy, K. M. S., "Intelligent Personal Communication System," 43*rd IEEE Vehicular Technology Conference*, pp. 696–699, 1993.

[Ata86] Atal, B. S., "High Quality Speech at Low Bit Rates: Multi-pulse and Stochastically Excited Linear Predictive Coders," *Proceedings of ICASSP*, pp. 1681–1684, 1986.

[Bay73] Bayless, J.W., et al., "Voice Signals: Bit-by-bit," *IEEE Spectrum*, pp. 28–34, October 1973.

[Bel62] Bello, P. A., and Nelin, B. D., "The Influence of Fading Spectrum on the Binary Error Probabilities of Incoherent and Differentially Coherent Matched Filter Receivers," *IRE Transactions on Communication Systems*, Vol. CS-10, pp. 160–168, June 1962.

[Bel79] Belfiori, C. A., and Park, J. H., "Decision Feedback Equalization," *Proceedings of IEEE*, Vol. 67, pp. 1143–1156, August 1979.

[Ber87] Bernhardt, R. C., "Macroscopic Diversity in Frequency Reuse Systems," *IEEE Journal on Selected Areas in Communications*, Vol-SAC 5, pp. 862–878, June 1987.

[Ber89] Bernhardt, R. C., "The Effect of Path Loss Models on the Simulated Performance of Portable Radio Systems," *IEEE Globecom*, pp. 1356–1360, 1989.

[Ber92] Bertsekas, D., and Gallager R., *Data Networks*, 2nd edition, Prentice Hall, Englewood Cliffs, NJ, 1992.

[Ber93] Berrou, C., Glavieux, A., and Thitimajshima, P., "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo Codes," *IEEE International Communication Conference (ICC)*, Geneva, May 1993, pp. 1064–1070.

[Bie77] Bierman, G. J., *Factorization Method for Discrete Sequential Estimation*, Academic Press, New York, 1977.

[Bin88] Bingham, J. A. C., *The Theory and Practice of Modem Design*, John Wiley & Sons, New York, 1988.

[Boi87] Boithias, L., *Radio Wave Propagation*, McGraw-Hill Inc., New York, 1987.

[Bos60] Bose, R. C., and Ray-Chaudhuri, D. K., "On a Class of Error Correcting Binary Group Codes," *Information and Control*, Vol. 3, pp. 68–70, March 1960.

[Bou88] Boucher, J. R., *Voice Teletraffic Systems Engineering*, Artech House, c. 1988.

[Bou91] Boucher, N., *Cellular Radio Handbook*, Quantum Publishing, c. 1991.

[Boy90] Boyles, S. M., Corn, R. L., and Moseley, L. R., "Common Channel Signaling: The Nexus of an Advanced Communications Network," *IEEE Communications Magazine*, pp. 57–63, July 1990.

[Bra68] Brady, P. T., "A Statistical Analysis of On-Off Patterns in 16 Conversations," *Bell System Technical Journal,* Vol. 47, pp. 73–91, 1968.

[Bra70] Brady, D. M., "An Adaptive Coherent Diversity Receiver for Data Transmission through Dispersive Media," *Proceedings of IEEE International Conference on Communications*, pp. 21–35, June 1970.

[Bra00] Braley, R. C., Gifford, I. C., and Heile, R. F., "Wireless Personal Area Networks: An Overview of the IEEE P802.15 Working Group," *ACM Mobile Computing and Communications Review*, Vol. 4, No. 1, p. 20–27, Feb. 2000.

[Buc00] Buckley, S., "3G Wireless: Mobility Scales new Heights," Telecommunications Magazine, November 2000.

[Bul47] Bullington, K., "Radio Propagation at Frequencies above 30 Megacycles," *Proceedings of the IEEE*, 35, pp. 1122–1136, 1947.

[Bul89] Bultitude, R. J. C., and Bedal, G. K., "Propagation Characteristics on Microcellular Urban Mobile Radio Channels at 910 MHz," *IEEE Journal on Selected Areas in Communications*, Vol. 7, pp. 31–39, January 1989.

[Cal88] Calhoun, G., *Digital Cellular Radio,* Artech House Inc., 1988.

[Cat69] Cattermole, K. W., *Principles of Pulse-Code Modulation*, Elsevier, New York, 1969.

[CCI86] Radio Paging Code No. 1, *The Book of the CCIR*, RCSG, 1986.

[Chu87] Chuang, J., "The Effects of Time Delay Spread on Portable Communications Channels with Digital Modulation," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 5, pp. 879–889, June 1987.

[Cla68] Clarke, R. H., "A Statistical Theory of Mobile-Radio Reception," *Bell Systems Technical Journal,* Vol. 47, pp. 957–1000, 1968.

[Col89] Coleman, A., et al., "Subjective Performance Evaluation of the REP-LTP Codec for the Pan-European Cellular Digital Mobile Radio System," *Proceedings of ICASSP*, pp. 1075–1079, 1989.

[Coo86a] Cooper, G. R., and McGillem, C. D., *Probabilistic Methods of Signal and System Analysis*, Holt, Rinehart, and Winston, New York, 1986.

[Coo86b] Cooper, G. R., and McGillem, C. D., *Modern Communications and Spread Spectrum*, McGraw Hill, New York, 1986.

[Cor97] Correia, L., and Prasad, R., "An Overview of Wireless Broadband Communications," *IEEE Communications Magazine*, pp. 28–33, January 1997.

[Cou93] Couch, L. W., *Digital and Analog Communication Systems*, 4th edition, Macmillan, New York, 1993.

[Cou98] Coulson, A. J., Williamson, A. G., and Vaughan, R. G., "A Statistical Basis for Log-Normal Shadowing Effects in Multipath Fading Channels," *IEEE Transactions on Communications*, Vol 46, pp. 494–502, April 1998.

[Cox72] Cox, D. C., "Delay Doppler Characteristics of Multipath Delay Spread and Average Excess Delay for 910 MHz Urban Mobile Radio Paths," *IEEE Transactions on Antennas and Propagation*, Vol. AP-20, No. 5, pp. 625–635, September 1972.

[Cox75] Cox, D. C., and Leck, R. P., "Distributions of Multipath Delay Spread and Average Excess Delay for 910 MHz Urban Mobile Radio Paths," *IEEE Transactions on Antennas and Propagation*, Vol. AP-23, No.5, pp. 206–213, March 1975.

[Cox83a] Cox, D. C., "Antenna Diversity Performance in Mitigating the Effects of Portable Radiotelephone Orientation and Multipath Propagation," *IEEE Transactions on Communications*, Vol. COM-31, No. 5, pp. 620–628, May 1983.

[Cox83b] Cox, D. C., Murray, R. R., and Norris, A. W., "Measurements of 800 MHz Radio Transmission into Buildings with Metallic Walls," *Bell Systems Technical Journal,* Vol. 62, No. 9, pp. 2695–2717, November 1983.

[Cox84] Cox, D. C., Murray, R., and Norris, A., "800 MHz Attenuation Measured in and around Suburban Houses," *AT&T Bell Laboratory Technical Journal*, Vol. 673, No. 6, July–August 1984.

[Cox87] Cox, D. C., Arnold, W., and Porter, P. T., "Universal Digital Portable Communications: A System Perspective," *IEEE Journal on Selected Areas of Communications,* Vol. SAC-5, No. 5, pp. 764, 1987.

[Cox89] Cox, D. C., "Portable Digital Radio Communication—An Approach to Tetherless Access," *IEEE Communication Magazine,* pp. 30–40, July 1989.

[Cox92] Cox D. C., "Wireless Network Access for Personal Communications," *IEEE Communications Magazine*, pp. 96–114, December 1992.

[Cro76] Crochiere R. E., et al., "Digital Coding of Speech in Sub-bands," *Bell Systems Technical Journal*, Vol. 55, No. 8, pp. 1069–1085, October 1976.

[Cro89] Crozier, S. N., Falconer, D. D., and Mahmoud, S., "Short Block Equalization Techniques Employing Channel Estimation for Fading, Time Dispersive Channels," *IEEE Vehicular Technology Conference*, San Francisco, pp. 142–146, 1989.

[CTI93] Cellular Telphone Industry Association, *Cellular Digital Packet Data System Specification*, Release 1.0, July 1993.

[Dad75] Dadson, C. E., Durkin, J., and Martin, E., "Computer Prediction of Field Strength in the Planning of Radio Systems," *IEEE Transactions on Vehicular Technology*, Vol. VT-24, No. 1, pp. 1–7, February 1975.

[deB72] deBuda, R., "Coherent Demodulation of Frequency Shift Keying with Low Deviation Ratio," *IEEE Transactions on Communications*, Vol. COM-20, pp. 466–470, June 1972.

[Dec93] Dechaux, C., and Scheller, R., "What are GSM and DECT?" *Electrical Communication*, pp. 118–127, 2nd quarter, 1993.

[Del93] Deller, J. R., Proakis, J. G., and Hansen, J. H. L., *Discrete-time Processing of Speech Signals*, Macmillan Publishing Company, New York, 1993.

[DeR94] DeRose, J. F., *The Wireless Data Handbook*, Quantum Publishing, Inc., 1994.

[Det89] Dettmer, R., "Parts of a Speech transcoder for CT2," *IEE Review*, September 1989.

[Dev86] Devasirvatham, D. M. J., "Time Delay Spread and Signal Level Measurements of 850 MHz Radio Waves in Building Environments," *IEEE Transactions on Antennas and Propagation*, Vol. AP-34, No. 2, pp. 1300–1305, November 1986.

[Dev90a] Devasirvatham, D. J., Krain, M. J., and Rappaport, D. A., "Radio Propagation Measurements at 850 MHz, 1.7 GHz, and 4.0 GHz Inside Two Dissimilar Office Buildings," *Electronics Letters*, Vol. 26, No. 7, pp. 445–447, 1990.

[Dev90b] Devasirvatham, D. M. J., Banerjee, C., Krain, M. J., and Rappaport, D. A., "Multi-Frequency Radiowave Propagation Measurements in the Portable Radio Environment," *IEEE International Conference on Communications*, pp. 1334–1340, 1990.

[Dey66] Deygout J., "Multiple Knife-edge Diffraction of Microwaves," *IEEE Transactions on Antennas and Propagation*, Vol. AP-14, No. 4, pp. 480–489, 1966.

[Dix84] Dixon, R. C., *Spread Spectrum Systems*, 2nd Edition, John Wiley and Sons, New York, 1984.

[Dix94] Dixon, R. C., *Spread Spectrum Systems with Commercial Applications*, 3rd Edition, John Wiley & Sons Inc., New York, 1994.

[Don93] Donaldson, R. W., "Internetworking of Wireless Communication Networks," *Proceedings of the IEEE*, pp. 96–103, 1993.

[Dur73] Durante, J. M., "Building Penetration Loss at 900 MHz," *IEEE Vehicular Technology Conference*, 1973.

[Dur98] Durgin, G. D., Rappaport, T. S., and Xu, H., "Measurements and Models for Radio Path Loss and Penetration Loss in and Around Homes and Trees at 5.8 GHz," *IEEE Transactions on Communication*, Vol. 46, No. 11, pp. 1484–1496, November 1998.

[Dur98a] Durgin, G. D., and Rappaport, T. S., "A Basic Relationship Between Multipath Angular Spread and Narrow-Band Fading in a Wireless Channel," *IEE Electronics Letters*, Vol. 34, pp. 2431–2432, December 1998.

[Dur98b] Durgin, G. D., Rappaport, T. S., and Xu, H., "Radio Path Loss and Penetration Loss Measurements in and around Homes and Trees at 5.85 GHz," 1998 AP-S International Symposium, Atlanta, GA, pp. 618–634, June 21–26, 1998.

[Dur99] Durgin, G. D., and Rappaport, T. S., "Three Parameters for Relating Small-Scale Temporal Fading to Multipath Angles-of-Arrival," *PIMRC'99*, Osaka, Japan, September 1999, pp. 1077–1081.

[Dur99a] Durgin, G. D., and Rappaport, T. S., "Effects of Multipath Angular Spread on the Spatial Cross-Correlation of Received Volatage Envelopes," *IEEE Vehicular Technology Conference*, Houston, TX, May 1999, Vol. 2, pp. 996–1000.

[Dur99b] Durgin, G. D., and Rappaport, T. S., " Level Crossing Rates and Average Fade Duration of Wireless Channels with Spatially Complicated Multipath," Globecom'99, Brazil, December 1999, pp. 427–431.

[Dur00] Durgin, G. D., and Rappaport, T. S., "Theory of Multipath Shape Factors for Small-Scale Fading Wireless Channels," *IEEE Transactions on Antennas and Propagation*, Vol. 48, No. 5, pp. 682–693, May 2000.

[Ebi91] Ebine, Y., Takahashi, T., and Yamada, Y., "A Study of Vertical Space Diversity for a Land Mobile Radio," *Electronics Communication Japan*, Vol. 74, No. 10, pp. 68–76, 1991.

[Edw69] Edwards, R., and Durkin, J., "Computer Prediction of Service Area for VHF Mobile Radio Networks," *Proceedings of the IEE*, Vol. 116, No. 9, pp. 1493–1500, 1969.

[EIA90] EIA/TIA Interim Standard, "Cellular System Dual Mode Mobile Station—Land Station Compatibility Specifications," IS-54, *Electronic Industries Association*, May 1990.

[EIA91] EIA/TIA Interim Standard, "Cellular System Mobile Station—Land Station Compatibility Specification IS-88," Rev. A, November 1991.

[EIA92] "TR 45: Mobile Station - Base Station Compatibility Standard for Dual-mode Wideband Spread Spectrum Cellular System," PN-3118, *Electronics Industry Association*, December 1992.

[Eng93] Eng, T., and Milstein, L. B., "Capacities of Hybrid FDMA/CDMA Systems in Multipath Fading," *IEEE MILCOM Conference Records*, pp. 753–757, 1993.

[Eps53] Epstein, J., and Peterson, D. W., "An Experimental Study of Wave Propagation at 840 M/C," *Proceedings of the IRE*, 41, No. 5, pp. 595–611, 1953.

[Ert98] Ertel, R., Cardieri, P., Sowerby, K. W., Rappaport, T. S., and Reed, J. H., "Overview of Spatial Channel Models for Antenna Array Communication Systems," *Special Issue: IEEE Personal Communications*, Vol. 5, No. 1, pp.10–22, February 1998.

[Est77] Estaban, D., and Galand, C., "Application of Quadrature Mirror Filters to Split Band Voice Coding Schemes," *Proceedings of ICASSP*, pp. 191–195, May 1977.

[EUR91] European Cooperation in the Field of Scientific and Technical Research EURO-COST 231, "Urban Transmission Loss Models for Mobile Radio in the 900 and 1800 MHz Bands," Revision 2, The Hague, September 1991.

[Fan63] Fano, R. M., "A Heuristic Discussion of Probabilistic Coding," *IEEE Transactions on Information Theory*, Vol. IT-9, pp. 64–74, April 1963.

[FCC91] *FCC Notice of Inquiry for Reframing Spectrum below 470 MHz*, PLMR docket 91–170, November 1991.

[Feh91] Feher, K., "Modems for Emerging Digital Cellular Mobile Radio Systems," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 2, pp. 355–365, May 1991.

[Feu94] Feuerstein, M. J., Blackard, K. L., Rappaport, T. S., Seidel, S. Y., and Xia, H. H., "Path Loss, Delay Spread, and Outage Models as Functions of Antenna Height for Microcellular System Design," *IEEE Transactions on Vehicular Technology*, Vol. 43, No. 3, pp. 487–498, August 1994.

[Fil95] Filiey, G. B., and Poulsen, P. B., "MIRS Technology: On the Fast Track to Making the Virtual Office a Reality," *Communications*, pp. 34–39, January 1995.

[Fla79] Flanagan, J. L., et al., "Speech Coding," *IEEE Transactions on Communications*, Vol. COM-27, No. 4, pp. 710–735, April 1979.

[For78] Forney, G. D., "The Viterbi Algorithm," *Proceedings of the IEEE*, Vol. 61, No. 3, pp. 268–278, March 1973.

[Fuh97] Fuhl, J., Rossi, J.-P., and Bonek, E., "High-Resolution 3-D Direction-of-Arrival Determination for Urban mobile Radio," *IEEE Transactions on Antennas and Propagation*, Vol. 45, pp. 672–682, April 1997.

[Ful98] Fulghum, T. and Molnar, K., "The Jakes Fading Model Incorporating Angular Spread for a Disk of Scatterers," *IEEE Vehicular Technology Conference*, Ottawa, Canada, May 1998, pp. 489–493.

[Fun93] Fung, V., Rappaport, T. S., and Thoma, B., "Bit Error Simulation for π/4 DQPSK Mobile Radio Communication Using Two-ray and Measurement-based Impulse Response Models," *IEEE Journal on Selected Areas in Communication,* Vol. 11, No. 3, pp. 393–405, April 1993.

[Gan72] Gans, M. J., "A Power Spectral Theory of Propagation in the Mobile Radio Environment," *IEEE Transactions on Vehicular Technology,* Vol. VT-21, pp. 27–38, February 1972.

[Gar91] Gardner, W. A., "Exploitation of Spectral Redundancy in Cyclostationary Signals," *IEEE Signal Processing Magazine*, pp. 14–36, April 1991.

[Gar95] Gardner, W., QUALCOMM Inc., personal correspondence, June 1995.

[Gar99] Garg, V. K. and Wilkes, J. E., *Principles & Applications of GSM*, Prentice Hall, Upper Saddle River NJ, 1999.

[Gar00] Garg, V. K., *IS-95 CDMA and cdma2000*, Prentice Hall, Upper Saddle River, NJ, 2000.

[Ger82] Geraniotis, E. A., and Pursley, M. B., "Error Probabilities for Slow Frequency-Hopped Spread Spectrum Multiple-Access Communications Over Fading Channels," *IEEE Transactions on Communications,* Vol. COM-30, No. 5, pp. 996–1009, May 1982.

[Ger90] Gerson, I. A., and Jasiuk, M. A., "Vector Sum Excited Linear Prediction (VSELP): Speech Coding at 8 kbps," *Proceedings of ICASSP*, pp. 461–464, 1990.

[Gil91] Gilhousen, et al., "On the Capacity of Cellular CDMA System," *IEEE Transactions on Vehicular Technology,* Vol. 40, No. 2, pp. 303–311, May 1991.

[Git81] Gitlin, R. D., and Weinstein, S. B., "Fractionally Spaced Equalization: An Improved Digital Transversal Filter," *Bell Systems Technical Journal*, Vol. 60, pp. 275–296, February 1981.

[Gol49] Golay, M. J. E., "Notes on Digital Coding," *Proceedings of the IRE*, Vol. 37, p. 657, June 1949.

[Goo89] Goodman, D. J., Valenzula, R.A., Gayliard, K.T., and Ramamurthi, B., "Packet Reservation Multiple Access for Local Wireless Communication," *IEEE Transactions on Communications*, Vol. 37, No. 8, pp. 885–890, August 1989.

[Goo90] Goodman, D. J., "Cellular Packet Communications," *IEEE Transactions on Communications*, Vol. 38, No. 8, pp. 1272–1280, August 1990.

[Goo91] Goodman, D. J., "Trends in Cellular and Cordless Communications," *IEEE Communications Magazine*, pp. 31–39, June 1991.

[Gos78] Gosling, W., McGeehan, J. P., and Holland, P. G., "Receivers for the Wolfson SSB/VHF Land Mobile Radio System," *Proceedings of IERE Conference on Radio Receivers and Associated Systems*, Southampton, England, pp. 169–178, July 1978.

[Gow93] Gowd, K., et al., "Robust Speech Coding for Indoor Wireless Channel," *AT&T Technical Journal*, Vol. 72, No. 4, pp. 64–73, July/August 1993.

[Gra84] Gray, R. M., "Vector Quantization," *IEEE ASSP Magazine*, pp. 4–29, April 1984.

[Gri87] Griffiths, J., *Radio Wave Propagation and Antennas*, Prentice Hall International, 1987.

[Gud92] Gudmundson, B., Skold, J., and Ugland, J. K, "A Comparison of CDMA and TDMA systems," *Proceedings of the 42nd IEEE Vehicular Technology Conference*, Vol. 2, pp. 732–735, 1992.

[Ham50] Hamming, R. W., "Error Detecting and Error Correcting Codes," *Bell System Technical Journal*, April 1950.

[Has93] Hashemi, H., "The Indoor Radio Propagation Channel," *Proceedings of the IEEE,* Vol. 81, No. 7, pp. 943–968, July 1993.

[Hat90] Hata, Masaharu, "Empirical Formula for Propagation Loss in Land Mobile Radio Services," *IEEE Transactions on Vehicular Technology,* Vol. VT-29, No. 3, pp. 317–325, August 1980.

[Haw91] Hawbaker, D. A., *Indoor Wideband Radio Wave Propagation Measurements and Models at 1.3 GHz and 4.0 GHz*, Masters Thesis, Virginia Tech, Blacksburg, VA, May 1991.

[Hay86] Haykin, S., *Adaptive Filter Theory*, Prentice Hall, Englewood Cliffs, NJ, 1986.

[Hay94] Haykin, S., *Communication Systems*, John Wiley and Sons, New York, 1994.

[Hel89] Hellwig, K., Vary P., Massaloux, D., Petit, J. P., Galand, C., and Rasso, M., "Speech Codec for the European Mobile Radio Systems," *IEEE Global Telecommunication Conference & Exhibition,* Vol. 2, pp. 1065–1069, 1989.

[Hen01] Henty, B., "Throughput Measurements and Empirical Prediction Models for IEEE 802.11b Wireless LAN (WLAN) Installations," Masters Thesis, Virginia Tech, Blacksburg, VA, August 2001

[Ho94] Ho, P., Rappaport, T. S., and Koushik, M. P., "Antenna Effects on Indoor Obstructed Wireless Channels and a Deterministic Image-Based Wide-Band Propagation Model for In-Building Personal Communication Systems," *International Journal of Wireless Information Networks*, Vol. 1, No. 1, pp. 61–75, January 1994.

[Hod90] Hodges, M. R. L., "The GSM Radio Interface," *British Telecom Technological Journal,* Vol. 8, No. 1, pp. 31–43, January 1990.

[Hol92] Holtzman, J. M., "A Simple, Accurate Method to Calculate Spread-Spectrum Multiple-Access Error Probabilities," *IEEE Transactions on Communications*, Vol. 40, No. 3, March 1992.

[Hor86] Horikishi, J., et al., "1.2 GHz Band Wave Propagation Measurements in Concrete Buildings for Indoor Radio Communications," *IEEE Transactions on Vehicular Technology*, Vol. VT-35, No. 4, 1986.

[Hua91] Huang, W., "*Simulation of Adaptive Equalization in Two-Ray, SIRCIM and SMRCIM Mobile Radio Channels,*" Masters Thesis in Electrical Engineering, Virginia Tech, December 1991.

[IEE91] "Special Issue on Satellite Communications Systems and Services for Travelers," *IEEE Communications Magazine*, November 1991.

[Ish80] Ishizuka, M., and Hirade, K., "Optimum Gaussian filter and Deviated-Frequency-Locking Scheme for Coherent Detection of MSK," *IEEE Transactions on Communications*, Vol. COM-28, No.6, pp. 850–857, June 1980.

[ITU93] *ITU World Telecommunications Report*, December 1993.

[ITU94] *ITU Documents of TG8/1 (FPLMTS),* International Telecommunications Union, Radiocommunications Sector, Geneva, 1994.

[Jac94] Jacobsmeyer, J., "Improving Throughput and Availability of Cellular Digital Packet Data (CDPD)," *Proc. Virginia Tech 4th Symposium on Wireless Personal Communications*, pp. 18.1–18.12, June 1994.

[Jak70] Jakes, W. C., "New Techniques for Mobile Radio," *Bell Laboratory Rec.,* pp. 326–330, December 1970.

[Jak71] Jakes, W. C., "A Comparison of Specific Space Diversity Techniques for Reduction of Fast Fading in UHF Mobile Radio Systems," *IEEE Transactions on Vehicular Technology*, Vol. VT-20, No. 4, pp. 81–93, November 1971.

[Jak74] Jakes, W. C. Jr., *Microwave Mobile Communications*, Wiley-Interscience, 1974.

[Jay84] Jayant, N. S., Noll, P., *Digital Coding of Waveforms*, Prentice Hall, Englewood Cliffs, NJ, 1984.

[Jay86] Jayant, N. S., "Coding Speech at Low Bit Rates," *IEEE Spectrum*, pp. 58–63, August 1986.

[Jay90] Jayant, N. S., "High Quality Coding of Telephone Speech and Wideband Audio," *IEEE Communications Magazine*, pp. 10–19, January 1990.

[Jay92] Jayant, N. S., "Signal Compression: Technology, Targets, and Research Directions," *IEEE Journal on Selected Areas of Communications*, Vol. 10, No. 5, pp. 796–815, June 1992.

[Jen98] Jeng, S.-S., Xu, G., Lin, H.-P., and Vogel, W., J., "Experimental Studies of Spatial Signature Variation at 900 MHz for Smart Antenna Systems," *IEEE Transactions on Antennas and Propagation*, Vol. 46, pp. 953–962, July 1998.

[Joh82] Johnson, L. W., and Riess, R. D., *Numerical Analysis*, Addison-Wesley, 1982.

[JTC95] JTC Standards Project 066: "Baseline Text for TAG #3 PACS - UB," Motorola Inc., February 1995.

[Kah54] Kahn, L., "Ratio Squarer," *Proceedings of IRE (Correspondence)*, Vol. 42, pp. 1074, November 1954.

[Kim00] Kim, K. I., Ed., *Handbook of CDMA System Design, Engineering, and Optimization*, Prentice Hall, Upper Saddle River, NJ, 2000.

[Kle75] Kleinrock, L., and Tobagi, F. A., "Packet Switching in Radio Channels, Part 1: Carrier Sense Multiple-Access Models and Their Throughput-Delay Characteristics," *IEEE Transactions on Communications*, Vol. 23, No. 5, pp. 1400–1416, 1975.

[Kor85] Korn, I., *Digital Communications*, Van Nostrand Reinhold, 1985.

[Koz85] Kozono, S., et al., "Base Station Polarization Diversity Reception for Mobile Radio," *IEEE Transactions on Vehicular Technology*, Vol. VT-33, No. 4, pp. 301–306, November 1985.

[Kra50] Krauss, J. D., *Antennas*, McGraw-Hill, New York, 1950.

[Kre94] Kreuzgruber, P., et al., "Prediction of Indoor Radio Propagation with the Ray Splitting Model Including Edge Diffraction and Rough Surfaces," *1994 IEEE Vehicular Technology Conference*, Stockholm, Sweden, pp. 878–882, June 1994.

[Kuc91] Kucar, A. D., "Mobile Radio—An Overview," *IEEE Communications Magazine*, pp. 72–85, November 1991.

[Lam80] Lam, S. S., "A Carrier Sense Multiple Access Protocol for Local Networks," *Computer Networks*, Vol. 4, pp. 21–32, 1980.

[Lan96] Landron, O., Feuerstein, M. J., and Rappaport, T. S., "A Comparison of Theoretical and Empirical Reflection Coefficients for Typical Exterior Wall Surfaces in a Mobile Radio Environment," *IEEE Transactions on Antennas and Propagation*, Vol. 44, No. 3, pp. 341–351, March 1996.

[Lee72] Lee, W. C. Y., and Yeh, S. Y., "Polarization Diversity System for Mobile Radio," *IEEE Transactions on Communications*, Vol. 20, pp. 912–922, October 1972.

[Lee85] Lee, W. C. Y., *Mobile Communications Engineering*, McGraw Hill Publications, New York, 1985.

[Lee86] Lee, W. C. Y., "Elements of Cellular Mobile Radio systems," *IEEE Transactions on Vehicular Technology*, Vol. VT-35, No. 2, pp. 48–56, May 1986.

[Lee89a] Lee, W. C. Y., "Spectrum Efficiency in Cellular," *IEEE Transactions on Vehicular Technology*, Vol. 38, No. 2, pp. 69–75, May 1989.

[Lee89b] Lee, W. C. Y., *Mobile Cellular Telecommunications Systems*, McGraw Hill Publications, New York, 1989.

[Lee91a] Lee, W. C. Y., "Overview of Cellular CDMA," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 2, May 1991.

[Lee91b] Lee, W. C. Y., "Smaller Cells for Greater Performance," *IEEE Communications Magazine*, pp. 19–23, November 1991.

[Leh87] Lehnert, J. S., and Pursley, M. B., "Error Probabilities for Binary Direct-Sequence Spread-Spectrum Communications with Random Signature Sequences," *IEEE Transactions on Communications,* Vol. COM-35, No. 1, January 1987.

[Lem91] Lemieux, J. F., Tanany, M., and Hafez, H. M., "Experimental Evaluation of Space/Frequency/Polarization Diversity in the Indoor Wireless Channel," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 3, pp. 569–574, August 1991.

[Li93] Li, Y., *Bit Error Rate Simulation of a CDMA System for Personal Communications*, Masters Thesis in Electrical Engineering, Virginia Tech, 1993.

[LiC93] I., C.-L., Greenstein L. J., and Gitlin R.D., "A Microcell/Macrocell Cellular Architecture for Low- and High Mobility Wireless Users," *IEEE Vehicular Technology Transactions,* pp. 885–891, August 1993.

[Lib94a] Liberti, J. C., Jr., "CDMA Cellular Communication Systems Employing Adaptive Antennas," *Preliminary Draft of Research Including Literature Review and Summary of Work-in-Progress*, Virginia Tech, March 1994.

[Lib94b] Liberti, J. C. Jr., and Rappaport, T. S., "Analytical Results for Capacity Improvements in CDMA," *IEEE Transactions on Vehicular Technology,* Vol. 43, No. 3, pp. 680–690, August 1994.

[Lib95] Liberti, J. C. Jr., *Analysis of Code Division Multiple Access Mobile Radio Systems with Adapative Antennas,* Ph.D. Dissertation, Virginia Tech, Blacksburg, August, 1995.

[Lib99] Liberti, J. C. and Rappaport, T. S., *Smart Antennas for Wireless Communications: IS-95 and Third Generation Applications*, Prentice Hall, Upper Saddle River, NJ, 1999.

[Lin83] Lin, S., and Costello, D. J. Jr., *Error Control Coding: Fundamentals and Applications*, Prentice Hall, Englewood Cliffs, NJ, 1983.

[Lin84] Ling, F., and Proakis, J. G., "Nonstationary Learning Characteristics of Least Squares Adaptive Estimation Algorithms," *Proceedings ICASSP84*, San Diego, California, pp. 3.7.1–3.7.4, 1984.

[Liu89] Liu, C. L., and Feher, K., "Noncoherent Detection of p/4-Shifted Systems in a CCI-AWGN Combined Interference Environment," *Proceedings of the IEEE 40th Vehicular Technology Conference*, San Fransisco, 1989.

[Liu91] Liu, C., and Feher, K., "Bit Error Rate Performance of p/4 DQPSK in a Frequency Selective Fast Rayleigh Fading Channel," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 3, pp. 558–568, August 1991.

[Lo90] Lo, N. K. W., Falconer, D. D., and Sheikh, A. U. H., "Adaptive Equalization and Diversity Combining for a Mobile Radio Channel," *IEEE Globecom*, San Diego, December 1990.

[Lon68] Longley, A G., and Rice, P. L., "Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain; A Computer Method," *ESSA Technical Rep*ort, ERL 79-ITS 67, 1968.

[Lon78] Longley, A. G., "Radio Propagation in Urban Areas," *OT Report*, pp. 78-144, April 1978.

[Luc65] Lucky, R. W., "Automatic Equalization for Digital Communication," *Bell System Technical Journal*, Vol. 44, pp. 547–588, 1965.

[Luc89] Lucky, R. W., *Silicon Dreams: Information, Man and Machine*, St. Martin Press, New York, 1989.

[Lus78] Lusignan, B. B., "Single-sideband Transmission for Land Mobile Radio," *IEEE Spectrum*, pp. 33–37, July 1978.

[Mac79] MacDonald, V. H., "The Cellular Concept," *The Bell Systems Technical Journal*, Vol. 58, No. 1, pp. 15–43, January 1979.

[Mac93] Maciel, L. R., Bertoni, H. L., and Xia, H. H., "Unified Approach to Prediction of Propagation Over Buildings for all Ranges of Base Station Antenna Height," *IEEE Transactions on Vehicular Technology*, Vol. 42, No. 1, pp. 41–45, February 1993.

[Mak75] Makhoul, J., "Linear Prediction: A Tutorial Review," *Proceedings of IEEE*, Vol. 63, pp. 561–580, April 1975.

[Mal89] Maloberti, A., "Radio Transmission Interface of the Digital Pan European Mobile System," *IEEE Vehicular Technology Conference*, Orlando, FL, pp. 712–717, May 1989.

[Mal92] Malyan, A. D., Ng, L. J., Leung, V. C. M., and Donaldson, R. W., "A Microcellular Interconnection Architecture for Personal Communication Networks," *Proceedings of IEEE Vehicular Technology Conference*, pp. 502–505, May 1992.

[Man93] Mansfield, D. R., Millsteed, G., and Zukerman, M., "Congestion Controls in SS7 Signaling Networks," *IEEE Communications Magazine*, pp. 50–57, June 1993.

[Mar90] Marr, F. K., "Signaling System No.7 in Corporate Networks," *IEEE Communications Magazine*, pp. 72–77, July 1990.

[Max60] Max, J., "Quantizing for Minimizing Distortion," *IRE Transactions on Information Theory*, March 1960.

[McG84] McGeehan, J. P., and Bateman, A. J., "Phase Locked Transparent Tone-in-band (TTIB): A New Spectrum Configuration Particularly Suited to the Transmission of Data over SSB Mobile Radio Networks," *IEEE Transactions on Communications*, Vol. COM-32, No. 1, pp. 81–87, January 1984.

[Mei92] Meier-Hellstern, K. S., Pollini, G. P., and Goodman, D., "Network Protocols for the Cellular Packet Switch," *Proceedings of IEEE Vehicular Technology Conference*, Vol. 2, No. 2, pp. 705–710, 1992.

[Mei93] Meier-Hellstern, K. S., et al., "The Use of SS7 and GSM to Support High Density Personal Communications," *Wireless Communications: Future Directions*, Kluwer Academic Publishing, 1993.

[Mil62] Millington, G., Hewitt, R., and Immirzi, F. S., "Double Knife-edge Diffraction in Field Strength Predictions," *Proceedings of the IEE*, 109C, pp. 419–429, 1962.

[Mod92] Modarressi, A. R., and Skoog, R. A., "An Overview of Signal System No.7," *Proceedings of the IEEE*, Vol. 80, No. 4, pp. 590–606, April 1992.

[Mol91] Molkdar, D., "Review on Radio Propagation into and Within Buildings," *IEE Proceedings*, Vol. 138, No. 1, pp. 61–73, February 1991.

[Mol01] Molisch, A. F., Ed., *Wideband Wireless Digital Communications*, Prentice-Hall, Upper Saddle River, NJ, 2001.

[Mon84] Monsen, P., "MMSE Equalization of Interference on Fading Diversity Channels," *IEEE Transactions on Communications*, Vol. COM-32, pp. 5–12, January 1984.

[Mor89a] Moralee, D., "CT2 a New Generation of Cordless Phones," *IEE Review*, pp. 177–180, May 1989.

[Mor89b] Morrow, R. K., Jr., and Lehnert, J. S., "Bit-to-bit Error Deprndence in Slotted DS/SSMA Packet Systems with Random signature Sequences," IEEE Transactions on Communications, Vol. 37, No. 10, October 1989.

[Mor00] Morrow, R. K., and Rappaport, T. S. "Getting In," *Wireless Review*, pp. 42–44, March 1, 2000, *http://www.wirelessreview.com/issues/2000/00301/feat24.htm*

[Mou92] Mouly, M., and Pautet, M. B., *The GSM System for Mobile Communication*, ISBN: 2-9507190-0-7, 1992.

[Mul91] Mulder, R. J., "DECT—A Universal Cordless Access System," *Philips Telecommunications Review*, Vol. 49, No. 3, pp. 68–73, September 1991.

[Mur81] Murota, K., and Hirade, K., "GMSK Modulation for Digital Mobile Radio Telephony," *IEEE Transactions on Communications*, Vol. COM-29, No. 7, pp. 1044–1050, July 1981.

[NAC94] North American Cellular Network, "*An NACN Standard,*" Rev. 2.0, December 1994.

[Nag96] Naguib, A. F., and Paulraj, A., "Performance of Wireless CDMA with M-ary Orthogonal Modulation and Cell Site Arrays," *IEEE Journal on Selected Areas of Communications*, Vol. 14, pp. 1770–1783, December 1996.

[Nar90] Narasimhan, A., Chennakeshu, S., and Anderson, J. B., "An Adaptive Lattice Decision Equalizer for Digital Cellular Radio," *IEEE 40th Vehicular Technology Conference*, pp. 662–667, May 1990.

[New96a] Newhall, W. G., Saldanha, K., and Rappaport, T. S., "Propagation Time Delay Spread Measurements at 915 MHz in a Large Train Yard," *IEEE Vehicular Technology Conference*, Atlanta, GA, April 29–May 1, 1996, pp. 864–868.

[New96b] Newhall, W. G., Rappaport, T. S., and Sweeney, D. G., "A Spread Spectrum Sliding Correlator System for Propagation Measurements," *RF Design*, pp. 40–54, April 1996.

[Nob62] Noble, D., "The History of Land-Mobile Radio Communications," *IEEE Vehicular Technology Transactions*, pp. 1406–1416, May 1962.

[Nuc99] Nucols, E., "Implementation of Geometrically Based Single-Bounce Models for Simulation of Angle-of-Arrival of Multipath Delay Components in the Wireless Channel Simulation Tools, SMRCIM and SIRCIM," Masters Thesis, Virginia Tech, Blacksburg, VA, December 1999.

[Noe01] Noel, Frederic, "Higher Data Rates in GSM/Edge with Multicarrier," Masters Thesis, Chalmers University of Technology, April 2001, Technical Report EX024/2001.

[Nyq28] Nyquist, H., "Certain Topics in Telegraph Transmission Theory," *Transactions of the AIEE*, Vol. 47, pp. 617–644, Febuary 1928.

[Och89] Ochsner, H., "DECT — Digital European Cordless Telecommunications," *IEEE Vehicular Technology 39th Conference*, pp. 718–721, 1989.

[Oet83] Oeting, J., "Cellular Mobile Radio—An Emerging Technology," *IEEE Communications Magazine*, pp. 10–15, November 1983.

[Oga94] Ogawa, K., et al., "Toward the Personal Communication Era - the Radio Access Concept from Japan," *International Journal on Wireless Information Networks,* Vol. 1, No. 1, pp. 17–27, January 1994.

[Oku68] Okumura, T., Ohmori, E., and Fukuda, K., "Field Strength and Its Variability in VHF and UHF Land Mobile Service," *Review Electrical Communication Laboratory*, Vol. 16, No. 9–10, pp. 825–873, September–October 1968.

[Oss64] Ossana, J. Jr., "A Model for Mobile Radio Fading due to Building Reflections: Theoretical and Experimental Fading Waveform Power Spectra," *Bell Systems Technical Journal*, Vol. 43, No. 6, pp. 2935–2971, November 1964.

[Owe91] Owen, F. C. and Pudney, C., "DECT: Integrated Services for Cordless Telecommunications," *IEE Conference Publications*, No. 315, pp. 152–156, 1991.

[Owe93] Owens, F. J., *Signal Processing of Speech*, McGraw Hill, New York, 1993.

[Pad94] Padovani, R., "Reverse Link Performance of IS-95 Based Cellular Systems," *IEEE Personal Communications*, pp. 28–34, 3rd quarter, 1994.

[Pad95] Padyett, J., Gunther, E., and Hattari, T., "Overview of Wireless Personal Communications," *IEEE Communications Magazine*, January 1995.

[Pah95] Pahlavan, K., and Levesque, A. H., *Wireless Information Networks*, Chapter 5, John Wiley & Sons, New York, 1995.

[Pap91] Papoulis, A., *Probability, Random Variables, and Stochastic Processes*, 3rd Edition, McGraw Hill, New York, 1991.

[Par76] Parsons, J. D., et al., "Diversity Techniques for Mobile Radio Reception," *IEEE Transactions on Vehicular Technology*, Vol. VT-25, No. 3, pp. 75–84, August 1976.

[Pas79] Pasupathy, S., "Minimum Shift Keying: A Spectrally Efficient Modulation," *IEEE Communications Magazine*, pp. 14–22, July 1979.

[Pat99] Patwari, N., Durgin, G. D., Rappaport, T. S., and Boyle, R. J., "Peer-to-Peer Low Antenna Outdoor Radio Wave Propagation at 1.8 GHz," *IEEE Vehicular Technology Conference*, Houston, TX, May 1999, Vol. 1, pp. 371–375.

[Pec92] Pecar, J. A., O'Conner, R. J., and Garbin, D. A., *Telecommunications Factbook*, McGraw Hill, New York, 1992.

[Per92] Personal Digital Cellular, Japanese Telecommunication System Standard, RCR STD 27.B, 1992.

[Per93] Personal Handy Phone System, Japanese Telecommunication System Standard, RCR-STD 28, December 1993.

[Pic91] Pickholtz, R. L., Milstein, L. B., and Schilling, D., "Spread Spectrum for Mobile Communications," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 2, pp. 313–322, May 1991.

[Pri58] Price, R., and Green, P. E., "A Communication Technique for Multipath Channel," *Proceedings of the IRE*, pp. 555–570, March 1958.

[Pro89] Proakis, J. G., *Digital Communications*, McGraw-Hill, New York, 1989.

[Pro91] Proakis, J., "Adaptive Equalization for TDMA Digital Mobile Radio," *IEEE Transactions on Vehicular Technology*,Vol. 40, No. 2, pp 333–341, May 1991.

[Pro94] Proakis, J. G., and Salehi, M., *Communication Systems Engineering*, Prentice Hall, 1994.

[Pur77] Pursley, M. B., Sarwate, D. V., and Stark, W. E., "Performance Evaluation for Phase-Coded Spread-Spectrum Multiple-Access Communication—Part II: Code Sequence Analysis," *IEEE Transactions on Communications*, Vol. COM-25, No. 8, August 1987.

[Qur77] Qureshi, S. U. H., and Forney, G. D., "Performance Properties of a T/2 Equalizer," *IEEE Globecom*, pp. 11.1.1–11.1.14, Los Angeles, CA, December 1977.

[Qur85] Qureshi, S. U. H., "Adaptive Equalization," *Proceeding of IEEE*, Vol. 37, No. 9, pp. 1340–1387, September, 1985.

[Rai91] Raith, K., and Uddenfeldt, J., "Capacity of Digital Cellular TDMA Systems," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 2, pp. 323–331, May 1991.

[Ram65] Ramo, S., Whinnery, J. R., and Van Duzer, T., *Fields and Waves in Communication Electronics*, John Wiley & Sons, New York, 1965.

[Rap89] Rappaport, T. S., "Characterization of UHF Multipath Radio Channels in Factory Buildings," *IEEE Transactions on Antennas and Propagation*, Vol. 37, No. 8, pp. 1058–1069, August 1989.

[Rap90] Rappaport, T. S., Seidel, S.Y., and Singh, R., "900 MHz Multipath Propagation Measurements for U.S. Digital Cellular Radiotelephone," *IEEE Transactions on Vehicular Technology*, pp. 132–139, May 1990.

[Rap91a] Rappaport, T. S., et al., "Statistical Channel Impulse Response Models for Factory and Open Plan Building Radio Communication System Design," *IEEE Transactions on Communications*, Vol. COM-39, No. 5, pp. 794–806, May 1991.

[Rap91b] Rappaport, T. S., and Fung, V., "Simulation of Bit Error Performance of FSK, BPSK, and $\pi/4$ DQPSK in Flat Fading Indoor Radio Channels Using a Measurement-based Channel Model," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 4, pp. 731–739, November 1991.

[Rap91c] Rappaport, T. S., "The Wireless Revolution," *IEEE Communications Magazine*, pp. 52–71, November 1991.

[Rap92a] Rappaport, T. S., and Hawbaker, D. A., "Wide-band Microwave Propagation Parameters Using Circular and Linear Polarized Antennas for Indoor Wireless Channels," *IEEE Transactions on Communications*, Vol. 40, No. 2, pp. 240–245, February 1992.

[Rap92b] Rappaport, T. S., and Milstein, L. B., "Effects of Radio Propagation Path Loss on DS-CDMA Cellular Frequency Reuse Efficiency for the Reverse Channel," *IEEE Transactions on Vehicular Technology*, Vol. 41, No. 3, pp. 231–242, August 1992.

[Rap93a] Rappaport, T. S., Huang, W., and Feuerstein, M. J., "Performance of Decision Feedback Equalizers in Simulated Urban and Indoor Radio Channels," Special issue on land mobile/portable propagation, *IEICE Transactions on Communications*, Vol. E76-B, No. 2, February 1993.

[Rap93b] Rappaport, S. S., "Blocking, Hand-off and Traffic Performance for Cellular Communication Systems with Mixed Platforms," *IEE Proceedings,* Vol. 140, No. 5, pp. 389–401, October 1993.

[Rap95] *Cellular Radio & Personal Communications: Selected Readings*, edited by Rappaport, T. S., IEEE Press, New York, ISBN: 0-7803-2283-5, 1995.

[Rap96] Rappaport, T. S., "Coverage and Capacity," *Cellular Business*, pp. 90–96, February 1996.

[Rap97] Rappaport, T. S., and Brickhouse, R. A., "A Simulation Study of Urban In-Building Frequency Reuse," *IEEE Personal Communications Magazine*, pp. 19–23, February 1997.

[Rap00] Rappaport, T. S., "Isolating Interference," *Wireless Review*, pp. 33–35, May 1, 2000. *http://www.wirelessreview.com/issues/2000/00501/feat23.htm.*

[Ree60] Reed, I. S., and Solomon, G., "Polynomial Codes over Certain Finite Fields," *Journal of the Society for Industrial and Applied Mathematics,* June 1960.

[Reu74] Reudink, D. O., "Properties of Mobile Radio Propagation Above 400 MHz," *IEEE Transactions on Vehicular Technology,* Vol. 23, No. 2, pp. 1–20, November 1974.

[Rhe89] Rhee, M. Y., *Error Correcting Coding Theory,* McGraw-Hill, New York, 1989.

[Ric44] Rice, S. O., "Mathematical Analysis of Random Noise," *Bell Systems Technical Journal,* Vol. 23, pp. 282-332, July 1944; Vol. 24, pp. 46–156, January 1945;

[Ric48] Rice, S. O., "Statistical Properties of a Sine Wave Plus Random Noise," *Bell Systems Technical Journal*, Vol. 27, pp. 109–157, January 1948.

[Ric67] Rice, P. L., Longley, A. G., Norton, K. A., and Barsis, A. P., "Transmission Loss Predictions for Tropospheric Communication Circuits," *NBS Tech Note 101*; two volumes; issued May 7, 1965; revised May 1, 1966; revised January 1967.

[Rob01] Robert, M., "Bluetooth: A Short Tutorial," *Wireless Personal Communications: Bluetooth Tutorial and Other Technologies*, Tranter, W. H. et al., Eds. Kluwer Academic Publishers, 2001, pp. 249–270.

[Rob94] Roberts, J. A., and Bargallo, J. M., "DPSK Performance for Indoor Wireless Ricean Fading Channels," *IEEE Transactions on Communications*, pp. 592–596, April 1994.

[Roc89] Roca, R. T., "ISDN Architecture," *AT&T Technical Journal*, pp. 5–17, October 1989.

[Ros93] Rossi, J.-P. and Levi, A. J., "A Ray Model for Decimetric Radiowave Propagation in an Urban Area," *Radio Science*, Vol. 27, No. 6, pp. 971–979, 1993.

[Ros97] Rossi, J.-P., Barbot, J.-P., and Levy, A., J., "Theory and Measurement of the Angle of Arrival and Time Delay of UHF Radiowaves Using a Ring Array," *IEEE Transactions on Antennas and Propagation*, Vol. 45, pp. 876–884, May 1997.

[Rus93] Russel, T. A., Bostian, C. W., and Rappaport, T. S., "A Deterministic Approach to Predicting Microwave Diffraction by Buildings for Microcellular Systems," *IEEE Transactions on Antennas and Propagation*, Vol. 41, No. 12, pp. 1640–1649, December 1993.

[Sal87] Saleh, A. A. M., and Valenzeula, R. A., "A Statistical Model for Indoor Multipath Propagation," *IEEE Journal on Selected Areas in Communication*, Vol. JSAC-5, No. 2, pp. 128–137, Febuary 1987.

[Sal91] Salmasi, A., and Gilhousen, K. S., "On the System Design Aspects of Code Division Multiple Access (CDMA) Applied to Digital Cellular and Personal Communications Networks," *IEEE Vehicular Technology Conference,* pp. 57–62, 1991.

[San82] Sandvos, J. L., "A Comparison of Binary Paging Codes," *IEEE Vehicular Technology Conference*, pp. 392–402, 1982.

[Sch85a] Schroeder, M. R., "Linear Predictive Coding of Speech: Review and Current Directions," *IEEE Communications Magazine*, Vol. 23, No. 8, pp. 54–61, August 1985.

[Sch85b] Schroeder, M. R., and Atal, B. S., "Code-excited Linear Prediction (CELP): High Quality Speech at Very Low Bit Rates," *Proceedings of ICASSP*, pp. 937–940, 1985.

[Sch92] Schaubach, K. R., Davis, N. J. IV, and Rappaport, T. S., "A Ray Tracing Method for Predicting Path Loss and Delay Spread in Microcellular Environments," in *42nd IEEE Vehicular Technology Conference,* Denver, pp. 932–935, May 1992.

[Sei91] Seidel, S.Y., Rappaport, T. S., Jain, S., Lord, M., and Singh, R., "Path Loss, Scattering and Multipath Delay Statistics in Four European Cities for Digital Cellular and Microcellular Radiotelephone," *IEEE Transactions on Vehicular Technology*, Vol. 40, No. 4, pp. 721–730, November 1991.

[Sei92a] Seidel, S. Y., et al., "The Impact of Surrounding Buildings on Propagation for Wireless In-building Personal Communications System Design," *1992 IEEE Vehicular Technology Conference*, Denver, pp. 814–818, May 1992.

[Sei92b] Seidel, S. Y., and Rappaport, T. S., "914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings," *IEEE Transactions on Antennas and Propagation*, Vol. 40, No. 2, pp. 207–217, Febuary 1992.

[Sei94] Seidel, S. Y., and Rappaport, T. S., "Site-Specific Propagation Prediction for Wireless In-Building Personal Communication System Design," *IEEE Transactions on Vehicular Technology*, Vol. 43, No. 4, November 1994.

[Sha48] Shannon, C. E., "A Mathematical Theory of Communications," *Bell Systems Technical Journal,* Vol. 27, pp. 379–423 and 623–656, 1948.

[Skl93] Sklar, B., "Defining, Designing, and Evaluating Digital Communication Systems," *IEEE Communications Magazine,* pp. 92–101, November 1993.

[Skl01] Sklar, B., *Digital Communications*, 2nd Edition, Prentice-Hall, Upper Saddle River, NJ, 2001.

[Ski96] Skidmore, R., Rappaport, T. S., and Abbott, A. L., "Interactive Coverage Region and System Design Simulation for Wireless Communication Systems in Multifloored Environments: SMT Plus," *IEEE International Conference on Universal Personal Communications*, Cambridge, MA, September 29–October 2, 1996, pp. 646–650.

[Smi57] Smith, B., "Instantaneous Companding of Quantized Signals," *Bell System Technical Journal*, Vol. 36, pp. 653–709, May 1957.

[Smi75] Smith, J. I., "A Computer Generated Multipath Fading Simulation for Mobile Radio," *IEEE Transactions on Vehicular Technology*, Vol. VT-24, No. 3, pp. 39–40, August 1975.

[Sta86] Stark, H., and Woods, J. W., *Probability, Random Variables, and Estimation Theory for Engineers*, Prentice Hall, Englewood Cliffs, NJ, 1986.

[Sta90] Stallings W., *Local Networks*, Macmillan Publishing Company, New York, 1990.

[Sta99] Starr, T., Cioffi, J. M., and Silverman, P. J., *Understanding Digital Subscriber Line Technology*, Prentice-Hall, Upper Saddle River, NJ, 1999.

[Ste87] Stein, S., "Fading Channel Issues in System Engineering," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No.2, February 1987.

[Ste90] Steedman, R., "The Common Air Interface MPT 1375," in *Cordless Telecommunications in Europe*, W. H. W. Tuttlebee, editor, Springer-Verlag, 1990.

[Ste93] Steele, R., "Speech codecs for Personal Communications," *IEEE Communications Magazine*, pp. 76–83, November 1993.

[Ste94] Steele, R. ed., *Mobile Radio Communications*, IEEE Press, 1994.

[Stu81] Stutzman, W. L., and Thiele, G. A., *Antenna Theory and Design,* John Wiley & Sons, New York, 1981.

[Stu93] Stutzman, W. L., *Polarization in Electromagnetic Systems*, Artech House, Boston, 1993.

[Sun86] Sundberg, C., "Continuous Phase Modulation," *IEEE Communications Magazine*, Vol. 24, No.4, pp. 25–38, April 1986.

[Sun94] Sung, C. W., and Wong, W. S., "User Speed Estimation and Dynamic Channel Allocation in Hierarchical Cellular System," *Proceedings of IEEE 1994 Vehicular Technology Conference*, Stockholm, Sweden, pp. 91–95, 1994.

[Suz77] Suzuki, H., "A Statistical Model for Urban Radio Propagation," *IEEE Transactions on Communications*, Vol. 25, pp. 673–680, July 1977.

[Tan81] Tanenbaum, A. S., *Computer Networks*, Prentice Hall Inc., 1981.

[TD-SCDMA Forum] TD-SCDMA Forum, *www.tdscdma-forum.org*.

[Tek91] Tekinay, S., and Jabbari, B., "Handover and Channel Assignment in Mobile Cellular Networks," *IEEE Communications Magazine*, pp. 42–46, November 1991.

[Tel01] Telecommunications News, Special Wireless Issue, Agilent Technologies, Issue 22, June 10, 2001

[TIA93] TIA/EIA Interim Standard-95, "Mobile Station—Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," July 1993.

[Tie01] Tiedemann, E. G., "CDMA2000-1X: New Capabilities for CDMA Networks," *IEEE Vehicular Technology Society Newsletter*, Vol. 48, No. 4, November 2001.

[Tob75] Tobagi, F. A., and Kleinrock, L., "Packet Switching in Radio Channels, Part II: The Hidden-Terminal Problem in Carrier Sense Multiple Access and the Busy-Tone Solution," *IEEE Transactions on Communication*, Vol. 23, No. 5, pp. 1417–1433, 1975.

[Tra01] Tranter, W. H., Woerner, B. D., Reed, J. H., Rappaport, T. S., and Robert, M., Eds., *Wireless Personal Communications: Bluetooth Tutorial and Other Technologies*, Kluwer Academic Publishers, 2001.

[Tra02] Tranter, W. H., Shanmugan, K., Kosbar, K., and Rappaport, T. S., *Simulation of Modern Communication Systems with Wireless Applications*, Prentice Hall, Upper Saddle River, NJ, 2002.

[Tre83] Treichler, J. R., and Agee, B. G., "A New Approach to Multipath Correction of Constant Modulus Signals," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-31, pp. 459–471, 1983.

[Tri79] Tribolet, J. M., and Crochiere, R. E., "Frequency Domain Coding of Speech," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-27, pp. 512–530, October 1979.

[Tuc93] Tuch, B., "Development of WaveLAN, and ISM Band Wireless LAN," *AT&T Technical Journal,* pp. 27–37, July/August 1993.

[Tur72] Turin, G. L. et al., "A Statistical Model of Urban Multipath Propagation," *IEEE Transactions on Vehicular Technology*, Vol. VT-21, pp. 1–9, February 1972.

[Tur87] Turkmani, A. M. D., Parson, J. D., and Lewis, D. G., "Radio Propagation into Buildings at 441, 900, and 1400 MHz," *Proceedings of the 4th International Conference on Land Mobile Radio,* December 1987.

[Tur92] Turkmani, A. M. D., and Toledo, A. F., "Propagation into and within Buildings at 900, 1800, and 2300 MHz," *IEEE Vehicular Technology Conference,* 1992.

[Ung87] Ungerboeck, G., "Trellis Coded Modulation with Redundant Signal Sets Part 1: Introduction," *IEEE Communication Magazine*, Vol. 25, No. 2, pp. 5–21, February 1987.

[Val93] Valenzuela, R. A., "A Ray Tracing Approach to Predicting Indoor Wireless Transmission," *IEEE Vehicular Technology Conference Proceedings*, pp. 214–218, 1993.

[Van92] Van Nielen, M. J. J., "UMTS: A Third Generation Mobile System," *IEEE Third International Symposium on Personal, Indoor & Mobile Radio Communications*, pp. 17–21, 1992.

[Van87] Van Rees, J., "Measurements of the Wideband Radio Channel Characteristics for Rural, Residential and Suburban Areas," *IEEE Transactions on Vehicular Technology*, Vol. VT-36, pp.1–6, February 1987.

[Var88] Vary, P., et al., "Speech Codec for the Pan-European Mobile Radio System," *Proceedings of ICASSP*, pp. 227–230, 1988.

[Vau90] Vaughan, R. G., "Polarization Diversity in Mobile Communications," *IEEE Transactions on Vehicular Technology*, Vol. 39, No. 3, pp. 177–186, August 1990.

[Vau93] Vaughan, R. G., and Scott, N. L., "Closely Spaced Monopoles for Mobile Communications," *Radio Science*, Vol. 28, No. 6, pp. 1259–1266, November/December 1993.

[Vio88] Violette, E. J., Espeland, R. H., and Allen, K. C., "Millimeter-Wave Propagation Characteristics and Channel Performance for Urban-Suburban Environments," *National Telecommunications and Information Administration*, NTIA Report 88–239, December 1988.

[Vit67] Viterbi, A. J., "Error Bounds for Convolutional Codes and an Asymptotically Optimum Decoding Algorithm," *IEEE Transactions on Information Theory,* Vol. IT-13, pp. 260–269, April 1967.

[Vit79] Viterbi, A. J., and Omura, J. K., *Principles of Digital Communication and Coding*, McGraw Hill, New York, 1979.

[Von54] Von Hipple, A.R., *Dielectric Materials and Applications*, Publication of MIT Press, MA, 1954.

[Wag94] Wagen, J., and Rizk, K., "Ray Tracing Based Prediction of Impulse Responses in Urban Microcells," *1994 IEEE Vehicular Technology Conference,* Stockholm, Sweden, pp. 210–214, June 1994.

[Wal88] Walfisch, J., and Bertoni, H. L., "A Theoretical Model of UHF Propagation in Urban Environments," *IEEE Transactions on Antennas and Propagation*, Vol. AP-36, pp. 1788–1796, October 1988.

[Wal92] Walker, E. H., "Penetration of Radio Signals into Buildings in Cellular Radio Environments," *IEEE Vehicular Technology Conference*, 1992.

[Wel78] Wells, R., "SSB for VHF Mobile Radio at 5 kHz Channel Spacing," *Proceedings of IERE Conference on Radio Receivers and Associated Systems*, Southampton, England, pp. 29–36, July 1978.

[Wid66] Widrow, B., "Adaptive Filter, 1: Fundamentals," *Stanford Electronics Laboratory*, Stanford University, Stanford, CA, Tech. Rep. 6764–6, December 1966.

[Wid85] Widrow, B., and Stearns, S. D., *Adaptive Signal Processing*, Prentice Hall, 1985.

[Win98] Winters, J. H., "Smart Antennas for Wireless Systems," *IEEE Personal Communications*, Vol. 1, pp. 23–27, February 1998.

[Wir01] Wireless Valley Communications, Inc, *SitePlanner 2001 Product Manual*, Blacksburg, Virginia, c. 2001, www.wirelessvalley.com

[Woe94] Woerner, B. D., Reed, J. H., and Rappaport, T. S., "Simulation Issues for Future Wireless Modems," *IEEE Communications Magazine,* pp. 19–35, July 1994.

[Xia92] Xia, H., and Bertoni, H. L., "Diffraction of Cylindrical and Plane Waves by an Array of Absorbing Half Screens," *IEEE Transactions on Antennas and Propagation*, Vol. 40, No. 2, pp. 170–177, February 1992.

[Xia93] Xia, H., et al., "Radio Propagation Characteristics for Line-of-Sight Microcellular and Personal Communications," *EEE Transactions on Antennas and Propagation*, Vol. 41, No. 10, pp. 1439–1447, October 1993.

[Xio94] Xiong, F., "Modem Techniques in Satellite Communications," *IEEE Communications Magazine*, pp. 84–97, August 1994.

[Xu00] Xu, H., Boyle, R. J., Rappaport, T. S., and Schaffner, J. H., "Measurements and Models for 38 GHz Point-to-Multipoint Radiowave Propagation," *IEEE Journal on Selected Areas in Communications: Wireless Communications Series*, Vol. 18, No. 3, pp. 310–321, March 2000.

[Yac93] Yacoub, M. D., *Foundations of Mobile Radio Engineering*, CRC Press, 1993.

[Yao92] Yao, Y. D., and Sheikh, A. U. H., "Bit Error Probabilities of NCFSK and DPSK Signals in Microcellular Mobile Radio Systems," *Electronics Letters*, Vol. 28, No. 4, pp. 363–364, February 1992.

[You79] Young, W. R., "Advanced Mobile Phone Service: Introduction, Background, and Objectives," *Bell Systems Technical Journal*, Vol. 58, pp. 1–14, January 1979.

[Zag91a] Zaghloul, H., Morrison, G., and Fattouche, M., "Frequency Response and Path Loss Measurements of Indoor Channels," *Electronics Letters*, Vol. 27, No. 12, pp. 1021–1022, June 1991.

[Zag91b] Zaghloul, H., Morrison, G., and Fattouche, M., "Comparison of Indoor Propagation Channel Characteristics at Different Frequencies," *Electronics Letters*, Vol. 27, No. 22, pp. 2077–2079, October 1991.

[Zho90] Zhou, K., Proakis, J. G., and Ling, F., "Decision Feedback Equalization of Time Dispersive Channels with Coded Modulation," *IEEE Transactions on Communications*, Vol. 38, pp. 18–24, January 1990.

[Zie90] Ziemer, R. E., and Peterson, R. L., *Digital Communications*, Prentice Hall, Englewood Cliffs, NJ, 1990.

[Zie92] Ziemer, R. E., and Peterson, R. L., *Introduction to Digital Communications*, Macmillan Publishing Company, 1992.

[Zog87] Zogg, A., "Multipath Delay Spread in a Hilly Region at 210 MHz," *IEEE Transactions on Vehicular Technology*, Vol. VT-36, pp. 184–187, November 1987.

INDEX

Numerics

1:N protection switching, 390
1xRTT, 32
2.5G (2.5 generation), 29–34
2G (second generation), 26–29, 30, 31, 35, 39, 55, 415, 549
3 dB bandwidth, 281
3G (third generation), 23, 26, 29, 30, 32, 33, 34–40, 51, 55
3GPP, 35, 37, 450, 661
3GPP2, 35, 38, 450, 661
3xRTT, 32

A

Adaptive delta modulation (ADM), 437
ADPCM, 416, 423–425
Advanced intelligent network (AIN), 522
ALOHA, 464, 465
Amplitude modulation, 256, 257–264
  modulation index, 257
  percentage modulation, 257
  pilot tone SSB, 261
    tone-in-band, 262
  SSB, 260
    balanced modulator, 261
    filter method, 260
AMPS, 7, 27, 474, 533–543, 547, 549, 557, 567, 582, 594, 613–614
  blank-and-burst encoding, 539
  compander, 538
  deviation limiter, 538
  electronic serial number, 499, 536
  paging channel, 537
  pre-emphasis, 538
  SAT tone, 535, 539
  Signaling tone, 536, 539
  Station class mark, 536
  System identification number, 535
  Voice mobile attenuation code, 535
Angle modulation, 264
  frequency modulation, 256
  phase modulation, 265
ANSI J-STD-007, 28
ANSI J-STD-008, 28, 675
ANSI J-STD-011, 28
Antenna diversity. *See* space diversity
Antenna downtilting, 88
Antenna gain, 107
Antenna polarization diversity, 356
Antenna temperature, 612
APC, 416
ARDIS, 508

Asynchronous applications, 591
Asynchronous transfer mode (ATM), 513
AT&T, 4, 157, 493, 533
AT&T Wireless, 28
Attenuation factor, 161, 163
    see also floor attenuation factor (FAF)
Authentication center, 520, 553
Autonomous registration, 499
Average fade duration, 224
Average holding time, 603
AWGN, 294, 355

B

Bandwidth efficiency, 394
Base station, 9, 10, 13
BCH code, 400, 540
Bell Laboratories, 2, 4, 157, 533
Bell Operating Companies, 494
Berlekamp–Massey algorithm, 405, 407
BFSK, 312
    bandwidth, 313
    complementary channel, 334
    detection, 313
    error probability for noncoherent detection, 314
    PSD, 313
    transmission channel, 334
B-ISDN, 500
Bistatic radar equation, 136
Blank-and-burst, 536
Blind algorithms, 360
Block codes, 356, 395
    cyclic, 396
    forward error correction, 395
    linearity, 396
    systematic, 396
Blocked calls cleared, 78
Blocked calls delayed, 80
Bluetooth, 25, 26, 47, 52–54, 457
Boltzmann's constant, 612
BPSK, 295, 344
    bandwidth, 296
    geometric representation, 293
    PSD, 296
    receiver, 297
Branch, 381
Breathing cell, 73
Brick-wall filter, 287
Burst noise, 256
Busy-idle, 467

C

C-450, 8, 594
CAD, 48
Capacity, 5, 6, 13, 28, 34, 2, 57, 58, 59, 60, 62, 66, 67–77, 78, 79, 86–96, 138, 167, 184, 279, 338, 388, 394, 412, 415, 436, 438, 447, 449, 459, 460, 461, 469–487, 492, 493, 495, 502, 510, 512, 528, 531, 533, 536, 540, 541, 566, 567, 580, 584, 590, 593
Capture, 458
Capture ratio, 468
Carson's rule. *See* FM bandwidth
CD-900, 426, 438
CDMA, 5, 36, 448, 458
    capacity, 481
    near-far effect, 74, 458
    self-jamming, 459
cdma2000, 32, 36
cdmaOne, 27, 28, 34, 38
CDPD, 7, 400, 401, 405, 506
    MDBS, 507
    MD-IS, 507
    MDLP, 507
    M-ES, 507
    RRMP, 507
Cell broadcast, 550
Cell planning, 535
Cell splitting, 86, 86–88, 90, 96
Cellular packet-switched architecture, 523
    base station interface unit, 525
    cellular controller interface unit, 527
    gateway interface unit, 524
    trunk interface unit, 525
        PAD, 525
    visitor interface unit, 524
    wireless terminal interface unit, 525
Central office, 493
CEPT, 501, 549

Channel assignment, 62, 65
adaptive, 473
dynamic, 62, 548
fixed, 62
Channel coding, 356, 393, 394
distance of a code, 396
weight of a code, 396
Channel decoding, 409
Fano's sequential algorithm, 410
feedback decoding, 410
stack sequential algorithm, 410
Viterbi algorithm, 409
Channel planning, 72–73
Channel vocoders, 429
Characteristics of speech signals, 417
ACF, 417
PDF, 417
PSD, 418
spectral flatness measure, 418
Chien search algorithm, 405
Cingular, 28
Circuit switching, 503
Cisco Systems, Inc., 47
Clarke and Gans fading model, 214, 220
Clear sky, 44
Click noise, 276
Cluster size, 60
Co-channel reuse ratio, 68
Code book, 422
index, 422
Code division multiple access. *See* CDMA
Coded digital verification color code. *See* USDC (IS-136), channels, CDVCC
Codeword polynomial, 401
Codewords, 395
Coherence bandwidth, 202
Coherence distance, 230, 232, 241, 243
Coherence time, 179, 203
Comfort noise subsystem, 563
Common channel signaling, 496, 500, 522
architecture, 511
database service management system, 512
in-band signaling, 510
service management system, 512
signaling transfer point, 512
switching end point, 511
Companding, 420, 538
A-law, 420
μ-law, 419, 420
Complex voltage fluctuations, 234
Complimentary code keying orthogonal frequency division multiplexing (CCK-OFDM), 46
Computational loading, 63
Computer-aided design (CAD), 48
Connectionless protocol, 507
Constant envelope, 264
Constant modulus algorithm, 360
Constraint length, 408
Contention protocols
hybrid access, 464
random, 464
scheduled access, 464
Control file messages, 537
Control messages, 537
Convolutional codes, 356, 407, 409
COST (Cooperative for Scientific and Technical Research), 154
Cost function, 360
CPE, 51, 494
CPFSK, 314
CSMA
1-persistent, 467
CSMA/CD, 467
nonpersistent, 467
p-persistent, 467
CT2, 6, 8, 423, 438, 499, 580, 595
duplexing, 582
modulation, 582
speech coding, 582
Customer premises equipment. *See* CPE
CVSDM, 416
Cyclic code, 399

D

D-AMPS. *See* USDC
DAS, 93
Data sense multiple access, 467

dBd, 108
dBi, 108
DCS, 596
DCS-1800, 8, 438
DCS-1900, 7, 28
Decision feedback equalizer, 369
  lattice implementation, 370
  MMSE, 370
  predictive DFE, 370
DECT, 6, 8, 36, 423, 437, 438, 499, 582–586, 590, 595
  antenna diversity, 586
  architecture, 582–584
  channel coding, 586
  channel types, 585
  DLC layer, 584
  MAC layer, 583
  modulation, 586
  network layer, 584
  physical layer, 583
  speech coding, 585
Delay line, 273
DEM, 146
Demodulation of AM, 262
  coherent, 262
  noncoherent, 262, 264
Demodulation of BFSK
  coherent, 313
  noncoherent, 314
Demodulation of FM, 268
  PLL detector, 270
  quadrature detector, 270
  slope detector, 269
  zero-crossing detector, 270
Depolarization matrix, 117
Diagnostic acceptability measure (DAM), 444
Diagnostic rhyme test (DRT), 442
Dielectrics, 114, 115, 121
Diffraction, 113, 126–135
  Fresnel zones, 126
  Huygen's principle, 126
Diffraction models, 126–135
Digital elevation models. *See* DEM
Digital european cordless telephone. *See* DECT
Digital hierarchy, 501
Digital signals, 281
  absolute bandwidth, 281
  half-power bandwidth, 281
  null-to-null bandwidth, 281
  PSD, 281
Digital subscriber line. *See* DSL, 41
Digital traffic channel, *See* USDC (IS-136), channels, DTC
Direct RF pulse system, 192
Direct sequence SS, 331
  error probability, 337
  near–far problem, 338, 339
  processing gain, 333
  receiver, 333
Directed retry, 536
Discrete cosine transform, 428
Dispersion
  frequency, 205
  time, 205
Distributed antenna systems. *See* DAS
Diversity, 355, 380–390
DM, 416
DoCoMo, 30
Doppler frequency, 224, 225
Doppler shift, 179–180, 347
Doppler spectrum, 615
Doppler spread, 203–205, 222, 261, 262, 339, 44, 347, 348, 355, 373
  fading effects, 208–209, 220
  in Clarke's model, 217–218
Doupoly, 4
DPCM, 416
DPSK, 298
  error probability, 299
  receiver, 299
  transmitter, 298
Dropped call, 64
DS formats, 501
DSL, 41
DSMA, 467
DSS1, 512
DS–SS, 46
DTX, 474

Duplexer, 10, 11, 447
Duplexing, 447
Durkin's model, 146

E

EDGE, 30, 32, 33, 34, 33–34, 35, 37, 38
Effective isotropic radiated power (EIRP), 107
Effective noise temperature, 612
Effective radiated power (ERP), 107
EGPRS. *See* Enhanced GPRS
Electronic serial number. *See* AMPS
e-mail, 29, 506, 523
End-of-call message, 539
Enhanced GPRS (*also* EGPRS), 33
Equalization, 355, 356
Equalizers, 355
  adaptive, 357, 372–378
    algorithms, 372–378
  classification, 364
  computational complexity, 372
  fractionally spaced, 380
  linear, 366–368
  mean squared error, 363
  misadjustment, 372
  nonlinear, 368–371
  numerical properties, 372
  prediction error, 363
  rate of convergence, 372
  summary, 379
Equipment identity register, 553
Ericsson multiple breakpoint model, 161
Erlang, 77
  Erlang B, 79, 602–606
  Erlang C, 80, 607–610
ERMES, 8
Error control coding, 34, 279, 343, 390, 393, 395, 457, 503, 504
  algorithms, 30
Error locator polynomial, 405, 407
Error probability for frequency selective fading, 344
Error probability for slow fading, 342
ETACS, 8, 27, 534–543, 594
  area identification number, 535
ETSI, 23, 549
Euclidean distance, 294, 422
Excess delay, 183
Excess delay spread, 199
Extended Hata model, 154
Extension field, 397

F

f1/f2 cell, 73
Fading, 177
  Doppler, 220
  fast, 208
  flat, 205
  frequency selective, 207
  large-scale, 105, 380
  slow, 209
  small-scale, 106, 113, 177, 178, 178–179, 185, 188, 192, 205–210, 228, 256, 380, 381, 459, 619
  time selective, 205
Fano algorithm, 410
Far-field, 108
Fast associated control channel. *See* USDC (IS-136), channels, FACCH
Fast FSK. *See* MSK
FDMA, 5, 448, 449
Feed forward, 364, 366, 369, 370
Feedback, 270, 290, 331, 364, 366, 368, 369, 370, 371, 385, 386, 400, 404, 410, 411, 424, 462, 464, 525, 527, 529, 548
Fixed cellular, 21
FFSR, 262
FHMA, 457
  erasures, 457
  fast frequency hopping, 457
  slow frequency hopping, 457
FH–SS, 46
Finite fields, 396
FIR filter, 366
Fixed network transmission hierarchy, 501
Fixed wireless access, 25
FLEX, 7
Floor attenuation factor (FAF), 160
FM bandwidth, 266–7
  Carson's rule, 266, 267, 313
Footprint, 58

Formants, 429
Forward band, 447
Forward channel, 10, 11
    control, 10, 14
    voice, 14, 534, 535
FPLMTS, 20, 501
Fraunhofer region, 108
Free space propagation model, 107–110, 120
    Friis equation, 107
Frequency diversity, 356, 390
Frequency division duplexing (FDD), 10, 447
Frequency division multiple access. *See* FDMA
Frequency division multiplex, 390
Frequency domain channel sounding, 196
Frequency domain coding, 425
    adaptive, 428
    block transform, 425
    sub-band, 425
Frequency hopping
    error probability, 338
    hop duration, 334
    hopping cell, 566
    hopset, 334
    instantaneous bandwidth, 334
    single channel modulation, 334
    slotted, 339
    total hopping bandwidth, 334
Frequency modulation, 264, 265
    bandwidth, 266
    capture effect, 257
    detection gain, 276
    direct method, 267
    indirect method, 267
    SNR, 276
Frequency reuse, 5, 15, 57, 58–60, 62, 68, 70, 71, 72, 73, 74, 86, 87, 88, 90, 91, 96, 471, 474, 477, 478, 480, 481, 483, 486, 496, 541, 585
Frequency shift keying (FSK), 6
    See also BFSK, CPFSK, MFSK
Frequency-to-amplitude converter, 268
Fresnel zone geometry, 126
    excess path length, 126
    Fresnel zone, 125, 127
    Fresnel-Kirchoff diffraction parameter, 126
Full-duplex, 9, 10, 11

G

G.721, 423
Galois field, 397
Gaussian approximation, 629
Gaussian filter, 290
General packet radio service. *See* GPRS
Generator matrix, 408
Generator polynomial, 400, 401, 408
Geometric representation, 291
    constellation diagram, 293
GIS database, 167
Global balance equation, 605
Global system mobile. *See* GSM
GMSK, 290, 318
    PSD, 319
    receiver, 320
    transmitter, 320
Golay code, 399
GPRS, 30, 31, 32, 33, 34, 37, 542
Grade of service, 77–86, 540, 601
Ground reflection model, 120
    method of images, 122
GSC, 7
GSM, 8, 9, 26, 28, 29, 438, 474, 499, 549–555, 596
    Abis interface, 551
    ARFCN, 553
    base station controller, 551
    base station subsystem, 551
    broadcast channel (BCH), 557
    burst formatting, 566
    ciphering, 565
    common control channel (CCCH), 559
    control channel coding, 564
    control channels (CCH), 557
    data channel coding, 564
    dedicated control channel (DCCH), 559
    demodulation, 566
    equalization, 566
    frame structure, 561
    frequency hopping, 566
    interleaving, 565
    logical channel, 554
    modulation, 566
    network and switching subsystem, 553

operation support subsystem, 553
physical channel, 554
speech coding, 563
subscriber identity module, 550
TCH/FS, SACCH, FACCH coding, 563
traffic channels, 555
full-rate TCH, 556
half-rate TCH, 556
Guard channel, 65

H

Hadamard code, 399
Half duplex, 9, 10, 11
Half power beamwidth. *See* HPBW
Hamming code, 399
Hamming distance, 396, 410
Handoff, 6, 10, 13, 14, 15, 62–64, 86, 88, 92, 96, 452, 454, 461, 493, 497, 500, 507, 518, 520, 522, 525, 527, 530, 536, 538, 543, 551, 560, 569, 583, 591
cell dragging, 66
dwell time, 64
hard, 34, 67, 73
prioritizing, 65
mobile assisted. *see* MAHO
soft, 34, 67, 73, 459, 460, 568
strategies, 62–67
Handover (*see also* handoff), 551
Hard decision decoding, 409
Hata model, 153–154
Hidden transmitter, 468
High data rate, 39
High performance radio local area network. *See* HIPERLAN, 49
Hilbert transform, 260
HIPERACCESS, 43
HIPERLAN, 43, 49
HIPERLINK, 43
Home location register, 520, 553
HomeRF, 46, 457
HPBW, 168
HSCSD, 30, 30–31, 32
Hunting sequence, 101
Hybrid multiple access techniques
DS/FHMA, 460
DSMA/CD, 507
FCDMA, 459
TCDMA, 460
TDFH, 461
Hyperframe, 563

I

iDen, 7
IEEE 802.11, 20, 46, 47, 49
IEEE 802.11a, 46, 50, 329
IEEE 802.11b, 46, 47, 48, 53
IEEE 802.11g, 46
IEEE 802.15, 53
IEEE 802.16, 43
IF, 74
I-mode, 30
Improved Gaussian approximation, 635
Impulse response model, 181–191, 340
IMSI, 553
IMT-2000, 20, 501
Incremental redundancy, 33
Indoor propagation, 227
studies, 197
Indoor propagation models, 157–166
Information polynomial, 401, 403
Input vector, 422
Interexchange carrier, 493
Interference, 67–77, 86, 90, 127, 177, 192, 194, 195, 214, 230, 279, 330, 333, 334, 338, 346–350, 436, 438, 449, 451, 454, 456, 459, 461, 462, 463, 473, 474, 475, 476, 477, 478, 480, 481, 483, 484, 485, 486, 523, 535, 536, 539, 541, 563, 565, 566, 568, 572, 578, 580, 584, 585, 586, 590, 591, 621, 623, 625, 626, 629, 630, 633, 634, 635, 637, 638
adjacent channel, 74–76, 547
C/I ratio, 469
co-channel, 68–72, 257, 346, 469
cross-rail, 344
forward channel, 469
intersymbol. *See also* ISI, 178, 344

Interference (*continued*)
multiple access. *See* MAI
out-of-band, 68
reverse channel, 469
S/I ratio, 533
SIR (*also* S/I ratio), 69, 70
Interleaving, 393, 457, 531, 542, 546, 547, 555, 565, 566, 568, 571, 576, 586,
block, 393
convolutional, 393
Intermediate frequency. *See* IF
Internet protocol, 507
Irreducible polynomial, 398, 400
IS-136, 5, 27, 28, 29, 30, 31, 33, 37, 38, 73, 438, 442, 541–549, 67, 590, 596, 591
IS-41, 499
IS-54. *See also* USDC, 5, 28, 438, 499, 541–549, 590
Rev.C, 549
IS-94, 548
IS-95, 5, 7, 27, 28, 35, 38, 39, 67, 73, 392, 411, 435, 438, 499, 542, 549, 567–580, 591
channel specifications, 567
forward channel, 569–575
forward channel block interleaver, 571
forward channel convolutional encoder, 569
forward channel data scrambler, 572
forward channel long PN sequence, 571
forward channel orthogonal coverage, 573
forward channel power control subchannel, 572
forward channel quadrature modulation, 574
reverse channel, 575–580
reverse channel block interleaver, 576
reverse channel convolutional encoder, 576
reverse channel direct sequence spreading, 578
reverse channel orthogonal modulation, 576
reverse channel quadrature modulation, 580
reverse channel variable data rate, 576
Walsh function matrix, 573
IS-95A, 32, 34, 36, 38
IS-95B, 32, 34, 35, 36, 38
ISDN, 512
access signaling, 512
basic rate interface, 512
bearer channels, 512
data channels, 512
network signaling, 512
primary rate interface, 512
ISI, 355, 356, 391, 547
in GMSK, 320
ISM bands, 591
Isochronous, 591
Isolation, 11
Isotropic radiator, 107
Isotropic source, 108
ITFS, 593
ITS model. *See* Longley Rice model
ITU, 21
ITU World Radio Conference (WRC-2000), 21
ITU-R, 20, 21
IXC, 519
IxEV, 32

J

Japanese digital cellular (JDC), 590
JTACS, 8, 27

K

Kalman RLS, 378
Knife-edge diffraction model, 129

L

LANFielder, 49
Last-mile, 40
Lattice filter, 367
Least mean square algorithm (LMS), 373, 374, 375
MMSE, 375
normal equation, 375
LEO, 21
Level crossing rate, 223
License-free spectrum, 46
Line coding, 282
Manchester codes, 282, 540
NRZ code, 282
RZ code, 282
Linear predictive coder (LPC), 28, 429, 431–436, 442, 545, 563
Listen before talk, 591
Lloyd Max algorithm, 419

LMDS, 26, 40–45, 54
LMS. *See* least mean square algorithm
Local access and transport area, 493
Local multipoint distribution systems. *See* LMDS
Locator receiver, 64, 536
Log-distance indoor model, 161
Log-distance path loss model, 138–139, 156
Log-distance power law, 227
Log-normal shadowing, 139–141
    path loss exponent, 140
    standard deviation, 140
Logic tables, 408
Longley Rice model, 145
    area mode, 145
    point-to-point mode, 145
    urban factor, 145
Low Earth Orbit satellite. *See* LEO

M

MAHO, 64, 454, 473, 500, 543, 544, 548, 590
MAI, 329, 337, 338, 339, 393
MAN. *See* metropolitan area network
Manchester code. *See* line coding
Markov chain, 604
M-ary, 322
    MPSK, 323
Maximal ratio combining, 383
Maximum excess delay, 183, 199
Maximum likelihood decoding, 409
Maximum ratio combining, 385
MC. *See* multicarrier
M-commerce, 29
MCS, 33
MDR. *See* Medium data rate, 34
MDS, 593
Mean excess delay, 199
Mean opinion score (MOS), 444
Mean square distortion, 419
Medium data rate (MDR), 34
Metropolitan area network (MAN), 523, 529
MFSK, 328
    bandwidth, 328, 329
    error probability (coherent detection), 328
    error probability (noncoherent detection), 328
Microcell, 6, 64, 65, 66, 86, 87, 88, 93, 120, 125, 227, 229, 437, 473, 491, 548, 587, 591
    see also zone microcell
    wideband PCS model, 155–157
Microscopic diversity techniques, 380
MIRS, 6, 7
MLSE, 370
MMDS, 329, 593
MMSE, 367
Mobile assisted handoff. *See* MAHO, 543
Mobile commerce (m-commerce), 29
Mobile identification number, 15, 534, 535
Mobile satellite networks, 20
Mobile station, 10, 13
Mobile Switching Center. *See* MSC
Mobile Telephone Switching Office. *See* MTSO
Modified final judgement, 493
Modulating signal, 257
Modulation, 255
    bandwidth efficiency, 278
    constant envelope, 311
    linear techniques, 294
    performance in fading and multipath channels, 339
    power efficiency, 278
    spread spectrum, 329
        frequency hopped, 334
Motorola, 6, 7, 20, 21, 42, 508, 540, 545
MPSK
    bandwidth, 325
    error probability, 324
    PSD, 324
MSC, 10, 13, 535
MSE, 419
MSK, 314, 344, 345
    bandwidth, 316
    geometric representation, 323
    PSD, 316
    receiver, 316
    transmitter, 316
MTSO, 13
Multicarrier (MC), 38
Multicarrier transmissions, 34

Multiframe
control channel, 557
speech, 556
Multipath propagation, 195, 231, 239, 241, 248, 330, 55, 388
small-scale, 177–180
Multiple Access Interference. See MAI
Multiple access techniques
code division. *See* CDMA
frequency division. *See* FDMA
frequency hopped. *See* FHMA
hybrid, 459
narrowband, 449
packet radio (PR), 449, 462
space division. *See* SDMA
spread spectrum (SSMA), 456
time division. *See* TDMA
wideband, 449
Multiple knife-edge diffraction model, 134
Multiple modulation and coding schemes (MCS), 33

N

N-AMPS, 7, 540
DSAT, 540
DST, 540
Nearest neighbors cells, 73
Near–far effect, 468, 568
NEC, 8
Network database, 529
distributed hierarchy, 529
Newton's identities, 407
Nextel, 2, 6, 29
NMT-450, 8, 9, 594
NMT-900, 8, 594
Noise figure, 101, 172, 611, 613
Noise floor, 68, 101, 138, 199
Nonminimum phase, 370, 390, 391
North American Digital Cellular (NADC), 27, 28, 541
NRZ code. *See* line coding
NTACS, 8
NTT, 8, 28, 30
Nyquist criterion, 282
Nyquist filters, 286

O

OFDM, 329
Offset QPSK. *See* OQPSK
Okumura model, 150–153
OQPSK, 295, 303–304, 305, 315, 316, 344, 345, 547
Orbital Sciences Corp., 21
OSI model, 505
Outage probability, 340
Overhead messages, 537

P

π/4 DQPSK, 547
performance in fading, 346
π/4 QPSK, 295, 305, 305–311
detection techniques, 308–311
geometric representation, 305
receiver, 308
transmission techniques,305–308
π/4 QPSK
receiver
baseband differential detection, 308
FM discriminator, 311
IF differential detector, 310
Pacific digital cellular. *See* PDC
Packet radio (PR), 462
CSMA, 466
protocols, 463
pure ALOHA, 464
reservation, 467–469
slotted ALOHA, 465
Packet reservation multiple access (PRMA), 528
Packet switching, 504–5, 513, 514, 523–7
PACS, 7, 438, 499, 587–590, 595, 596
channels, 589
modulation, 589
multiple access technique, 590
speech coding, 589
system architecture, 587
Page, 10, 11
Paging, 11
Paging message, 535
Paging system access number, 11
PAN, 52–54
Parity polynomial, 400, 401

Partial syndromes, 404
Partition loss, 157
    hard partition, 157
    soft partition, 157
Path loss, 108
    coverage area, 141
    large-scale, 167
    models, 138
    small-scale, 167
PBX, 494, 548
PCM, 416, 423
PCN, 20, 522
PCS, 1, 2, 3, 6, 9, 10, 20, 25, 26, 29, 43, 93, 106, 154, 155–157, 438, 491, 501, 522–527, 533, 549, 567, 580, 587, 587–590, 591
PDC, 8, 9, 27, 28, 30, 438, 474, 590, 596
Personal access communication systems. *See* PACS
Personal area networks. *See* PAN
Personal communication networks. *See* PCN
Personal communication services. *See* PCS
Personal handyphone system. *See* PHS
Phase modulation, 264
PHS, 7, 8, 438, 590, 595, 596
Pilot tones, 256
Plane of incidence, 114
PN sequences, 330
    maximal length, 331
POCSAG, 6, 7
Point of presence (POP), 494
Point-to-point, 40
Point-to-multipoint, 40
Polar, 282
Polarization diversity, 387
    correlation coefficient, 390
    theoretical model, 388
Polarization diversity reception, 388
Portable, 9
POTS (plain old telephone service), 28
Power, 581
Power amplifiers
    Class A, 256
    Class AB, 256
    Class C, 256
Power control, 73, 76–77, 338, 458, 459, 474, 475, 476–477, 478, 481, 484, 485, 535, 567, 568, 572, 573, 578, 581, 590, 634, 637, 640, 641
Power delay profile, 185
Power efficient, 256
Power fluctuations, 234
Power flux density, 111
Power-sum symmetric functions, 407
Primitive polynomial, 400, 401
Property restoral blind algorithms, 360
Processing gain, 194–196, 333, 334, 391, 460, 475
PSTN, 2, 493, 535
Pulse shaping techniques, 282

Q

QAM, 325
    bandwidth, 327
    error probability, 327
    geometric representation, 325
    PSD, 327
QPSK, 295, 300, 344, 345, 547
    bandwidth, 301
    geometric representation, 300
    probability of error, 300
    PSD, 301
    receiver, 303
    staggered. *See* also OQPSK, 303
    transmitter, 301
Quadrature detector, 273
Quadrature tank circuit, 273
Quantization techniques, 418
    adaptive, 421
    nonuniform, 419
    uniform, 418
    vector. *See* VQ, 422
Quotient polynomial, 401

R

Radar cross section model, 136
Radio capacity, 469–487
    for CDMA, 474
    for CDMA with multiple cells, 477
    for FDMA, 473
    for SDMA, 484
    for TDMA, 473

Radio General Assembly, 21
Radio signal strength indications. *See* RSSI
Radio transmission technology. *See* RTT
Raised cosine rolloff filter, 287
RAKE receiver, 330, 356, 385, 391, 568
RAM mobile data (RMD), 508
Range extension, 93
Rate of quantizer, 422
Ray tracing, 167
    primary, 163
Rayleigh fading, 210, 234
    two-ray model, 226
Recursive least squares algorithm (RLS), 373, 376
Reed–Solomon (RS) code, 400
    decoding, 404
    encoding, 401
Reflection, 113, 114, 114–120, 177, 214, 227, 228, 367, 380, 388, 432, 434, 440
    Brewster angle, 119
    Fresnel reflection coefficient, 114
    from conductors, 120
    from dielectrics, 114–119
ReFLEX, 6
Remainder polynomial, 401, 403
Repeaters, 93
Reverse band, 447
Reverse channel, 11
    control, 14
    voice, 14, 534, 535
Ricean fading, 213
Rms delay spread, 199
Roaming, 10, 18, 499
RPE-LTP vocoder, 440
RSSI, 62, 459
RTT, 38
RZ code. *See* line coding

S

Saleh and Valenzuela model, 227
Scattering, 114, 135–138
    loss factor, 136
    object, 136
SDMA, 484, 449, 461
Search window, 391
Second generation. *See* 2G
Sectoring, 86, 90–92, 93, 94, 96, 533
Setup channels, 14
Shadowing, 139
Shannon's channel capacity formula, 394
Shape factors, 229–247
    approximate spatial autocovariance function, 619–620
Short messaging service. *See* SMS
Signal penetration into buildings, 166–167
Signaling tone, 538, 539
Signal-to-noise ratio. *See* SNR
Simplex, 9
Simplified expression for improved Gaussian approximation, 637
Simulcasting, 11
Single sideband (SSB), 260
SIRCIM, 189, 227
SISP, 167
Site specific. *See* also SISP, 163
    modeling, 167
SitePlanner, 48, 49, 93, 94, 167
SiteSpy, 49
Sleep mode, 549
Slope detector, 269
Slope filter, 269
Slow associated control channel. *See* USDC (IS-136), channels, SACCH
Small-scale
    see also Fading
Small-scale channel modeling, 185
Small-scale indoor channel impulse response measurements. *See* SIRCIM
Small-scale link performance, 356
Small-scale multipath channel, 185
Small-scale multipath measurements, 192–197
Small-scale power delay profile, 197
small-scale received power, 187
SMRCIM, 189, 190, 227, 229, 231, 248, 671
SMS, 29, 550
SNR, 6, 68, 138, 225, 256, 276–277, 280, 343, 348, 374, 380, 381, 382, 383, 384, 385, 386, 387, 392, 394, 395, 411, 412, 442, 475, 476, 611, 613, 614

Soft decision decoding, 409
SOHO, 23
Source bits, 393
Space diversity, 385
    equal gain combining, 387
    feedback, 386
    maximal ratio combining, 387
    selection, 386
Space-time processing, 356
Spatial autocovariance, 240, 242–243, 245, 619–620
Spatial channel parameters, 616
Spatial diversity, 356, 586
Spatial filtering, 40, 41, 184
Spatial selectivity, 234, 236, 615
Spatial separation, 68, 197
Spatial-temporal channel model, 229
Spectral coherence restoral algorithm, 360
Spectral widening, 303
Spectrum regrowth, 303
Speech coders, 416
    choice of codec, 436
    for different cellular systems, 438
    frequency domain coding, 425
    GSM codec, 440
    hierarchy, 416
    performance evaluation, 442
    QCELP, 13 435, 580
    tandem signaling, 444
    USDC codec, 442
    vocoders, 416, 429
    waveform coders, 416
Speech coding, 423
Speech compression, 426
Spread spectrum sliding correlator, 193
SQNR, 419
Square root raised cosine filter, 547
SS7, 514
    congestion control, 519
    Global cellular network interoperability, 520
        call delivery, 522
        intersystem handoff, 522
        registration, 521
    message transfer part, 516
        level 1, 516
        level 2, 516
        level 3, 516
    network services part, 515
    performance, 519
    Signaling connection control part (SCCP), 517
    signaling traffic, 518
    user part, 517
        ISUP, 517
        OMAP, 518
        TCAP, 518
SSB, 260
Stack algorithm, 410
State diagrams, 408
Stochastic gradient algorithm. *See* least mean square algorithm (LMS), 375
Stochastically excited linear predictive coders (SELP), 545
Sub-band
    quadrature mirror filter, 426
Subscriber, 9, 10
Superframe, 563
Supervisory audio tone. *See* AMPS, SAT tone
Synchronous optical network (SONET), 44
Syndrome calculation, 406
System capacity, 28, 67–77, 86, 580

T

TACS, 594
Tap gain vector, 377
TDD. *See* time division duplex
TDMA, 5, 448, 453
    efficiency, 455
    number of channels, 455
TD-SCDMA, 36–40
Telecommunications Industry Association. *See* TIA
Temporary directory number, 522
Thermal noise, 611
Threshold extension, 277
Third generation. *See* 3G
Threshold, 276
Throughput, 463
TIA, 5

Time diversity, 356, 390
Time division duplex (TDD), 10, 11, 447
Time division multiple access. *See* TDMA
Timing advancement, 558
Traffic occupancy, 463
Traffic routing in wireless networks, 502
  connection oriented service, 502
  connectionless service, 503
Training sequence, 360
Transceiver, 10, 11
Transformation matrix, 117
Transparent tone-in-band (TTIB), 262
Transversal filter. See FIR filter, 359
Tree diagrams, 408
Trellis coded modulation (TCM), 412
Trellis diagrams, 408
Trunking, 4, 62, 77–86, 520, 528
  efficiency, 86, 92, 94, 96
  theory, 78
Turbo codes, 356, 412
Two-wave channel model, 236

U

Umbrella cell, 66
UMTS, 35, 36, 37–38, 501, 530–531
Unipolar, 282
United States Geological Survey. *See* USGS
Universal mobile telecommunications service. *See* UMTS
US digital cellular. *See* USDC
USDC (IS-136), 5, 7, 9, 373, 438, 474, 535, 541–549, 560
  channel coding, 545
  channels, 543
    CDVCC, 543
    DTC, 543
    FACCH, 543
    frame structure, 544
    SACCH, 543
  codec, 442
  demodulation, 548
  equalization, 548
  interleaving, 546
  modulation, 547
  speech coding, 545
User service time, 603
USGS, 146
UTRA, 36
UWC-136, 36

V

Vector quantization. *See* VQ
Vector sum excited linear predictive coder (VSELP), 442, 545
Virtual home entertainment, 37
Virtual switching. *See* Packet switching, 504
Visitor location register, 520, 553
Viterbi algorithm, 409
Vocoder
  cepstrum, 429, 430
  channel, 429
  formant, 429, 430
  linear predictive coder, 429, 431
    see also LPC
    code excited, 434
    multipulse excited, 434
    predictor coefficients, 432
    residual excited, 436
    stochastic. *See* code excited, 434
  voice excited, 429, 431
Voice activity, 475
Voice activity detector, 474, 528, 563
Voltage-controlled oscillator (VCO), 267, 268
VQ, 422
  algorithms, 423
    multistage, 423
    shape-gain, 423
    tree-structured, 423
  code book, 422, 423
Vulnerable period, 463

W

WACS. *See* PACS
Walfisch and Bertoni model, 155
WARC, 21, 23
W-CDMA, 32, 36
Wearable computers, 54
Wide area network (WAN), 507
Wideband data signaling, 538
Wideband microcell model, 155

Wi-Fi, 46
Wireless applications protocol (WAP), 29, 30
Wireless cable television, 593
Wireless Ethernet Compatibility Alliance, 46
Wireless internet service provider. *See* WISP
Wireless local loop. *See* WLL
Wireless local area networks. *See* WLAN
Wireless Valley Communications Inc., 48, 49, 94
WISP, 51
WLAN, 25, 26, 42, 46–52, 53, 54, 329, 533
WLL, 40–45
World Administrative Radio Conference. *See* WARC
WRC-2000, 21

X

X.25
    DCE, 505
    DSE, 505
    DTE, 505
    protocol, 505

Z

Zero forcing algorithm, 374
Zone microcell, 86, 93