Contents

Preface xv

1 Introduction: Generalized Model of Advanced Wireless Networks 1
- 1.1 Network Model 3
  - *1.1.1 Node Percolation* 3
  - *1.1.2 Link Percolation—Cognitive Links* 4
- 1.2 Network Connectivity 5
- 1.3 Wireless Network Design with Small World Properties 7
  - *1.3.1 Cell Rewiring* 7
  - *1.3.2 Traffic Distribution Aware Rewiring* 9
  - *1.3.3 Multicell Rewiring* 10
- 1.4 Frequency Channels Backup 11
  - *1.4.1* $m/k_f/s$ *Contract* 11
  - *1.4.2 Random Redundancy Assignment* (R^2A) 11
  - *1.4.3 On Demand Redundancy Assignment* 12
- 1.5 Generalized Network Model 13
- 1.6 Routing Protocols Over *s*-Lattice Network 14
  - *1.6.1 Application Specific Routing Protocol* 16
- 1.7 Network Performance 16
  - *1.7.1 Average Path Length* 18
  - *1.7.2 Clustering* 18
- 1.8 Node, Route, Topology, and Network Robustness 19
- 1.9 Power Consumption 20
- 1.10 Protocol Complexity 20
- 1.11 Performance Evaluation 21
  - *1.11.1 Average Path Length* 21
  - *1.11.2 Clustering* 23
  - *1.11.3 Node Robustness* 23
  - *1.11.4 Network Robustness* 23

1.11.5 Power Consumption 24
1.11.6 Protocol Complexity 25
1.12 Book Layout 27
1.12.1 Chapter 1: Introduction: Generalized Model of Advanced Wireless Networks 28
1.12.2 Chapter 2: Adaptive Network Layer 28
1.12.3 Chapter 3: Mobility Management 28
1.12.4 Chapter 4: Ad Hoc Networks 28
1.12.5 Chapter 5: Sensor Networks 28
1.12.6 Chapter 6: Security 29
1.12.7 Chapter 7: Networks Economy 29
1.12.8 Chapter 8: Multi-Hop Cellular Networks 29
1.12.9 Chapter 9: Cognitive Networks 29
1.12.10 Chapter 10: Stochastic Geometry 29
1.12.11 Chapter 11: Heterogeneous Networks 30
1.12.12 Chapter 12: Access Point Selection 30
1.12.13 Chapter 13: Self-Organizing Networks 30
1.12.14 Chapter 14: Complex Networks 30
1.12.15 Chapter 15: Massive MIMO 30
1.12.16 Chapter 16: Network Optimization Theory 31
1.12.17 Chapter 17: Network Information Theory 31
1.12.18 Chapter 18: Network Stability 31
1.12.19 Chapter 19: Multi-Operator Spectrum Sharing 31
1.12.20 Chapter 20: Large Scale Networks and Mean Field Theory 31
1.12.21 Chapter 21: mmWave 3D Networks 32
1.12.22 Chapter 22: Cloud Computing in Wireless Network 32
1.12.23 Chapter 23: Wireless Networks and Matching Theory 32
1.12.24 Chapter 24: Dynamic Wireless Network Infrastructure 33
Appendix A.1 33
References 34

2 Adaptive Network Layer **35**
2.1 Graphs and Routing Protocols 35
2.2 Graph Theory 54
2.3 Routing with Topology Aggregation 56
2.3.1 Network and Aggregation Models 58
References 60

3 Mobility Management **65**
3.1 Cellular Networks 65
3.1.1 Mobility Management in Cellular Networks 67
3.1.2 Location Registration and Call Delivery 71
3.1.3 Location Update and Terminal Paging 74
3.1.4 WATM Handoff Management in 4G Wireless Networks 88
3.1.5 Mobility Management for Satellite Networks 89

3.2 Cellular Systems with Prioritized Handoff 89
3.2.1 Performance Examples 99
3.3 Cell Residing Time Distribution 100
3.4 Mobility Prediction in Pico- and Micro-Cellular Networks 105
3.4.1 PST-QoS Guarantees Framework 107
3.4.2 Most Likely Cluster Model 108
Appendix A.3 Distance Calculation in an Intermediate Cell 116
References 122

4 Ad Hoc Networks 126
4.1 Routing Protocols 126
4.1.1 Ad Hoc Routing Protocols 127
4.1.2 Reactive Protocols 134
4.2 Hybrid Routing Protocol 146
4.3 Scalable Routing Strategies 152
4.4 Multipath Routing 160
4.5 Clustering Protocols 162
4.5.1 Introduction 162
4.5.2 Clustering Algorithm 164
4.6 Cashing Schemes for Routing 175
4.7 Distributed QoS Routing 181
4.7.1 Forwarding the Received Tokens 185
4.7.2 Bandwidth Constrained Routing 186
4.7.3 Forwarding the Received Tokens 187
References 190

5 Sensor Networks 194
5.1 Introduction 194
5.2 Sensor Network Parameters 196
5.3 Sensor Network Architecture 199
5.3.1 Physical Layer 199
5.3.2 Data Link Layer 200
5.3.3 Network Layer 202
5.3.4 Transport Layer 207
5.3.5 Application Layer 208
5.4 Mobile Sensor Network Deployment 209
5.5 Directed Diffusion 212
5.6 Aggregation in Wireless Sensor Networks 216
5.7 Boundary Estimation 220
5.7.1 Number of RDPs in $\mathcal{P}$ 222
5.7.2 Kraft Inequality 222
5.7.3 Upper Bounds on Achievable Accuracy 223
5.7.4 System Optimization 224
5.8 Optimal Transmission Radius in Sensor Networks 227
5.9 Data Funneling 233
5.10 Equivalent Transport Control Protocol in Sensor Networks 236
References 237

6 Security **244**
6.1 Authentication 244
6.1.1 Attacks on Simple Cryptographic Authentication 247
6.1.2 Canonical Authentication Protocol 250
6.2 Security Architecture 253
6.3 Key Management 257
6.4 Security in Ad Hoc Networks 261
6.4.1 Self-Organized Key Management 265
6.5 Security in Sensor Networks 268
References 269

7 Network Economics **272**
7.1 Fundamentals of Network Economics 272
7.1.1 Externalities 273
7.1.2 Pricing of Services 274
7.1.3 Congestion Pricing 275
7.1.4 Congestion Game 276
7.1.5 Modeling Service Differentiation 277
7.1.6 Competition 278
7.1.7 Auctions 279
7.1.8 Bidding for QoS 280
7.1.9 Bandwidth Auction 281
7.1.10 Investments 282
7.2 Wireless Network Microeconomics: Data Sponsoring 286
7.2.1 Background Solutions 287
7.2.2 Sponsored Data Model 287
7.3 Spectrum Pricing for Market Equilibrium 291
7.3.1 Network and Pricing Model 291
7.3.2 Optimization of Spectrum Pricing 292
7.3.3 Distributed Solutions 295
7.3.4 Stability of Distributed Pricing Models 297
7.4 Sequential Spectrum Sharing 300
7.4.1 Sequential Spectrum Sharing and Interrelated Market Model 301
7.4.2 Iterative Negotiation Algorithms 304
7.5 Data Plan Trading 308
7.5.1 Modeling User's Buyer/Seller Trading Incentives 309
7.5.2 ISP Trading Policies 313
References 315

8 Multi-Hop Cellular Networks **318**
8.1 Modeling Multi-Hop Multi-Operator Multi-Technology Wireless Networks 318
8.2 Technology Background 319
8.3 System Model and Notation 321
8.4 m^3 Route Discovery Protocols 323
8.4.1 Minimum Distance Routing 323
8.4.2 Limited Interference Routing/Scheduling 324

8.5 Performance of m^3 Route Discovery Protocols 327
8.6 Protocol Complexity 329
8.7 Traffic Offloading Incentives 330
8.7.1 Collaborative Negotiation between MNO and SSO 335
8.8 Performance Illustrations 335
8.8.1 m^3 Route Discovery Protocols 336
8.8.2 Capacity and Throughput for the Modified m^3 Route Discovery Protocols 338
8.8.3 Traffic Offloading Incentives 341
8.8.4 Implementation and Impact of Mobility 343
References 344

9 Cognitive Networks 346
9.1 Technology Background 346
9.1.1 Fundamentals 346
9.1.2 Network and Transport Layer Protocols 348
9.2 Spectrum Auctions for Multi-hop Cognitive Networks 350
9.2.1 Background Technology 352
9.2.2 System Model 353
9.2.3 Heuristic Truthful Auction 356
9.2.4 Randomized Auction 359
9.3 Compound Auctioning in Multi-hop Cognitive Cellular Networks 363
9.3.1 Network Model 364
9.3.2 Spectrum Aware Routing Discovery Protocol 367
9.3.3 Joint Resource Auction and Tipping Scheme 370
9.3.4 Reinforcement Learning Based Auction Scheme 372
9.3.5 Group Buying Based Auction Design 373
9.3.6 Further Extension to General Scenarios 377
9.3.7 System Performance 378
References 388

10 Stochastic Geometry 391
10.1 Background Theory 391
10.1.1 Point Process 391
10.1.2 Outage Probability 394
10.1.3 Multi-tier Networks 396
References 398

11 Heterogeneous Networks 402
11.1 Preliminaries 402
11.2 Self-Organized Small Cell Networks 404
11.2.1 Background Technology 404
11.2.2 System Model 405
11.2.3 Self-Organized SCN 409
11.3 Dynamic Network Architecture 411
11.3.1 System Model 412

11.3.2 Optimum Network Architecture 415
11.3.3 Dynamic Tracking of the Optimum Topology 422
11.3.4 Performance Illustrations 427
11.4 Economics of Heterogeneous Networks 434
11.4.1 Macrocell Service Only 434
11.4.2 Introducing Femtocells 436
11.4.3 Impact of Users' Reservation Payoffs 438
11.4.4 Femtocell Frequency Reuse 440
11.4.5 Femtocell Operational Cost 440
11.4.6 Limited Femtocell Coverage 441
References 443

12 Access Point Selection **446**
12.1 Background Technology 446
12.2 Network Selection Game 449
12.3 Joint Access Point Selection and Power Allocation 453
12.3.1 Single AP Network 454
12.3.2 Joint AP Selection and Power Control 457
12.3.3 Distributed Algorithms 459
12.4 Joint AP Selection and Beamforming Optimization 463
12.4.1 Network Model 463
References 474

13 Self-Organizing Networks **478**
13.1 Self-Organizing Network Optimization 478
13.2 System Model 478
13.3 Joint Optimization of Tilts and AP Association 481
13.3.1 System Objective Function 481
13.3.2 Optimization Problem 482
References 484

14 Complex Networks **486**
14.1 Evolution Towards Large-Scale Networks 486
14.1.1 Types of Networks 487
14.2 Network Characteristics 491
14.3 Random Graphs 494
References 496

15 Massive MIMO **499**
15.1 Linearly Precoded Multicellular Downlink System 499
15.1.1 Background Technology 500
15.2 System Model 503
15.2.1 Channel Uncertainty Modeling 504
15.2.2 Stochastic Optimization 505
15.3 Optimization for Perfect Channel State Information 505

15.4 Robust Designs for WSRM Problem 509
15.4.1 Approximation 1 510
15.4.2 Approximation 2 512
Appendix A.15 519
Appendix B.15 519
References 521

16 Network Optimization Theory 523
16.1 Introduction 523
16.2 Layering as Optimization Decomposition 524
16.2.1 TCP Congestion Control 525
16.2.2 TCP Reno/RED 526
16.2.3 TCP Vegas/DropTail 526
16.2.4 Optimization of MAC Protocol 527
16.2.5 Utility Optimal MAC Protocol/Social Optimum 530
16.3 Cross-Layer Optimization 533
16.3.1 Congestion Control and Routing 533
16.3.2 Congestion Control and Physical Resource Allocation 536
16.3.3 Congestion and Contention Control 538
16.3.4 Congestion Control, Routing, and Scheduling 542
16.4 Optimization Problem Decomposition Methods 543
16.4.1 Decoupling Coupled Constraints 543
16.4.2 Dual Decomposition of the Basic NUM 544
16.4.3 Coupling Constraints 547
16.4.4 Decoupling Coupled Objectives 548
16.4.5 Alternative Decompositions 550
References 554

17 Network Information Theory 557
17.1 Capacity of Ad Hoc Networks 557
17.1.1 Arbitrary Networks 558
17.1.2 Random Networks 559
17.1.3 Arbitrary Networks: Upper Bound on Transport Capacity 560
17.1.4 Arbitrary Networks: Lower Bound on Transport Capacity 564
17.1.5 Random Networks: Lower Bound on Throughput Capacity 565
17.2 Information Theory and Network Architectures 569
17.2.1 Upper Bounds Under High Attenuation 571
17.2.2 Multihop and Feasible Lower Bounds Under High Attenuation 573
17.3 Cooperative Transmission in Wireless Multihop *Ad Hoc* Networks 577
References 584

18 Stability of Advanced Network Architectures 585
18.1 Stability of Cooperative Cognitive Wireless Networks 585
18.2 System Model 586
18.2.1 Network Architecture 586
18.2.2 Channel 588
18.2.3 Cooperative Communication 589

18.3 System Optimization 590
18.4 Optimal Control Policy 592
18.5 Achievable Rates 594
18.5.1 Cooperative Network Stability Region 594
18.5.2 Non-Cooperative Network Stability Region 597
18.6 Stabilizing Transmission Policies 598
18.6.1 Network Parameters 598
18.6.2 Stationary Transmission Policy 599
18.6.3 Lyapynov Drift Analysis of the STAT Policy 600
18.6.4 Stability of the Dynamic Transmission Policy 604
References 605

19 Multi-Operator Spectrum Sharing 607
19.1 Business Models for Spectrum Sharing 607
19.1.1 Background Technology 607
19.1.2 Multi-Operator Cooperation Models 610
19.1.3 System Performance 619
19.1.4 Performance Illustrations 631
19.2 Spectrum Sharing in Multi-hop Networks 638
19.2.1 Multi-Operator Cooperation Models 639
19.2.2 System Analysis 642
19.2.3 System Performance 652
References 656

20 Large Scale Networks and Mean Field Theory 659
20.1 MFT for Large Heterogeneous Cellular Networks 659
20.1.1 System Model 660
20.1.2 Macro BS Optimization Problem 660
20.1.3 Mean Field Game Among Femto BSs 662
20.1.4 Interference Average Estimation 663
20.2 Large Scale Network Model Compression 664
20.2.1 Model Definition 665
20.2.2 Mean Field Analysis 667
20.3 Mean Field Theory Model of Large Scale DTN Networks 668
20.4 Mean Field Modeling of Adaptive Infection Recovery in Multicast DTN Networks 674
20.4.1 Background Technology 674
20.4.2 System Model 677
20.4.3 Recovery Schemes for Multicast DTN 679
20.4.4 System Performance 684
20.4.5 Extensions of the Model and Implementation Issues 687
20.4.6 Illustrations 690
20.5 Mean Field Theory for Scale-Free Random Networks 701
20.5.1 Network Models 701
20.5.2 The Scale-Free Model by Barabasi 703

20.5.3 Mean Field Network Model 705
20.5.4 Incomplete BA Network Models 706
20.6 Spectrum Sharing and MFT 709
20.6.1 Optimal Wireless Service Provider Selection Strategy Using MFT 709
20.6.2 WSP Selection Strategy for Finite Number of Terminals 711
20.7 Modeling Dynamics of Complex System 711
20.7.1 Dynamic System Model 712
20.7.2 Birth–Death Network Model 717
20.7.3 Network Rewiring 719
20.7.4 Multiple Time Scale System Optimization 719
Appendix A.20 Iterative Algorithm to Solve Systems of Nonlinear ODEs (DiNSE-Algorithm) 721
Appendix B.20 Infection Rate of Destinations for DNCM 722
Appendix C.20 Infection Rate for Basic Epidemic Routing 722
References 722

21 mmWave Networks 726
21.1 mmWave Technology in Subcellular Architecture 726
21.1.1 Limitations of mmWave Technology 727
21.1.2 Network Model 728
21.1.3 Network Performance 731
21.1.4 Performance of Dense mmWave Networks 735
21.2 Microeconomics of Dynamic mmWave Networks 737
21.2.1 Dynamic Small Cell Networks 737
21.2.2 DSC Network Model 738
21.2.3 DSC Network Performance 739
References 747

22 Cloud Computing in Wireless Networks 750
22.1 Technology Background 750
22.2 System Model 752
22.3 System Optimization 756
22.4 Dynamic Control Algorithm 758
22.4.1 Resource Allocation at the Terminals 758
22.4.2 Resource Allocation at the Servers 761
22.5 Achievable Rates 761
22.5.1 Supportable Input Rate Region at the Terminals 761
22.5.2 Supportable Input Rate Region at Servers 763
22.6 Stabilizing Control Policies 763
22.6.1 Lyapunov Drift 763
22.6.2 Randomized Stationary Policy 765
22.6.3 Frame Based Policy 766
22.6.4 Dynamic Control Policy 767
References 769

23 Wireless Networks and Matching Theory **771**
23.1 Background Technology: Matching Markets 772
23.1.1 Two-Sided Matching 772
23.1.2 One-Sided Matching 775
23.2 Distributed Stable Matching in Multiple Operator Cellular Network with Traffic Offloading 776
23.2.1 System Model 777
23.2.2 Problem Formulation 778
23.3 College Admissions Game Model for Cellular Networks with Traffic Offloading 779
23.3.1 System Model 779
23.3.2 Modeling Access Point Selection as College Admissions Matching 781
23.4 Many to Many Matching Games for Caching in Wireless Networks 783
23.4.1 System Model 783
23.4.2 Proactive Caching and Matching Theory 784
23.4.3 Proactive Caching Algorithm 786
23.5 Many to One Matching with Externalities in Cellular Networks with Traffic Offloading 787
23.5.1 System Model 787
23.5.2 Offloading Cell Association as a Matching Game with Externalities 789
23.6 Security in Matching of Device to Device Pairs in Cellular Networks 791
23.6.1 System Model 792
23.6.2 True Preferences 793
23.6.3 Cheating: Coalition Strategy 794
References 795

24 Dynamic Wireless Network Infrastructure **797**
24.1 Infrastructure Sharing in Multi-Operator Cellular Networks 797
24.1.1 System Model 798
24.1.2 Infrastructure Sharing Mechanism 799
24.2 User Provided Connectivity 802
24.2.1 System Model 802
24.2.2 Aggregate Service Value 804
24.3 Network Virtualization 806
24.3.1 Service-Oriented Network Virtualization in Telecommunications 807
24.4 Software Defined Networks 810
24.4.1 Current SDN Architectures 811
24.4.2 SDN Architecture Components 812
24.4.3 SDN Control Models 813
24.4.4 SDN and Infrastructure Based Wireless Access Networks 814
24.5 SDN Security 816
24.5.1 Security in Programmable Networks 816
24.5.2 Security Threats in SDN Networks 817
24.5.3 Security Solutions for SDN Network 818
References 819

Index **827**