# Contents

<table>
<thead>
<tr>
<th>Preface</th>
<th>xiii</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Part I Basics of Wireless Networks</strong></td>
<td></td>
</tr>
<tr>
<td><strong>1 Introduction</strong></td>
<td>3</td>
</tr>
<tr>
<td>1.1 Basics of a Wireless Communication System</td>
<td>3</td>
</tr>
<tr>
<td>1.1.1 Electromagnetic Spectrum and Frequency Range</td>
<td>3</td>
</tr>
<tr>
<td>1.1.2 Signal Characterization</td>
<td>5</td>
</tr>
<tr>
<td>1.1.3 Modulation</td>
<td>8</td>
</tr>
<tr>
<td>1.1.4 Wireless Channel and Signal Propagation</td>
<td>12</td>
</tr>
<tr>
<td>1.1.5 Channel Capacity</td>
<td>21</td>
</tr>
<tr>
<td>1.1.6 SINR and Channel Model for Packet Communication Systems</td>
<td>22</td>
</tr>
<tr>
<td>1.2 Medium Access in Wireless Networks</td>
<td>27</td>
</tr>
<tr>
<td>1.2.1 Channel Partitioning–Based MAC</td>
<td>28</td>
</tr>
<tr>
<td>1.2.2 Random Access–Based MAC</td>
<td>34</td>
</tr>
<tr>
<td>1.2.3 Duplexing</td>
<td>34</td>
</tr>
<tr>
<td>1.3 Wireless Access Technologies</td>
<td>35</td>
</tr>
<tr>
<td>1.3.1 Cellular Wireless Technology</td>
<td>35</td>
</tr>
<tr>
<td>1.3.2 WLAN, WMAN, and WPAN Technologies</td>
<td>39</td>
</tr>
<tr>
<td>1.4 Exercises</td>
<td>45</td>
</tr>
<tr>
<td>References</td>
<td>46</td>
</tr>
<tr>
<td><strong>2 Wireless Networks and Resource Allocation</strong></td>
<td>49</td>
</tr>
<tr>
<td>2.1 Protocol Layers for Data Communication</td>
<td>49</td>
</tr>
<tr>
<td>2.1.1 Physical Layer</td>
<td>49</td>
</tr>
<tr>
<td>2.1.2 Data Link Layer</td>
<td>50</td>
</tr>
<tr>
<td>2.1.3 Network Layer</td>
<td>51</td>
</tr>
<tr>
<td>2.1.4 Transport Layer</td>
<td>51</td>
</tr>
<tr>
<td>2.1.5 Session, Presentation, and Application Layers</td>
<td>51</td>
</tr>
<tr>
<td>2.2 Classification of Wireless Networks</td>
<td>52</td>
</tr>
<tr>
<td>2.2.1 Classification Based on Infrastructure</td>
<td>52</td>
</tr>
<tr>
<td>2.2.2 Classification Based on Spectrum Access</td>
<td>55</td>
</tr>
<tr>
<td>2.2.3 Classification Based on Heterogeneity</td>
<td>55</td>
</tr>
</tbody>
</table>
### Contents

#### Part I Physical Layer Issues in Wireless Networks

2.3 Physical Layer Issues in Wireless Networks 56  
2.3.1 Basic Components 56  
2.3.2 Digital Transmission Techniques 58  
2.3.3 Link Adaptation 62  
2.3.4 Diversity Transmission Techniques 65  
2.3.5 Smart Reception/Diversity Combining Techniques 65

#### Part II Techniques for Modeling and Analysis of Radio Resource Allocation Methods in Wireless Networks

3 Optimization Techniques 117  
3.1 Basics of Optimization 117  
3.1.1 Convex Functions 117  
3.1.2 Optimality Conditions for Unconstrained Optimization 119  
3.1.3 Line Search Methods for Unconstrained Optimization 121  
3.2 Convex Optimization 123  
3.2.1 Introduction 123  
3.2.2 Duality 124  
3.2.3 KKT Conditions 125  
3.2.4 Algorithms 127  
3.3 Integer Programming 132  
3.3.1 Cutting Plane Method 132  
3.3.2 Branch and Bound Algorithm 135  
3.4 Stochastic Optimization 140  
3.4.1 Introduction 140  
3.4.2 Robust Optimization 141  
3.5 Dynamic Programming 143  
3.5.1 Introduction 143  
3.5.2 Examples of Dynamic Programming 145  
3.6 Exercises 147  
References 153

4 Game Theory 154  
4.1 Fundamentals of Game Theory 154  
4.1.1 Brief History 154

© in this web service Cambridge University Press  
www.cambridge.org
4.1.2 Definition of a Game 155
4.2 Non-cooperative Game 159
4.2.1 Static Game 159
4.2.2 Dynamic Game 162
4.2.3 Bayesian Game 166
4.2.4 Evolutionary Game 168
4.3 Cooperative Game 172
4.3.1 Nash Bargaining Solution 172
4.3.2 Coalition Game 174
4.4 Auction Theory 178
4.4.1 Introduction to Auction Theory 178
4.4.2 Special Auction 180
4.5 Exercises 182

References 186

Part III Physical Layer Resource Allocation in Wireless Networks

5 General System Model and Preliminary Concepts 191
5.1 System Model for a General Multi-Cell Wireless Network 191
5.1.1 Modeling Path-Gains 192
5.1.2 SINR Model 194
5.1.3 Transmit Power Vector Corresponding to a Given SINR Vector 195
5.2 System Model for a Single-Cell Wireless Network 198
5.2.1 Modeling Path-Gains 198
5.3 SINR Feasibility in Interference-Limited Wireless Networks 200
5.3.1 Existence of a Positive Transmit Power Vector Corresponding to a Given SINR Vector 201
5.3.2 Existence of a Constrained Transmit Power Vector Corresponding to a Given SINR Vector 203
5.4 Exercises 205

References 206

6 Power Control in Cellular Wireless Networks 207
6.1 Objectives of Power Control 207
6.1.1 Performance Measure and Objective Functions 208
6.1.2 Distributed Versus Centralized Approach 210
6.2 Different Power Control Optimization Problems 210
6.3 Closed-Loop and Open-Loop Power Control 215
6.3.1 Open-Loop Power Control 215
6.3.2 Closed-Loop Power Control 216
6.4 Distributed Power Control Algorithms 216
6.4.1 Criteria for Evaluation and Analysis of Distributed Power Control 217
## Table of Contents

6.4.2 Existing Theoretical Frameworks for Fixed-Point and Convergence Analysis 217  
6.5 Distributed Target-SINR Tracking Power Control (TPC) 220  
6.6 Distributed Opportunistic Power Control (OPC) 222  
6.7 Distributed Dynamic Target-SINR Tracking Power Control (DTPC) 223  
6.8 Exercises 227  
References 230

### 7 Distributed Joint Power and Admission Control

7.1 Introduction 231  
7.2 Distributed Joint Power and Admission Control Algorithms 233  
   7.2.1 TPC with Permanent Removal (TPC-PR) 233  
   7.2.2 TPC with the Capability of Temporary Removal (TR) 234  
   7.2.3 TPC with Both Temporary and Permanent Removal (TPC-TPR) 235  
   7.2.4 TPC with the Capability of Temporary Removal and Feasibility Check (DFC) 235  
   7.2.5 TPC with Soft Removal (TPC-SR) 239  
7.3 Exercises 243  
References 244

### 8 Joint Power and Admission Control in Cognitive Radio Networks

8.1 Introduction 245  
8.2 System Model and Background 246  
8.3 Protection Constraints for Primary Users and Different JPAC Problems in CRNs 249  
8.4 Characterization of Feasible Interference Region 251  
   8.4.1 Total Received-Power-Temperature: Expressing PUs’ Protection Constraints Based on FRPR 252  
   8.4.2 Total Inter-Cell Interference Temperature: Expressing PUs’ Protection Constraints Based on FIIR 253  
   8.4.3 Total Cognitive Interference Temperature: Expressing PUs’ Protection Constraints Based on FCIR 255  
   8.4.4 Example and Discussion 257  
8.5 Existing Centralized JPAC Algorithms to Maximize the Number of Supported SUs Subject to PUs’ Protection Constraint 259  
   8.5.1 A General SSA 260  
   8.5.2 Interference Constraint-Aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) 263  
   8.5.3 Link-Gain Ratio Algorithm (LGRA) and Effective Link-Gain Ratio Algorithm (ELGRA) 264  
8.6 Distributed JPAC Algorithms for CRNs 267  
   8.6.1 TPC with PU-Protection Algorithm (TPC-PP) 267  
   8.6.2 Improved TPC-PP (ITPC-PP) 270
## Table of Contents

### Part III Physical Layer Resource Allocation in Wireless Networks

#### 8 Resource Allocation for Single-Carrier Systems

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Introduction</td>
<td>262</td>
</tr>
<tr>
<td>8.2 Resource Allocation for Single-Carrier Systems</td>
<td>263</td>
</tr>
<tr>
<td>8.3 Resource Allocation for Multi-Carrier Systems</td>
<td>266</td>
</tr>
<tr>
<td>8.4 Open Research Issues</td>
<td>269</td>
</tr>
<tr>
<td>References</td>
<td>272</td>
</tr>
</tbody>
</table>

#### 9 Cell Association in Cellular Networks

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 Introduction</td>
<td>276</td>
</tr>
<tr>
<td>9.2 System Model and Notations</td>
<td>276</td>
</tr>
<tr>
<td>9.3 Distributed Joint Cell Association and Power Control</td>
<td>278</td>
</tr>
<tr>
<td>9.4 Distributed Cell Association Schemes in Wireless Networks</td>
<td>281</td>
</tr>
<tr>
<td>9.4.1 Reference Signal Received Power (RSRP)-Based Cell Association Scheme</td>
<td>281</td>
</tr>
<tr>
<td>9.4.2 Biasing-Based Cell Range Expansion (CRE) in Wireless Networks with Heterogeneous BSs</td>
<td>282</td>
</tr>
<tr>
<td>9.5 Open Research Issues</td>
<td>284</td>
</tr>
<tr>
<td>9.6 Exercises</td>
<td>286</td>
</tr>
<tr>
<td>References</td>
<td>287</td>
</tr>
</tbody>
</table>

#### 10 Sub-Carrier/Sub-Channel Allocation in OFDMA Networks

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1 Introduction</td>
<td>291</td>
</tr>
<tr>
<td>10.2 OFDM-Based Multiple Access</td>
<td>292</td>
</tr>
<tr>
<td>10.3 Adaptive Radio Resource Allocation in OFDM Systems</td>
<td>293</td>
</tr>
<tr>
<td>10.3.1 System-Centric Approaches</td>
<td>294</td>
</tr>
<tr>
<td>10.3.2 Application-Centric Approaches</td>
<td>302</td>
</tr>
<tr>
<td>10.4 Open Research Issues</td>
<td>303</td>
</tr>
<tr>
<td>References</td>
<td>304</td>
</tr>
</tbody>
</table>

### Part IV Link Layer Resource Allocation in Wireless Networks

#### 11 Resource Allocation in Relay-Based Networks

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1 Introduction</td>
<td>308</td>
</tr>
<tr>
<td>11.2 Overview of Cooperative Diversity</td>
<td>309</td>
</tr>
<tr>
<td>11.2.1 Amplify-and-Forward Relaying</td>
<td>309</td>
</tr>
<tr>
<td>11.2.2 Decode-and-Forward Relaying</td>
<td>310</td>
</tr>
<tr>
<td>11.2.3 Selection or Opportunistic Relaying</td>
<td>311</td>
</tr>
<tr>
<td>11.2.4 Incremental Relaying</td>
<td>312</td>
</tr>
<tr>
<td>11.2.5 Two-Way Relaying</td>
<td>313</td>
</tr>
<tr>
<td>11.2.6 Other Enhancements</td>
<td>317</td>
</tr>
<tr>
<td>11.3 Resource Allocation for Single-Carrier Systems</td>
<td>318</td>
</tr>
<tr>
<td>11.3.1 Power Allocation for AF Relaying</td>
<td>318</td>
</tr>
<tr>
<td>11.3.2 Power Allocation for Selection AF Relaying</td>
<td>320</td>
</tr>
<tr>
<td>11.3.3 Joint Relay Selection and Power Allocation for ANC Two-Way Relaying</td>
<td>321</td>
</tr>
</tbody>
</table>
## Contents

11.4 Resource Allocation for Multi-Carrier Systems 323
11.4.1 Resource Allocation for AF Multi-Carrier Wireless Networks 324
11.4.2 Resource Allocation for DF Multi-Carrier Wireless Networks 333
11.4.3 Resource Allocation for Multi-User ANC Two-Way Relay Networks 337
11.5 Further Discussion 341
11.6 Exercises 342
References 348

### 12 Channel Allocation for Infrastructure-Based 802.11 WLANs

12.1 Introduction 352
12.2 System under Consideration 353
12.2.1 Network Topology 353
12.2.2 Channelization 353
12.2.3 Medium Access Control 355
12.3 Channel Assignment and AP Placement in IEEE 802.11 WLANs 356
12.3.1 Channel Assignment 356
12.3.2 AP Placement 356
12.4 Challenges in Channel Assignment in IEEE 802.11 WLANs 356
12.5 Channel Assignment Schemes in Centrally Managed Environments 358
12.5.1 Channel Assignment with AP Placement 358
12.5.2 Channel Assignment without AP Placement 363
12.6 Channel Assignment Schemes in Uncoordinated Environments 365
12.6.1 Least Congested Channel Search (LCCS) 365
12.6.2 MinMax Approach 366
12.6.3 MinMax II Approach 367
12.6.4 Hminmax/Hsum: Weighted Coloring Approach 367
12.6.5 Pick-Rand and Pick-First Approach 368
12.6.6 Pick-Rand and Pick-First II Approach 368
12.6.7 Channel Hopping Approach 368
12.6.8 Measurement-Based No-Coord 369
12.7 Comparison among Various Channel Assignment Schemes 369
12.8 Current Practice in Channel Assignment 371
12.9 Open Research Issues 372
References 373

### Part V Cross-Layer Modeling for Resource Allocation in Wireless Networks

13 Joint PHY/RLC Design in Cellular Wireless Networks 379
13.1 Introduction 379
13.2 Radio Link Control (RLC) Protocols: ARQ and HARQ 379
13.3 Link Adaptation with Adaptive Modulation and Coding (AMC) 381
## Contents

13.4 Channel Modeling
  13.4.1 I.I.D. Channel Models 383
  13.4.2 Two-State Markov Channel Model 383
  13.4.3 Finite-State Markov Channel Model 386

13.5 ARQ Protocols with I.I.D. Errors 386

13.6 ARQ Protocols in Two-State Markov Channel 388
  13.6.1 GBN-ARQ Protocol in Two-State Markov Channel 389
  13.6.2 SR-ARQ Protocol in Two-State Markov Channel 391

13.7 Truncated ARQ Protocol with Link Adaptation under I.I.D. Channels 392

13.8 Delay Analysis of GBN-ARQ Protocol with Link Adaptation under FSMC 393
  13.8.1 System and Protocol Description 394
  13.8.2 Queuing Model 395
  13.8.3 Derivations of Matrix Blocks in (13.57) 397
  13.8.4 Delay Analysis 400
  13.8.5 Numerical Example 401

13.9 Hybrid ARQ Protocol with Transmission Size Adaptation 402

13.10 Exercises 405

References 412

Index 415