WirelessMAN®

Inside the IEEE 802.16™ Standard for Wireless Metropolitan Area Networks

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Dedication

The authors dedicate this effort to the many members of, and participants in, the IEEE 802.16 Working Group on Broadband Wireless Access. Their tireless efforts since 1998 have led to the completion of a dozen standards with the potential to bring the world closer together. At the very least, the project has already brought a world of participants closer together.
Acknowledgments

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Portions of this work were contributed by NIST and are not subject to copyright protection in the United States.

The authors further acknowledge Doceotech, Incorporated, which provided some of the figures in this book. These figures, reprinted with permission, are drawn from one of the company’s courses providing training for engineers on wireless technologies.
Authors

Carl Eklund received his M.S. in engineering physics from Helsinki University of Technology in 1996. He joined the Communication Systems Laboratory of Nokia Research Center in 1998, working mainly on radio protocol design and standardization. In the IEEE 802.16 effort, he chaired the MAC Task Group that developed the IEEE 802.16 medium access control layer (MAC) protocol for IEEE Std 802.16-2001. He also served as the technical editor for the protocol implementation conformance statement (PICS) and test suite structure and test purposes (TSS&TP) specifications for IEEE Std 802.16-2001. Eklund currently is a principal engineer in the Radio Communications Laboratory of Nokia Research Center, Helsinki, Finland. Since October 2005, he has been heading the research and standardization program for WiMAX and IEEE 802.16 in Nokia.

Roger B. Marks initiated, in 1998, the effort leading to the formation of the IEEE 802.16 Working Group on Broadband Wireless Access, chairing it since inception and serving as Technical Editor of the group’s first two standards. He also serves actively on the IEEE 802 Executive Committee and holds the position of China Liaison Official. Marks is a physicist with the (U.S.) National Institute of Standards and Technology (NIST) in Boulder, Colorado, USA. He received his A.B. in physics in 1980 from Princeton University and his Ph.D. in applied physics in 1988 from Yale University. A Fellow of the IEEE and an IEEE Distinguished Lecturer, Marks developed the IEEE Radio and Wireless Conference and chaired it from 1996 through 1999. He is the author of over 90 publications and the recipient of numerous awards, including the Individual Governmental Vision Award from the Wireless Communications Association and the IEEE Technical Field Award in measurement technology. He has received the U.S. Department of Commerce Gold, Silver (three times), and Bronze Medals.
Subbu Ponnuswamy was one of the early participants in the IEEE 802.16 Working Group and a contributor to the IEEE 802.16 and IEEE 802.11 standards. He is also a coauthor of a WiMAX course for development engineers, offered by Doceotech. He has many years of industry experience in the design and development of wireless local area network (LAN) and metropolitan area network (MAN) products, including those based on the IEEE 802.16 and IEEE 802.11 standards. As the director of engineering at Kiwi Networks, Ponnuswamy led the design and development of interference-resilient IEEE 802.16 and IEEE 802.11 systems in the license-exempt bands for indoor and outdoor applications. He also led IEEE 802.11 MAC application-specific integrated circuit (ASIC) and software development at Vivato for smart antenna systems. During his tenure at Malibu Networks, he designed and developed a quality-of-service-centric broadband wireless MAC. He has also held various technical positions with Honeywell, Sequent Computer Systems, and Lincom Wireless. He is currently with Aruba Networks. Ponnuswamy is the author of many publications and patents in the areas of wireless communication, real-time systems, and multiprocessor communication networks. He graduated with an M.S. in computer engineering from Wayne State University and a B.E. in electronics and communication engineering from the University of Madras, India. He is a member of the Association for Computing Machinery (ACM) and the IEEE Communications Society.

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IEEE 802.16 MAC. He holds 11 patents and has numerous patent applications, all related to broadband wireless access. He received his master’s degree from Stanford University.

Nico J.M. van Waes received an M.S.E.E from the Technical University Delft in the Netherlands in 1994 and a Ph.D. from New Jersey Institute of Technology in 1998. He joined the Wireless Router Division of Nokia Networks in 1999 as a systems engineer, working primarily on physical layer (PHY) and radio frequency (RF) issues as well as standardization. From 1999 till 2004, van Waes held various standards-related public positions such as chief technical editor of IEEE Std 802.16a™, IEEE P802.16.2a, and early versions of IEEE P802.16d; area coordinator and editor for ETSI BRAN HiperMAN; and chair of the OFDM Forum’s fixed wireless access (FWA) working group. From 2004 till 2005, he led Nokia Research Center’s efforts in IEEE P802.11n standardization. Since early 2006, van Waes has been a manager with Nokia IPR, responsible among others for the IEEE 802.16 and IEEE 802.11 portfolios. He has half a dozen patents filed and is the author of several published papers.
Foreword

Because of the explosive global growth of the Internet and its applications, this authoritative, comprehensive, and well-written insider’s guide to broadband wireless standards is truly a book whose time has come. Published by the Standards Information Network/IEEE Press, a unit of the Institute of Electrical and Electronics Engineers (IEEE), WirelessMAN serves as a companion to IEEE Std 802.16, the WirelessMAN standard for broadband wireless metropolitan area networks. This book provides an overview of the technology, explaining the rationale behind the choices made. This overview of the complex technical specification is valuable for the tens of thousands of engineers involved in R&D and deployment of relevant technologies—as well as to less technical opinion leaders in related fields of marketing, sales, finance, government affairs, and media/public relations. WirelessMAN is so clearly organized and written that it can be a rewarding reading experience even for those with no formal technical training.

The authors are and have been leaders of the related standardization projects. IEEE Std 802.16 was developed by the IEEE 802.16 Working Group on Broadband Wireless Access, beginning in 1999. The book’s authors include the IEEE 802.16 founding chair, Dr. Roger B. Marks; its vice chair, Kenneth L. Stanwood; and three of its most visionary and dedicated practitioners, Carl Eklund, Subbu Ponnuswamy, and Nico J.M. van Waes. Those involved in standards work can appreciate that it is a process whose success depends upon far more than just vision and technical expertise. That’s only the beginning. To be as successful as the WirelessMAN standards effort has been, it’s necessary also to draw on the skill sets commonly associated with master politicians and corporate strategists because the stakes can be so huge—especially in this instance, where the goal is nothing short of gradually replacing multibillion-dollar proprietary technologies with lower cost, standards-based interoperable products. If the upside is high for some players, so is the downside for others. In other words, creating a successful standard is
not in everyone’s interest, and so whatever method of collegial input is used may also be abused.

The IEEE 802.16 Working Group has made impressive progress in its standards effort, as measured by objective data. It has held more than 43 weeklong sessions around the world, from the group’s official founding in 1999 to the publication of this book in 2006. By working cooperatively, the group has developed and advanced its standards in near-record time. The current version of its fixed wireless standard was most recently updated as IEEE Std 802.16-2004 [B20], and an amendment adding mobility support (IEEE Std 802.16e™-2005 [B24]) was published in late 2005. The IEEE 802.16 standard is at the core of the fast-growing certification effort by the WiMAX Forum®, whose expanding activities have been generating news and magazine articles at the rate of six hundred a month at times.

By attending the organizational strategy meeting in July 1998 of the predecessor group that led to the IEEE 802.16 Working Group, I had the privilege of observing the growth of this process right from the beginning despite my lack of any formal training in the relevant technology. Fortunately, I did have good advice from my mentor in this area, Dr. Weston E. Vivian, the longtime University of Michigan professor who holds the distinction of being the first person ever elected to the U.S. Congress with a doctorate in either engineering or science. His counsel was to “sit in on every technical meeting you can – and don’t say much.” The assumption was that over time, even I would learn something. That strategy meeting was called by Roger Marks at the Boulder, Colorado, offices of the National Institute of Standards and Technology (NIST) to create what became known as the National Wireless Electronic Systems Testbed before its assimilation the next year into the IEEE standards process. The few others at the meeting had enormous subject-matter expertise, most with doctorates in electronic engineering and affiliations with major companies. Despite the additional handicap of not being in a position to make substantive commitments because Wireless Communications Association International (WCA) is technology neutral, I attended as an observer, encouraged by knowledge that standards were regarded by our members as potentially vital, but also extremely difficult to achieve in practice.
We at WCA have been extremely impressed by the dedication of the WirelessMAN pioneers, including its founding chair. Although WCA continues to adhere to a technology-neutral standpoint in order to showcase all relevant technologies on a fair basis, it seems appropriate nevertheless to share a few personal observations at this juncture: First, the leadership of this group is particularly dedicated, well-organized, and enthusiastic about creating new networks. These standards meetings are all-day, weeklong affairs, and more than once I have called upon leaders in the middle of their night to learn of developments. Second, and more important, WirelessMAN, an authoritative insider’s account, is certain to prove valuable as a guide to understanding the history and implications of the technology—not just the IEEE 802.16 version, but in the context of competing and complementary broadband technologies, both wireless and wireline. The book is highly recommended for designers of components, systems, and test equipment based on the WirelessMAN standards, plus a variety of other telecommunications professionals and students. This is an important and useful book for anyone in this fast-exploding field.

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Preface

Broadband access has become a critical bottleneck in the ongoing information technology revolution across the globe. The growing popularity of multimedia applications has made the requirements on broadband access even more demanding. In order to serve this growing market need, the reach of existing broadband networks needs to be extended, and new broadband infrastructures need to be deployed in developing nations where no wired broadband infrastructures exist.

The advent of standards-based and interoperable wireless local area networks (WLANs) and wireless personal area networks (WPANs) has resulted in widespread adoption of wireless networks in homes as well as in consumer and enterprise markets. The productivity gains and increased flexibility that comes with wireless have transformed the way many businesses operate.

Broadband wireless access (BWA) is the next logical step in extending fiber optic backbone networks to enhance broadband proliferation and to provide broadband access in areas where no other methods are available. BWA is also attractive as a network infrastructure that can be deployed much more quickly than its wired counterparts. Moreover, broadband wireless has the potential to offer capacity on demand.

Proprietary BWA solutions have existed for some time, with limited market penetration in licensed and license-exempt bands. However, the lack of a global standard and lack of multivendor interoperable equipment have hampered widespread adoption. Given the infrastructure-intensive nature of broadband wireless deployments, widespread adoption requires interest from a wide range of service providers. All of the potential providers, large or small, are seeking standardized rather than proprietary solutions. With nomadic and mobile systems, roaming operations force questions of cross-vendor interoperability to the forefront. However, even for non-nomadic fixed broadband wireless networks, in which roaming is virtually nonexistent, operators are hesitant to accept unnecessary risk in the current economic conditions.
climate, and the use of proprietary equipment from a small number of vendors is an unnecessary risk. Good standards activities, such as those that are well established in IEEE 802®, not only bring operators reasonably priced equipment but also put them on a curve of declining costs and growing performance. The IEEE 802.16 standard for wireless metropolitan area networks (MANs) has been developed by the IEEE 802.16 Working Group to address this BWA market. The activity has been in progress since 1999; it has been highly productive, and the standard continues to evolve.

As you will find in this book, IEEE 802.16 is quite different from other IEEE 802 standards. The technology is more oriented toward carrier-class services whose infrastructure development is designed and deployed by professionals affiliated with experienced telecommunications operators. Also, compared to some other IEEE 802 standards, IEEE 802.16 leaves more of the implementation decisions to the implementor, particularly at the base station (BS) side. This provides the system developer with the opportunity to develop a simple, low-cost system or to apply extra effort to create a substantially better performing system that may fetch a higher price. The goal is a wide deployment of a broad range of IEEE 802.16-based systems that are interoperable but highly differentiated. This should help to keep the market dynamic and innovative and provide many attractive options to the carriers.

Objective

The objective of this book is to provide a detailed overview of the IEEE 802.16 standard for fixed BWA, including detailed descriptions of the IEEE 802.16 medium access control layer (MAC) and physical layer (PHY) operation, with emphasis on the design and the technology behind the standard. This book explains why certain design choices were made and how recent technological developments, real-world experience, and lessons learned from previous projects were used throughout the IEEE 802.16 development process to make critical tradeoffs.

The book also reviews the chronological development of the IEEE 802.16 MAC and PHY and the rationale behind the development decisions. It provides a summary of ongoing projects, related standards, and future extensions to IEEE 802.16. The optional and mandatory parts of the
IEEE 802.16 standard are clearly identified and explained throughout the book, wherever applicable.

**Organization**

Chapter 1 provides an introduction to BWA and identifies the key market segments and basic requirements. Chapter 2 overviews the IEEE 802.16 Working Group, including the organizations under which it works and the procedures it uses, summarizing the history of the group and its past and current projects. Chapter 3 defines the basic MAC, PHY, radio frequency (RF) and other protocol concepts necessary for understanding the IEEE 802.16 standard. The final introductory chapter, Chapter 4, describes the overall architecture of IEEE 802.16 and introduces various components and key features of IEEE 802.16 in detail.

The rest of the book describes the components of the IEEE 802.16 architecture in a top-down fashion. Chapter 5 describes the asynchronous transfer mode (ATM) convergence sublayer (CS) and packet convergence sublayer (PCS) of IEEE Std 802.16. In Chapter 6, the basic concepts of the IEEE 802.16 MAC, supporting all of the IEEE 802.16 PHY alternatives, are covered. Chapter 7 provides details of the IEEE 802.16 MAC operation, including network entry, initialization, PHY support, automatic repeat request (ARQ) and quality of service (QoS). The security sublayer, including encryption methods and key exchange mechanisms, is described in Chapter 8. Chapter 9 describes the mesh extensions to the IEEE 802.16 MAC and the additional scheduling methods defined to support the mesh option.

The next three chapters describe three major PHY alternatives specified in IEEE 802.16. Chapter 10 addresses the single-carrier (WirelessMAN-SC) PHY specified for use above 10 GHz. Chapter 11 describes the orthogonal frequency division multiplexing (WirelessMAN-OFDM) PHY for frequencies below 11 GHz, and Chapter 12 describes the orthogonal frequency division multiple access (WirelessMAN-OFDMA) PHY for the same frequencies.

Chapter 13 explores the IEEE 802.16 standard’s support for multiple antenna systems, including adaptive antenna systems (AAS), as an extension of the IEEE 802.16 point-to-multipoint (PMP) topology. Chapter 14 addresses the
Preface

performance of the MAC and various PHYs. A summary of the IEEE 802.16 conformance standards and an introduction to the interoperability work being done by the WiMAX Forum are given in Chapter 15. Chapter 16 provides a summary of related standards and standardization activities.

Appendix A provides a list of IEEE 802.16 headers, subheaders, and MAC management messages for ready reference.

Reading and style

This book is intended for anyone who wishes to understand the IEEE 802.16 standard and operation, including designers, engineers, students, and deployment professionals. This book is self-contained, and no specific knowledge of any other wireless protocols is assumed. However, a basic knowledge of communication protocols and concepts is necessary for understanding the key MAC and PHY chapters of this book. An extensive bibliography is given at the end for anyone who would like to read more on specific topics that are not covered here in detail.

While the introductory chapters provide basic information for all types of readers, the MAC- and PHY-specific chapters can be treated independently, with the exception of the MAC-PHY interface, by designers who are interested in designing only the MAC or PHY portion of a IEEE 802.16 system. The mesh and AAS chapters require the understanding of the MAC architecture and PHY interface defined in earlier chapters. This book can be used for self-study of the IEEE 802.16 standard, as a reference, or as a designer’s handbook.

Advanced readers should look at the book as a companion to IEEE Std 802.16. Readers should note that IEEE 802 standards are available for free download through the Get IEEE 802® program <http://standards.ieee.org/getieee802>. Readers may also wish to consult the web pages of the IEEE 802.16 Working Group on Broadband Wireless Access <http://WirelessMAN.org>, which include thousands of working group and contributed documents upon which the standard, including its amendments, are based.
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## Acronyms and abbreviations

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<td>triple data encryption standard</td>
</tr>
<tr>
<td>AAS</td>
<td>adaptive antenna systems</td>
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<tr>
<td>ABR</td>
<td>available bit rate</td>
</tr>
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<td>ACID</td>
<td>ARQ channel identifier</td>
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<tr>
<td>ACK</td>
<td>acknowledgment</td>
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<td>AES</td>
<td>advanced encryption standard</td>
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<td>AISN</td>
<td>ARQ identifier sequence number</td>
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<tr>
<td>AK</td>
<td>authorization key</td>
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<tr>
<td>AMC</td>
<td>adaptive modulation and coding</td>
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<td>AoA</td>
<td>angle of arrival</td>
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<td>AoD</td>
<td>angle of departure</td>
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<td>AP</td>
<td>access point</td>
</tr>
<tr>
<td>ARQ</td>
<td>automatic repeat request</td>
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<tr>
<td>ASIC</td>
<td>application-specific integrated circuit</td>
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<td>ATDD</td>
<td>adaptive time division duplexing</td>
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<td>asynchronous transfer mode</td>
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<td>block convolutional code</td>
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<td>BE</td>
<td>best effort</td>
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<td>BER</td>
<td>bit error rate</td>
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<td>binary phase shift keying</td>
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<td>BRAN</td>
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<td>broadband radio service</td>
</tr>
<tr>
<td>BS</td>
<td>base station</td>
</tr>
<tr>
<td>BSN</td>
<td>block sequence number</td>
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<td>BTC</td>
<td>block turbo code</td>
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<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
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<tr>
<td>BW</td>
<td>bandwidth</td>
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<tr>
<td>BWA</td>
<td>broadband wireless access</td>
</tr>
<tr>
<td>CAC</td>
<td>call admission control</td>
</tr>
<tr>
<td>CAZAC</td>
<td>constant amplitude zero autocorrelation</td>
</tr>
<tr>
<td>CBC</td>
<td>cipher block chaining</td>
</tr>
<tr>
<td>CBLER</td>
<td>coded block error rate</td>
</tr>
<tr>
<td>CBR</td>
<td>constant bit rate</td>
</tr>
<tr>
<td>CC</td>
<td>convolutional coding</td>
</tr>
<tr>
<td>CCM</td>
<td>counter with CBC-MAC</td>
</tr>
<tr>
<td>CDMA</td>
<td>code division multiple access</td>
</tr>
<tr>
<td>C/I</td>
<td>carrier to interference ratio</td>
</tr>
<tr>
<td>CID</td>
<td>connection identifier</td>
</tr>
<tr>
<td>CINR</td>
<td>carrier to interference-plus-noise ratio</td>
</tr>
<tr>
<td>CIR</td>
<td>channel impulse response</td>
</tr>
<tr>
<td>CLR</td>
<td>cell loss ratio</td>
</tr>
<tr>
<td>CP</td>
<td>cyclic prefix</td>
</tr>
<tr>
<td>CoS</td>
<td>class of service</td>
</tr>
<tr>
<td>CPE</td>
<td>customer premises equipment</td>
</tr>
<tr>
<td>CPS</td>
<td>common part sublayer</td>
</tr>
<tr>
<td>CRC</td>
<td>cyclic redundancy check</td>
</tr>
<tr>
<td>CS</td>
<td>convergence sublayer</td>
</tr>
<tr>
<td>CSCF</td>
<td>centralized scheduling configuration</td>
</tr>
<tr>
<td>CSCH</td>
<td>centralized scheduling</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>carrier sense multiple access/collision avoidance</td>
</tr>
<tr>
<td>CTC</td>
<td>convolutional turbo code</td>
</tr>
<tr>
<td>CTS</td>
<td>clear to send</td>
</tr>
<tr>
<td>DAMA</td>
<td>demand-assigned multiple access</td>
</tr>
<tr>
<td>DBPC</td>
<td>downlink burst profile change</td>
</tr>
<tr>
<td>DCD</td>
<td>downlink channel descriptor</td>
</tr>
<tr>
<td>DCF</td>
<td>distributed coordination function</td>
</tr>
<tr>
<td>DES</td>
<td>data encryption standard</td>
</tr>
<tr>
<td>DFS</td>
<td>dynamic frequency selection</td>
</tr>
<tr>
<td>DHCP</td>
<td>Dynamic Host Configuration Protocol</td>
</tr>
</tbody>
</table>
DIUC  downlink interval usage code
DL    downlink
DLFP  downlink frame prefix
DMZ   diversity MAP zone
DOCSIS® data over cable service interface specification
DSA   dynamic service addition
DSC   dynamic service change
DSCH  distributed scheduling
DSCP  differentiated services code point
DSD   dynamic service deletion
DSL   digital subscriber line
DVB   digital video broadcast
EAP   Extensible Authentication Protocol
EDCA  enhanced distributed channel access
EGC   equal gain combining
EIRP  effective isotropic radiated power
EKS   encryption key sequence
FC    fragment control [field]
FCH   frame control header
FDD   frequency division duplexing
FDE   frequency-domain equalizer
FDM   frequency division multiplexing
FDMA  frequency division multiple access
FEC   forward error correction
FFSH  fast-feedback allocation subheader
FFT   fast Fourier transform
FHDC  frequency-hopped diversity coding
FHSS  frequency-hopping spread spectrum
FIFO  first-in, first-out
FSDD  frequency shift division duplexing
FSH   fragmentation subheader
FSN   fragment sequence number
FTP   File Transfer Protocol
FUSC  full usage of subchannels
GBN  go-back-n
GF  Galois field
GFR  guaranteed frame rate
GMSH  grant management subheader
GP  guard period
GPS  global positioning system
GSM  Global System for Mobile Communications
HARQ  hybrid automatic repeat request
HCCA  HCF coordinated channel access
HCF  hybrid coordination function
HCS  header check sequence
H-FDD  half-duplex frequency division duplexing
HSDPA  high-speed downlink packet access
HT  header type
HTTP  Hypertext Transfer Protocol
I  in-phase
ID  identifier
IE  information element
IFFT  inverse fast Fourier transform
IP  Internet Protocol
ISI  intersymbol interference
IUC  interval usage code
IV  initialization vector
KEK  key encryption key
LAN  local area network
LDPCC  low-density parity check coding
LLC  logical link control
LMDS  local multipoint distribution service
LMSC  LAN/MAN Standards Committee
LOS  line-of-sight
LSB  least significant bit
MAC  medium access control layer
MAN metropolitan area network
MBS maximum burst size
MIB management information base
MIMO multiple-input, multiple-output
MMDS multichannel multipoint distribution service
MPDU MAC protocol data unit
MPLS multiprotocol label switching
MRC maximum ratio combining
MSB most significant bit
MSDU MAC service data unit
MSH mesh subheader
MS mobile station
NACK negative acknowledgment
NLOS non-line-of-sight
nrtPS nonreal-time polling service
nrtVBR nonreal-time variable bit rate
OFDM orthogonal frequency division multiplexing
OFDMA orthogonal frequency division multiple access
O-FUSC optional full usage of subchannels
O-PUSC optional partial usage of subchannels
OSI Open System Interconnection
PAN personal area network
PAPR peak to average power ratio
PAR project authorization request
PCF point coordination function
PCR peak cell rate
PCS packet convergence sublayer
PDU protocol data unit
PER packet error rate
PHS payload header suppression
PHSF payload header suppression field
PHSI payload header suppression index
PHSM payload header suppression mask
PHSS  payload header suppression size
PHSV  payload header suppression valid
PHY   physical layer
PICS  protocol implementation conformance statement
PKM   privacy key management
PM    poll-me
PMP   point-to-multipoint
PN    packet number
PoS   point of sale
PRBS  pseudo-random binary sequence
PS    physical slot
PSH   packing subheader
PtP   point-to-point
PUSC  partial usage of subchannels
Q     quadrature
QAM   quadrature amplitude modulation
QoS   quality of service
QPSK  quadrature phase-shift keying
RCID  reduced connection identifier
RCT   radio conformance test
RF    radio frequency
RLC   radio link control
RS    Reed-Solomon
RS-CC  Reed-Solomon concatenated with convolutional coding
RSSI  received signal strength indicator
RSV or Rsv reserved
RTG   receive-transmit transition gap
rtPS  real-time polling service
RTS   request to send
rtVBR real-time variable bit rate
SA    security association
SAID  security association identifier
SAP   service access point
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>single carrier</td>
</tr>
<tr>
<td>SCR</td>
<td>sustained cell rate</td>
</tr>
<tr>
<td>SDMA</td>
<td>spatial division multiple access</td>
</tr>
<tr>
<td>SDO</td>
<td>standards developing organization</td>
</tr>
<tr>
<td>SDU</td>
<td>service data unit</td>
</tr>
<tr>
<td>SFID</td>
<td>service flow identifier</td>
</tr>
<tr>
<td>SHA-1</td>
<td>Secure Hash Algorithm 1</td>
</tr>
<tr>
<td>SI</td>
<td>slip indicator</td>
</tr>
<tr>
<td>S/I</td>
<td>signal to interference ratio</td>
</tr>
<tr>
<td>SISO</td>
<td>single-input, single-output</td>
</tr>
<tr>
<td>SLA</td>
<td>service-level agreement</td>
</tr>
<tr>
<td>SM</td>
<td>spatial multiplexing</td>
</tr>
<tr>
<td>SNMP</td>
<td>Simple Network Management Protocol</td>
</tr>
<tr>
<td>SNR</td>
<td>signal to noise ratio</td>
</tr>
<tr>
<td>SOHO</td>
<td>small office/home office</td>
</tr>
<tr>
<td>SPID</td>
<td>subpacket identifier</td>
</tr>
<tr>
<td>SR</td>
<td>selective repeat</td>
</tr>
<tr>
<td>SS</td>
<td>subscriber station</td>
</tr>
<tr>
<td>SSRTG</td>
<td>subscriber station receive-transmit transition gap</td>
</tr>
<tr>
<td>SSTG</td>
<td>subscriber station transition gap</td>
</tr>
<tr>
<td>SSTTG</td>
<td>subscriber station transmit-receive transition gap</td>
</tr>
<tr>
<td>STBC</td>
<td>space-time block coding</td>
</tr>
<tr>
<td>STC</td>
<td>space-time coding</td>
</tr>
<tr>
<td>STTD</td>
<td>space-time transmit diversity</td>
</tr>
<tr>
<td>TCM</td>
<td>trellis-coded modulation</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TDD</td>
<td>time division duplexing</td>
</tr>
<tr>
<td>TDM</td>
<td>time division multiplexing</td>
</tr>
<tr>
<td>TDMA</td>
<td>time division multiple access</td>
</tr>
<tr>
<td>TEK</td>
<td>traffic encryption key</td>
</tr>
<tr>
<td>TFTP</td>
<td>Trivial File Transfer Protocol</td>
</tr>
<tr>
<td>TLV</td>
<td>Type-Length-Value</td>
</tr>
<tr>
<td>ToS</td>
<td>type of service</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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</tr>
<tr>
<td>TSS&amp;TP</td>
<td>test suite structure and test purposes</td>
</tr>
<tr>
<td>TTG</td>
<td>transmit-receive transition gap</td>
</tr>
<tr>
<td>UBR</td>
<td>unspecified bit rate</td>
</tr>
<tr>
<td>UCD</td>
<td>uplink channel descriptor</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>UGS</td>
<td>unsolicited grant service</td>
</tr>
<tr>
<td>UIUC</td>
<td>uplink interval usage code</td>
</tr>
<tr>
<td>UL</td>
<td>uplink</td>
</tr>
<tr>
<td>VC</td>
<td>virtual channel</td>
</tr>
<tr>
<td>VCI</td>
<td>virtual channel identifier</td>
</tr>
<tr>
<td>VLAN</td>
<td>virtual local area network</td>
</tr>
<tr>
<td>VoIP</td>
<td>voice over Internet Protocol</td>
</tr>
<tr>
<td>VP</td>
<td>virtual path</td>
</tr>
<tr>
<td>VPI</td>
<td>virtual path identifier</td>
</tr>
<tr>
<td>Wi-Fi®</td>
<td>wireless fidelity</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
</tr>
<tr>
<td>WLAN</td>
<td>wireless local area network</td>
</tr>
<tr>
<td>WPAN</td>
<td>wireless personal area network</td>
</tr>
<tr>
<td>WRAN</td>
<td>wireless regional area network</td>
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</tbody>
</table>
Chapter 1  Broadband wireless access (BWA)

Applicable market segments and requirements

The IEEE 802.16 Working Group on Broadband Wireless Access has been developing IEEE Std 802.16™ since 1999. Its original air interface standard was completed in 2001, but it has continued to evolve and will continue to evolve. The basic goal of the standard is to provide specific technologies and protocols to specify the air interface of BWA systems.

The central aim of IEEE 802.16 technology is to support broadband access; that is, to support access (i.e., connection to core networks) at broadband rates (which, according to a popular International Telecommunication Union (ITU) definition, means providing service at a rate of at least 1.544 Mbit/s, although we take the definition somewhat more loosely). Since IEEE 802.16 provides broadband access with a wireless connection, it could perhaps be said to provide “wireless broadband access.” In the early days, the IEEE 802.16 Working Group considered this word order, finally settling on “broadband wireless access.” It appears that this might emphasize that the work involved a broadband extension of the wireless access concept rather than a wireless implementation of broadband access concepts. In fact, because this standard does both, it exemplifies the ongoing trends toward convergence in telecommunications and data communications. The final choice of word order was rather arbitrary.

As the world’s backbone telecommunications networks flourished in the twentieth century, vast data-carrying capacity is now available in fiber-optic lines. Unfortunately, this bandwidth is directly available only to those with direct access to the infrastructure, which is a very small fraction of the potential users. In the developed world, powerful fiber infrastructure may connect large commercial buildings but not the neighboring medium-sized commercial facilities. In many parts of the developing world, connection to
the world’s fiber infrastructure is still only a plan, or perhaps only a dream. When such a connection does take place, it will initially be at a single port of entry for an entire country. Distribution is critical.

Broadband access is about bridging the gap between the core infrastructure networks and the user’s networks. This bridge can itself be built with wires or fibers, but the basic structure of the problem means that this requires a massive proliferation of cabling in order to serve users in a wide variety of places. This is a fundamental barrier to cabling. It is costly to install and maintain. Cabling hung from utility poles requires a series of permissions and rights-of-way. It is costly to deploy and subject to damage caused by everything from weather to traffic accidents. Buried cabling is more reliable (although still subject to cuts), but trenching is expensive and slow, or even prohibitive, due to the disruption to communities and traffic patterns. Doug Lockie, a veteran of the BWA business, has noted many times that “backhoes don’t follow Moore’s Law.” His point is that no amount of exponential improvement in cost and performance of network equipment will enable cost-effective network deployment as long as cable installation is the fundamental limitation.

If broadband access is wireless, many of these construction problems can be bypassed. Compared to wired broadband access, wireless broadband access leans more heavily on technological innovation and less heavily on the physical plant. This is one reason it seems to hold more promise for the future. Of course, the wireless medium has its own limitations and costs; these are associated primarily with spectrum access, restrictions, and limitations. It remains to be seen how the costs and benefits of the wired and wireless cases will balance. It seems clear that cabling will be the leader at the core network side, where data are massively consolidated, and wireless will shine nearer the user, where data are more user-specific. The details of which technologies will be most competitive in various market segments will depend on many details, including the local infrastructure and regulatory environment.

Competition, of course, is driven by demand, and demand cannot always be satisfied by a single technical solution. If all homes and enterprises in an area have direct access to wired broadband, many of the consumers will probably be satisfied. On the other hand, some might still be willing to consider
alternative providers based on price, performance, features, or reliability; therefore, alternatives such as wireless broadband access may see an opportunity. But demand in the telecommunications world can also come from another direction: from the top down. Namely, many operators of core networks intend to provide service to retail customers. If these operators lack access networks, they are forced into leasing or partnership arrangements with the access provider. In an area with only one access provider (or only very few), the network operator may be forced into an unfavorable position. In such cases, demand for alternative access may be driven in top-down fashion by the operators.

In many cases, governments are seeking to foster more players and more competition in the broadband network marketplace. The market is sometimes slow to respond to demand, frequently because of natural barriers. For instance, the wired access market is difficult to penetrate, not only because it is slow and costly but, as noted earlier, because the development of local wired access facilities is burdened by regulation, especially because it is disruptive to environments (such as, for example, cities that cannot tolerate streets being trenched, or rural areas in which power lines affect wildlife migration). Barriers to wireless access networks are generally less prohibitive; therefore, wireless networks can be erected relatively inexpensively and also quite quickly. This, of course, depends heavily on spectrum availability and conditions.

One aspect of cabled infrastructure that is hard to avoid is its stationary nature. It is difficult to imagine cable being so densely deployed that it is readily available everywhere in a region the size of a city, or larger. Cable operators pick and choose their locations. Wireless signals, on the other hand, have the ability to cover a metropolitan-sized (or larger) area quite densely so that signals are broadly available, even to moving users. This allows for usage models that simply cannot be accommodated with cabled systems. The great technological and marketplace achievements of the mobile telephone business have helped to demonstrate the appeal of such a system and the flexibility it offers. Meanwhile, the success of portable computers, especially those networked with wireless local area networks (WLANs) (based on IEEE Std 802.11™) have demonstrated the appeal of untethered broadband access. This background points to a future in which broadband access moves toward
an increasingly portable, nomadic, and mobile usage model. The possibility of this evolution strengthens the hand of wireless broadband access relative to its wired alternatives.

As already noted, IEEE Std 802.16 is an evolutionary standard. The standard was designed originally for the support of stationary, enterprise-class deployments. However, the long-term goal was always to evolve the standard along with the developing technology to the point at which it could be economically feasible to move deeper into the access network and closer to the user. As of 2003, the standard was first enhanced with technology suitable for residential-class applications. Around the same time, work began to evolve the technology further, toward systems that could support mobile as well as stationary terminals. The IEEE 802.16e amendment, approved in December 2005, brings support for mobile as well as fixed terminals. We do not significantly discuss IEEE Std 802.16e™ in this book. However, in the standard’s evolution, it continues to build on the foundations that were previously laid. Therefore, understanding the stationary (“fixed”) technology is an essential basis for understanding the fixed/mobile advances.

As IEEE Std 802.16 has grown (see [B13] and [B38]), much of the evolution has occurred in the physical layer (PHY), which is the primary arbiter of the physical environment in which the technology can operate. All of this development, however, is based on the essence of the standard: its medium access control layer (MAC) specification. This MAC, which supports all of the standard’s PHY options, was originally designed for the first application: carrier-quality, enterprise-based telecommunications services. Because of this history, the IEEE 802.16 standard can support the most demanding service requirements, even as it evolves toward more consumer-friendly applications. This is a key factor in the applicability of the standard. One of the primary MAC-related features of the standard’s technology is its support for differentiated quality of service (QoS) among its users. An IEEE 802.16 base station (BS) can simultaneously support a variety of customer service requirements, for example, very demanding services such as real-time video.

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1 Numbers in brackets refer the reader to additional resources listed in the bibliography of this book.
conferencing along with T1/E1 service, voice over Internet Protocol (VoIP), and best-effort Internet.

Spectrum, as the wireless medium, is a very precious infrastructure commodity. Any standard intended to support wireless communications, in any application, must be critically conservative in its use of this resource. IEEE 802.16 takes pains to conserve spectrum and emphasize spectral efficiency, at the expense of protocol complexity. This approach generally enhances its applicability, although perhaps some applications might be better suited to lower complexity protocols with lower efficiency.

IEEE Std 802.16 is called the WirelessMAN standard for wireless metropolitan area networks. “Metropolitan” in this sense indicates not the target geography but instead the target scale. The standard supports networks that are about the size of a city. It is by no means limited to urban applications. Some of the most likely applications are in rural areas in which high-quality broadband access is not readily available. The term metropolitan area network (MAN) predates the term WirelessMAN by many years. IEEE 802®, under which IEEE 802.16 is chartered, is formally known as the “LAN/MAN Standards Committee.” It was called the “LAN Standards Committee” when formed in 1980, but the name grew with the group’s portfolio.

IEEE 802.16 is an air interface standard, not a manual for service deployment. It is intended to support transport of any higher layer network requirement and in any application in which someone sees fit to apply it. The goal is flexibility. The developers of the standard may have had some applications in mind, but a good, open standard can be put to a variety of users by people who did not develop it. If a developing area is seeking to install a unified wireless network for voice, data, and video services, thereby obviating the need for a multiplicity of more narrowly focused systems as would be seen in a developed city, then IEEE 802.16 may be a good choice. Likewise, if a city is seeking to enhance the availability of broadband services to its population by constructing a public wireless data network, then IEEE 802.16 may also be an excellent candidate, serving either as a backhaul network supporting the ready deployment of WLAN access points (APs) or as an access network bringing a connection directly to a user. Some operators may seek to provide service to a fixed antenna, either on the outside of a building or indoors. Other operators
may seek to communicate directly with portable computers with on-board IEEE 802.16 radios.

In some cases, IEEE Std 802.16 might be a pure consumer system, with no commercial operator. Such use could be, for example, purely inside a home or enterprise, where the standard’s QoS support gives it a leg up on alternative technologies. Or perhaps hobbyist or quasi-professional users will set up license-exempt systems for neighborhood communications. The applications are limitless, as they were intended to be.

Given this flexibility, it is difficult to completely address the specific market applications to which IEEE Std 802.16 may be applied. An amalgam of typical deployment scenarios is sketched in Figure 1-1. Many services are supported, consumer as well as commercial, mobile as well as fixed, and backhaul-only as well as directly to the end user. Such a mixed set of services signifies a mature and successful MAN. Perhaps we shall someday see such a network based on IEEE Std 802.16.

Below, we continue this introductory chapter, providing examples of how IEEE Std 802.16 might be applied to some idealized market situations.

**COMMERCIAL FIXED BROADBAND WIRELESS: FIBER EXTENSION**

In large metropolitan areas throughout much of the developed world, commercial office towers are connected to core networks by high-capacity fiber optic links, with broadband network services provided to the tenants. In the meantime, other smaller businesses, even those located across the street or on the next block, go without proper network facilities for a lack of fiber connectivity. IEEE 802.16 networks can fairly easily extend the reach of the fiber links. Suitable spectrum is available for this purpose in many areas. For example, the United States licensed 1150 MHz of spectrum in the 28–31 GHz range in 1998 for a service called local multipoint distribution service (LMDS); since then, additional higher frequency spectrum has become available on a license-exempt basis or with a low-cost license. Supply for spectrum at such frequencies outweighs demand primarily because of the less favorable propagation properties of electromagnetic radiation in this band. In particular, attenuation in air is rather high so that propagation distances are
typically limited to around 3 km to 5 km. Also, attenuation increases dramatically in the presence of rainfall so that power control over a significant range is required. Diffraction is limited so that only line-of-sight (LOS) propagation is practical for communications. Furthermore, electronic components at these frequencies are relatively expensive. On the other hand, spectrum is plentiful enough for massive bandwidth, and short propagation distances and LOS propagation (supported by the compact, high-gain directional antennas available at these short wavelengths) allow for high frequency reuse.

Tall towers, which often have fiber connectivity, are good platforms for LOS BS antennas because the view from the top typically includes hundreds of
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prospective customers. Commercial buildings allow for rooftop antennas, the cost of which (both the hardware and the professional installation) is spread over a number of commercial customers. In LOS links, multipath propagation is usually minimal; therefore, relatively simple modulation schemes may be effective. The extension of fiber requires the ability to support high data rates (> 100 Mbit/s), with high reliability and service-level guarantees. The ability to transport voice, video, and data traffic with appropriate quality is also an important requirement.

The first version of IEEE Std 802.16, approved in 2001, included a PHY specification, called single-carrier WirelessMAN (WirelessMAN-SC), suitable for use in the high-frequency bands associated with fiber extension. At the time, prospects for the deployment of the standard seemed rosy. However, the bursting of the “telecom bubble” early in the twenty-first century put an end to many promising plans. Currently, conditions are becoming more favorable for reconsideration of these applications. If so, then the WirelessMAN-SC air interface will be a good candidate to support such deployments. It supports the requirements, and it allows for stepped investment commensurate with market capacity requirements.

RESIDENTIAL FIXED BROADBAND WIRELESS: DIGITAL SUBSCRIBER LINE (DSL) AND CABLE MODEM ALTERNATIVE

In the developed world, broadband access has become a virtual necessity in the residential market. Homes are frequently the site of full-time or off-duty business, and broadband Internet access is in demand for education, information, voice, video, shopping, and entertainment. Cable modem and DSL networks have become the primary technologies addressing these home markets in many countries. However, such networks do not extend everywhere. Not all areas are served by cable television networks, and not all have been upgraded for cable modem service. While telephone networks are widely deployed in the developed world, not all lines have been upgraded for DSL service, and many homes are too far from the central office for DSL transmission.

Where DSL and/or cable modem service is available, BWA may nevertheless play a role. Customers may be seeking alternatives based on price,
performance, and/or reliability. Also, wireless service may have advantages, such as, in some cases, the ability to move a portable terminal throughout a service area. As previously noted, network operators who are dissatisfied with their inability to directly access their retail customers except through a local access provider may also be motivated to deploy a wireless access alternative.

In the developing world, and in many rural areas of the developed world, broadband access is simply unavailable. Wireless access may be particularly attractive in sparsely populated rural areas in which the cost of cabling is prohibitive.

Different design considerations may apply in rural and urban areas. For instance, in rural areas, economic considerations may require that a BS cell size be quite large, up to tens of kilometers. In these cases, LOS propagation with rooftop-mounted directional antennas may be appropriate. On the other hand, urban and suburban applications typically assume non-line-of-sight (NLOS) operation due to the proliferation of obstacles, the high incidence of multipath propagation, and the carrier frequency used (typically under 11 GHz). These networks may use licensed or license-exempt bands.

Attractive licensed frequencies are available in the United States in the broadband radio service (BRS) bands [formerly known as multichannel multipoint distribution service (MMDS)] at around 2.5 GHz to 2.69 GHz. Outside the United States, other licensed bands, such as 3.5 GHz, are more common.

License-exempt operation has some additional challenges in MANs. Popular WLANs, which similarly operate in license-exempt 2.4 GHz and 5 GHz bands, are typically deployed in buildings and other areas under the control of a single entity deploying the network. This controlled environment is similar to a licensed deployment, since interference is limited to neighbors normally isolated to some degree by space and walls. However, license-exempt outdoor BWA deployments bring a different set of challenges, as a single entity cannot enforce its rules on other legal transmitters that may interfere. Any BWA solution has to take this into account.

In all of these cases, operators favor solutions that allow self-installation of customer equipment, since professional installation significantly affects the cost. Ideally, the customer equipment is in the form of a portable device that
can be placed indoors. Such installation not only reduces the deployment cost but also offers the advantage of portability.

With residential customers becoming more technologically demanding, a competitive residential service offering is becoming suitable to small businesses as well. Because IEEE Std 802.16 is designed to support mixed services, it has no problem supporting such a customer mix. We can easily envision a multitude of applications for such a system. For instance, T1/E1 customers could be provisioned, and commercial WLAN hot spots, which typically require backhaul by 10BaseT (often over DSL), could be made entirely wireless using IEEE 802.16 backhaul. This would allow greatly increased flexibility in the placement of the IEEE 802.11 APs. Backhaul of other devices, such as cellular BSs, is another likely service.

IEEE Std 802.16 added support for a PHY at frequencies below 11 GHz beginning in 2003 with IEEE Std 802.16a™. This work, further refined in IEEE Std 802.16-2004 [B20] (the most recent revision of the standard), includes the specification of three PHY alternatives, known as orthogonal frequency division multiplexing (WirelessMAN-OFDM), orthogonal frequency division multiple access (WirelessMAN-OFMDA), and single carrier below 11 GHz (WirelessMAN-SCa). The first two, in particular, are well suited to NLOS operation in a multipath environment.

While IEEE Std 802.16-2004 specifies a standard for fixed access, the actual applications may allow a significant level of flexibility. For example, the user device may be nomadic, meaning that it can move as long as it does not operate while doing so. Such operation, as would be typical of a portable terminal such as a laptop computer equipped with wireless fidelity (Wi-Fi®), is well within the target market of deployments based on IEEE Std 802.16-2004. Even a certain amount of movement during operation is tolerable. Intercell handover, however, is beyond the scope of IEEE Std 802.16-2004. For this, users should turn to the IEEE 802.16e specification that was approved by IEEE as an amendment in December 2005.

At the time of publication, a number of companies have announced products claiming compliance to IEEE Std 802.16-2004.
QUALITY OF SERVICE (QoS)

In order to be competitive in a modern networking environment in which a single BS must support a multiplicity of widely varying transport demands over an inherently fluctuating wireless medium, a BWA network must include rigorous support for differentiated QoS as a fundamental design feature.

This requires support for flexible MAC and PHY framing to optimally use the available airtime adaptively. A centrally controlled MAC is also a necessity for BWA systems because distributed access methods, such as carrier sense multiple access (CSMA), cannot work efficiently in environments where some user devices are unable to hear other ones, due to distance, directional antennas, intervening terrain, etc.

The higher probability of errors in wireless environments introduces another challenge to the wireless QoS problem, especially in NLOS environments. The impact of errors on QoS can be minimized with sophisticated adaptive modulation and coding, error correction, error detection, and retransmission algorithms at both the MAC and PHY.

It is unnecessary, and in fact inappropriate, for a standard to enforce a specific QoS scheduling algorithm. However, a practical standard must define scheduling behaviors that allow the system to enforce uniform QoS. IEEE Std 802.16 does so by use of techniques analogous to those of the asynchronous transfer mode (ATM), where different scheduling behaviors are defined without specifying any particular scheduling algorithm.

The ability to provide QoS in both directions is also a critical requirement for efficiently managing the available spectrum and to support bidirectional applications such as voice and video conferencing.

THROUGHPUT REQUIREMENTS

Apart from basic QoS and reliability requirements, BWA systems must provide support a sufficiently high data transmission rate in order to be commercially successful. For backhaul systems, these throughput requirements are generally higher; depending on the load, systems should be able to carry a significant fraction of a fiber optic network’s traffic. Moreover,
given the nature of the aggregated traffic over backhaul networks, the throughput requirements may be symmetrical [i.e., identical in both uplink (UP) and downlink (DL) directions], depending on the configuration.

On the other hand, the last-mile access or edge networks have to provide throughput comparable to that of competing technologies, such as DSL or cable. If BWA is used to support business needs, then the networks should be capable of supporting multiple business-class links such as T1, T3, DS3, or OC-3. Most importantly, the ability of the BWA network to scale efficiently with reasonable per-subscriber throughput is a critical requirement.

The increasing popularity of various multimedia, on-demand, and interactive applications is likely to increase the demand for network throughput and scalability in all application scenarios. IEEE Std 802.16 foresees the need for this evolution and is designed to support it.
Bibliography


[B17] ETSI TS 121 101, Universal Mobile Telecommunications System (UMTS); Technical Specifications and Technical Reports for a UTRAN-based 3GPP system.


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This is the second edition of Bob O'Hara and Al Petrick's *IEEE 802.11 Handbook*. It has been referred to as the "LAN Bible". The new edition covers IEEE 802.11d, 802.11e, 802.11F, 802.11g, 802.11h, 802.11i, 802.11j, 802.11n, and more! The book is 365 pages, includes a Preface written by Stuart J. Kerry, Chairman of 802.11, a comprehensive list of abbreviations and acronyms, and handy index.

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