Contents

Preface xv
Acknowledgements xix
List of contributors xxiii

1 Spatial modulation for cooperative networks 1
1.1 Introduction 1
1.2 Protocol I: DSM 5
1.2.1 Transmission model 5
1.2.2 Demodulation at the destination 9
1.2.3 Error probability and diversity order analysis 12
1.2.4 Average energy consumption and average rate of DSM 16
1.3 Protocol II: DSM-STBC 20
1.3.1 Transmission model 20
1.3.2 Demodulation at the destination 24
1.3.3 Remarks 26
1.4 Numerical and simulation results 26
1.5 Conclusion 31
Acknowledgements 32
References 33

2 Relaying for massive MIMO 39
2.1 Introduction 39
2.1.1 Single-hop massive MIMO systems 42
2.1.2 Dual-hop massive MIMO systems 43
2.2 System configurations 44
2.2.1 Antenna configuration 45
2.2.2 Acquisition of channel state information and duplexing modes 46
2.2.3 Transmission frame structure 48
2.3 Favourable propagation in massive MIMO 50
2.3.1 Channel modelling 51
2.4 Channel estimation 53
2.5 Massive MIMO configurations and signal processing aspects 54
2.5.1 General end-to-end signal model 54
2.5.2 Signal processing aspects 55
2.6 Fundamental performance metrics 57

2.7 Case study 58
2.7.1 Transmit power scaling at user nodes 59
2.7.2 Transmit power scaling at relay nodes 62
2.7.3 Transmit power scaling at user and relay nodes 63
2.7.4 Numerical results 65
2.7.5 System design insights 66
2.8 Summary 67
References 67

3 SUDAS: mmWave relaying for 5G outdoor-to-indoor communications 71
3.1 Introduction 71
3.2 5G communication systems 72
3.2.1 Massive MIMO 73
3.2.2 Small cells and mmWaves 73
3.2.3 Combinations of massive MIMO and mmWave 75
3.2.4 SUDAS – overview 75
3.2.5 SUDAS – working principle 76
3.2.6 SUDAS – application scenarios 78
3.2.7 Comparisons with VMIMO 80
3.3 SUDAC – implementation 81
3.3.1 Amplify-and-forward 82
3.3.2 Compress-and-forward 83
3.4 Mathematical system model 84
3.4.1 SUDAS downlink communication model 84
3.4.2 System throughput 86
3.5 Numerical results 87
3.5.1 Average system throughput versus transmit power 87
3.5.2 Average system throughput versus number of SUDACs 88
3.6 SUDAS – challenges 89
3.6.1 Keyhole effect 89
3.6.2 Carrier aggregation 90
3.6.3 Resource allocation for multiple MNOs 90
3.6.4 Mobility 91
3.6.5 Synchronization and channel estimation 92
3.6.6 Power consumption 92
3.7 Conclusions 93
Acknowledgements 93
References 93

4 Linear processing techniques for multi-antenna relaying systems with interference 97
4.1 Introduction 97
4.1.1 Interference mitigation in relaying systems 97
4.1.2 Interference exploitation for wireless-powered relaying systems 99
4.1.3 Organization of the chapter 100

4.2 Linear processing techniques 101
4.2.1 Maximum ratio combining 101
4.2.2 Zero-forcing 102
4.2.3 Minimum mean square error 102
4.3 Linear processing for interference suppression in relaying systems 103
4.3.1 MRC/MRT scheme 104
4.3.2 ZF/MRT scheme 106
4.3.3 MMSE/MRT scheme 108
4.3.4 Large N analysis 110
4.3.5 Comparison of the schemes 110
4.3.6 Numerical results 111
4.4 Linear processing for interference exploitation in wireless-powered relaying systems 113
4.4.1 MRC/MRT scheme 115
4.4.2 ZF/MRT scheme 118
4.4.3 MMSE/MRT scheme 119
4.4.4 Numerical results 121
4.5 Conclusions 121
4.5.1 Future directions 123
References 124

5 Relaying in full-duplex radio communication systems 129
5.1 Introduction 129
5.1.1 Duplex modes for relay systems 130
5.1.2 Loopback self-interference 132
5.1.3 Organization of the chapter 133
5.2 System model 134
5.2.1 End-to-end signal models 135
5.2.2 Signal-to-interference-and-noise ratios 139
5.3 Transmit power control in FD relaying 140
5.3.1 AF relaying 142
5.3.2 DF relaying 144
5.3.3 Performance analysis 145
5.4 FD vs. HD relaying 151
5.4.1 Analysis of short-term performance 152
5.4.2 Analysis of long-term performance 162
5.5 Conclusions 170
References 170

6 Relay selection in modern communication systems 175
6.1 Introduction 175
6.2 FD relay selection 175
6.2.1 System model 176
6.2.2 Optimal relay selection 177
6.2.3 Max–min relay selection 178
6.2.4 Loop interference relay selection 179
6.2.5 Partial relay selection 179

6.2.6 Max–min with loop interference relay selection 180
6.2.7 Optimal relay selection with hybrid relaying 181
6.2.8 Numerical results 182
6.3 Buffer-aided relay selection 184
6.3.1 System model 185
6.3.2 Max–min relay selection 187
6.3.3 Max–max relay selection (bound) 188
6.3.4 Max-link relay selection 188
6.3.5 Numerical results 194
6.4 Wireless powered relay selection with wireless battery charging 197
6.4.1 System model 198
6.4.2 Random relay selection 200
6.4.3 Relay selection based on the closest distance 201
6.4.4 Distributed beamforming 202
6.4.5 Numerical results 203
6.5 Conclusion 205
References 205

7 Relaying in green communication systems 207
7.1 Introduction 207
7.2 Motivation 208
7.3 System model and description 209
7.3.1 Basic system model 209
7.3.2 Metrics for energy evaluation 210
7.3.3 Definition of optimization problems 212
7.3.4 Power consumption model 214
7.4 Comparison of EE of relay protocols for three-node scenario 217
7.4.1 Relaying protocols 217
7.4.2 Optimization and comparison of ECR minimization 219
7.4.3 Study of special cases 224
7.4.4 Numerical results 227
7.4.5 Conclusion 230
7.5 Energy efficiency analysis of relay cooperation 231
7.6 Conclusions 239
Acknowledgements 239
References 239

8 Energy-efficient relaying 243
8.1 Introduction 243
8.1.1 Energy efficiency 243
8.1.2 Recent results 245
8.2 Energy-efficient relay protocol design 245
8.2.1 Power control and relay design in three-way relay channels 246
8.3 Energy-efficient power allocation with AF relaying 249
8.3.1 Centralized power allocation 251
8.3.2 Distributed power allocation 254

8.4 Energy-efficient resource allocation with multiple-antenna AF relaying 256
8.4.1 Relay interference neutralization 256
8.4.2 Receive filters allocation 259
8.4.3 Centralized power allocation 260
8.4.4 Distributed power allocation 263
8.5 Multi-stream MIMO AF system 264
8.6 Numerical results 266
8.7 Conclusions 270
References 270

9 Cognitive relaying for information and energy cooperation 273
9.1 Introduction 273
9.1.1 Wireless challenges and motivation 273
9.1.2 Literature review 274
9.1.3 Organization of the chapter 277
9.2 Network model 278
9.3 Information cooperation 280
9.3.1 Problem formulation 280
9.3.2 Special structure of relaying matrix and reformulation 280
9.3.3 An efficient algorithm and distributed implementation 282
9.4 Information and energy cooperation 288
9.4.1 System setting 288
9.4.2 The ideal primary-cognitive cooperation 289
9.4.3 A practical power-splitting cooperation 291
9.5 Performance evaluation 294
9.5.1 Benchmark and proposed schemes 295
9.5.2 Outage performance due to the information cooperation 295
9.5.3 Improved rate region 296
9.5.4 Average SU rate 296
9.5.5 Outage performance due to the additional energy cooperation 298
9.6 Concluding remarks and future directions 299
Appendix A: Proof of Theorem 9.1 299
Appendix B: Proof of Proposition 9.1 300
Appendix C: Closed-form solution to Problem (9.60) 300
References 302

10 Relaying in non-ideal conditions 305
10.1 Introduction 305
10.2 Relaying with feedback delay 305
10.3 Relaying with link correlation 311
10.4 Relaying with non-Gaussian interference 320
10.5 Relaying with wireless power 328
References 335

11 Relaying and physical layer security **339**
11.1 Introduction 339
11.2 Deaf cooperation in multiple relay networks 342
11.2.1 CJ versus NF 343
11.2.2 Deaf helpers selection 345
11.2.3 Empirical evaluation 348
11.3 Deaf cooperation with multiple antennas 349
11.3.1 CJ versus NF in multi-antenna deaf cooperation 352
11.3.2 The reversely degraded multi-antenna relay–eavesdropper channel 353
11.3.3 Empirical evaluation 354
11.4 Active cooperation in multiple relay networks 356
11.4.1 DF with multiple relays 357
11.4.2 Empirical evaluation 362
11.5 Conclusions 363
References 364

12 Relaying technologies for smart grid **367**
12.1 Introduction 367
12.1.1 PLCs for SGs 368
12.1.2 Wireless mesh network for SGs 368
12.1.3 Chapter overview 369
12.2 Communication networks for SGs 369
12.2.1 An overview of SG communication architecture 369
12.2.2 Communication technologies for SGs 370
12.2.3 Challenges of communication technologies in SGs 372
12.2.4 Relaying strategies in SG communication networks 374
12.3 Relaying technologies for indoor PLC networks 374
12.3.1 Indoor PLC network: example, advantages, and challenges 374
12.3.2 Relaying strategies for indoor PLC networks 376
12.3.3 Numerical results and discussions 379
12.4 Relaying technologies for SG wireless communications 382
12.4.1 Unidirectional two-relay system with collaborative beamforming 384
12.4.2 Bidirectional relaying for information-exchange system 386
12.4.3 Virtual-MIMO in SG wireless communications 389
12.5 Conclusions 395
References 396

13 Simultaneous wireless information and power transfer in relay interference channels **401**
13.1 Introduction 401
13.2 Preliminaries of SWIPT and game theory 403
13.2.1 Basic receiver structures of SWIPT 404
13.2.2 Basic concepts of non-cooperative game theory 405

13.3 System model and problem formulation 406
13.3.1 System model 406
13.3.2 Problem formulation 409
13.4 Distributed power splitting via game theory 410
13.4.1 Non-cooperative game formulation 410
13.4.2 Existence and uniqueness of the NE 411
13.4.3 Distributed algorithm 416
13.5 Numerical results 418
13.5.1 Verification of best response function and algorithm convergence 418
13.5.2 System average performance and effects of system parameters 420
13.6 Conclusions 424
References 424

14 Relaying in optical wireless communication 429
14.1 Introduction 429
14.2 The optical wireless channel 430
14.2.1 Fading statistics 431
14.2.2 Optical detection and receiver noise 432
14.3 Relaying configurations 433
14.3.1 Relaying signaling schemes 435
14.4 Performance of relay-assisted OWC systems 436
14.4.1 Performance of DF relaying systems 436
14.4.2 Performance of AF relaying systems 439
14.4.3 Diversity gain analysis 441
14.5 Relay-assisted quantum communication 443
14.5.1 Relay-assisted QKD 443
14.5.2 Qubit error rate performance analysis 444
14.6 Mixed RF-FSO relay transmission 447
14.6.1 Subcarrier intensity modulation 449
14.7 Optical orthogonal frequency multiplexing and effects of signal clipping 453
14.7.1 Signal shaping 455
14.7.2 PAPR reduction 456
14.7.3 Combined effects of non-linearities and turbulence in FSO communication 458
References 459

15 Multibeam joint processing satellites: cooperative relays, high above 465
15.1 An introduction to multibeam satellite networks 465
15.2 Practical constraints 467
15.2.1 Channel state information acquisition 467
15.2.2 Frequency reuse 467
15.2.3 Feeder link 469

15.2.4 Framing 469
15.2.5 The non-linear satellite channel 470
15.3 System model 470
15.3.1 Multicast model 471
15.3.2 Multibeam satellite channel 472
15.3.3 Average user throughput 473
15.4 Sum rate and throughput maximization 473
15.4.1 Per-antenna power constrained sum-rate maximization 474
15.4.2 Throughput maximization under availability constraints 475
15.4.3 Performance evaluation 477
15.5 Linear precoding over non-linear channels 482
15.5.1 The non-linear multibeam channel 482
15.5.2 Effects of non-linear amplification 485
15.5.3 Counteracting non-linearities 487
15.6 Receiver implementation 491
15.6.1 DVB-S2X superframe structure 492
15.6.2 Synchronization and channel acquisition 494
15.7 Conclusions 497
References 497

Index **501**