
Fundamentals of WiMAX

Understanding Broadband Wireless Networking

Jeffrey G. Andrews, Ph.D.

*Department of Electrical and Computer Engineering
The University of Texas at Austin*

Arunabha Ghosh, Ph.D.

AT&T Labs Inc.

Rias Muhamed

AT&T Labs Inc.



**PRENTICE
HALL**

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

Many of the designations used by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed with initial capital letters or in all capitals.

The authors and publisher have taken care in the preparation of this book, but make no expressed or implied warranty of any kind and assume no responsibility for errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of the use of the information or programs contained herein.

The publisher offers excellent discounts on this book when ordered in quantity for bulk purchases or special sales, which may include electronic versions and/or custom covers and content particular to your business, training goals, marketing focus, and branding interests. For more information, please contact:

U.S. Corporate and Government Sales
(800) 382-3419
corpsales@pearsontechgroup.com

For sales outside the United States, please contact:

International Sales
international@pearsoned.com



This Book Is Safari Enabled

The Safari® Enabled icon on the cover of your favorite technology book means the book is available through Safari Bookshelf. When you buy this book, you get free access to the online edition for 45 days.

Safari Bookshelf is an electronic reference library that lets you easily search thousands of technical books, find code samples, download chapters, and access technical information whenever and wherever you need it.

To gain 45-day Safari Enabled access to this book:

- Go to <http://www.prenhallprofessional.com/safarienabled>
- Complete the brief registration form
- Enter the coupon code JRR8-NBAQ-SCDV-9ZQB-FNJU

If you have difficulty registering on Safari Bookshelf or accessing the online edition, please e-mail customer-service@safari-bookshelf.com.

Visit us on the Web: www.prenhallprofessional.com

Library of Congress Cataloging-in-Publication Data

Andrews, Jeffrey G.

Fundamentals of WiMAX : understanding broadband wireless networking / Jeffrey G. Andrews, Arunabha Ghosh, Rias Muhamed.

p. cm.

Includes bibliographical references and index.

ISBN 0-13-222552-2 (hbk : alk. paper)

1. Wireless communication systems. 2. Broadband communication systems. I. Ghosh, Arunabha. II. Muhamed, Rias. III. Title.

TK5103.2.A56 2007

621.382—dc22

2006038505

Copyright © 2007 Pearson Education, Inc.

All rights reserved. Printed in the United States of America. This publication is protected by copyright, and permission must be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. For information regarding permissions, write to:

Pearson Education, Inc.
Rights and Contracts Department
One Lake Street
Upper Saddle River, NJ 07458
Fax: (201) 236-3290

ISBN 0132225522

Text printed in the United States on recycled paper at Courier Westford in Westford, Massachusetts

3rd Printing October 2007

Ex.1016.00002

for the 1,900MHz PCS (personal communications services) band that could deliver two voice lines and a 128kbps data connection to subscribers. This system, developed under the code name "Project Angel," also had the distinction of being one of the first commercial wireless systems to use adaptive antenna technology. After field trials for a few years and a brief commercial offering, AT&T discontinued the service in December 2001, citing cost run-ups and poor take-rate as reasons.

During the same time, several small start-up companies focused solely on providing Internet-access services using wireless. These wireless Internet service provider (WISP) companies typically deployed systems in the license-exempt 900MHz and 2.4GHz bands. Most of these systems required antennas to be installed at the customer premises, either on rooftops or under the eaves of their buildings. Deployments were limited mostly to select neighborhoods and small towns. These early systems typically offered speeds up to a few hundred kilobits per second. Later evolutions of license-exempt systems were able to provide higher speeds.

1.1.2 First-Generation Broadband Systems

As DSL and cable modems began to be deployed, wireless systems had to evolve to support much higher speeds to be competitive. Systems began to be developed for higher frequencies, such as the 2.5GHz and 3.5GHz bands. Very high speed systems, called *local multipoint distribution systems* (LMDS), supporting up to several hundreds of megabits per second, were also developed in millimeter wave frequency bands, such as the 24GHz and 39GHz bands. LMDS-based services were targeted at business users and in the late 1990s enjoyed rapid but short-lived success. Problems obtaining access to rooftops for installing antennas, coupled with its shorter-range capabilities, squashed its growth.

In the late 1990s, one of the more important deployments of broadband wireless happened in the so-called *multichannel multipoint distribution services* (MMDS) band at 2.5GHz. The MMDS band was historically used to provide *wireless cable* broadcast video services, especially in rural areas where cable TV services were not available. The advent of satellite TV ruined the wireless cable business, and operators were looking for alternative ways to use this spectrum. A few operators began to offer one-way wireless Internet-access service, using telephone line as the return path. In September 1998, the Federal Communications Commission (FCC) relaxed the rules of the MMDS band in the United States to allow two-way communication services, sparking greater industry interest in the MMDS band. MCI WorldCom and Sprint each paid approximately \$1 billion to purchase licenses to use the MMDS spectrum, and several companies started developing high-speed fixed wireless solutions for this band.

The first generation of these fixed broadband wireless solutions were deployed using the same towers that served wireless cable subscribers. These towers were typically several hundred feet tall and enabled LOS coverage to distances up to 35 miles, using high-power transmitters. First-generation MMDS systems required that subscribers install at their premises outdoor antennas high enough and pointed toward the tower for a clear LOS transmission path. Sprint and MCI launched two-way wireless broadband services using first-generation MMDS systems

Table 1.1 Important Dates in the Development of Broadband Wireless

Date	Event
February 1997	AT&T announces development of fixed wireless technology code named "Project Angel"
February 1997	FCC auctions 30MHz spectrum in 2.3GHz band for wireless communications services (WCS)
September 1997	American Telecasting (acquired later by Sprint) announces wireless Internet access services in the MMDS band offering 750kbps downstream with telephone dial-up modem upstream
September 1998	FCC relaxes rules for MMDS band to allow two-way communications
April 1999	MCI and Sprint acquire several wireless cable operators to get access to MMDS spectrum
July 1999	First working group meeting of IEEE 802.16 group
March 2000	AT&T launches first commercial high-speed fixed wireless service after years of trial
May 2000	Sprint launches first MMDS deployment in Phoenix, Arizona, using first-generation LOS technology
June 2001	WiMAX Forum established
October 2001	Sprint halts MMDS deployments
December 2001	AT&T discontinues fixed wireless services
December 2001	IEEE 802.16 standards completed for > 11GHz.
February 2002	Korea allocates spectrum in the 2.3GHz band for wireless broadband (WiBro)
January 2003	IEEE 802.16a standard completed
June 2004	IEEE 802.16-2004 standard completed and approved
September 2004	Intel begins shipping the first WiMAX chipset, called Rosedale
December 2005	IEEE 802.16e standard completed and approved
January 2006	First WiMAX Forum-certified product announced for fixed applications
June 2006	WiBro commercial services launched in Korea
August 2006	Sprint Nextel announces plans to deploy mobile WiMAX in the United States

in a few markets in early 2000. The outdoor antenna and LOS requirements proved to be significant impediments. Besides, since a fairly large area was being served by a single tower, the capacity of these systems was fairly limited. Similar first-generation LOS systems were deployed internationally in the 3.5GHz band.

1.1.3 Second-Generation Broadband Systems

Second-generation broadband wireless systems were able to overcome the LOS issue and to provide more capacity. This was done through the use of a cellular architecture and implementation of advanced-signal processing techniques to improve the link and system performance under multipath conditions. Several start-up companies developed advanced proprietary solutions that provided significant performance gains over first-generation systems. Most of these new systems could perform well under non-line-of-sight conditions, with customer-premise antennas typically mounted under the eaves or lower. Many solved the NLOS problem by using such techniques as *orthogonal frequency division multiplexing* (OFDM), *code division multiple access* (CDMA), and multiantenna processing. Some systems, such as those developed by SOMA Networks and Navini Networks, demonstrated satisfactory link performance over a few miles to desktop subscriber terminals without the need for an antenna mounted outside. A few megabits per second throughput over cell ranges of a few miles had become possible with second-generation fixed wireless broadband systems.

1.1.4 Emergence of Standards-Based Technology

In 1998, the Institute of Electrical and Electronics Engineers (IEEE) formed a group called 802.16 to develop a standard for what was called a *wireless metropolitan area network*, or wireless MAN. Originally, this group focused on developing solutions in the 10GHz to 66GHz band, with the primary application being delivering high-speed connections to businesses that could not obtain fiber. These systems, like LMDS, were conceived as being able to tap into fiber rings and to distribute that bandwidth through a point-to-multipoint configuration to businesses within line-of-sight. The IEEE 802.16 group produced a standard that was approved in December 2001. This standard, Wireless MAN-SC, specified a physical layer that used single-carrier modulation techniques and a media access control (MAC) layer with a burst time division multiplexing (TDM) structure that supported both frequency division duplexing (FDD) and time division duplexing (TDD).

After completing this standard, the group started work on extending and modifying it to work in both licensed and license-exempt frequencies in the 2GHz to 11GHz range, which would enable NLOS deployments. This amendment, IEEE 802.16a, was completed in 2003, with OFDM schemes added as part of the physical layer for supporting deployment in multipath environments. By this time, OFDM had established itself as a method of choice for dealing with multipath for broadband and was already part of the revised IEEE 802.11 standards. Besides the OFDM physical layers, 802.16a also specified additional MAC-layer options, including support for orthogonal frequency division multiple access (OFDMA).

Further revisions to 802.16a were made and completed in 2004. This revised standard, IEEE 802.16-2004, replaces 802.16, 802.16a, and 802.16c with a single standard, which has also been adopted as the basis for HIPERMAN (high-performance metropolitan area network) by ETSI (European Telecommunications Standards Institute). In 2003, the 802.16 group began work on enhancements to the specifications to allow vehicular mobility applications. That revision, Ex.1016.00005

Slidebar 1.1 A Brief History of OFDM

Although OFDM has become widely used only recently, the concept dates back some 40 years. This brief history of OFDM cites some landmark dates.

- 1966:** Chang shows that multicarrier modulation can solve the multipath problem without reducing data rate [4]. This is generally considered the first official publication on multicarrier modulation. Some earlier work was Holsinger's 1964 MIT dissertation [5] and some of Gallager's early work on waterfilling [6].
- 1971:** Weinstein and Ebert show that multicarrier modulation can be accomplished using a DFT [7].
- 1985:** Cimini at Bell Labs identifies many of the key issues in OFDM transmission and does a proof-of-concept design [8].
- 1993:** DSL adopts OFDM, also called discrete multitone, following successful field trials/competitions at Bellcore versus equalizer-based systems.
- 1999:** The IEEE 802.11 committee on wireless LANs releases the 802.11a standard for OFDM operation in 5GHz UNI band.
- 2002:** The IEEE 802.16 committee releases an OFDM-based standard for wireless broadband access for metropolitan area networks under revision 802.16a.
- 2003:** The IEEE 802.11 committee releases the 802.11g standard for operation in the 2.4GHz band.
- 2003:** The multiband OFDM standard for ultrawideband is developed, showing OFDM's usefulness in low-SNR systems.

802.16e, was completed in December 2005 and was published formally as IEEE 802.16e-2005. It specifies scalable OFDM for the physical layer and makes further modifications to the MAC layer to accommodate high-speed mobility.

As it turns out, the IEEE 802.16 specifications are a collection of standards with a very broad scope. In order to accommodate the diverse needs of the industry, the standard incorporated a wide variety of options. In order to develop interoperable solutions using the 802.16 family of standards, the scope of the standard had to be reduced by establishing consensus on what options of the standard to implement and test for interoperability. The IEEE developed the specifications but left to the industry the task of converting them into an interoperable standard that can be certified. The WiMAX Forum was formed to solve this problem and to promote solutions based on the IEEE 802.16 standards. The WiMAX Forum was modeled along the lines of the Wi-Fi Alliance, which has had remarkable success in promoting and providing interoperability testing for products based on the IEEE 802.11 family of standards.

The WiMAX Forum enjoys broad participation from the entire cross-section of the industry, including semiconductor companies, equipment manufacturers, system integrators, and service

providers. The forum has begun interoperability testing and announced its first certified product based on IEEE 802.16-2004 for fixed applications in January 2006. Products based on IEEE 802.16e-2005 are expected to be certified in early 2007. Many of the vendors that previously developed proprietary solutions have announced plans to migrate to fixed and/or mobile WiMAX. The arrival of WiMAX-certified products is a significant milestone in the history of broadband wireless.

1.2 Fixed Broadband Wireless: Market Drivers and Applications

Applications using a fixed wireless solution can be classified as *point-to-point* or *point-to-multipoint*. Point-to-point applications include interbuilding connectivity within a campus and microwave backhaul. Point-to-multipoint applications include (1) broadband for residential, small office/home office (SOHO), and small- to medium-enterprise (SME) markets, (2) T1 or fractional T1-like services to businesses, and (3) wireless backhaul for Wi-Fi hotspots. Figure 1.2 illustrates the various point-to-multipoint applications.

Consumer and small-business broadband: Clearly, one of the largest applications of WiMAX in the near future is likely to be broadband access for residential, SOHO, and SME markets. Broadband services provided using fixed WiMAX could include high-speed Internet access, telephony services using voice over IP, and a host of other Internet-based applications. Fixed wireless offers several advantages over traditional wired solutions. These advantages include lower entry and deployment costs; faster and easier deployment and revenue realization; ability to build out the network as needed; lower operational costs for network maintenance, management, and operation; and independence from the incumbent carriers.

From a customer premise equipment (CPE)² or subscriber station (SS) perspective, two types of deployment models can be used for fixed broadband services to the residential, SOHO, and SME markets. One model requires the installation of an outdoor antenna at the customer premise; the other uses an all-in-one integrated radio modem that the customer can install indoors like traditional DSL or cable modems. Using outdoor antennas improves the radio link and hence the performance of the system. This model allows for greater coverage area per base station, which reduces the density of base stations required to provide broadband coverage, thereby reducing capital expenditure. Requiring an outdoor antenna, however, means that installation will require a truck-roll with a trained professional and also implies a higher SS cost. Clearly, the two deployment scenarios show a trade-off between capital expenses and operating expense: between base station capital infrastructure costs and SS and installation costs. In developed countries, such as the United States, the high labor cost of truck-roll, coupled with consumer dislike for outdoor antennas, will likely favor an indoor SS deployment, at least for the residential application. Further, an indoor self-install SS will also allow a business model that can exploit the retail distribution channel and offer consumers a variety of SS choices. In devel-

2. The CPE is referred to as a subscriber station (SS) in fixed WiMAX.

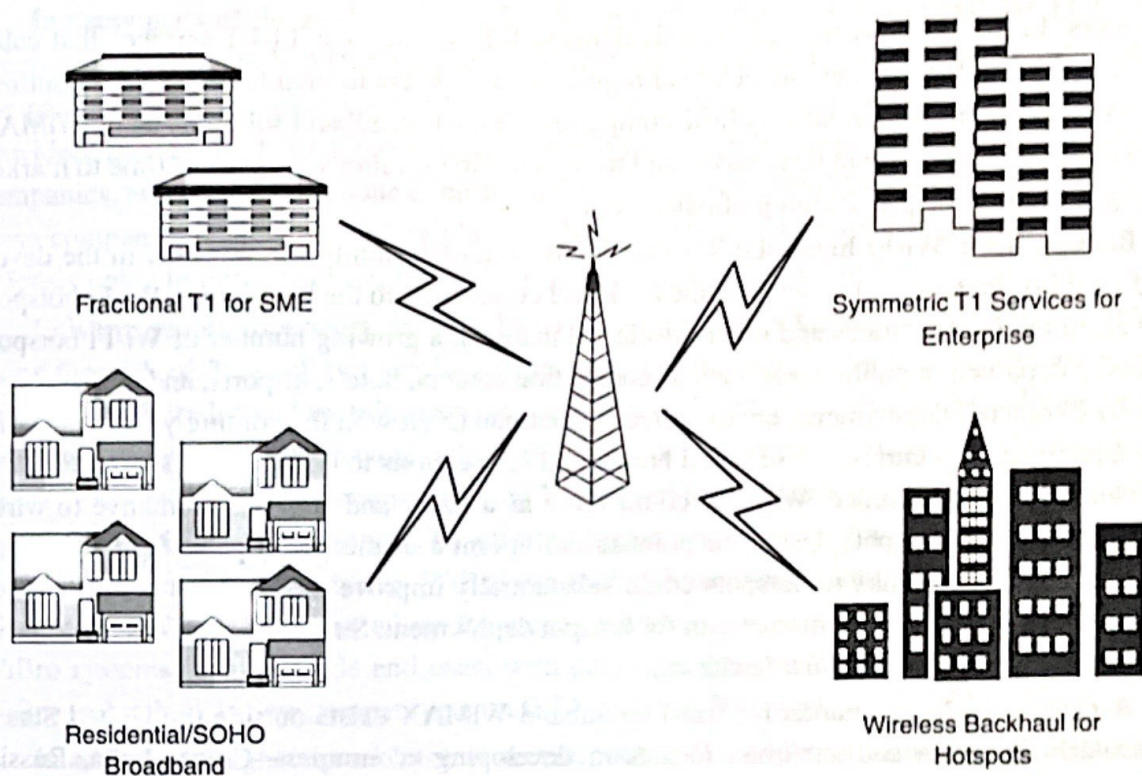


Figure 1.2 Point-to-multipoint WiMAX applications

oping countries, however, where labor is cheaper and aesthetic and zoning considerations are not so powerful, an outdoor-SS deployment model may make more economic sense.

In the United States and other developed countries with good wired infrastructure, fixed wireless broadband is more likely to be used in rural or underserved areas, where traditional means of serving them is more expensive. Services to these areas may be provided by incumbent telephone companies or by smaller players, such as WISPs, or local communities and utilities. It is also possible that competitive service providers could use WiMAX to compete directly with DSL and cable modem providers in urban and suburban markets. In the United States, the FCC's August 2005 decision to rollback cable plant sharing needs is likely to increase the appeal of fixed wireless solutions to competitive providers as they look for alternative means to reach subscribers. The competitive landscape in the United States is such that traditional cable TV companies and telephone companies are competing to offer a full bundle of telecommunications and entertainment services to customers. In this environment, satellite TV companies may be pushed to offering broadband services including voice and data in order to stay competitive with the telephone and cable companies, and may look to WiMAX as a potential solution to achieve this.

T1 emulation for business: The other major opportunity for fixed WiMAX in developed markets is as a solution for competitive T1/E1, fractional T1/E1, or higher-speed services for the business market. Given that only a small fraction of commercial buildings worldwide have access to fiber, there is a clear need for alternative high-bandwidth solutions for enterprise