# Contents

## Preface

- Preface  xiii

## List of Acronyms

- List of Acronyms xv

## 1 Related Work and Preliminary Considerations

- 1.1 Introduction .................................. 1
- 1.2 Related Work .................................. 2
  - 1.2.1 A Routing-Based Approach ..................... 2
  - 1.2.2 An Information-Theoretic Approach ................. 3
  - 1.2.3 A Dynamic Control Approach .................... 4
  - 1.2.4 A Game-Theoretic Approach ..................... 4
- 1.3 A New Perspective for the Design of Ad Hoc Wireless Networks ...... 5
- 1.4 Overview of the Underlying Assumptions in the Following Chapters ....... 9
- 1.5 The Main Philosophy Behind the Book ........................... 11

## 2 A Communication-Theoretic Framework for Multi-hop Ad Hoc Wireless Networks: Ideal Scenario

- 2.1 Introduction .................................. 15
- 2.2 Preliminaries .................................. 16
  - 2.2.1 Topology ................................... 16
  - 2.2.2 Route Discovery ........................... 17
  - 2.2.3 Average Number of Hops ....................... 18
- 2.3 Communication-Theoretic Basics .......................... 18
  - 2.3.1 Bit Error Rate at the End of a Multi-hop Route ........ 18
  - 2.3.2 Link Signal-to-Noise Ratio ..................... 20
- 2.4 BER Performance Analysis ............................ 23
  - 2.4.1 Uncoded Transmission .......................... 23
  - 2.4.2 Coded Transmission ......................... 27
- 2.5 Network Behavior ................................ 29
  - 2.5.1 Minimum Spatial Energy Density and Minimum Transmit Power for Full Connectivity ............................... 30
  - 2.5.2 Connectivity: Average Sustainable Number of Hops ........ 34
  - 2.5.3 Lifetime of a Node .......................... 40
- 2.6 Concluding Remarks ............................... 41
3 A Communication-Theoretic Framework for Multi-hop Ad Hoc Wireless Networks: Realistic Scenario

3.1 Introduction ........................................... 43
3.2 Preliminaries .......................................... 44
3.3 Communication-Theoretic Basics ..................... 46
3.4 Inter-node Interference ............................... 48
  3.4.1 Geometric Considerations ....................... 48
  3.4.2 Traffic Model ..................................... 49
3.5 RESGO MAC Protocol .................................. 50
  3.5.1 Scenario with Strong LOS and Interference from Nodes in Tier 1 50
  3.5.2 Scenario with Strong LOS and Interference from Nodes in Tiers 1 and 2 .57
  3.5.3 Scenario with Strong Multipath (Rayleigh Fading) .............. 58
  3.5.4 Discussion ....................................... 63
3.6 RESLIGO MAC Protocol ............................... 64
  3.6.1 Scenario with Strong LOS ......................... 66
  3.6.2 Scenario with Strong Multipath (Rayleigh Fading) .............. 69
  3.6.3 Discussion ....................................... 72
3.7 Network Behavior ..................................... 73
  3.7.1 Minimum Spatial Energy Density and Minimum Transmit Power for Full Connectivity ...... 73
  3.7.2 Scenario with Strong LOS ......................... 73
  3.7.3 Scenario with Strong Multipath (Rayleigh Fading) .............. 75
  3.7.4 Connectivity: Average Sustainable Number of Hops .......... 78
3.8 Conclusions .......................................... 83

4 Connectivity in Ad Hoc Wireless Networks: A Physical Layer Perspective 85

4.1 Introduction ........................................... 85
4.2 Quasi-regular Topology ............................... 86
  4.2.1 A Formal Definition of Quasi-regular Topology .......... 87
  4.2.2 A Communication-Theoretic Approach ................ 88
  4.2.3 What Happens if Each Node has Two Spatial Neighbors? .... 93
  4.2.4 What Happens if There is Inter-node Interference? ....... 96
4.3 Random Topology ..................................... 100
  4.3.1 Related Work ..................................... 100
  4.3.2 Connectivity in Ad Hoc Wireless Networks with Random Topology 102
  4.3.3 Evaluation of the Likelihood of Broadcast Percolation .... 104
  4.3.4 What Happens if There is Inter-node Interference? ....... 108
4.4 Concluding Remarks and Discussion .................. 109

5 Effective Transport Capacity in Ad Hoc Wireless Networks 111

5.1 Introduction ........................................... 111
5.2 Model and Assumptions ............................... 113
5.3 Preliminaries .......................................... 115
  5.3.1 Route Bit Error Rate ............................. 115
  5.3.2 Link Signal-to-Noise Ratio ....................... 115
  5.3.3 Average Sustainable Number of Hops .................. 117
5.4 Single-Route Effective Transport Capacity ............ 117
7.6.5 Effects of Mobility ........................................191
7.6.6 Implications on Practical Scenarios ......................192
7.7 Concluding Remarks ............................................193

8 Optimal Common Transmit Power for Ad Hoc Wireless Networks 195
8.1 Introduction .....................................................195
8.2 Model and Assumptions .........................................196
  8.2.1 Network Topology ........................................196
  8.2.2 Routing ....................................................197
  8.2.3 Medium Access Control Protocol .........................199
8.3 Connectivity ....................................................199
  8.3.1 Square Grid Topology ....................................200
  8.3.2 Two-Dimensional Poisson Topology .......................201
8.4 BER at the End of a Multi-hop Route .........................202
  8.4.1 Square Grid Topology ....................................202
  8.4.2 Random Topology .........................................204
8.5 Optimal Common Transmit Power ...............................204
  8.5.1 Optimal Common Transmit Power for Networks with Square Grid
        Topology ..................................................204
  8.5.2 Optimal Common Transmit Power for Networks with Random
        Topology ..................................................205
8.6 Performance Metrics ...........................................205
  8.6.1 Node and Network Lifetime ...............................205
  8.6.2 Effective Transport Capacity ............................206
8.7 Results and Discussion .......................................208
  8.7.1 Optimal Transmit Power and Data Rate ...................208
  8.7.2 Optimal Transmit Power and Node Spatial Density .......210
  8.7.3 Effects of Strong Propagation Path Loss ...............211
  8.7.4 Connectivity Robustness to Node Spatial Density Changes .213
  8.7.5 Practical Determination of the Optimal Transmit Power ....215
8.8 Related Work ..................................................216
8.9 Conclusions ...................................................217

9 The Routing Problem in Ad Hoc Wireless Networks: A Cross-Layer
  Perspective ....................................................219
9.1 Introduction ....................................................219
9.2 Experimental Evidence ........................................220
9.3 Preliminaries: Analytical Models and Assumptions ..........221
  9.3.1 Physical Layer ...........................................221
  9.3.2 Medium Access Control ..................................225
  9.3.3 Basic Networking Assumptions ...........................226
9.4 Route Selection: Simulation Study ............................227
  9.4.1 Network Topology ........................................227
  9.4.2 BER-Based Routing versus Shortest-Path Routing .......227
9.5 Network Performance Evaluation ...............................235
  9.5.1 Average Hop Length Models ................................235
  9.5.2 Retransmission Model ....................................239
9.5.3 Packet Error Rate .............................................. 239
9.5.4 Delay ......................................................... 240
9.6 Discussion ....................................................... 243
9.6.1 Cross-layer Routing: A Practical Perspective ................. 243
9.6.2 Mobility ....................................................... 246
9.7 Related Work .................................................... 246
9.8 Conclusions ...................................................... 248

10 Concluding Remarks .................................................. 249
10.1 Introduction ...................................................... 249
10.2 Extensions of the Theoretical Framework: Open Problems .... 249
10.2.1 Performance of Ad Hoc Wireless Networks: Random Versus Uniform Topologies ........................................ 249
10.2.2 Impact of Clustering on the BER Performance in Ad Hoc Wireless Networks ............................................... 251
10.2.3 Impact of Receiver Sensitivity on the Performance of Ad Hoc Wireless Networks ......................................... 253
10.2.4 Spectral Efficiency–Connectivity Tradeoff in Ad Hoc Wireless Networks ..................................................... 254
10.2.5 MIMO-OFDM Wireless Communications ..................... 256
10.2.6 Smart Antennas and Directional Antennas ..................... 256
10.3 Network Architectures ............................................. 256
10.4 Network Application Architectures ................................ 257
10.5 Standards ......................................................... 258
10.6 Applications ....................................................... 263
10.7 Conclusions ....................................................... 264

Appendix A Analysis of the Inter-node Interference ...................... 265
A.1 Introduction ...................................................... 265
A.2 Exact Computation of the Average Link BER in a Scenario with Strong LOS .................................................... 265
A.2.1 Interference from Nodes in Tier 1 ................................ 266
A.2.2 Interference from Nodes in Tiers 1 and 2 ......................... 271
A.2.3 Interference from Nodes in Tier 2 ................................ 273
A.2.4 Simulation Scenario ........................................... 274
A.3 Exact Computation of the Average Link BER in a Scenario with Strong Multipath (Rayleigh Fading) ......................... 276
A.3.1 Interference from Nodes in Tier 1 ................................ 277
A.3.2 Interference from Nodes in Tiers 1 and 2 ......................... 278
A.3.3 Interference from Nodes in Tiers 1, 2 and 3 ....................... 278
A.4 LOS and Multipath (Rice Fading) ................................ 280
A.5 Gaussian Assumption for the Interference Noise ................... 280
A.5.1 Route Bit Error Rate ........................................... 282
A.5.2 Interference Power ............................................ 284

Appendix B Proof of Theorem 1, Chapter 5 ................................ 287

Appendix C Route Discovery .............................................. 293
Appendix D  Validation of Analytical Results  295
  D.1 Validation of Network Goodput  295
  D.2 Validation of Delay  295
  D.3 Validation of Average Number of Simultaneously Active Routes  297

Appendix E  Derivation of Joint CDF of $W$ and $\Phi$  299

References  307

Index  327