FiWi Access Networks

The evolution of broadband access networks toward bimodal fiber-wireless (FiWi) access networks, described in this book, may be viewed as the endgame of broadband access. After discussing the economic impact of broadband access and current worldwide deployment statistics, all the major legacy wireline and wireless broadband access technologies are reviewed. State-of-the-art GPON and EPON fiber access networks are described, including their migration to next-generation systems such as OCDMA and OFDMA PONs. The latest developments of wireless access networks are covered, including VHT WLAN, Gigabit WiMAX, LTE, and WMN. The advantages of FiWi access networks are demonstrated by applying powerful network coding, heterogeneous optical and wireless protection, hierarchical frame aggregation, hybrid routing, and QoS continuity techniques across the optical–wireless interface. The book is an essential reference for anyone working on optical fiber access networks, wireless access networks, or converged FiWi systems.

Martin Maier is an Associate Professor at the Institut National de la Recherche Scientifique (INRS), University of Québec, and the Founder and Creative Director of the Optical Zeitgeist Laboratory. He received his PhD degree in electrical engineering from the Technical University Berlin, Germany and amongst his awards he was a co-recipient of the 2009 IEEE Communications Society Best Tutorial Paper Award. He is the author of Optical Switching Networks (Cambridge University Press, 2008).

Navid Ghazisaidi is an R&D Systems Engineer at Ericsson Inc., San Jose, USA. He received his PhD degree in Telecommunications from the University of Québec, Canada and participated in the prestigious European research projects BIONETS (BIOlogically-inspired autonomic NETworks and Services) and ACCORDANCE (A Converged Copper-Optical-Radio OFDMA-based Access Network with high Capacity and flExibility).
“The area of FiWi networks is central to the current evolution path of networks but presents significant challenges, in particular in integrating disparate systems. This book provides a cogent and highly useful exposition of the main technologies in FiWi, including not only traditional techniques, but also very recent developments such as network coding. This book is a tool both for working engineers and for researchers entering the FiWi area from the optics or from the wireless domains”.

Professor Muriel Médard, Massachusetts Institute of Technology
FiWi Access Networks

MARTIN MAIER
Université du Québec, Montréal

NAVID GHAZISAI DI
R&D PDU Broadband Access, Ericsson Inc.
To my parents
M.M.
To the love of my life
N.G.
Contents

List of figures xiii
List of tables xvii
Preface xix
Acknowledgments xxi

Part I Introduction 1

1 Broadband access 3
1.1 Definition 3
1.2 Economic impact 4
1.3 Coverage 5
1.4 Forecast 10

2 Legacy broadband technologies 15
2.1 Fixed wireline broadband technologies 15
2.1.1 Digital subscriber line 15
2.1.2 Cable modem 20
2.1.3 Broadband over power line 23
2.2 Fixed wireless broadband technologies 25
2.2.1 MMDS 25
2.2.2 Free space optics 27
2.2.3 Satellite 28
2.3 Mobile wireless broadband technologies 30
2.3.1 GPRS 30
2.3.2 EDGE 32
2.3.3 UMTS 35

Part II Fiber access networks 39

3 GPO N 45
3.1 Architecture 45
3.1.1 Video overlay 45
3.1.2 Protection 46
## Contents

3.2 Wavelength allocation 47
3.3 GPON encapsulation method 48
  3.3.1 Frame formats 48
  3.3.2 GEM 49
3.4 Bandwidth allocation 50

4 EPON 51
  4.1 Architecture 52
  4.2 Multipoint control protocol 53
  4.3 Dynamic bandwidth allocation (DBA) 54
    4.3.1 Statistical multiplexing methods 55
    4.3.2 Absolute QoS assurances 57
    4.3.3 Relative QoS assurances 60
    4.3.4 Decentralized DBA algorithms 62
  4.4 10G-EPON 63

5 Next-generation PON 65
  5.1 NG-PON1 67
    5.1.1 XG-PON 67
    5.1.2 Long-reach XG-PON 67
    5.1.3 WDM XG-PON 68
  5.2 NG-PON2 68
    5.2.1 Wavelength-routing PON 69
    5.2.2 OCDMA PON 70
    5.2.3 OFDMA PON 71

Part III Wireless access networks 73

6 WiFi 75
  6.1 Legacy WLAN 75
  6.2 QoS in WLAN 78
    6.2.1 EDCA 79
    6.2.2 HCCA 80
  6.3 HT WLAN 81
    6.3.1 Frame aggregation 81
    6.3.2 Reverse direction protocol 82
    6.3.3 Bandwidth efficiency techniques 83
  6.4 VHT WLAN 84
    6.4.1 VHTL6 84
    6.4.2 VHT60 85
    6.4.3 VHT applications 85
## Contents

### 7 WiMAX

7.1 Fixed WiMAX
   7.1.1 PHY layer
   7.1.2 MAC layer
7.2 Mobile WiMAX
   7.2.1 QoS in mobile WiMAX
   7.2.2 Mobile WiMAX handover
7.3 Next-generation WiMAX
   7.3.1 Multihop relay WiMAX
   7.3.2 Gigabit WiMAX

### 8 LTE

8.1 PHY layer
8.2 MAC layer
   8.2.1 Resource allocation
   8.2.2 Retransmission
8.3 Power saving
8.4 Handover
8.5 LTE-Advanced

### 9 Wireless mesh networks

9.1 Characteristics
9.2 WiFi-based WMN
   9.2.1 Routing protocols
   9.2.2 MAC protocols
9.3 WiMAX-based WMN
   9.3.1 Architecture
   9.3.2 Scheduling

### Part IV FiWi access networks

10 RoF vs. R&F networks
   10.1 Enabling technologies
      10.1.1 RoF technologies
      10.1.2 R&F technologies
   10.2 State-of-the-art testbeds
      10.2.1 RoF testbed
      10.2.2 R&F testbed
   10.3 Challenges and open issues
   10.4 Summary

11 Architectures
   11.1 Cellular architectures
Contents

11.1 Moving cell 129
11.1.1 Moving cell 129
11.1.2 Moving extended cell 129
11.1.3 Outdoor vs. indoor 130
11.2 WiMAX-based architectures 130
11.2.1 Integrated EPON-WiMAX 130
11.2.2 SuperMAN 131
11.3 WiFi-based architectures 133
11.3.1 Unidirectional ring 133
11.3.2 Bidirectional ring 134
11.3.3 Hybrid star-ring 135
11.3.4 Unidirectional ring-PON 136
11.4 Summary 137

12 Network planning and reconfiguration 138
12.1 ONU placement 138
12.2 Inter-ONU communications 139
12.2.1 Peer-to-peer communications 139
12.2.2 FiWi vs. WMN networks 141
12.2.3 Direct inter-ONU communications 141
12.3 Reconfiguration 142
12.3.1 MARIN 143
12.3.2 GROW-Net 143
12.4 Summary 145

13 Techno-economic analysis 146
13.1 Total cost of network ownership 147
13.1.1 CAPEX 147
13.1.2 OPEX 147
13.2 Comparative analysis of EPON and WiMAX 148
13.2.1 Techno-economic model 148
13.2.2 Techno-economic evaluation 149
13.3 Numerical results 153
13.4 Summary 158

14 Network coding 160
14.1 Networking coding in PON 160
14.2 Network coding in NG-PONs 161
14.2.1 Inter-flow network coding 162
14.2.2 Intra-flow network coding 163
14.2.3 Metro-access networks 163
14.3 Network coding in FiWi access networks 165
14.3.1 Performance enhancement 165
14.3.2 Resilience 167
14.4 Numerical results 167
14.5 Summary 170

15 Optical and wireless protection 171
15.1 Survivability analysis 173
15.1.1 NG-PON without protection 173
15.1.2 FiWi: NG-PON with wireless protection 175
15.1.3 FiWi: NG-PON with both wireless and optical protection 176
15.1.4 Failure-free connections among ONUs 177
15.2 Numerical results 177
15.3 Summary 186

16 Hierarchical frame aggregation 187
16.1 Integration of next-generation WLAN and EPON 187
16.1.1 ONU MPP 188
16.1.2 MP 189
16.2 Hierarchical frame aggregation techniques 190
16.3 Capacity of wireless mesh front-end 191
16.4 Numerical and experimental results 192
16.5 Summary 195

17 Routing and QoS continuity 196
17.1 Wireless routing algorithms 196
17.1.1 DARA 196
17.1.2 DDRA 197
17.1.3 CaDAR 197
17.1.4 RADAR 198
17.2 Integrated routing algorithms 199
17.2.1 CaDAR with optical delay awareness 199
17.2.2 Availability-aware routing 200
17.2.3 Multipath routing 201
17.3 Energy-aware routing 201
17.4 QoS continuity 202
17.4.1 QoS-aware scheduling 203
17.4.2 Enhanced MPCP and admission control 203
17.4.3 QoS mapping 204
17.4.4 Optical burst wireless mesh architecture 204
17.5 Summary 205

18 Smart grid communications 207
18.1 Smart grid vision 208
18.2 Smart grid communications infrastructure 209
18.2.1 SmartGridCity Project 209
18.2.2 Requirements 210
18.3 Über-FiWi network 211
  18.3.1 Architecture 211
  18.3.2 Implementation 213
  18.3.3 Operation 214
  18.3.4 Performance 215
18.4 Summary 217

References 218
Index 236
Figures


1.7 FTTx network architectures.

2.1 Digital subscriber line (xDSL) communication model. After Cioffi et al. (1999). ©1999 IEEE.

2.2 Spectrum allocation of VDSL and traditional narrowband POTS/ISDN services. After Cioffi et al. (1999). ©1999 IEEE.

2.3 Hybrid fiber-coax (HFC) network architecture. After Dutta-Roy (1999). ©1999 IEEE.

2.4 Smart home network using power line communications (PLC). After Lin et al. (2002). ©2002 IEEE.

2.5 Broadband over power line (BPL) modem with Ethernet connection to the computer. After Qiu (2007). ©2007 IEEE.

2.6 MMDS network architecture.

2.7 LMDS network architecture.

2.8 Satellite broadband access network. After Bem et al. (2000). ©2000 IEEE.

2.9 Satellite broadband access and core network with intersatellite links (ISLs). After Bem et al. (2000). ©2000 IEEE.


2.11 High-level view of EDGE. After Molkdar et al. (2002). ©2002 IEEE.

2.12 UMTS network architecture. After Moustafa et al. (2002). ©2002 IEEE.


List of figures


3.2 ITU-T G.983.3 wavelength allocation. 47

4.1 EPON architecture. 52
4.3 Classification of dynamic bandwidth allocation (DBA) algorithms for EPON. After McGarry et al. (2004). ©2004 IEEE. 54
4.5 Waveband allocation in EPON. 64
4.6 Waveband allocation in 10G-EPON. 64

5.2 OCDMA PON architecture with coexisting legacy TDM and WDM ONUs. After Fouli and Maier (2007). ©2007 IEEE. 70

6.1 General WLAN architecture. 76
6.2 Channel access in WLAN networks using DCF. 77
6.3 RTS/CTS mechanism in WLAN networks using DCF. 78
6.5 Frame aggregation schemes in next-generation WLAN: (a) A-MSDU, and (b) A-MPDU. 82
6.6 PSMP burst transmission in a HT WLAN. After IEEE P802.11n (2009). ©2009 IEEE. 83

7.1 IEEE 802.16 WiMAX reference model. After Li et al. (2007). ©2007 IEEE. 87
7.2 Downlink subframe structure of IEEE 802.16 WiMAX. After Eklund et al. (2002). ©2002 IEEE. 88
7.4 Mobile WiMAX handover mechanisms: (a) hard handover (HHO) and (b) macro-diversity handover (MDHO). After Ray et al. (2010). ©2010 IEEE. 92

8.2 Multihop cooperative LTE-Advanced network architecture. 104
9.1 IEEE 802.11s wireless mesh network architecture. 107
10.1 Radio-over-SMF network downlink using EAMs for different radio client signals. After Tang et al. (2004). ©2004 IEEE. 118
10.2 Simultaneous modulation and transmission of FTTH baseband signal and RoF RF signal using an external integrated modulator consisting of three Mach-Zehnder modulators (MZMs). After Lin et al. (2007a). ©2007 IEEE.


11.2 SuperMAN architecture: integration of RPR and WiMAX.

11.3 Optical–wireless interface between RPR and WiMAX networks.

11.4 Optical unidirectional fiber ring interconnecting WiFi-based wireless access points. After Muralidharan et al. © 2007 IEEE.

11.5 Optical interconnected bidirectional fiber rings integrated with WiFi-based wireless access points. After Lin et al. (2003). ©2003 IEEE.

11.6 Optical hybrid star-ring network integrated with WiFi-based wireless access points. After Bhandari and Park (2006). ©2006 IEEE.

11.7 Optical unidirectional WDM ring interconnecting multiple PONs integrated with a WiFi-based wireless mesh network. After Shaw et al. (2007a). ©2007 IEEE.


12.2 MARIN gateway architecture. After Wong et al. (2007). ©2007 IEEE.

13.1 Techno-economic model.

13.2 Power consumption vs. mean access data rate for EPON and WiMAX.

13.3 OPEX vs. network element failure probability $p_{NE}$ for $n_{ONU} = n_{SS} = 32$ and a fixed mean access data rate of 75 Mb/s.

13.4 Total cost vs. range for $n_{ONU} = n_{SS} = 32$ and a fixed mean access data rate of 75 Mb/s.

13.5 Number of subscribers in EPON and WiMAX networks under voice, video, and triple-play traffic for urban terrain.

13.6 Power consumption vs. mean access data rate for next-generation (NG) EPON and WiMAX networks.

13.7 Cost per subscriber of current and next-generation (NG) EPON and WiMAX networks under triple-play traffic for three different terrain types.

14.1 Network coding in a conventional passive optical network (PON).

14.2 Inter-flow network coding in ring-star metro network.

14.3 (a) Example of intra-flow NC in FiWi networks, (b) illustrative transmission pattern, and (c) time-space diagram.

14.4 FiWi network survivability.

14.5 Performance enhancement through network coding (NC) in EPON: for a constant external traffic load (0.5 Gb/s) and increasing intra-PON traffic load values, we plot (a) mean aggregate throughput, (b) average OLT downstream
queue size, and (c) mean delay. The solid and dashed curves are plotted with and without NC, respectively. The results in (a) and (c) are shown for intra-PON (black) and external (grey) traffic.

15.1 LR-PON and last common splitter of ONU \( i \) and ONU \( j \) for \( d_i = 5, d_j = 4, \) and \( k(i,j) = 1 \).

15.2 Impact of number of stages and number of ONUs on the probability \( q_i \) of an intact optical connection of ONU \( i \) to the OLT.

15.3 Average number \( D \) of failure-free connections among \( N = 1024 \) ONUs vs. fiber link failure probability \( p \) (same for all stages).

15.4 NG-PON topologies: (a) binary tree, (b) full tree, (c) pyramid, and (d) cube.

15.5 Average number \( D \) of failure-free connections vs. fiber link failure probability \( p \) in binary tree with different splitting ratio \( S \) for \( M = 64 \) and \( N = 1024 \).

15.6 Average number \( D \) of failure-free connections vs. fiber link failure probability \( p \) in binary tree and full tree with splitting ratio \( S = 32 \) for different \( M (N = 1024 \) fixed).

15.7 Performance comparison of different selection schemes for a five-stage pyramid NG-PON topology with splitting ratio \( S = 32 \) interconnecting \( N = 466 \) ONUs and various fiber link failure probability scenarios: (a) descending, (b) ascending, (c) ascending–descending, and (d) descending–ascending.

15.8 Performance comparison of different selection schemes for a five-stage cube NG-PON topology with splitting ratio \( S = 117 \) interconnecting \( N = 465 \) ONUs under the ascending fiber link failure probability scenario.

15.9 Average number \( D \) of failure-free connections vs. number \( M \) of wirelessly upgraded ONUs for a five-stage cube NG-PON topology \((S = 117,N = 465)\) with and without optical protection.

16.1 Network architecture and node structures of integrated next-generation WLAN-based WMN and EPON.

16.2 Impact of advanced aggregation techniques on network performance under data traffic.

16.3 Impact of advanced aggregation techniques on network performance under triple-play traffic.

16.4 Impact of hierarchical frame aggregation on integrated EPON-WLAN network performance under triple-play (voice, video, and data) traffic: (a) using the MAP neighborhood VRMP selection scheme and (b) comparing two different VRMP selection schemes.

18.1 Über-FiWi network architecture.

18.2 Ontario electricity time-of-use price periods. ©2010 Ontario Energy Board.

18.3 Total power consumption (in kW) with and without intra-home and inter-home scheduling.

18.4 Total cost (in CAN$) with and without intra-home and inter-home scheduling.
# Tables

1.1 Bandwidth requirements for SDTV and HDTV streams with and without compression (Kautz and Walker [2005]).

2.1 Availability of FSO, RF, and hybrid FSO/RF systems (Nadeem et al. [2009]).

2.2 Number of mobile subscriptions (in thousands) in cellular network technology evolution (Callendar [2010]).

2.3 EDGE high-level specifications (Molkdar et al. [2002]).

2.4 UMTS traffic classes (Moustafa et al. [2002]).

6.1 IEEE 802.11 WiFi standard family (Kuran and Tugcu [2007]).

6.2 Traffic class mapping in EDCA.

7.1 IEEE 802.16 WiMAX standard family.

7.2 QoS categories and specifications of IEEE 802.16e mobile WiMAX (Li et al. [2007]).

7.3 Features of IEEE 802.16m Gigabit WiMAX (Papapanagiotou et al. [2009]).

11.1 Comparison of different FiWi network architectures.

13.1 Path loss parameter values for various terrain types.

13.2 Typical EPON and WiMAX CAPEX & OPEX (given in US $).

16.1 Experimental results: Impact of hierarchical frame aggregation techniques on FiWi network performance for 60 second VoIP connection.
Preface

Fiber-wireless (FiWi) access networks may be viewed as the endgame of broadband access. FiWi access networks aim at leveraging on the respective strengths of emerging next-generation optical fiber and wireless access technologies and smartly merging them into future-proof broadband solutions. Currently, many research efforts in industry, academia, and various standardization bodies focus on the design and development of next-generation broadband access networks, ranging from short-term evolutionary next-generation passive optical networks with coexistence requirements with installed fiber infrastructures, so-called NG-PON1, to mid-term revolutionary disruptive optical access network architectures without any coexistence requirements, also known as NG-PON2, all the way to 4G mobile WiMAX and cellular long term evolution (LTE) radio access networks. To deliver peak data rates of up to 200 Mb/s per user and realize what some people refer to as the vision of complete fixed-mobile convergence (Ali et al. [2010]) it is crucial to replace today’s legacy circuit-switched wireline and microwave backhaul technologies with integrated FiWi broadband access networks. To unleash the full potential of FiWi access networks, emerging optical and wireless access network technologies have to be truly integrated at the physical, data link, network, and/or service layers instead of simply mixing and matching them. An interesting example of integrated FiWi access networks is the use of orthogonal frequency division multiplexing (OFDM), which has been successfully deployed in wireless networks but is only recently making its way into PONs, not only to provide a number of desirable characteristics, e.g., increased aggregate bandwidth, scalability, longer reach, lower equipment cost/complexity, and lower power consumption, but also to enable the convergence of a wide range of diverse broadband access technologies, including GPON, EPON, WiMAX, LTE, HFC, and xDSL (Kanonakis et al. [2010], Milosavljevic et al. [2010]).

This book comprehensively describes the state of the art and latest developments of FiWi access networks from a multitude of perspectives. It starts out with introducing the new definition of the term broadband as outlined by the FCC in its latest broadband deployment report released on July 20, 2010, and then elaborates on the economic impact of broadband access on individuals and enterprises and society at large. Next, we highlight the major findings of OECD’s latest report on broadband coverage, taking into account the most important wireline and wireless broadband technologies such as xDSL, cable modem, fiber-to-the-home/building (FTTH/B), broadband over power line (BPL), satellite, etc. After describing current broadband deployments across OECD countries, we summarize recent trends and discuss which broadband access
technologies will play an increasingly important role over the next couple of decades and which won’t. The second part of the introduction reviews the most important fixed wireline as well as fixed and mobile wireless legacy broadband technologies, including free space optics and UMTS among others, and discusses their pros and cons.

The second and third parts of the book are intended to set the stage and explain the technical details of state-of-the-art fiber and wireless access networks, respectively. More precisely, Part II describes at length both GPON and EPON and introduces the most promising NG-PON1 and NG-PON2 candidates such as XG-PON, long-reach and wavelength division multiplexing (WDM) PON, optical code division multiple access (OCDMA) PON, and OFDMA PON. Part III provides the reader with in-depth information about the latest developments of WiFi, WiMAX, LTE, and wireless mesh networks.

The fourth and final part of the book is dedicated to FiWi access networks. In Part IV, we first elaborate on the difference between conventional radio-over-fiber (RoF) and so-called radio-and-fiber (R&F) networks and their underlying enabling technologies. To learn about their technological maturity and better understand their respective shortcomings, we report on state-of-the-art RoF and R&F testbeds and identify remaining challenges and open issues. We survey previously proposed FiWi access network architectures, ranging from moving cellular network to SuperMAN architectures, and then delve into the technical details of FiWi access networks. We investigate various network planning and reconfiguration techniques to optimize the placement of optical network units (ONUs) and inter-ONU communications. Furthermore, we perform a comparative techno-economic analysis of EPON and WiMAX, which are two key building blocks of FiWi access networks, and investigate their performance for urban, suburban, and rural areas. We look into how and to what extent network coding can be exploited to enhance the performance of NG-PONs and FiWi access networks. Another interesting aspect of bimodal FiWi access networks is their capability to reroute traffic through a wireless mesh front-end in order to improve their survivability. Toward this end, we study the merits and limitations of optical and wireless protection schemes by means of probabilistic analysis for various failure scenarios. In next-generation wireless local area networks (WLANs), frame aggregation is the major performance enhancing mechanism at the medium access control (MAC) sublayer. To further improve the performance of WLAN-based FiWi access networks, we examine novel hierarchical frame aggregation techniques, which are particularly beneficial in carrying video traffic more efficiently. We describe the state of the art of wireless and integrated routing algorithms that aim at optimizing the performance of FiWi access networks in terms of delay, throughput, packet loss, load balancing, and other important metrics such as path availability and power consumption. In addition, we elaborate on various techniques to provide service differentiation and end-to-end QoS continuity across the optical–wireless interface of FiWi access networks. Finally, we would like to point the interested reader to new exciting opportunities of adopting FiWi broadband access networks in other relevant economic sectors such as energy and transportation in order to convert the traditional electric power grid, the largest man-made CO$_2$ emission source, into the future smart grid and thereby enhance the efficiency of energy use and achieve a dramatically increased overall CO$_2$ reduction across different sectors.
This book would not have been possible without the help and contributions of many of our collaborators and colleagues. We would like to thank Dr. Mohammad S. Kiaei for his concise description of the IEEE standard 802.3av covering the salient features of the new physical layer of high-speed 10 Gb/s Ethernet passive optical network (10G-EPON). We are grateful to Professor Chadi M. Assi from Concordia University, Montréal, for his fruitful collaboration in surveying the state of the art of FiWi access network architectures. In particular, we would like to thank Dr. Francesco Paolucci from Scuola Superiore Sant’Anna, Pisa, Italy, for his contributions to the design and performance evaluation of SuperMAN during his four-month research visit at INRS, Montréal. We are especially grateful to Dr. Kerim Fouli and Professor Muriel Médard from the Massachusetts Institute of Technology (MIT), Cambridge, USA, for their excellent work on network coding in next-generation PONs (NG-PONs). We also would like to thank Professor Michael Scheutzow from Technical University of Berlin, Germany, for his probabilistic analysis of the survivability of FiWi access networks and insightful discussions while visiting INRS. At Cambridge University Press, we would like to thank Mia Balashova, Sarah Finlay, and Dr. Phil Meyler for their great support and guidance throughout the whole process of preparing the manuscript. Finally, and most importantly, special thanks go to Martin’s beautiful wife Alexie for her patience, love, and belief, and their two wonderful children, who have not missed a single opportunity to play under their dad’s desk when he was trying to work on the manuscript at home with more or less success. Navid would like to take this opportunity to express his deep gratitude and appreciation to his parents and his three brothers for their support, love, and encouragement.