Contents

List of contributors *page* xvi
Preface xxi

Part I Communication architectures and models for green radio networks **1**

1 Fundamental trade-offs on the design of green radio networks **3**
Yan Chen, Shunqing Zhang, and Shugong Xu

1.1 Introduction 3
1.2 Insight from Shannon's capacity formula 5
1.2.1 SE–EE trade-off 6
1.2.2 BW–PW trade-off 7
1.2.3 DL–PW trade-off 8
1.2.4 DE–EE trade-off 10
1.2.5 Summary 10
1.3 Impact of practical constraints 12
1.4 Latest research and future directions 14
1.4.1 SE–EE trade-off 14
1.4.2 BW–PW trade-off 16
1.4.3 DL–PW trade-off 17
1.4.4 DE–EE trade-off 18
1.5 Conclusion 20

2 Algorithms for energy-harvesting wireless networks **24**
Vinod Sharma, Utpal Mukherji, and Vinay Joseph

2.1 Introduction 24
2.2 Energy-harvesting technologies 26
2.3 Point-to-point channel 28
2.3.1 Model and notation 28
2.3.2 Stability 29
2.3.3 Delay optimal policies 30
2.3.4 Generalizations 31
2.3.5 Simulations 32

2.3.6 Model with sleep option 34
2.3.7 Fundamental limits of transmission 37
2.4 MAC policies 39
2.4.1 Orthogonal channels 40
2.4.2 Opportunistic scheduling for fading channels: orthogonal channels 40
2.4.3 Opportunistic scheduling for fading channels: CSMA 42
2.4.4 Simulations for MAC protocols 42
2.5 Multi-hop networks 44
2.5.1 Problem formulation 45
2.5.2 Simulations 48
2.6 Conclusion 50

3 PHY and MAC layer optimization for energy-harvesting wireless networks 53
Neelesh B. Mehta and Chandra R. Murthy

3.1 Introduction 53
3.2 Physical layer design 55
3.2.1 No CSI at transmitter and retransmissions 55
3.2.2 Power management with channel state information 61
3.2.3 Simulation results 66
3.3 Cross-layer implications in a multi-node network 67
3.3.1 Multiple access selection algorithms 69
3.3.2 Energy harvesting, storage, and usage model 70
3.3.3 Energy neutrality implication 70
3.3.4 Performance analysis 70
3.3.5 Numerical results 73
3.4 Conclusion 74

4 Mechanical relaying techniques in cellular wireless networks 78
Panayiotis Kolios, Vasilis Friderikos, and Katerina Papadaki

4.1 Introduction 78
4.2 Background 79
4.2.1 DTN architecture 79
4.2.2 Routing in DTNs 80
4.3 Mechanical relaying 81
4.3.1 Mobile internet traffic mix 83
4.3.2 Mechanical relaying strategies 86
4.4 Real-world measurements 89
4.5 Related standardization efforts 92
4.6 Conclusion 93

Part II Physical communications techniques for green radio networks 97

5 Green modulation and coding schemes in energy-constrained wireless networks 99
Jamshid Abouei, Konstantinos N. Plataniotis, and Subbarayan Pasupathy

5.1 Introduction 99
5.2 System model and assumptions 101
5.2.1 Performance metric 101
5.2.2 Channel model 102
5.3 Energy consumption of uncoded scheme 103
5.3.1 M-ary FSK 103
5.3.2 M-ary QAM 106
5.3.3 Offset-QPSK 108
5.3.4 Numerical evaluations 110
5.4 Energy-consumption analysis of LT coded modulation 113
5.4.1 Energy efficiency of coded system 114
5.4.2 Energy optimality of LT codes 116
5.5 Numerical results 118
5.5.1 Experimental setup 118
5.5.2 Optimal configuration 119
5.6 Conclusion 122

6 Cooperative techniques for energy-efficient wireless communications 125
Osama Amin, Sara Bavarian, and Lutz Lampe

6.1 Introduction 125
6.2 Energy-efficiency metrics for wireless networks 126
6.2.1 Instantaneous EE metrics 128
6.2.2 Average EE metrics 129
6.3 Energy-efficient cooperative networks 130
6.3.1 Single relay cooperative network 131
6.3.2 Multi-relay cooperative network 136
6.3.3 Multi-hop cooperative network 137
6.4 Optimizing the EE performance of cooperative networks 139
6.4.1 Modulation constellation size 139
6.4.2 Power allocation 141
6.5 Energy efficiency in cooperative base stations 143
6.6 Conclusion 146

7 Effect of cooperation and network coding on energy efficiency of wireless transmissions 150
Nof Abuzainab and Anthony Ephremides

7.1 Introduction 150
7.2 Relay cooperation in single link wireless transmissions 152

7.2.1 System model 152
7.2.2 Cooperation protocols 153
7.3 User cooperation in wireless multicast transmissions 155
7.3.1 System model 155
7.3.2 Cooperation protocols 156
7.4 Energy-cost minimization 158
7.5 Stable throughput computation 158
7.6 Performance evaluation 159
7.6.1 Relay cooperation 159
7.6.2 User cooperation 161
7.7 Conclusion 162

Part III Base station power-management techniques for green radio networks 165

8 Opportunistic spectrum and load management for green radio networks 167
Oliver Holland, Christian Facchini, A. Hamid Aghvami, Orlando Cabral, and Fernando Velez

8.1 Introduction 167
8.2 Opportunistic spectrum and load management concepts 169
8.2.1 Opportunistic load management to power down radio network equipment 169
8.2.2 Opportunistic spectrum management to improve propagation characteristics 171
8.2.3 Power saving by channel bandwidth increase or better bandwidth balancing 173
8.3 Assessment of power-saving potential 174
8.3.1 Example reflecting GSM networks 174
8.3.2 Example reflecting LTE networks 180
8.3.3 Example reflecting HSDPA networks 185
8.3.4 Power saving by channel bandwidth increase or better bandwidth balancing 187
8.4 Conclusion 188

9 Energy-saving techniques in cellular wireless base stations 190
Tao Chen, Honggang Zhang, Yang Yang, and Kari Horneman

9.1 Introduction 190
9.2 Energy-consumption model of RBS 191
9.3 EE metric 192
9.4 RBS energy-saving methods 194
9.4.1 Time-domain approaches 195
9.4.2 Frequency-domain approaches 196
9.4.3 Spatial-domain approaches 197
9.4.4 Performance comparison 198

9.5 Layered structure for energy saving 199
9.5.1 System model and assumptions 199
9.5.2 Energy-consumption model of RBS 200
9.5.3 Energy-aware handover mechanism 201
9.5.4 Simulation study 203
9.6 Conclusion 206

10 Power management for base stations in a smart grid environment 209
Xiao Lu, Dusit Niyato, and Ping Wang

10.1 Introduction 209
10.2 Power management for wireless base station 210
10.2.1 Green communications in centralized wireless networks 210
10.2.2 Approaches for power management in a base station 212
10.2.3 Open research issues 215
10.3 Power-consumption model for a base station 216
10.3.1 Components of a base station 216
10.3.2 Assumptions and power-consumption model for a macro base station 218
10.3.3 Assumptions and power-consumption model for a micro base station 218
10.4 Optimization of power management in a smart grid environment 220
10.4.1 System model 220
10.4.2 Demand-response for base station in smart grid 222
10.4.3 Optimization formulation for power management 223
10.4.4 Performance evaluation 226
10.5 Conclusion 230

11 Cooperative multicell processing techniques for energy-efficient cellular wireless communications 236
Mohammad Reza Nakhai, Tuan Anh Le, Auon Muhammad Akhtar, and Oliver Holland

11.1 Introduction 236
11.2 Cell splitting 238
11.3 A multicell processing model 239
11.3.1 Transmission and channel model 239
11.3.2 User-position-aware multicell processing 242
11.4 Multicell beamforming strategies 243
11.4.1 MBF using instantaneous CSIT 243
11.4.2 MBF using second-order statistical CSIT 245
11.4.3 An iterative MBF using second-order statistical CSIT 246
11.5 Coordinated beamforming 248
11.6 Backhaul protocol 250
11.6.1 A protocol for information circulation in the backhaul 250

11.6.2 Power calculation for the ring protocol 251
11.6.3 An effective sum-rate 252
11.7 Performance evaluation 252
11.7.1 Performance evaluation under ideal backhaul 252
11.7.2 Performance evaluation under limited backhaul 254
11.8 Cooperative routing 255
11.8.1 Power-aware cooperative routing algorithm 256
11.9 Conclusion 258

Part IV Wireless access techniques for green radio networks 261

12 Cross-layer design of adaptive packet scheduling for green radio networks 263
Ashok Karmokar, Alagan Anpalagan, and Ekram Hossain

12.1 Introduction 263
12.2 Related work 264
12.3 Importance of cross-layer optimized design 265
12.4 Why cross-layer adaptation is important for green radio networks 266
12.5 Cross-layer interactions, models, and actions 267
12.6 Cross-layer vs. single-layer adaptation techniques 271
12.7 How to solve the cross-layer design problem 273
12.8 Power savings in the cross-layer optimized system 276
12.9 Other literature on energy-efficient cross-layer techniques 278
12.10 Challenges and future directions 281
12.11 Conclusion 282

13 Energy-efficient relaying for cooperative cellular wireless networks 286
Yifei Wei, Mei Song, and F. Richard Yu

13.1 Introduction 286
13.2 Energy saving in cellular wireless networks 288
13.2.1 Energy-saving techniques 288
13.2.2 Energy-efficiency criteria 289
13.3 Energy-efficient cooperative communication based on selective relay 290
13.3.1 Relay selection schemes 291
13.4 System model for the relay selection problem 293
13.4.1 S2R channel 294
13.4.2 R2D channel 294
13.4.3 Energy model 295
13.4.4 Objectives 296
13.5 Problem formulation 296
13.5.1 Relay states 296
13.5.2 System reward 297
13.5.3 Solution to the restless bandit problem 298

13.6 Distributed relay selection scheme 300
13.6.1 Available relay candidates 300
13.6.2 Relay selection process 301
13.6.3 Cost evaluation 302
13.7 Simulation results and discussions 302
13.7.1 System reward 303
13.7.2 Error propagation mitigation 303
13.7.3 Spectral efficiency improvement 305
13.7.4 Network lifetime 305
13.8 Conclusion 306

14 Energy performance in TDD-CDMA multi-hop cellular networks 309
Hoang Thanh Long, Xue Jun Li, and Peter Han Joo Chong

14.1 Introduction 309
14.2 Structure of relay stations and power consumption 309
14.2.1 Random relay station (RRS) structure 311
14.3 Time-slot allocation schemes 312
14.3.1 Fixed time-slot allocation (FTSA) 313
14.3.2 Dynamic time-slot allocation (DTSA) 313
14.3.3 Multi-link fixed time-slot allocation (ML-FTSA) 314
14.3.4 Multi-link dynamic time-slot allocation (ML-DTSA) 315
14.4 System model 315
14.5 Simulation results and discussions 317
14.5.1 Blocking and dropping probabilities for high and low data rate traffic 320
14.5.2 Energy consumption for single-hop and multi-hop transmission using FRS 322
14.5.3 Energy consumption for RRS structure 325
14.6 Conclusion 328

15 Resource allocation for green communication in relay-based cellular networks 331
Umesh Phuyal, Satish C. Jha, and Vijay K. Bhargava

15.1 Introduction 331
15.2 Enabling green communication in cellular wireless networks 332
15.2.1 Component level 332
15.2.2 Equipment level 332
15.2.3 Network level 332
15.2.4 Computational complexity versus transmit-power-saving 333
15.3 Relay-based green CCN 333
15.3.1 Implementation issues and challenges 334
15.3.2 Advantages of fixed relay-based CCN 336
15.3.3 Green performance metrics for resource allocation 337

15.4 Resource-allocation schemes for CCN: a brief survey 337
15.4.1 Throughput maximization schemes 338
15.4.2 QoS-aware transmit power minimization schemes 338
15.4.3 Energy-aware green schemes 339
15.5 Design of a green power allocation scheme 339
15.5.1 System model 340
15.5.2 Green power allocation scheme 342
15.5.3 Performance analysis of GPA scheme 344
15.5.4 Adaptive interrupted transmission 345
15.5.5 Simulation results 345
15.6 Green performance versus system capacity 351
15.6.1 Performance analysis 352
15.7 Conclusion 354

Part V Green radio test-bed, experimental results, and standardization activities 357

16 How much energy is needed to run a wireless network? 359
Gunther Auer, Vito Giannini, István Gódor, Oliver Blume, Albrecht Fehske, Jose Alonso Rubio, Pål Frenger, Magnus Olsson, Dario Sabella, Manuel J. Gonzalez, Muhammad Ali Imran, and Claude Desset

16.1 Introduction 359
16.2 Energy-efficiency evaluation framework (E^3F) 360
16.2.1 Small-scale, short-term system-level evaluations 361
16.2.2 Global E^3F 361
16.3 Power model 363
16.3.1 Base station power-consumption breakdown 363
16.3.2 BS power consumption at variable load 366
16.4 Traffic model 367
16.4.1 Deployment areas of Europe 367
16.4.2 Long-term large-scale traffic models 368
16.4.3 Statistical short-term traffic models 372
16.5 Green metrics 372
16.5.1 Efficiency metrics vs. consumption metrics 373
16.5.2 Energy-consumption metrics in cellular networks 374
16.6 Case study: energy efficiency of LTE 375
16.6.1 Assessment methodology 375
16.6.2 Small-scale short-term evaluations 376
16.6.3 Large-scale long-term evaluations 377
16.7 LTE technology potential in real deployments 377
16.7.1 Global radio access networks 378
16.7.2 LTE system evaluation 380
16.7.3 Evolution of LTE energy-efficiency over time 380
16.8 Fundamental challenges and future potential 381
16.9 Conclusion 382

17 Standardization, fora, and joint industrial projects on green radio networks 385
Alberto Conte, Hakon Helmers, and Philippe Sehier

17.1 Introduction 385
17.2 Standardization fora 386
17.2.1 ETSI 387
17.2.2 3GPP 389
17.2.3 TIA and 3GPP2 394
17.2.4 ATIS 395
17.2.5 IETF/EMAN 395
17.2.6 CCSA 396
17.3 Consortium and joint projects 396
17.3.1 NGMN alliance 396
17.3.2 FP7 EARTH project 398
17.3.3 GreenTouch initiative 400
17.4 Synthesis and classification of energy-saving solutions for wireless networks 403
17.4.1 Technology and component level 403
17.4.2 Base station adaptation to traffic load 404
17.4.3 Network architecture 405
17.4.4 Heterogeneous networks 405
17.4.5 Air interface 406
17.4.6 Dynamic NW adaptation to traffic load 407
17.5 Conclusion 407

Index 409