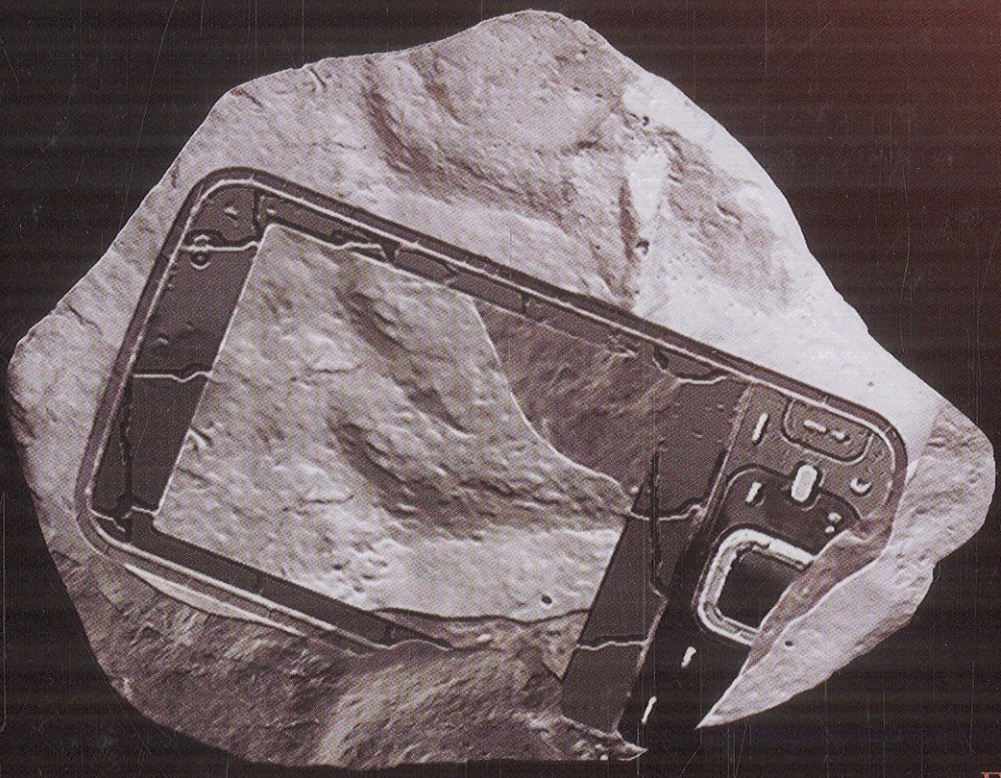
# WiMAX Evolution

## Emerging Technologies and Applications



Editors
Marcos D. Katz
Frank H. P. Fitzek

WILEY

# Contents

**List of Contributors** xv

**Foreword** xxi

**Preface** xxiii

**Acknowledgements** xxvii

**List of Acronyms** xxix

**I Introduction** 1

**1 Introduction to WiMAX Technology** 3
*Wonil Roh and Vladimir Yanover*

1.1 Overview of State-of-the-art WiMAX Technology . . . . . 4
1.1.1 Structure of the System Profile . . . . . 4
1.1.2 Key PHY Features . . . . . 5
1.1.3 Key MAC Features . . . . . 7
1.1.4 Advanced Networking Features . . . . . 9
1.2 WiMAX Evolution Path . . . . . 9
1.2.1 Release 1.5 . . . . . 10
1.2.2 Release 2.0 . . . . . 12
References . . . . . 12

**II WiMAX Validation: Validating Current Fixed and Mobile WiMAX through Advanced Testbeds** 15

**2 WiMAX Performance in Practice** 17
*Kostas Pentikousis, Esa Piri, Jarno Pinola and Ilkka Harjula*

2.1 Empirical Evaluations of WiMAX . . . . . 18
2.2 Fixed WiMAX Testbed Evaluation . . . . . 20
2.2.1 Audio and Video Traffic over WiMAX . . . . . 21
2.2.2 Traffic Generation . . . . . 22

2.2.3 Host Clock Synchronization . . . 22
2.2.4 Baseline Capacity Measurements . . . 25
2.3 VoIP Over Fixed WiMAX . . . 26
2.3.1 VoIP Overhead . . . 26
2.3.2 Synthetic G.723.1 VoIP Over WiMAX . . . 27
2.3.3 Synthetic G.729.1 VoIP Over WiMAX . . . 27
2.3.4 Synthetic Speex VoIP over WiMAX . . . 28
2.3.5 VoIP Aggregation . . . 29
2.4 IPTV over fixed WiMAX . . . 34
2.5 Mobile WiMAX Testbed Evaluation . . . 36
2.5.1 The VTT CNL Mobile WiMAX Testbed . . . 37
2.5.2 Baseline Capacity Measurements . . . 38
2.6 Summary . . . 39
2.7 Further Reading . . . 40
References . . . 41

**III Novel Scenarios** **45**

**3 Novel WiMAX Scenarios for Future Broadband Wireless Access Networks** **47**
*Pedro Neves, Kostas Pentikousis, Susana Sargento, Marília Curado, Paulo Simões and Francisco Fontes*

3.1 Introduction . . . 47
3.2 WMAN Network Provider . . . 48
3.2.1 Broadband Wireless Access . . . 48
3.2.2 Advanced Mobile WiMAX . . . 54
3.3 Telemedicine Applications . . . 57
3.3.1 Remote Patient Monitoring . . . 58
3.3.2 On-site Medical Assistance . . . 59
3.4 Environmental Monitoring . . . 60
3.4.1 Seismic Activity . . . 60
3.4.2 Fire Prevention . . . 61
3.4.3 Other Applications . . . 65
3.5 Conclusions . . . 66
References . . . 66

**4 Pricing in WiMAX Networks** **69**
*Ioannis Papapanagiotou, Jie Hui and Michael Devetsikiotis*

4.1 Introduction . . . 69
4.2 Economics in Network Engineering . . . 70
4.2.1 Building a Business Model . . . 70
4.2.2 Control and Pricing . . . 71
4.3 Building the Pricing Schemes . . . 73
4.3.1 Utility, Demand Functions and Optimization Objectives . . . 73
4.3.2 Flat-rate Pricing . . . 74
4.3.3 User-based Pricing . . . 75

4.4 Pricing in Different WiMAX Topologies . . . . . 76
4.4.1 Point-to-point Unlimited Capacity . . . . . 76
4.4.2 Mesh Mode Operation . . . . . 77
4.4.3 Point-to-point Limited Capacity . . . . . 78
4.4.4 WiMAX/WiFi Architecture . . . . . 81
4.5 Conclusion . . . . . 83
References . . . . . 83

**IV Advanced WiMAX Architectures** **85**

**5 WiMAX Femtocells** **87**
*Chris Smart, Clare Somerville and Doug Pulley*

5.1 Introduction . . . . . 87
5.1.1 A Brief History of Cell Sizes . . . . . 87
5.1.2 Definition of a Femtocell . . . . . 87
5.2 Architecture of a WiMAX Femtocell . . . . . 88
5.2.1 WiMAX Network Architectures for a Femtocell . . . . . 88
5.2.2 Femtocell Deployment Configurations . . . . . 89
5.3 Femtocell Fundamentals . . . . . 90
5.3.1 Synchronization . . . . . 91
5.3.2 Self-configuration . . . . . 92
5.3.3 Remote Configuration . . . . . 94
5.3.4 User Configuration . . . . . 95
5.3.5 Backhaul Security . . . . . 95
5.3.6 Handovers . . . . . 95
5.4 Femtocell–Macrocell Interference . . . . . 97
5.4.1 Interference Scenarios . . . . . 97
5.4.2 Downlink Coverage Definitions . . . . . 98
5.4.3 Downlink Coverage Analysis . . . . . 99
5.4.4 Setting the Maximum Femtocell Transmit Power . . . . . 101
References . . . . . 103

**6 Cooperative Principles in WiMAX** **105**
*Qi Zhang, Frank H.P. Fitzek and Marcos D. Katz*

6.1 Introduction . . . . . 105
6.2 Cooperative Diversity Schemes in Mobile Multihop Relay Based WiMAX (802.16j) . . . . . 112
6.3 Cooperative Schemes for Multicast Broadcast Services in WiMAX . . . . . 115
6.3.1 Cooperative Transmission for Multimedia Multicast Services . . . . . 116
6.3.2 Cooperative Retransmission Scheme for Reliable Multicast Services Using Network Coding . . . . . 118
6.4 Network Coding Implementation in the Commercial WiMAX Mobile Device 123
6.5 Conclusion . . . . . 125
References . . . . . 126

**7 The Role of WiMAX Technology in Distributed Wide Area Monitoring Applications** **129**
*Francesco Chiti, Romano Fantacci, Leonardo Maccari, Dania Marabissi and Daniele Tarchi*

7.1 Monitoring with the WSN Paradigm . . . 129
7.2 Overall System Architecture . . . 131
7.3 Efficient Access Management Schemes . . . 133
7.3.1 System Model and Problem Formulation . . . 135
7.4 Secure Communications Approaches . . . 136
References . . . 142

**8 WiMAX Mesh Architectures and Network Coding** **145**
*Parag S. Mogre, Matthias Hollick, Christian Schwingenschloegl, Andreas Ziller and Ralf Steinmetz*

8.1 Introduction . . . 145
8.2 Background on the IEEE 802.16 MeSH Mode . . . 147
8.3 Design Principles for Network Coding in the IEEE 802.16 MeSH Mode . . . 149
8.4 Enabling WNC for the IEEE 802.16 MeSH Mode . . . 153
8.4.1 Modeling the Coding Gain . . . 154
8.4.2 Network Coding Framework . . . 155
8.4.3 Reservation Strategies . . . 156
8.4.4 Implementation Issues . . . 158
8.5 Related Work . . . 160
8.6 Conclusions and Outlook . . . 161
References . . . 162

**9 ASN-GW High Availability through Cooperative Networking in Mobile WiMAX Deployments** **163**
*Alexander Bachmutsky*

9.1 Introduction . . . 163
9.2 Classic HA Implementation . . . 165
9.3 Network-based Resiliency Solutions for Routing . . . 167
9.4 WiMAX Network Elements R4/R6 Health Management . . . 168
9.5 R6 Load Balancing . . . 172
9.6 ASN-GW Failure and Recovery . . . 172
9.7 *N*:*N* Redundancy . . . 177
9.8 Multi-instance ASN-GW . . . 180
9.9 The Proposal Summary . . . 181
9.10 Conclusions . . . 182

**V WiMAX Extensions** **183**

**10 Robust Header Compression for WiMAX Femto Cells** **185**
*Frank H.P. Fitzek, Gerrit Schulte, Esa Piri, Jarno Pinola, Marcos D. Katz, Jyrki Huusko, Kostas Pentikousis and Patrick Seeling*

10.1 Introduction . . . 185
10.2 ROHC in a Nutshell . . . 186
10.3 Scenario Under Investigation . . . 188
10.4 WiMAX and ROHC Measurement Setup . . . 190
10.5 WiMAX and ROHC Measurements Results . . . 192
10.5.1 ROHC on WiMAX Downlink . . . 192
10.5.2 ROHC on WiMAX Uplink . . . 194
10.5.3 ROHC Capacity Gain . . . 195
10.6 Conclusion . . . 196
References . . . 197

**11 A WiMAX Cross-layer Framework for Next Generation Networks 199**
*Pedro Neves, Susana Sargento, Ricardo Matos, Giada Landi, Kostas Pentikousis, Marília Curado and Francisco Fontes*

11.1 Introduction . . . 199
11.2 IEEE 802.16 Reference Model . . . 200
11.3 Cross-layer Design for WiMAX Networks . . . 203
11.3.1 Cross-layer Mechanisms for QoS Support . . . 203
11.3.2 Cross-layer Mechanisms for Seamless Mobility Optimization . . . 206
11.4 WEIRD: A Practical Case of WiMAX Cross-layer Design . . . 210
11.4.1 WEIRD Architecture . . . 212
11.5 WEIRD Framework Performance Evaluation . . . 215
11.5.1 Cross-layer Signaling Measurements . . . 215
11.5.2 QoS Evaluation . . . 219
11.6 Summary . . . 222
References . . . 224

**12 Speech Quality Aware Resource Control for Fixed and Mobile WiMAX 227**
*Thomas Michael Bohnert, Dirk Staehle and Edmundo Monteiro*

12.1 Introduction . . . 227
12.2 Quality of Experience versus Quality of Service Assessment . . . 228
12.3 Methods for Speech Quality Assessment . . . 230
12.3.1 Auditory Quality Assessment . . . 230
12.3.2 Instrumental Quality Assessment . . . 230
12.4 Continuous Speech Quality Assessment for VoIP . . . 231
12.4.1 VoIP Components and their Impact on Speech Quality . . . 231
12.4.2 Continuous Assessment of Time-varying QoE . . . 233
12.4.3 Instationary Quality Distortion and Human Perception . . . 235
12.5 Speech Quality Aware Admission Control for Fixed IEEE 802.16 Wireless MAN . . . 237
12.5.1 IEEE 802.16d Background and the Deployment Scenario . . . 237
12.5.2 The Principle of Admission Control and its Application to VoIP . . . 238
12.5.3 Experimental Setup and Parameterization . . . 239
12.5.4 Performance Results . . . 240
12.6 The Idea of an $R$-score-based Scheduler . . . 243
12.6.1 Scenario . . . 243

12.6.2 The Most Simple *R*-Score Scheduler . . . 244
12.6.3 Performance Evaluation . . . 245
12.7 Conclusion . . . 248
References . . . 249

**13 VoIP over WiMAX** **251**
*Rath Vannithamby and Roshni Srinivasan*

13.1 Introduction . . . 251
13.2 Features to Support VoIP over WiMAX . . . 252
13.2.1 Silence Suppression using ertPS . . . 252
13.2.2 HARQ . . . 253
13.2.3 Channel Aware Scheduling . . . 254
13.2.4 Protocol Header Compression . . . 255
13.3 Enhanced Features for Improved VoIP Capacity . . . 255
13.3.1 VoIP Traffic Characteristics . . . 255
13.3.2 Dynamic Resource Allocation for VoIP . . . 255
13.3.3 Individual Persistent Scheduling . . . 257
13.3.4 Group Scheduling . . . 260
13.4 Simulation Results . . . 260
13.5 Conclusion . . . 262
References . . . 263

**14 WiMAX User Data Load Balancing** **265**
*Alexander Bachmutsky*

14.1 Introduction . . . 265
14.2 Local Breakout Use for Load Balancing . . . 265
14.2.1 Local Breakout at the Base Station Level . . . 266
14.2.2 Local Breakout at the ASN-GW Level . . . 267
14.3 Network-level Load Balancing over Tunneled Interfaces . . . 267
14.3.1 Is WiMAX Special for the Case of Traffic Load Balancing? . . . 269
14.3.2 Analysis of Possible Solutions . . . 269
14.4 Conclusions . . . 276

**15 Enabling Per-flow and System-wide QoS and QoE in Mobile WiMAX** **277**
*Thomas Casey, Xiongwen Zhao, Nenad Veselinovic, Jari Nurmi and Riku Jäntti*

15.1 Introduction . . . 277
15.2 Overview . . . 279
15.2.1 Incoming Traffic . . . 279
15.2.2 System and Resources . . . 280
15.2.3 QoS and QoE . . . 281
15.3 Per-flow-based QoS and QoE . . . 282
15.3.1 MAC scheduler considerations . . . 283
15.3.2 Scheduler Optimization Based on the QoS and QoE Measures . . . 284
15.4 System-wide Tools for Enabling QoS and QoE . . . 287
15.4.1 Load Balancing . . . 287

15.4.2 HO Prioritization . . . 299
15.5 Conclusions . . . 303
References . . . 303

**VI WiMAX Evolution and Future Developments 305**

**16 MIMO Technologies for WiMAX Systems: Present and Future 307**
*Chan-Byoung Chae, Kaibin Huang and Takao Inoue*

16.1 Introduction . . . 307
16.2 IEEE802.16e: Single-user MIMO Technologies . . . 308
16.2.1 Open-loop Solutions . . . 309
16.2.2 Closed-loop Solutions . . . 311
16.2.3 Limitations . . . 311
16.3 IEEE802.16m: Evolution Towards Multiuser MIMO Technologies – Part I. Nonlinear Processing . . . 312
16.3.1 System Model . . . 312
16.3.2 Vector Perturbation . . . 314
16.3.3 Performance of a Vector Perturbation System . . . 316
16.4 IEEE802.16m: Evolution Towards Multiuser MIMO Technologies – Part II. Linear Processing . . . 316
16.4.1 Linear Multiuser MIMO: Perfect Channel State Information . . . 317
16.4.2 Linear Multiuser MIMO: Limited Feedback . . . 322
16.4.3 Linear Multiuser MIMO: Multiuser Diversity . . . 325
16.5 Conclusion . . . 331
References . . . 331

**17 Hybrid Strategies for Link Adaptation Exploiting Several Degrees of Freedom in WiMAX Systems 335**
*Suvra Sekhar Das, Muhammad Imadur Rahman and Yuanye Wang*

17.1 Introduction . . . 335
17.2 Link Adaptation Preliminaries . . . 336
17.2.1 Trade-offs and Optimization Target . . . 337
17.3 Link Adaptation Algorithms . . . 339
17.3.1 SAMPDA Algorithm . . . 340
17.4 Link Adaptation Scenario . . . 341
17.4.1 Link Adaptation Process . . . 341
17.4.2 System Parameters . . . 342
17.4.3 Frame Structure . . . 343
17.5 Role of Power Adaptation in Collaboration with Bit Adaptation . . . 344
17.5.1 AMC and Power Adaptation at the Same Rate . . . 345
17.5.2 AMC and Power Adaptation at Different Rates . . . 348
17.5.3 Overhead Analysis . . . 354
17.6 Link Adaptation Considering Several System Issues . . . 356
17.6.1 Subchannelization . . . 357
17.6.2 Fixed Coding Rate . . . 357

17.6.3 AMC Rate . . . 361
17.7 Summary . . . 363
17.7.1 Guidelines for Hybrid Link Adaptation . . . 363
17.7.2 Conclusion from Bit and Power Allocation Analysis . . . 364
17.7.3 Future Work . . . 365
References . . . 365

**18 Applying WiMAX in New Scenarios: Limitations of the Physical Layer and Possible Solutions** **367**
*Ilkka Harjula, Paola Cardamone, Matti Weissenfelt, Mika Lasanen, Sandrine Boumard, Aaron Byman and Marcos D. Katz*

18.1 WiMAX in New Scenarios . . . 367
18.2 Channel Model for Mountainous Environments . . . 369
18.2.1 COST 259/273 . . . 369
18.2.2 3GPP/3GPP2 Statistical Channel Model . . . 369
18.2.3 SUI Models and IEEE 802.16a Channel Models . . . 370
18.2.4 WINNER Phase I and II Channel Models . . . 370
18.3 Mountainous Scenario and Channel Modeling . . . 371
18.3.1 Analytical Modeling of the Channel in the Presence of Mountains . . . 371
18.3.2 Extension of the WINNER Phase I Channel Model for the Mountainous Scenario . . . 371
18.4 Beamforming Algorithms and Simulation . . . 372
18.4.1 Pre-FFT Receive EVD Beamforming . . . 373
18.4.2 Post-FFT Receive EVD Beamforming . . . 374
18.4.3 Simulation Results . . . 374
18.5 A Timing Synchronization Study in a Mountain Environment . . . 377
18.6 Analysis and Conclusions . . . 382
References . . . 383

**19 Application of Radio-over-Fiber in WiMAX: Results and Prospects** **385**
*Juan Luis Corral, Roberto Llorente, Valentín Polo, Borja Vidal, Javier Martí, Jonás Porcar, David Zorrilla and Antonio José Ramírez*

19.1 Introduction . . . 385
19.1.1 Radio-over-Fiber systems . . . 385
19.1.2 Analog Transmission on Fiber State-of-the-Art . . . 387
19.1.3 Market Overview and Technology Forecast . . . 387
19.2 Optical Transmission of WiMAX Signals . . . 388
19.2.1 Optical Link Key Elements . . . 388
19.2.2 Transmission Performance . . . 390
19.3 WiMAX-on-Fiber Applications . . . 394
19.3.1 Target Applications . . . 394
19.3.2 Transmission Impairments . . . 395
19.3.3 Field Trials . . . 396
19.4 Conclusions . . . 398
References . . . 398

**20 Network Planning and its Part in Future WiMAX Systems** **401**
*Avraham Freedman and Moshe Levin*

20.1 Introduction . . . 401
20.2 The Network Planning Process . . . 403
20.2.1 Data Collection . . . 403
20.2.2 Network Planning . . . 404
20.2.3 Planning Verification and Update . . . 410
20.3 The Impact of WiMAX on Network Planning . . . 411
20.3.1 Flexibility of WiMAX Deployment . . . 411
20.3.2 WiMAX Network Planning . . . 412
20.4 Planning of Future WiMAX Networks . . . 414
20.4.1 Advanced Spatial Techniques . . . 414
20.4.2 Relays, Femtocells and Mesh Networks . . . 415
20.4.3 Cognitive Radios, Self-configuring and Cooperative Networks . . . 416
20.5 Modeling: the Key to Integration of Planning Information . . . 417
20.5.1 The Problem . . . 418
20.5.2 Suggested Solutions . . . 419
20.6 Conclusions . . . 420
References . . . 422

**21 WiMAX Network Automation: Neighbor Discovery, Capabilities Negotiation, Auto-configuration and Network Topology Learning** **425**
*Alexander Bachmutsky*

21.1 Introduction . . . 425
21.2 WiMAX Network Elements Auto-discovery . . . 426
21.3 Automatic Learning of the WiMAX Network Topology . . . 430
21.4 Capabilities Exchange . . . 433
21.5 Automatic WiMAX Version Management . . . 434
21.6 Automated Roaming . . . 437
21.7 Conclusion: Network Automation as a WiMAX Differentiator . . . 438
References . . . 439

**22 An Overview of Next Generation Mobile WiMAX: Technology and Prospects** **441**
*Sassan Ahmadi*

22.1 Introduction . . . 441
22.2 Summary of IEEE 802.16m System Requirements . . . 442
22.3 Areas of Improvement and Extension in Mobile WiMAX . . . 445
22.4 IEEE 802.16m Architecture and Protocol Structure . . . 447
22.5 IEEE 802.16m Mobile Station State Diagram . . . 452
22.6 IEEE 802.16m Physical Layer . . . 456
22.7 IEEE 802.16m MAC Layer . . . 460
22.8 Conclusions . . . 462
References . . . 462

**Index** **463**