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Fundamentals of **WiMAX**

Understanding Broadband Wireless Networking

Jeffrey G. Andrews • Arunabha Ghosh • Rias Muhamed

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Fundamentals of WiMAX

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Introduction to Broadband Wireless

Broadband wireless sits at the confluence of two of the most remarkable growth stories of the telecommunications industry in recent years. Both wireless and broadband have on their own enjoyed rapid mass-market adoption. Wireless mobile services grew from 11 million subscribers worldwide in 1990 to more than 2 billion in 2005 [1]. During the same period, the Internet grew from being a curious academic tool to having about a billion users. This staggering growth of the Internet is driving demand for higher-speed Internet-access services, leading to a parallel growth in broadband adoption. In less than a decade, broadband subscription worldwide has grown from virtually zero to over 200 million [2]. Will combining the convenience of wireless with the rich performance of broadband be the next frontier for growth in the industry? Can such a combination be technically and commercially viable? Can wireless deliver broadband applications and services that are of interest to the endusers? Many industry observers believe so.

Before we delve into broadband wireless, let us review the state of broadband access today. *Digital subscriber line* (DSL) technology, which delivers broadband over twisted-pair telephone wires, and *cable modem* technology, which delivers over coaxial cable TV plant, are the predominant mass-market broadband access technologies today. Both of these technologies typically provide up to a few megabits per second of data to each user, and continuing advances are making several tens of megabits per second possible. Since their initial deployment in the late 1990s, these services have enjoyed considerable growth. The United States has more than 50 million broadband subscribers, including more than half of home Internet users. Worldwide, this number is more than 200 million today and is projected to grow to more than 400 million by 2010 [2]. The availability of a wireless solution for broadband could potentially accelerate this growth.

What are the applications that drive this growth? Broadband users worldwide are finding that it dramatically changes how we share information, conduct business, and seek entertainment.

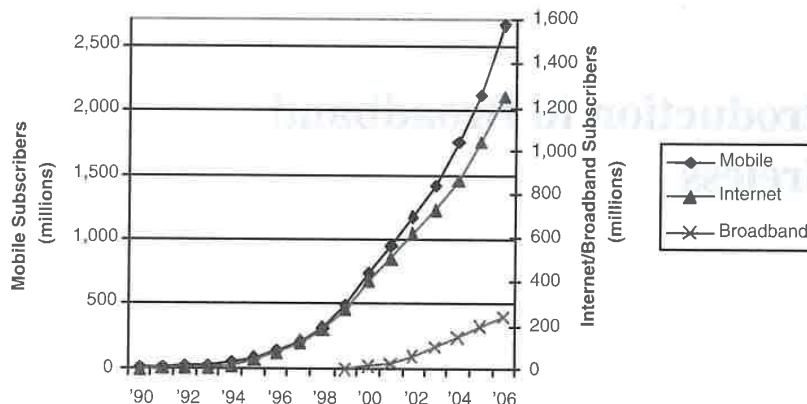


Figure 1.1 Worldwide subscriber growth 1990–2006 for mobile telephony, Internet usage, and broadband access [1, 2, 3]

Broadband access not only provides faster Web surfing and quicker file downloads but also enables several multimedia applications, such as real-time audio and video streaming, multimedia conferencing, and interactive gaming. Broadband connections are also being used for voice telephony using voice-over-Internet Protocol (VoIP) technology. More advanced broadband access systems, such as fiber-to-the-home (FTTH) and very high data rate digital subscriber loop (VDSL), enable such applications as entertainment-quality video, including high-definition TV (HDTV) and video on demand (VoD). As the broadband market continues to grow, several new applications are likely to emerge, and it is difficult to predict which ones will succeed in the future.

So what is broadband wireless? Broadband wireless is about bringing the broadband experience to a wireless context, which offers users certain unique benefits and convenience. There are two fundamentally different types of broadband wireless services. The first type attempts to provide a set of services similar to that of the traditional fixed-line broadband but using wireless as the medium of transmission. This type, called *fixed wireless broadband*, can be thought of as a competitive alternative to DSL or cable modem. The second type of broadband wireless, called *mobile broadband*, offers the additional functionality of portability, nomadicity,¹ and mobility. Mobile broadband attempts to bring broadband applications to new user experience scenarios and hence can offer the end user a very different value proposition. WiMAX (worldwide interoperability for microwave access) technology, the subject of this book, is designed to accommodate both fixed and mobile broadband applications.

1. *Nomadicity* implies the ability to connect to the network from different locations via different base stations; *mobility* implies the ability to keep ongoing connections active while moving at vehicular speeds.

In this chapter, we provide a brief overview of broadband wireless. The objective is to present the background and context necessary for understanding WiMAX. We review the history of broadband wireless, enumerate its applications, and discuss the business drivers and challenges. In Section 1.7, we also survey the technical challenges that need to be addressed while developing and deploying broadband wireless systems.

1.1 Evolution of Broadband Wireless

The history of broadband wireless as it relates to WiMAX can be traced back to the desire to find a competitive alternative to traditional wireline-access technologies. Spurred by the deregulation of the telecom industry and the rapid growth of the Internet, several competitive carriers were motivated to find a wireless solution to bypass incumbent service providers. During the past decade or so, a number of wireless access systems have been developed, mostly by start-up companies motivated by the disruptive potential of wireless. These systems varied widely in their performance capabilities, protocols, frequency spectrum used, applications supported, and a host of other parameters. Some systems were commercially deployed only to be decommissioned later. Successful deployments have so far been limited to a few niche applications and markets. Clearly, broadband wireless has until now had a checkered record, in part because of the fragmentation of the industry due to the lack of a common standard. The emergence of WiMAX as an industry standard is expected to change this situation.

Given the wide variety of solutions developed and deployed for broadband wireless in the past, a full historical survey of these is beyond the scope of this section. Instead, we provide a brief review of some of the broader patterns in this development. A chronological listing of some of the notable events related to broadband wireless development is given in Table 1.1.

WiMAX technology has evolved through four stages, albeit not fully distinct or clearly sequential: (1) narrowband wireless local-loop systems, (2) first-generation line-of-sight (LOS) broadband systems, (3) second-generation non-line-of-sight (NLOS) broadband systems, and (4) standards-based broadband wireless systems.

1.1.1 Narrowband Wireless Local-Loop Systems

Naturally, the first application for which a wireless alternative was developed and deployed was voice telephony. These systems, called *wireless local-loop* (WLL), were quite successful in developing countries such as China, India, Indonesia, Brazil, and Russia, whose high demand for basic telephone services could not be served using existing infrastructure. In fact, WLL systems based on the digital-enhanced cordless telephony (DECT) and code division multiple access (CDMA) standards continue to be deployed in these markets.

In markets in which a robust local-loop infrastructure already existed for voice telephony, WLL systems had to offer additional value to be competitive. Following the commercialization of the Internet in 1993, the demand for Internet-access services began to surge, and many saw providing high-speed Internet-access as a way for wireless systems to differentiate themselves. For example, in February 1997, AT&T announced that it had developed a wireless access system

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 wireless broadband 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 LOS businesses. 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,

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and a group called *network*, or wireless, to 66GHz band, frequencies that could be put into fiber rings and LOS businesses. In 2001, this standard modulation technology (TDM) and frequency duplexing

modifying it to the 4GHz range, which was completed in 2003, is relevant in multipath environments for dealing with interference. Besides the standard, including support

standard, IEEE 802.16e has also been developed (network) by ETSI. That revision, began work on

Sidebar 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 UNII 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 802.18e-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.

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1.2 Fixed Broadband Wireless: Market Drivers and Applications

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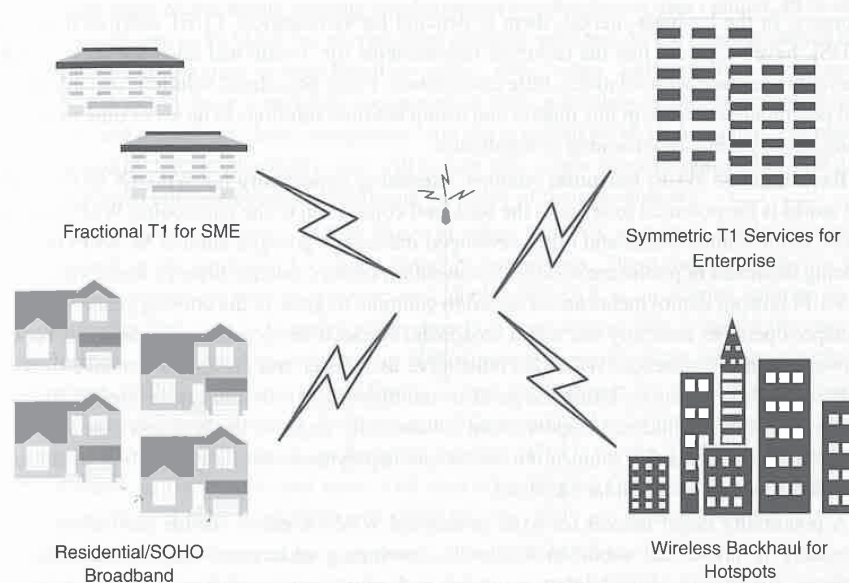


Figure 1.2 Point-to-multipoint WiMAX applications

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

customers. In the business market, there is demand for symmetrical T1/E1 services that cable and DSL have so far not met the technical requirements for. Traditional telco services continue to serve this demand with relatively little competition. Fixed broadband solutions using WiMAX could potentially compete in this market and trump landline solutions in terms of time to market, pricing, and dynamic provisioning of bandwidth.

Backhaul for Wi-Fi hotspots: Another interesting opportunity for WiMAX in the developed world is the potential to serve as the backhaul connection to the burgeoning Wi-Fi hotspots market. In the United States and other developed markets, a growing number of Wi-Fi hotspots are being deployed in public areas such as convention centers, hotels, airports, and coffee shops. The Wi-Fi hotspot deployments are expected to continue to grow in the coming years. Most Wi-Fi hotspot operators currently use wired broadband connections to connect the hotspots back to a network point of presence. WiMAX could serve as a faster and cheaper alternative to wired backhaul for these hotspots. Using the point-to-multipoint transmission capabilities of WiMAX to serve as backhaul links to hotspots could substantially improve the business case for Wi-Fi hotspots and provide further momentum for hotspot deployment. Similarly, WiMAX could serve as 3G (third-generation) cellular backhaul.

A potentially larger market for fixed broadband WiMAX exists outside the United States, particularly in urban and suburban locales in developing economies—China, India, Russia, Indonesia, Brazil and several other countries in Latin America, Eastern Europe, Asia, and Africa—that lack an installed base of wireline broadband networks. National governments that are eager to quickly catch up with developed countries without massive, expensive, and slow network rollouts could use WiMAX to leapfrog ahead. A number of these countries have seen sizable deployments of legacy WLL systems for voice and narrowband data. Vendors and carriers of these networks will find it easy to promote the value of WiMAX to support broadband data and voice in a fixed environment.

1.3 Mobile Broadband Wireless: Market Drivers and Applications

Although initial WiMAX deployments are likely to be for fixed applications, the full potential of WiMAX will be realized only when used for innovative nomadic and mobile broadband applications. WiMAX technology in its IEEE 802.16e-2005 incarnation will likely be deployed by fixed operators to capture part of the wireless mobility value chain in addition to plain broadband access. As endusers get accustomed to high-speed broadband at home and work, they will demand similar services in a nomadic or mobile context, and many service providers could use WiMAX to meet this demand.

The first step toward mobility would come by simply adding nomadic capabilities to fixed broadband. Providing WiMAX services to portable devices will allow users to experience bandwidth not just at home or work but also at other locations. Users could take their broadband connection with them as they move around from one location to another. Nomadic access may not allow for seamless roaming and handover at vehicular speeds but would allow pedestrian-speed mobility and the ability to connect to the network from any location within the service area.

services that cable services continue to be using WiMAX. As time to market,

WiMAX in the development of Wi-Fi hotspots and coffee shops. In many years. Most Wi-Fi hotspots back to native to wired networks. WiMAX is a case for Wi-Fi. WiMAX could serve

in the United States, India, Russia, Europe, Asia, and governments that are active, and slow countries have seen providers and carriers support broadband

Challenges

The full potential of broadband applications deployed by fixed and mobile broadband networks, they will be able to use

capabilities to fixed and experience broadband connectivity. Broadband connectivity may not be a leisurely-speed service area.

In many parts of the world, existing fixed-line carriers that do not own cellular, PCS, or 3G spectrum could turn to WiMAX for provisioning mobility services. As the industry moves along the path of quadruple-play service bundles—voice, data, video, and mobility—some service providers that do not have a mobility component in their portfolios—cable operators, satellite companies, and incumbent phone companies—are likely to find WiMAX attractive. For many of these companies, having a mobility plan will be not only a new revenue opportunity but also a defensive play to mitigate churn by enhancing the value of their product set.

Existing mobile operators are less likely to adopt WiMAX and more likely to continue along the path of 3G evolution for higher data rate capabilities. There may be scenarios, however, in which traditional mobile operators may deploy WiMAX as an overlay solution to provide even higher data rates in targeted urban centers or metrozones. This is indeed the case with Korea Telecom, which has begun deploying WiBro service in metropolitan areas to complement its ubiquitous CDMA2000 service by offering higher performance for multimedia messaging, video, and entertainment services. WiBro is a mobile broadband solution developed by Korea's Electronics and Telecommunications Research Institute (ETRI) for the 2.3GHz band. In Korea, WiBro systems today provide end users with data rates ranging from 512kbps to 3Mbps. The WiBro technology is now compatible with IEEE 802.16e-2005 and mobile WiMAX.

In addition to higher-speed Internet access, mobile WiMAX can be used to provide voice-over-IP services in the future. The low-latency design of mobile WiMAX makes it possible to deliver VoIP services effectively. VoIP technologies may also be leveraged to provide innovative new services, such as voice chatting, push-to-talk, and multimedia chatting.

New and existing operators may also attempt to use WiMAX to offer differentiated personal broadband services, such as mobile entertainment. The flexible channel bandwidths and multiple levels of quality-of-service (QoS) support may allow WiMAX to be used by service providers for differentiated high-bandwidth and low-latency entertainment applications. For example, WiMAX could be embedded into a portable gaming device for use in a fixed and mobile environment for interactive gaming. Other examples would be streaming audio services delivered to MP3 players and video services delivered to portable media players. As traditional telephone companies move into the entertainment area with IP-TV (Internet Protocol television), portable WiMAX could be used as a solution to extend applications and content beyond the home.

1.4 WiMAX and Other Broadband Wireless Technologies

WiMAX is not the only solution for delivering broadband wireless services. Several proprietary solutions, particularly for fixed applications, are already in the market. A few proprietary solutions, such as i-Burst technology from ArrayComm and Flash-OFDM from Flarion (acquired by Qualcomm) also support mobile applications. In addition to the proprietary solutions, there are standards-based alternative solutions that at least partially overlap with WiMAX, particularly for the portable and mobile applications. In the near term, the most significant of these alternatives are third-generation cellular systems and IEEE 802.11-based Wi-Fi systems. In this section, we

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the tune of 25 W—in license-exempt bands in rural areas to facilitate less costly deployments in underserved areas. It should be noted that there is another 80MHz of license-exempt spectrum, in the 2.4GHz band, which could also be used for WiMAX. Given the already high usage in this band, particularly from Wi-Fi, it is not very likely that WiMAX will be deployed in the 2.4GHz band, particularly for point-to-multipoint applications.

Although the 2.3GHz, 2.5GHz, 3.5GHz, and 5.7GHz bands are the most attractive for WiMAX in the near term, other bands could see future WiMAX deployments. Examples of these are the UHF (ultra high frequency) and AWS bands.

UHF bands: Around the world, as television stations transition from analog to digital broadcasting, a large amount of spectrum below 800MHz could become available. For example, in the United States, the FCC has identified frequency bands 698MHz–746MHz to be vacated by broadcasters as they transition to digital TV. Of these bands, 18MHz of spectrum has already been auctioned, and the remaining 60MHz is expected to be auctioned in a couple of years. The slow pace of digital TV adoption has delayed these auctions, and it is not likely that this spectrum will be usable for broadband wireless until at least 2009–2010. The FCC has also begun looking into the possibility of allocating more spectrum in the sub-700MHz bands, perhaps for unlicensed use as well. UHF band spectrum has excellent propagation characteristics compared to the other microwave bands and hence is valuable, particularly for portable and mobile services. The larger coverage range possible in this band makes the economics of deployment particularly attractive for suburban and rural applications.

AWS band: In August 2006, the FCC auctioned 1.710GHz–1.755GHz paired with 2.110GHz–2.155GHz as spectrum for advanced wireless services (AWS) in the United States. This band offers 90MHz of attractive spectrum that could be viable for WiMAX in the longer term.

Beyond these, it is possible that WiMAX could be deployed in bands designated for 3G. Particularly in Europe, greenfield 3G operators could choose to deploy WiMAX if regulatory relief to do so is obtained. Another interesting possibility is the 1.5GHz L-band used by mobile satellite today. Clearly, WiMAX systems could be deployed in a number of spectrum bands. The challenge is get the allocations and regulations across the globe harmonized in order to gain the advantage of economies of scale. In the next section, we discuss this and other business challenges to broadband wireless in general and WiMAX in particular.

1.6 Business Challenges for Broadband Wireless and WiMAX

Despite the marketing hype and the broad industry support for the development of WiMAX, its success is not a forgone conclusion. In fact, broadband wireless in general and WiMAX in particular face a number of challenges that could impede their adoption in the marketplace.

The rising bar of traditional broadband: In the fixed broadband application space, WiMAX will have to compete effectively with traditional wired alternatives, such as DSL and cable, to achieve widespread adoption in mature markets, such as the United States. DSL and cable modem technologies continue to evolve at a rapid pace, providing increasing data rate

capabilities. For example, DSL services in the United States already offer 3Mbps–6Mbps of downstream throughput to the end user, and solutions based on the newer VDSL2 standard will soon deliver up to 50Mbps–100Mbps, depending on the loop length. With incumbent carriers pushing fiber deeper into the networks, the copper loop lengths are getting shorter, allowing for significantly improved data rates. Cable modem technologies offer even higher speeds than DSL. Even on the upstream, where bandwidth had been traditionally limited, data rates on the order of several megabits per second per user are becoming a reality in both DSL and cable. The extremely high data rates supported by these wired broadband solutions allow providers to offer not only data, voice, and multimedia applications but also entertainment TV, including HDTV.

It will be extremely difficult for broadband wireless systems to match the rising throughput performance of traditional broadband. WiMAX will have to rely on portability and mobility as differentiators as opposed to data rate. WiMAX may have an advantage in terms of network infrastructure cost, but DSL and cable benefit from the declining cost curves on their CPE, due to their mature-market state. Given these impediments, fixed WiMAX is more likely to be deployed in rural or underserved areas in countries with a mature broadband access market. In developing countries, where existing broadband infrastructure is weak, the business challenges for fixed WiMAX are less daunting, and hence it is much more likely to succeed.

Differences in global spectrum availability: As discussed earlier, there are considerable differences in the allocation and regulations of broadband spectrum worldwide. Although 2.5GHz, 3.5GHz, and 5.8GHz bands are allotted in many regions of the world, many growth markets require new allocations. Given the diverse requirements and regulatory philosophy of various national governments, it will be a challenge for the industry to achieve global harmonization. For WiMAX to be a global success like Wi-Fi, regulatory bodies need to allow full flexibility in terms of the services that can be offered in the various spectrum bands.

Competition from 3G: For mobile WiMAX, the most significant challenge comes from 3G technologies that are being deployed worldwide by mobile operators. Incumbent mobile operators are more likely to seek performance improvements through 3G evolution than to adopt WiMAX. New entrants and innovative challengers entering the mobile broadband market using WiMAX will have to face stiff competition from 3G operators and will have to find a way to differentiate themselves from 3G in a manner that is attractive to the users. They may have to develop innovative applications and business models to effectively compete against 3G.

Device development: For mobile WiMAX to be successful, it is important to have a wide variety of terminal devices. Embedding WiMAX chips into computers could be a good first step but may not be sufficient. Perhaps WiMAX can differentiate from 3G by approaching the market with innovative devices. Some examples could include WiMAX embedded into MP3 players, video players, or handheld PCs. Device-development efforts should also include multimode devices. A variety of broadband systems will likely be deployed, and it is critical that diverse networks interoperate to make ubiquitous personal broadband services a reality. Ensuring that device development happens concomitant with network deployment will be a challenge.

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1.7 Technical Challenges for Broadband Wireless

So far, we have discussed the history, applications, and business challenges of broadband wireless. We now address the technical challenges of developing and deploying a successful broadband wireless system. The discussion presented in this section sets the stage for the rest of the book, especially Part II, where the technical foundations of WiMAX are discussed in detail.

To gain widespread success, broadband wireless systems must deliver multimegabit per second throughput to end users, with robust QoS to support a variety of services, such as voice, data, and multimedia. Given the remarkable success of the Internet and the large variety of emerging IP-based applications, it is critical that broadband wireless systems be built to support these IP-based applications and services efficiently. Fixed broadband systems must, ideally, deliver these services to indoor locations, using subscriber stations that can be easily self-installed by the enduser. Mobile broadband systems must deliver broadband applications to laptops and handheld devices while moving at high speeds. Customers now demand that all this be done without sacrificing quality, reliability, or security. For WiMAX to be successful, it must deliver significantly better performance than current alternatives, such as 3G and Wi-Fi. This is indeed a high bar.

Meeting these stringent service requirements while being saddled with a number of constraints imposed by wireless make the system design of broadband wireless a formidable technical challenge. Some of the key technical design challenges are

- Developing reliable transmission and reception schemes to push broadband data through a hostile wireless channel
- Achieving high spectral efficiency and coverage in order to deliver broadband services to a large number of users, using limited available spectrum
- Supporting and efficiently multiplexing services with a variety of QoS (throughput, delay, etc.) requirements
- Supporting mobility through seamless handover and roaming
- Achieving low power consumption to support handheld battery-operated devices
- Providing robust security
- Adapting IP-based protocols and architecture for the wireless environment to achieve lower cost and convergence with wired networks

As is often the case in engineering, solutions that effectively overcome one challenge may aggravate another. Design trade-offs have to be made to find the right balance among competing requirements—for example, coverage and capacity. Advances in computing power, hardware miniaturization, and signal-processing algorithms, however, enable increasingly favorable trade-offs, albeit within the fundamental bounds imposed by laws of physics and information theory. Despite these advances, researchers continue to be challenged as wireless consumers demand even greater performance.

We briefly explain each of the technical challenges, and touch on approaches that have been explored to overcome them. We begin with the challenges imposed by the wireless radio channel.

1.7.1 Wireless Radio Channel

The first and most fundamental challenge for broadband wireless comes from the transmission medium itself. In wired communications channels, a physical connection, such as a copper wire or fiber-optic cable, guides the signal from the transmitter to the receiver, but wireless communication systems rely on complex radio wave propagation mechanisms for traversing the intervening space. The requirements of most broadband wireless services are such that signals have to travel under challenging NLOS conditions. Several large and small obstructions, terrain undulations, relative motion between the transmitter and the receiver, interference from other signals, noise, and various other complicating factors together weaken, delay, and distort the transmitted signal in an unpredictable and time-varying fashion. It is a challenge to design a digital communication system that performs well under these conditions, especially when the service requirements call for very high data rates and high-speed mobility. The wireless channel for broadband communication introduces several major impairments.

Distance-dependent decay of signal power: In NLOS environments, the received signal power typically decays with distance at a rate much faster than in LOS conditions. This distance-dependent power loss, called *pathloss*, depends on a number of variables, such as terrain, foliage, obstructions, and antenna height. Pathloss also has an inverse-square relationship with carrier frequency. Given that many broadband wireless systems will be deployed in bands above 2GHz under NLOS conditions, systems will have to overcome significant pathloss.

Blockage due to large obstructions: Large obstructions, such as buildings, cause localized blockage of signals. Radio waves propagate around such blockages via diffraction but incur severe loss of power in the process. This loss, referred to as *shadowing*, is in addition to the distance-dependent decay and is a further challenge to overcome.

Large variations in received signal envelope: The presence of several reflecting and scattering objects in the channel causes the transmitted signal to propagate to the receiver via multiple paths. This leads to the phenomenon of *multipath fading*, which is characterized by large (tens of dBs) variations in the amplitude of the received radio signal over very small distances or small durations. Broadband wireless systems need to be designed to cope with these large and rapid variations in received signal strength. This is usually done through the use of one or more diversity techniques, some of which are covered in more detail in Chapters 4, 5, and 6.

Intersymbol interference due to time dispersion: In a multipath environment, when the time delay between the various signal paths is a significant fraction of the transmitted signal's symbol period, a transmitted symbol may arrive at the receiver during the next symbol period and cause *intersymbol interference* (ISI). At higher data rates, the symbol time is shorter; hence, it takes only a smaller delay to cause ISI. This makes ISI a bigger concern for broadband wireless and mitigating it more challenging. Equalization is the conventional method for dealing

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with ISI but at high data rates requires too much processing power. OFDM has become the solution of choice for mitigating ISI in broadband systems, including WiMAX, and is covered in Chapter 4 in detail.

Frequency dispersion due to motion: The relative motion between the transmitter and the receiver causes carrier frequency dispersion called *Doppler spread*. Doppler spread is directly related to vehicle speed and carrier frequency. For broadband systems, Doppler spread typically leads to loss of signal-to-noise ratio (SNR) and can make carrier recovery and synchronization more difficult. Doppler spread is of particular concern for OFDM systems, since it can corrupt the orthogonality of the OFDM subcarriers.

Noise: Additive white Gaussian noise (AWGN) is the most basic impairment present in any communication channel. Since the amount of thermal noise picked up by a receiver is proportional to the bandwidth, the noise floor seen by broadband receivers is much higher than those seen by traditional narrowband systems. The higher noise floor, along with the larger pathloss, reduces the coverage range of broadband systems.

Interference: Limitations in the amount of available spectrum dictate that users share the available bandwidth. This sharing can cause signals from different users to interfere with one another. In capacity-driven networks, interference typically poses a larger impairment than noise and hence needs to be addressed.

Each of these impairments should be well understood and taken into consideration while designing broadband wireless systems. In Chapter 3, we present a more rigorous characterization of the radio channel, which is essential to the development of effective solutions for broadband wireless.

1.7.2 Spectrum Scarcity

The second challenge to broadband wireless comes from the scarcity of radio-spectrum resources. As discussed in Section 1.5, regulatory bodies around the world have allocated only a limited amount of spectrum for commercial use. The need to accommodate an ever-increasing number of users and offering bandwidth-rich applications using a limited spectrum challenges the system designer to continuously search for solutions that use the spectrum more efficiently. Spectral-efficiency considerations impact many aspects of broadband wireless system design.

The most fundamental tool used to achieve higher system-wide spectral efficiency is the concept of a *cellular architecture*, whereby instead of using a single high-powered transmitter to cover a large geographic area, several lower-power transmitters that each cover a smaller area, called a *cell*, are used. The cells themselves are often subdivided into a few sectors through the use of directional antennas. Typically, a small group of cells or sectors form a cluster, and the available frequency spectrum is divided among the cells or sectors in a cluster and allocated intelligently to minimize interference to one another. The pattern of frequency allocation within a cluster is then repeated throughout the desired service area and is termed *frequency reuse*.

For higher capacity and spectral efficiency, frequency reuse must be maximized. Increasing reuse, however, leads to a larger potential for interference. Therefore, to facilitate tighter reuse, the

Overview of WiMAX

After years of development and uncertainty, a standards-based interoperable solution is emerging for wireless broadband. A broad industry consortium, the Worldwide Interoperability for Microwave Access (WiMAX) Forum has begun certifying broadband wireless products for interoperability and compliance with a standard. WiMAX is based on wireless metropolitan area networking (WMAN) standards developed by the IEEE 802.16 group and adopted by both IEEE and the ETSI HIPERMAN group. In this chapter, we present a concise technical overview of the emerging WiMAX solution for broadband wireless. The purpose here is to provide an executive summary before offering a more detailed exposition of WiMAX in later chapters.

We begin the chapter by summarizing the activities of the IEEE 802.16 group and its relation to WiMAX. Next, we discuss the salient features of WiMAX and briefly describe the physical- and MAC-layer characteristics of WiMAX. Service aspects, such as quality of service, security, and mobility, are discussed, and a reference network architecture is presented. The chapter ends with a brief discussion of expected WiMAX performance.

2.1 Background on IEEE 802.16 and WiMAX

The IEEE 802.16 group was formed in 1998 to develop an air-interface standard for wireless broadband. The group's initial focus was the development of a LOS-based point-to-multipoint wireless broadband system for operation in the 10GHz–66GHz millimeter wave band. The resulting standard—the original 802.16 standard, completed in December 2001—was based on a single-carrier physical (PHY) layer with a burst time division multiplexed (TDM) MAC layer. Many of the concepts related to the MAC layer were adapted for wireless from the popular cable modem DOCSIS (data over cable service interface specification) standard.

The IEEE 802.16 group subsequently produced 802.16a, an amendment to the standard, to include NLOS applications in the 2GHz–11GHz band, using an *orthogonal frequency division multiplexing* (OFDM)-based physical layer. Additions to the MAC layer, such as support for *orthogonal frequency division multiple access* (OFDMA), were also included. Further revisions resulted in a new standard in 2004, called IEEE 802.16-2004, which replaced all prior versions and formed the basis for the first WiMAX solution. These early WiMAX solutions based on IEEE 802.16-2004 targeted fixed applications, and we will refer to these as fixed WiMAX [1]. In December 2005, the IEEE group completed and approved IEEE 802.16e-2005, an amendment to the IEEE 802.16-2004 standard that added mobility support. The IEEE 802.16e-2005 forms the basis for the WiMAX solution for nomadic and mobile applications and is often referred to as mobile WiMAX [2].

The basic characteristics of the various IEEE 802.16 standards are summarized in Table 2.1. Note that these standards offer a variety of fundamentally different design options. For example, there are multiple physical-layer choices: a single-carrier-based physical layer called WirelessMAN-SCa, an OFDM-based physical layer called WirelessMAN-OFDM, and an OFDMA-based physical layer called Wireless-OFDMA. Similarly, there are multiple choices for MAC architecture, duplexing, frequency band of operation, etc. These standards were developed to suit a variety of applications and deployment scenarios, and hence offer a plethora of design choices for system developers. In fact, one could say that IEEE 802.16 is a collection of standards, not one single interoperable standard.

For practical reasons of interoperability, the scope of the standard needs to be reduced, and a smaller set of design choices for implementation need to be defined. The WiMAX Forum does this by defining a limited number of system profiles and certification profiles. A *system profile* defines the subset of mandatory and optional physical- and MAC-layer features selected by the WiMAX Forum from the IEEE 802.16-2004 or IEEE 802.16e-2005 standard. It should be noted that the mandatory and optional status of a particular feature within a WiMAX system profile may be different from what it is in the original IEEE standard. Currently, the WiMAX Forum has two different system profiles: one based on IEEE 802.16-2004, OFDM PHY, called the fixed system profile; the other one based on IEEE 802.16e-2005 scalable OFDMA PHY, called the mobility system profile. A *certification profile* is defined as a particular instantiation of a system profile where the operating frequency, channel bandwidth, and duplexing mode are also specified. WiMAX equipment are certified for interoperability against a particular certification profile.

The WiMAX Forum has thus far defined five fixed certification profiles and fourteen mobility certification profiles (see Table 2.2). To date, there are two fixed WiMAX profiles against which equipment have been certified. These are 3.5GHz systems operating over a 3.5MHz channel, using the fixed system profile based on the IEEE 802.16-2004 OFDM physical layer with a point-to-multipoint MAC. One of the profiles uses frequency division duplexing (FDD), and the other uses time division duplexing (TDD).

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Table 2.1 Basic Data on IEEE 802.16 Standards

	802.16	802.16-2004	802.16e-2005
Status	Completed December 2001	Completed June 2004	Completed December 2005
Frequency band	10GHz–66GHz	2GHz–11GHz	2GHz–11GHz for fixed; 2GHz–6GHz for mobile applications
Application	Fixed LOS	Fixed NLOS	Fixed and mobile NLOS
MAC architec- ture	Point-to-multipoint, mesh	Point-to-multipoint, mesh	Point-to-multipoint, mesh
Transmission scheme	Single carrier only	Single carrier, 256 OFDM or 2,048 OFDM	Single carrier, 256 OFDM or scalable OFDM with 128, 512, 1,024, or 2,048 subcarriers
Modulation	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM
Gross data rate	32Mbps–134.4Mbps	1Mbps–75Mbps	1Mbps–75Mbps
Multiplexing	Burst TDM/TDMA	Burst TDM/TDMA/ OFDMA	Burst TDM/TDMA/ OFDMA
Duplexing	TDD and FDD	TDD and FDD	TDD and FDD
Channel band- widths	20MHz, 25MHz, 28MHz	1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz	1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz
Air-interface designation	WirelessMAN-SC	WirelessMAN-SCa WirelessMAN-OFDM WirelessMAN-OFDMA WirelessHUMAN ^a	WirelessMAN-SCa WirelessMAN-OFDM WirelessMAN-OFDMA WirelessHUMAN ^a
WiMAX implementation	None	256 - OFDM as Fixed WiMAX	Scalable OFDMA as Mobile WiMAX

a. WirelessHUMAN (wireless high-speed unlicensed MAN) is similar to OFDM-PHY (physical layer) but mandates dynamic frequency selection for license-exempt bands.

Table 2.2 Fixed and Mobile WiMAX Initial Certification Profiles

Band Index	Frequency Band	Channel Bandwidth	OFDM FFT Size	Duplexing	Notes
Fixed WiMAX Profiles					
1	3.5 GHz	3.5MHz	256	FDD	Products already certified
		3.5MHz	256	TDD	
		7MHz	256	FDD	
		7MHz	256	TDD	
2	5.8GHz	10MHz	256	TDD	
Mobile WiMAX Profiles					
1	2.3GHz–2.4GHz	5MHz	512	TDD	Both bandwidths must be supported by mobile station (MS)
		10MHz	1,024	TDD	
		8.75MHz	1,024	TDD	
2	2.305GHz–2.320GHz, 2.345GHz–2.360GHz	3.5MHz	512	TDD	
		5MHz	512	TDD	
		10MHz	1,024	TDD	
3	2.496GHz–2.69GHz	5MHz	512	TDD	Both bandwidths must be supported by mobile station (MS)
		10MHz	1,024	TDD	
4	3.3GHz–3.4GHz	5MHz	512	TDD	
		7MHz	1,024	TDD	
		10MHz	1,024	TDD	
5	3.4GHz–3.8GHz, 3.4GHz–3.6GHz, 3.6GHz–3.8GHz	5MHz	512	TDD	
		7MHz	1,024	TDD	
		10MHz	1,024	TDD	

With the completion of the IEEE 802.16e-2005 standard, interest within the WiMAX group has shifted sharply toward developing and certifying mobile WiMAX¹ system profiles based on this newer standard. All mobile WiMAX profiles use scalable OFDMA as the physical layer. At least initially, all mobility profiles will use a point-to-multipoint MAC. It should also be noted that all the current candidate mobility certification profiles are TDD based. Although TDD is often preferred, FDD profiles may be needed for in the future to comply with regulatory pairing requirements in certain bands.

1. Although designated as mobile WiMAX, it is designed for fixed, nomadic, and mobile usage scenarios.

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2.2 Salient Features of WiMAX

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For the remainder of this chapter, we focus solely on WiMAX and therefore discuss only aspects of IEEE 802.16 family of standards that may be relevant to current and future WiMAX certification. It should be noted that the IEEE 802.16e-2004 and IEEE 802.16-2005 standards specifications are limited to the control and data plane aspects of the air-interface. Some aspects of network management are defined in IEEE 802.16g. For a complete end-to-end system, particularly in the context of mobility, several additional end-to-end service management aspects need to be specified. This task is being performed by the WiMAX Forums Network Working Group (NWG). The WiMAX NWG is developing an end-to-end network architecture and filling in some of the missing pieces. We cover the end-to-end architecture in Section 2.6.

2.2 Salient Features of WiMAX

WiMAX is a wireless broadband solution that offers a rich set of features with a lot of flexibility in terms of deployment options and potential service offerings. Some of the more salient features that deserve highlighting are as follows:

OFDM-based physical layer: The WiMAX physical layer (PHY) is based on orthogonal frequency division multiplexing, a scheme that offers good resistance to multipath, and allows WiMAX to operate in NLOS conditions. OFDM is now widely recognized as the method of choice for mitigating multipath for broadband wireless. Chapter 4 provides a detailed overview of OFDM.

Very high peak data rates: WiMAX is capable of supporting very high peak data rates. In fact, the peak PHY data rate can be as high as 74Mbps when operating using a 20MHz² wide spectrum. More typically, using a 10MHz spectrum operating using TDD scheme with a 3:1 downlink-to-uplink ratio, the peak PHY data rate is about 25Mbps and 6.7Mbps for the downlink and the uplink, respectively. These peak PHY data rates are achieved when using 64 QAM modulation with rate 5/6 error-correction coding. Under very good signal conditions, even higher peak rates may be achieved using multiple antennas and spatial multiplexing.

Scalable bandwidth and data rate support: WiMAX has a scalable physical-layer architecture that allows for the data rate to scale easily with available channel bandwidth. This scalability is supported in the OFDMA mode, where the FFT (fast fourier transform) size may be scaled based on the available channel bandwidth. For example, a WiMAX system may use 128-, 512-, or 1,048-bit FFTs based on whether the channel bandwidth is 1.25MHz, 5MHz, or 10MHz, respectively. This scaling may be done dynamically to support user roaming across different networks that may have different bandwidth allocations.

Adaptive modulation and coding (AMC): WiMAX supports a number of modulation and forward error correction (FEC) coding schemes and allows the scheme to be changed on a per user and per frame basis, based on channel conditions. AMC is an effective mechanism to maximize throughput in a time-varying channel. The adaptation algorithm typically calls for the use

- Initial WiMAX profiles do not include 20MHz support; 74Mbps is combined uplink/downlink PHY throughput.

of the highest modulation and coding scheme that can be supported by the signal-to-noise and interference ratio at the receiver such that each user is provided with the highest possible data rate that can be supported in their respective links. AMC is discussed in Chapter 6.

Link-layer retransmissions: For connections that require enhanced reliability, WiMAX supports automatic retransmission requests (ARQ) at the link layer. ARQ-enabled connections require each transmitted packet to be acknowledged by the receiver; unacknowledged packets are assumed to be lost and are retransmitted. WiMAX also optionally supports hybrid-ARQ, which is an effective hybrid between FEC and ARQ.

Support for TDD and FDD: IEEE 802.16-2004 and IEEE 802.16e-2005 supports both time division duplexing and frequency division duplexing, as well as a half-duplex FDD, which allows for a low-cost system implementation. TDD is favored by a majority of implementations because of its advantages: (1) flexibility in choosing uplink-to-downlink data rate ratios, (2) ability to exploit channel reciprocity, (3) ability to implement in nonpaired spectrum, and (4) less complex transceiver design. All the initial WiMAX profiles are based on TDD, except for two fixed WiMAX profiles in 3.5GHz.

Orthogonal frequency division multiple access (OFDMA): Mobile WiMAX uses OFDM as a multiple-access technique, whereby different users can be allocated different subsets of the OFDM tones. As discussed in detail in Chapter 6, OFDMA facilitates the exploitation of frequency diversity and multiuser diversity to significantly improve the system capacity.

Flexible and dynamic per user resource allocation: Both uplink and downlink resource allocation are controlled by a scheduler in the base station. Capacity is shared among multiple users on a demand basis, using a burst TDM scheme. When using the OFDMA-PHY mode, multiplexing is additionally done in the frequency dimension, by allocating different subsets of OFDM subcarriers to different users. Resources may be allocated in the spatial domain as well when using the optional advanced antenna systems (AAS). The standard allows for bandwidth resources to be allocated in time, frequency, and space and has a flexible mechanism to convey the resource allocation information on a frame-by-frame basis.

Support for advanced antenna techniques: The WiMAX solution has a number of hooks built into the physical-layer design, which allows for the use of multiple-antenna techniques, such as beamforming, space-time coding, and spatial multiplexing. These schemes can be used to improve the overall system capacity and spectral efficiency by deploying multiple antennas at the transmitter and/or the receiver. Chapter 5 presents detailed overview of the various multiple-antenna techniques.

Quality-of-service support: The WiMAX MAC layer has a connection-oriented architecture that is designed to support a variety of applications, including voice and multimedia services. The system offers support for constant bit rate, variable bit rate, real-time, and non-real-time traffic flows, in addition to best-effort data traffic. WiMAX MAC is designed to support a large number of users, with multiple connections per terminal, each with its own QoS requirement.

Robust security: WiMAX supports strong encryption, using Advanced Encryption Standard (AES), and has a robust privacy and key-management protocol. The system also offers a

very flexible authentication architecture based on Extensible Authentication Protocol (EAP), which allows for a variety of user credentials, including username/password, digital certificates, and smart cards.

Support for mobility: The mobile WiMAX variant of the system has mechanisms to support secure seamless handovers for delay-tolerant full-mobility applications, such as VoIP. The system also has built-in support for power-saving mechanisms that extend the battery life of handheld subscriber devices. Physical-layer enhancements, such as more frequent channel estimation, uplink subchannelization, and power control, are also specified in support of mobile applications.

IP-based architecture: The WiMAX Forum has defined a reference network architecture that is based on an all-IP platform. All end-to-end services are delivered over an IP architecture relying on IP-based protocols for end-to-end transport, QoS, session management, security, and mobility. Reliance on IP allows WiMAX to ride the declining cost curves of IP processing, facilitate easy convergence with other networks, and exploit the rich ecosystem for application development that exists for IP.

2.3 WiMAX Physical Layer

The WiMAX physical layer is based on orthogonal frequency division multiplexing. OFDM is the transmission scheme of choice to enable high-speed data, video, and multimedia communications and is used by a variety of commercial broadband systems, including DSL, Wi-Fi, Digital Video Broadcast-Handheld (DVB-H), and MediaFLO, besides WiMAX. OFDM is an elegant and efficient scheme for high data rate transmission in a non-line-of-sight or multipath radio environment. In this section, we cover the basics of OFDM and provide an overview of the WiMAX physical layer. Chapter 8 provides a more detailed discussion of the WiMAX PHY.

2.3.1 OFDM Basics

OFDM belongs to a family of transmission schemes called *multicarrier modulation*, which is based on the idea of dividing a given high-bit-rate data stream into several parallel lower bit-rate streams and modulating each stream on separate carriers—often called subcarriers, or tones. Multicarrier modulation schemes eliminate or minimize intersymbol interference (ISI) by making the symbol time large enough so that the channel-induced delays—delay spread being a good measure of this in wireless channels³—are an insignificant (typically, <10 percent) fraction of the symbol duration. Therefore, in high-data-rate systems in which the symbol duration is small, being inversely proportional to the data rate, splitting the data stream into many parallel streams increases the symbol duration of each stream such that the delay spread is only a small fraction of the symbol duration.

OFDM is a spectrally efficient version of multicarrier modulation, where the subcarriers are selected such that they are all orthogonal to one another over the symbol duration, thereby

3. Delay spread is discussed in Chapter 3.

avoiding the need to have nonoverlapping subcarrier channels to eliminate intercarrier interference. Choosing the first subcarrier to have a frequency such that it has an integer number of cycles in a symbol period, and setting the spacing between adjacent subcarriers (subcarrier bandwidth) to be $B_{SC} = B/L$, where B is the nominal bandwidth (equal to data rate), and L is the number of subcarriers, ensures that all tones are orthogonal to one another over the symbol period. It can be shown that the OFDM signal is equivalent to the inverse discrete Fourier transform (IDFT) of the data sequence block taken L at a time. This makes it extremely easy to implement OFDM transmitters and receivers in discrete time using IFFT (inverse fast Fourier) and FFT, respectively.⁴

In order to completely eliminate ISI, guard intervals are used between OFDM symbols. By making the guard interval larger than the expected multipath delay spread, ISI can be completely eliminated. Adding a guard interval, however, implies power wastage and a decrease in bandwidth efficiency. The amount of power wasted depends on how large a fraction of the OFDM symbol duration the guard time is. Therefore, the larger the symbol period—for a given data rate, this means more subcarriers—the smaller the loss of power and bandwidth efficiency.

The size of the FFT in an OFDM design should be chosen carefully as a balance between protection against multipath, Doppler shift, and design cost/complexity. For a given bandwidth, selecting a large FFT size would reduce the subcarrier spacing and increase the symbol time. This makes it easier to protect against multipath delay spread. A reduced subcarrier spacing, however, also makes the system more vulnerable to intercarrier interference owing to Doppler spread in mobile applications. The competing influences of delay and Doppler spread in an OFDM design require careful balancing. Chapter 4 provides a more detailed and rigorous treatment of OFDM.

2.3.2 OFDM Pros and Cons

OFDM enjoys several advantages over other solutions for high-speed transmission.

- **Reduced computational complexity:** OFDM can be easily implemented using FFT/IFFT, and the processing requirements grow only slightly faster than linearly with data rate or bandwidth. The computational complexity of OFDM can be shown to be $O(B \log B T_m)$, where B is the bandwidth and T_m is the delay spread. This complexity is much lower than that of a standard equalizer-based system, which has a complexity $O(B^2 T_m)$.
- **Graceful degradation of performance under excess delay:** The performance of an OFDM system degrades gracefully as the delay spread exceeds the value designed for. Greater coding and low constellation sizes can be used to provide fallback rates that are significantly more robust against delay spread. In other words, OFDM is well suited for

4. FFT (fast Fourier transform) is a computationally efficient way of computing DFT (discrete Fourier transform).

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adaptive modulation and coding, which allows the system to make the best of the available channel conditions. This contrasts with the abrupt degradation owing to error propagation that single-carrier systems experience as the delay spread exceeds the value for which the equalizer is designed.

- **Exploitation of frequency diversity:** OFDM facilitates coding and interleaving across subcarriers in the frequency domain, which can provide robustness against burst errors caused by portions of the transmitted spectrum undergoing deep fades. In fact, WiMAX defines subcarrier permutations that allow systems to exploit this.
- **Use as a multiaccess scheme:** OFDM can be used as a multiaccess scheme, where different tones are partitioned among multiple users. This scheme is referred to as OFDMA and is exploited in mobile WiMAX. This scheme also offers the ability to provide fine granularity in channel allocation. In relatively slow time-varying channels, it is possible to significantly enhance the capacity by adapting the data rate per subscriber according to the signal-to-noise ratio of that particular subcarrier.
- **Robust against narrowband interference:** OFDM is relatively robust against narrow-band interference, since such interference affects only a fraction of the subcarriers.
- **Suitable for coherent demodulation:** It is relatively easy to do pilot-based channel estimation in OFDM systems, which renders them suitable for coherent demodulation schemes that are more power efficient.

Despite these advantages, OFDM techniques also face several challenges. First, there is the problem associated with OFDM signals having a high peak-to-average ratio that causes nonlinearities and clipping distortion. This can lead to power inefficiencies that need to be countered. Second, OFDM signals are very susceptible to phase noise and frequency dispersion, and the design must mitigate these imperfections. This also makes it critical to have accurate frequency synchronization. Chapter 4 provides a good overview of available solutions to overcome these OFDM challenges.

2.3.3 OFDM Parameters in WiMAX

As mentioned previously, the fixed and mobile versions of WiMAX have slightly different implementations of the OFDM physical layer. Fixed WiMAX, which is based on IEEE 802.16-2004, uses a 256 FFT-based OFDM physical layer. Mobile WiMAX, which is based on the IEEE 802.16e-2005⁵ standard, uses a scalable OFDMA-based physical layer. In the case of mobile WiMAX, the FFT sizes can vary from 128 bits to 2,048 bits.

Table 2.3 shows the OFDM-related parameters for both the OFDM-PHY and the OFDMA-PHY. The parameters are shown here for only a limited set of profiles that are likely to be deployed and do not constitute an exhaustive set of possible values.

5. Although the scalable OFDMA scheme is referred to as mobile WiMAX, it can be used in fixed, nomadic, and mobile applications.

Fixed WiMAX OFDM-PHY: For this version the FFT size is fixed at 256, which 192 subcarriers used for carrying data, 8 used as pilot subcarriers for channel estimation and synchronization purposes, and the rest used as guard band subcarriers.⁶ Since the FFT size is fixed, the subcarrier spacing varies with channel bandwidth. When larger bandwidths are used, the subcarrier spacing increases, and the symbol time decreases. Decreasing symbol time implies that a larger fraction needs to be allocated as guard time to overcome delay spread. As Table 2.3 shows, WiMAX allows a wide range of guard times that allow system designers to make appropriate trade-offs between spectral efficiency and delay spread robustness. For maximum delay spread robustness, a 25 percent guard time can be used, which can accommodate delay spreads up to 16 μ s when operating in a 3.5MHz channel and up to 8 μ s when operating in a 7MHz channel. In relatively benign multipath channels, the guard time overhead may be reduced to as little as 3 percent.

Table 2.3 OFDM Parameters Used in WiMAX

Parameter	Fixed WiMAX OFDM-PHY	Mobile WiMAX Scalable OFDMA-PHY ^a			
FFT size	256	128	512	1,024	2,048
Number of used data subcarriers ^b	192	72	360	720	1,440
Number of pilot subcarriers	8	12	60	120	240
Number of null/guardband subcarriers	56	44	92	184	368
Cyclic prefix or guard time (T _g /T _b)	1/32, 1/16, 1/8 , 1/4				
Oversampling rate (F _s /B _W)	Depends on bandwidth: 7/6 for 256 OFDM, 8/7 for multiples of 1.75MHz, and 28/25 for multiples of 1.25MHz, 1.5MHz, 2MHz, or 2.75MHz.				
Channel bandwidth (MHz)	3.5	1.25	5	10	20
Subcarrier frequency spacing (kHz)	15.625		10.94		
Useful symbol time (μ s)	64		91.4		
Guard time assuming 12.5% (μ s)	8		11.4		
OFDM symbol duration (μ s)	72		102.9		
Number of OFDM symbols in 5 ms frame	69		48.0		

a. Boldfaced values correspond to those of the initial mobile WiMAX system profiles.

b. The mobile WiMAX subcarrier distribution listed is for downlink PUSC (partial usage of subcarrier).

6. Since FFT size can take only values equal to 2^n , dummy subcarriers are padded to the left and right of the useful subcarriers.

which 192 subcarriers are used for synchronization and frequency estimation. The subcarrier spacing is always 10.94 kHz. This keeps the OFDM symbol duration, which is the basic resource unit, fixed and therefore makes scaling have minimal impact on higher layers. A scalable design also keeps the costs low. The subcarrier spacing of 10.94 kHz was chosen as a good balance between satisfying the delay spread and Doppler spread requirements for operating in mixed fixed and mobile environments. This subcarrier spacing can support delay-spread values up to 20 μ s and vehicular mobility up to 125 kmph when operating in 3.5 GHz. A subcarrier spacing of 10.94 kHz implies that 128, 512, 1,024, and 2,048 FFT are used when the channel bandwidth is 1.25 MHz, 5 MHz, 10 MHz, and 20 MHz, respectively. It should, however, be noted that mobile WiMAX may also include additional bandwidth profiles. For example, a profile compatible with WiBro will use an 8.75 MHz channel bandwidth and 1,024 FFT. This obviously will require a different subcarrier spacing and hence will not have the same scalability properties.

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Mobile WiMAX OFDMA-PHY: In Mobile WiMAX, the FFT size is scalable from 128 to 2,048. Here, when the available bandwidth increases, the FFT size is also increased such that the subcarrier spacing is always 10.94 kHz. This keeps the OFDM symbol duration, which is the basic resource unit, fixed and therefore makes scaling have minimal impact on higher layers. A scalable design also keeps the costs low. The subcarrier spacing of 10.94 kHz was chosen as a good balance between satisfying the delay spread and Doppler spread requirements for operating in mixed fixed and mobile environments. This subcarrier spacing can support delay-spread values up to 20 μ s and vehicular mobility up to 125 kmph when operating in 3.5 GHz. A subcarrier spacing of 10.94 kHz implies that 128, 512, 1,024, and 2,048 FFT are used when the channel bandwidth is 1.25 MHz, 5 MHz, 10 MHz, and 20 MHz, respectively. It should, however, be noted that mobile WiMAX may also include additional bandwidth profiles. For example, a profile compatible with WiBro will use an 8.75 MHz channel bandwidth and 1,024 FFT. This obviously will require a different subcarrier spacing and hence will not have the same scalability properties.

2.3.4 Subchannelization: OFDMA

The available subcarriers may be divided into several groups of subcarriers called subchannels. Fixed WiMAX based on OFDM-PHY allows a limited form of subchannelization in the uplink only. The standard defines 16 subchannels, where 1, 2, 4, 8, or all sets can be assigned to a subscriber station (SS) in the uplink. Uplink subchannelization in fixed WiMAX allows subscriber stations to transmit using only a fraction (as low as 1/16) of the bandwidth allocated to it by the base station, which provides link budget improvements that can be used to enhance range performance and/or improve battery life of subscriber stations. A 1/16 subchannelization factor provides a 12 dB link budget enhancement.

Mobile WiMAX based on OFDMA-PHY, however, allows subchannelization in both the uplink and the downlink, and here, subchannels form the minimum frequency resource-unit allocated by the base station. Therefore, different subchannels may be allocated to different users as a multiple-access mechanism. This type of multiaccess scheme is called orthogonal frequency division multiple access (OFDMA), which gives the mobile WiMAX PHY its name.

Subchannels may be constituted using either contiguous subcarriers or subcarriers pseudo-randomly distributed across the frequency spectrum. Subchannels formed using distributed subcarriers provide more frequency diversity, which is particularly useful for mobile applications. WiMAX defines several subchannelization schemes based on distributed carriers for both the uplink and the downlink. One, called *partial usage of subcarriers* (PUSC), is mandatory for all mobile WiMAX implementations. The initial WiMAX profiles define 15 and 17 subchannels for the downlink and the uplink, respectively, for PUSC operation in 5 MHz bandwidth. For 10 MHz operation, it is 30 and 35 channels, respectively.

The subchannelization scheme based on contiguous subcarriers in WiMAX is called *band adaptive modulation and coding* (AMC). Although frequency diversity is lost, band AMC allows system designers to exploit multiuser diversity, allocating subchannels to users based on their frequency response. Multiuser diversity can provide significant gains in overall system capacity, if

the system strives to provide each user with a subchannel that maximizes its received SINR. In general, contiguous subchannels are more suited for fixed and low-mobility applications.

2.3.5 Slot and Frame Structure

The WiMAX PHY layer is also responsible for slot allocation and framing over the air. The minimum time-frequency resource that can be allocated by a WiMAX system to a given link is called a *slot*. Each slot consists of one subchannel over one, two, or three OFDM symbols, depending on the particular subchannelization scheme used. A contiguous series of slots assigned to a given user is called that user's *data region*; scheduling algorithms could allocate data regions to different users, based on demand, QoS requirements, and channel conditions.

Figure 2.1 shows an OFDMA and OFDM frame when operating in TDD mode. The frame is divided into two subframes: a downlink frame followed by an uplink frame after a small guard interval. The downlink-to-uplink-subframe ratio may be varied from 3:1 to 1:1 to support different traffic profiles. WiMAX also supports frequency division duplexing, in which case the frame structure is the same except that both downlink and uplink are transmitted simultaneously over different carriers. Some of the current fixed WiMAX systems use FDD. Most WiMAX deployments, however, are likely to be in TDD mode because of its advantages. TDD allows for a more flexible sharing of bandwidth between uplink and downlink, does not require paired spectrum, has a reciprocal channel that can be exploited for spatial processing, and has a simpler transceiver design. The downside of TDD is the need for synchronization across multiple base stations to ensure interference-free coexistence. Paired band regulations, however, may force some operators to deploy WiMAX in FDD mode.

As shown in Figure 2.1, the downlink subframe begins with a downlink preamble that is used for physical-layer procedures, such as time and frequency synchronization and initial channel estimation. The downlink preamble is followed by a frame control header (FCH), which provides frame configuration information, such as the MAP message length, the modulation and coding scheme, and the usable subcarriers. Multiple users are allocated data regions within the frame, and these allocations are specified in the uplink and downlink MAP messages (DL-MAP and UL-MAP) that are broadcast following the FCH in the downlink subframe. MAP messages include the burst profile for each user, which defines the modulation and coding scheme used in that link. Since MAP contains critical information that needs to reach all users, it is often sent over a very reliable link, such as BPSK with rate 1/2 coding and repetition coding. Although the MAP messages are an elegant way for the base station to inform the various users of its allocations and burst profiles on a per-frame basis, it could form a significant overhead, particularly when there are a large number of users with small packets (e.g., VoIP) for which allocations need to be specified. To mitigate the overhead concern, mobile WiMAX systems can optionally use multiple sub-MAP messages where the dedicated control messages to different users are transmitted at higher rates, based on their individual SINR conditions. The broadcast MAP messages may also optionally be compressed for additional efficiency.

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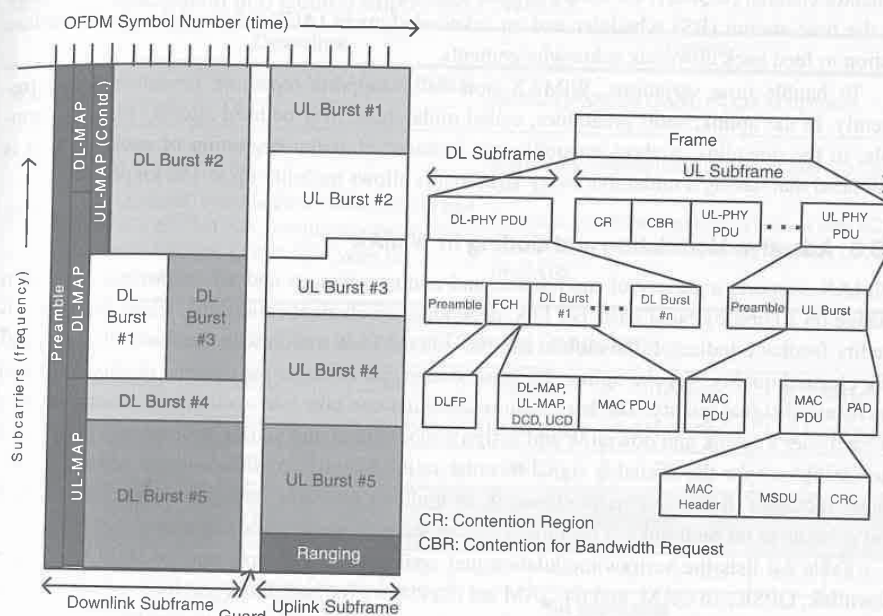


Figure 2.1 A sample TDD frame structure for mobile WiMAX

WiMAX is quite flexible in terms of how multiple users and packets are multiplexed on a single frame. A single downlink frame may contain multiple bursts of varying size and type carrying data for several users. The frame size is also variable on a frame-by-frame basis from 2 ms to 20 ms, and each burst can contain multiple concatenated fixed-size or variable-size packets or fragments of packets received from the higher layers. At least initially, however, all WiMAX equipment will support only 5 ms frames.

The uplink subframe is made up of several uplink bursts from different users. A portion of the uplink subframe is set aside for contention-based access that is used for a variety of purposes. This subframe is used mainly as a ranging channel to perform closed-loop frequency, time, and power adjustments during network entry as well as periodically afterward. The ranging channel may also be used by subscriber stations or mobile stations (SS/MS)⁷ to make uplink bandwidth requests. In addition, best-effort data may be sent on this contention-based channel, particularly when the amount of data to send is too small to justify requesting a dedicated channel. Besides the ranging channel and traffic bursts, the uplink subframe has a channel-quality

7. The subscriber terminal mobile station (MS) is mobile WiMAX, and subscriber station (SS) is fixed WiMAX. Henceforth, for simplicity, we use MS to denote both.

indicator channel (CQICH) for the SS to feed back channel-quality information that can be used by the base station (BS) scheduler and an acknowledgment (ACK) channel for the subscriber station to feed back downlink acknowledgements.

To handle time variations, WiMAX optionally supports repeating preambles more frequently. In the uplink, short preambles, called midambles, may be used after 8, 16, or 32 symbols; in the downlink, a short preamble can be inserted at the beginning of each burst. It is estimated that having a midamble every 10 symbols allows mobility up to 150 kmph.

2.3.6 Adaptive Modulation and Coding in WiMAX

WiMAX supports a variety of modulation and coding schemes and allows for the scheme to change on a burst-by-burst basis per link, depending on channel conditions. Using the channel-quality feedback indicator, the mobile can provide the base station with feedback on the downlink channel quality. For the uplink, the base station can estimate the channel quality, based on the received signal quality. The base station scheduler can take into account the channel quality of each user's uplink and downlink and assign a modulation and coding scheme that maximizes the throughput for the available signal-to-noise ratio. Adaptive modulation and coding significantly increases the overall system capacity, as it allows real-time trade-off between throughput and robustness on each link. This topic is discussed in more detail in Chapter 6.

Table 2.4 lists the various modulation and coding schemes supported by WiMAX. In the downlink, QPSK, 16 QAM, and 64 QAM are mandatory for both fixed and mobile WiMAX; 64 QAM is optional in the uplink. FEC coding using convolutional codes is mandatory. Convolutional codes are combined with an outer Reed-Solomon code in the downlink for OFDM-PHY. The standard optionally supports turbo codes and low-density parity check (LDPC) codes at a variety of code rates as well. A total of 52 combinations of modulation and coding schemes are defined in WiMAX as burst profiles. More details on burst profiles are provided in Chapter 8.

2.3.7 PHY-Layer Data Rates

Because the physical layer of WiMAX is quite flexible, data rate performance varies based on the operating parameters. Parameters that have a significant impact on the physical-layer data rate are channel bandwidth and the modulation and coding scheme used. Other parameters, such as number of subchannels, OFDM guard time, and oversampling rate, also have an impact.

Table 2.5 lists the PHY-layer data rate at various channel bandwidths, as well as modulation and coding schemes. The rates shown are the aggregate physical-layer data rate that is shared among all users in the sector for the TDD case, assuming a 3:1 downlink-to-uplink bandwidth ratio. The calculations here assume a frame size of 5 ms, a 12.5 percent OFDM guard interval overhead, and a PUSC subcarrier permutation scheme. It is also assumed that all usable OFDM data symbols are available for user traffic except one symbol used for downlink frame overhead. The numbers shown here do not assume spatial multiplexing using multiple antennas at the transmitter or the receiver, the use of which can further increase the peak rates in rich multipath channels.

of absence are negotiated with the serving BS. WiMAX defines three power-saving classes, based on the manner in which sleep mode is executed. When in Power Save Class 1 mode, the sleep window is exponentially increased from a minimum value to a maximum value. This is typically done when the MS is doing best-effort and non-real-time traffic. Power Save Class 2 has a fixed-length sleep window and is used for UGS service. Power Save Class 3 allows for a one-time sleep window and is typically used for multicast traffic or management traffic when the MS knows when the next traffic is expected. In addition to minimizing MS power consumption, sleep mode conserves BS radio resources. To facilitate handoff while in sleep mode, the MS is allowed to scan other base stations to collect handoff-related information.

Idle mode allows even greater power savings, and support for it is optional in WiMAX. Idle mode allows the MS to completely turn off and to not be registered with any BS and yet receive downlink broadcast traffic. When downlink traffic arrives for the idle-mode MS, the MS is paged by a collection of base stations that form a paging group. The MS is assigned to a paging group by the BS before going into idle mode, and the MS periodically wakes up to update its paging group. Idle mode saves more power than sleep mode, since the MS does not even have to register or do handoffs. Idle mode also benefits the network and BS by eliminating handover traffic from inactive MSs.

2.4.4 Mobility Support

In addition to fixed broadband access, WiMAX envisions four mobility-related usage scenarios:

1. **Nomadic.** The user is allowed to take a fixed subscriber station and reconnect from a different point of attachment.
2. **Portable.** Nomadic access is provided to a portable device, such as a PC card, with expectation of a best-effort handover.
3. **Simple mobility.** The subscriber may move at speeds up to 60 kmph with brief interruptions (less than 1 sec) during handoff.
4. **Full mobility:** Up to 120 kmph mobility and seamless handoff (less than 50 ms latency and <1% packet loss) is supported.

It is likely that WiMAX networks will initially be deployed for fixed and nomadic applications and then evolve to support portability to full mobility over time.

The IEEE 802.16e-2005 standard defines a framework for supporting mobility management. In particular, the standard defines signaling mechanisms for tracking subscriber stations as they move from the coverage range of one base station to another when active or as they move from one paging group to another when idle. The standard also has protocols to enable a seamless handover of ongoing connections from one base station to another. The WiMAX Forum has used the framework defined in IEEE 802.16e-2005 to further develop mobility management within an end-to-end network architecture framework. The architecture also supports IP-layer mobility using mobile IP.

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Three handoff methods are supported in IEEE 802.16e-2005; one is mandatory and other two are optional. The mandatory handoff method is called the *hard handover* (HHO) and is the only type required to be implemented by mobile WiMAX initially. HHO implies an abrupt transfer of connection from one BS to another. The handoff decisions are made by the BS, MS, or another entity, based on measurement results reported by the MS. The MS periodically does a radio frequency (RF) scan and measures the signal quality of neighboring base stations. Scanning is performed during *scanning intervals* allocated by the BS. During these intervals, the MS is also allowed to optionally perform initial ranging and to associate with one or more neighboring base stations. Once a handover decision is made, the MS begins synchronization with the downlink transmission of the target BS, performs ranging if it was not done while scanning, and then terminates the connection with the previous BS. Any undelivered MPDUs at the BS are retained until a timer expires.

The two optional handoff methods supported in IEEE 802.16e-2005 are *fast base station switching* (FBSS) and *macro diversity handover* (MDHO). In these two methods, the MS maintains a valid connection simultaneously with more than one BS. In the FBSS case, the MS maintains a list of the BSs involved, called the *active set*. The MS continuously monitors the active set, does ranging, and maintains a valid connection ID with each of them. The MS, however, communicates with only one BS, called the *anchor BS*. When a change of anchor BS is required, the connection is switched from one base station to another without having to explicitly perform handoff signaling. The MS simply reports the selected anchor BS on the CQICH.

Macro diversity handover is similar to FBSS, except that the MS communicates on the downlink and the uplink with all the base stations in the active set—called a *diversity set* here—simultaneously. In the downlink, multiple copies received at the MS are combined using any of the well-known diversity-combining techniques (see Chapter 5). In the uplink, where the MS sends data to multiple base stations, selection diversity is performed to pick the best uplink.

Both FBSS and MDHO offer superior performance to HHO, but they require that the base stations in the active or diversity set be synchronized, use the same carrier frequency, and share network entry-related information. Support for FBSS and MDHO in WiMAX networks is not fully developed yet and is not part of WiMAX Forum Release 4 network specifications.

2.4.5 Security Functions

Unlike Wi-Fi, WiMAX systems were designed at the outset with robust security in mind. The standard includes state-of-the-art methods for ensuring user data privacy and preventing unauthorized access, with additional protocol optimization for mobility. Security is handled by a privacy sublayer within the WiMAX MAC. The key aspects of WiMAX security are as follow.

Support for privacy: User data is encrypted using cryptographic schemes of proven robustness to provide privacy. Both AES (Advanced Encryption Standard) and 3DES (Triple Data Encryption Standard) are supported. Most system implementations will likely use AES, as it is the new encryption standard approved as compliant with Federal Information Processing Standard

5.7.1 Preamble and Pilot

There are two ways to transmit training symbols: preamble or pilot tones. Preambles entail sending a certain number of training symbols prior to the user data symbols. In the case of OFDM, one or two preamble OFDM symbols are typical. Pilot tones involve inserting a few known pilot symbols among the subcarriers. Channel estimation in MIMO-OFDM systems can be performed in a variety of ways, but it is typical to use the preamble for synchronization⁶ and initial channel estimation and the pilot tones for tracking the time-varying channel in order to maintain accurate channel estimates.

In MIMO-OFDM, the received signal at each antenna is a superposition of the signals transmitted from the N_t transmit antennas. Thus, the training signals for each transmit antenna need to be transmitted without interfering with one another in order to accurately estimate the channel. Figure 5.17 shows three MIMO-OFDM patterns that avoid interfering with one another: independent, scattered, and orthogonal patterns [37].

The independent pattern transmits training signals from one antenna at a time while the other antennas are silent, thus guaranteeing orthogonality between each training signal in the time domain. Clearly, an $N_t \times N_r$ channel can be estimated over N_t training signal times. The scattered-pilot pattern prevents overlap of training signals in the frequency domain by transmitting each antenna's pilot symbols on different subcarriers, while other antennas are silent on that subcarrier. Finally, the orthogonal pattern transmits training signals that are mathematically orthogonal, similar to CDMA. The independent pattern is often the most appropriate for MIMO-OFDM, since the preamble is usually generated in the time domain. For transmitting the pilot tones, any of these methods or some combination of them can be used.

In MIMO-OFDM, frequency-domain channel information is required in order to detect the data symbols on each subcarrier (recall the FEQ of Chapter 4). Since the preamble consists of pilot symbols on many of the subcarriers,⁷ the channel-frequency response of each subcarrier can be reliably estimated from preamble with simple interpolation techniques. In normal data OFDM symbols, there are typically a very small number of pilot tones, so interpolation between these estimated subchannels is required [18, 35]. The training-symbol structure for the preamble and pilot tones is shown in Figure 5.18, with interpolation for pilot symbols. One-dimensional interpolation over either the time or frequency domain or two-dimensional interpolation over both the time and frequency domains can be performed with an assortment of well-known interpolation algorithms, such as linear and FFT. In the next section, we focus on channel estimation in the time and frequency domain, using the preamble and pilot symbols, and assume that interpolation can be performed by the receiver as necessary.

6. Synchronization for OFDM is discussed in detail in Chapter 4.

7. Each preamble uses only 1/3 or 1/6 of all the subcarriers in order to allow different sectors in the cell to be distinguished.

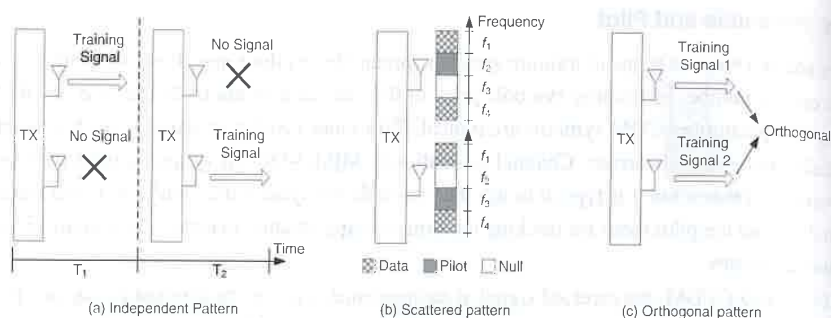


Figure 5.17 Three different patterns for transmitting training signals in MIMO-OFDM

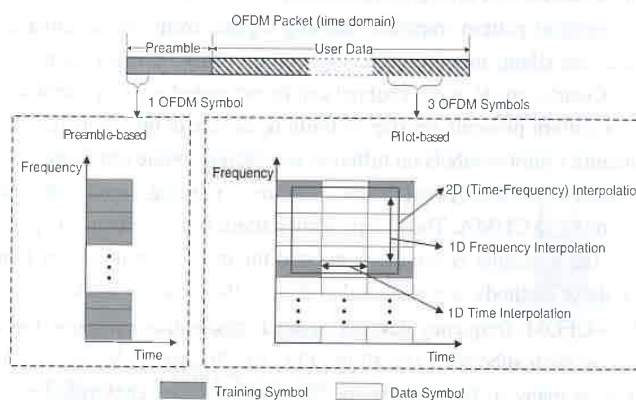


Figure 5.18 Training symbol structure of preamble-based and pilot-based channel estimation methods

5.7.2 Time versus Frequency-Domain Channel Estimation

MIMO-OFDM channels can be estimated in either the time or the frequency domain. The received time-domain signal can be directly used to estimate the channel impulse response; frequency-domain channel estimation is performed using the received signal after processing it with the FFT. Here, we review both the time- and the frequency-domain channel-estimation methods, assuming that each channel is clear of interference from the other transmit antennas, which can be ensured by using the pilot designs described previously. Thus, the antenna indices i and j are neglected in this section, and these techniques are directly applicable to single-antenna OFDM systems as well.

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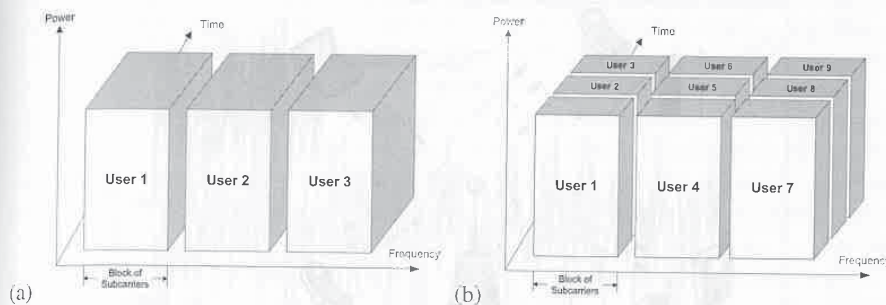


Figure 6.1 (a) FDMA and (b) a combination of FDMA with TDMA

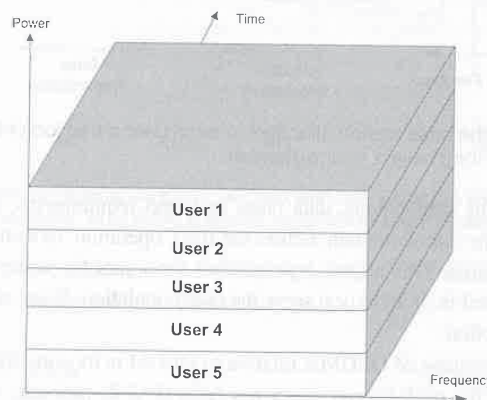


Figure 6.2 CDMA's users share time and frequency slots but use codes that allow the users to be separated by the receiver

secutive OFDM symbols; that is, the data symbol is multiplied by a length N code sequence and then sent on a specific subcarrier for the next N OFDM symbols. Frequency-domain spreading, which generally has slightly better performance than time-domain spreading [13], entails each data symbol being sent simultaneously on N different subcarriers. MC-CDMA is not part of the WiMAX standards but could be deemed appropriate in the future, especially for the uplink.

6.1.5 Advantages of OFDMA

OFDMA is essentially a hybrid of FDMA and TDMA: Users are dynamically assigned subcarriers (FDMA) in different time slots (TDMA) as shown in Figure 6.3. The advantages of OFDMA start with the advantages of single-user OFDM in terms of robust multipath suppression and frequency diversity. In addition, OFDMA is a flexible multiple-access technique that can accommodate many

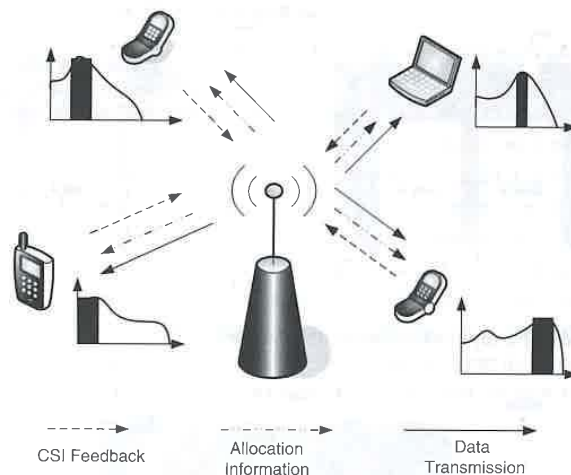


Figure 6.3 In OFDMA, the base station allocates to each user a fraction of the subcarriers, preferably in a range where they have a strong channel.

users with widely varying applications, data rates, and QoS requirements. Because the multiple access is performed in the digital domain, before the IFFT operation, dynamic and efficient bandwidth allocation is possible. This allows sophisticated time- and frequency- domain scheduling algorithms to be integrated in order to best serve the user population. Some of these algorithms are discussed in the next section.

One significant advantage of OFDMA relative to OFDM is its potential to reduce the transmit power and to relax the peak-to-average-power ratio (PAPR) problem, which was discussed in detail in Chapter 4. The PAPR problem is particularly acute in the uplink, where power efficiency and cost of the power amplifier are extremely sensitive quantities. By splitting the entire bandwidth among many MSs in the cell, each MS uses only a small subset of subcarriers. Therefore, each MS transmits with a lower PAPR—recall that PAPR increases with the number of subcarriers—and with far lower total power than if it had to transmit over the entire bandwidth. Figure 6.4 illustrates this. Lower data rates and bursty data are handled much more efficiently in OFDMA than in single-user OFDM or with TDMA or CSMA, since rather than having to blast at high power over the entire bandwidth, OFDMA allows the same data rate to be sent over a longer period of time using the same total power.

6.2 Multiuser Diversity and Adaptive Modulation

In OFDMA, the subcarrier and the power allocation should be based on the channel conditions in order to maximize the throughput. In this section, we provide necessary background discussion on the key two principles that enable high performance in OFDMA: multiuser diversity and adaptive modulation. Multiuser diversity describes the gains available by selecting a user or sub-



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- **BLER and received SINR:** In adaptive-modulation theory, the transmitter needs to know only the statistics and instantaneous channel SINR. From the channel SINR, the transmitter can determine the optimum coding/modulation strategy and transmit power [8]. In practice, however, the BLER should be carefully monitored as the final word on whether the data rate should be increased (if the BLER is low) or decreased to a more robust setting.
- **Automatic repeat request (ARQ):** ARQ allows rapid retransmissions, and hybrid-ARQ generally increases the ideal BLER operating point by about a factor of 10: for example, from 1 percent to 10 percent. For delay-tolerant applications, it may be possible to accept a BLER approaching even 70 percent, if Chase combining is used in conjunction with H-ARQ to make use of unsuccessful packets.
- **Power control versus waterfilling:** In theory, the best power-control policy from a capacity standpoint is the so-called waterfilling strategy, in which more power is allocated to strong channels and less power allocated to weak channels [11, 12]. In practice, the opposite may be true in some cases. For example, in Figure 6.8, almost nothing is gained with a 13dB SINR versus an 11dB SINR: In both cases, the throughput is 3bps/Hz. Therefore, as the SINR improved from 11dB to 13dB, the transmitter would be well advised to lower the transmit power, in order to save power and generate less interference to neighboring cells [3].
- **Adaptive modulation in OFDMA:** In an OFDMA system, each user is allocated a block of subcarriers, each having a different set of SINRs. Therefore, care needs to be paid to which constellation/coding set is chosen, based on the varying SINRs across the subcarriers.

6.3 Resource-Allocation Techniques for OFDMA

There are a number of ways to take advantage of multiuser diversity and adaptive modulation in OFDMA systems. Algorithms that take advantage of these gains are not specified by the WiMAX standard, and all WiMAX developer are free to develop their own innovative procedures. The idea is to develop algorithms for determining which users to schedule, how to allocate subcarriers to them, and how to determine the appropriate power levels for each user on each subcarrier. In this section, we will consider some of the possible approaches to resource allocation. We focus on the class of techniques that attempt to balance the desire for high throughput with fairness among the users in the system. We generally assume that the outgoing queues for each user are full, but in practice, the algorithms discussed here can be modified to adjust for queue length or delay constraints, which in many applications may be as, if not more, important than raw throughput.²

Referring to the downlink OFDMA system shown in Figure 6.3, users estimate and feedback the channel state information (CSI) to a centralized base station, where subcarrier and power allocation are determined according to users' CSI and the resource-allocation procedure. Once the subcarriers for each user have been determined, the base station must inform each user

2. Queueing theory and delay-constrained scheduling is a rich topic in its own right, and doing it justice here is outside the scope of this chapter.

which subcarriers have been allocated to it. This subcarrier mapping must be broadcast to all users whenever the resource allocation changes: The format of these messages is discussed in Chapter 8. Typically, the resource allocation must be performed on the order of the channel coherence time, although it may be performed more frequently if a lot of users are competing for resources.

The resource allocation is usually formulated as a constrained optimization problem, to either (1) minimize the total transmit power with a constraint on the user data rate [21, 39] or (2) maximize the total data rate with a constraint on total transmit power [18, 24, 25, 43]. The first objective is appropriate for fixed-rate applications, such as voice, whereas the second is more appropriate for bursty applications, such as data and other IP applications. Therefore, in this section, we focus on the rate-adaptive algorithms (category 2), which are more relevant to WiMAX systems. We also note that considerable related work on resource allocation has been done for multicarrier DSL systems [2, 6, 7, 41]; the coverage and references in this section are by no means comprehensive. Unless otherwise stated, we assume in this section that the base station has obtained perfect instantaneous channel-state information for all users. Table 6.1 summarizes the notation that will be used throughout this section.

6.3.1 Maximum Sum Rate Algorithm

As the name indicates, the objective of the maximum sum rate (MSR) algorithm, is to maximize the sum rate of all users, given a total transmit power constraint [43]. This algorithm is optimal if the goal is to get as much data as possible through the system. The drawback of the MSR algorithm is that it is likely that a few users close to the base station, and hence having excellent channels, will be allocated all the system resources. We now briefly characterize the SINR, data rate, and power and subcarrier allocation that the MSR algorithm achieves.

Table 6.1 Notations

Notation	Meaning
K	Number of users
L	Number of subcarriers
$h_{k,l}$	Envelope of channel gain for user k in subcarrier l
$P_{k,l}$	Transmit power allocated for user k in subcarrier l
σ^2	AWGN power spectrum density
P_{tot}	Total transmit power available at the base station
B	Total transmission bandwidth

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bits in the block, and s is $M/2$, where M is the order of the modulation alphabet (2 for QPSK, 4 for 16 QAM, and 6 for 64 QAM), and d is an arbitrary parameter whose value is set to 16:

$$\begin{aligned} n_k &= \left(\frac{N_c}{d}\right)k_{\text{mod}(d)} + \text{floor}\left(\frac{k}{d}\right) \\ k &= s \cdot \text{floor}\left(\frac{m_k}{s}\right) + \left(m_k + N_c - \text{floor}\left(\frac{d \cdot m_k}{N_c}\right)\right)_{\text{mod}(d)} \end{aligned} \quad (8.1)$$

The deinterleaver, which performs the inverse of this operation, also works in two steps. The index of the j th bit after the first and the second steps of the deinterleaver is given by

$$\begin{aligned} n_j &= s \cdot \text{floor}\left(\frac{j}{s}\right) + \left(j + \text{floor}\left(\frac{d \cdot j}{N_c}\right)\right)_{\text{mod}(d)} \\ j &= dm_j - \left((N_c - 1) \cdot \text{floor}\left(\frac{d \cdot m_j}{N_c}\right)\right) \end{aligned} \quad (8.2)$$

When convolutional turbo codes are used, the interleaver is bypassed, since a subblock interleaver is used within the encoder, as explained in the previous section.

8.4 Symbol Mapping

During the symbol mapping stage, the sequence of binary bits is converted to a sequence of complex valued symbols. The mandatory constellations are QPSK and 16 QAM, with an optional 64 QAM constellation also defined in the standard, as shown in Figure 8.7. Although the 64 QAM is optional, most WiMAX systems will likely implement it, at least for the downlink.

Each modulation constellation is scaled by a number c , such that the average transmitted power is unity, assuming that all symbols are equally likely. The value of c is $\sqrt{1/2}$, $\sqrt{1/10}$, and $\sqrt{1/42}$ for the QPSK, 16 QAM, and 64 QAM modulations, respectively. The symbols are further multiplied by a pseudorandom unitary number to provide additional layer 1 encryption:

$$s_k = 2\left(\frac{1}{2} - w_k\right)s_k, \quad (8.3)$$

where k is the subcarrier index, and w_k is a pseudorandom number generated by a shift register of memory order 11. Preamble and midamble symbols are further scaled by $2\sqrt{2}$, which signifies an eight fold boost in the power and allows for more accurate synchronization and various parameter estimations, such as channel response and noise variance.

8.5 OFDM Symbol Structure

As discussed in Chapter 4, in an OFDM system, a high-data-rate sequence of symbols is split into multiple parallel low-data rate-sequences, each of which is used to modulate an orthogonal tone, or subcarrier. The transmitted baseband signal, which is an ensemble of the signals in all the subcarriers, can be represented as

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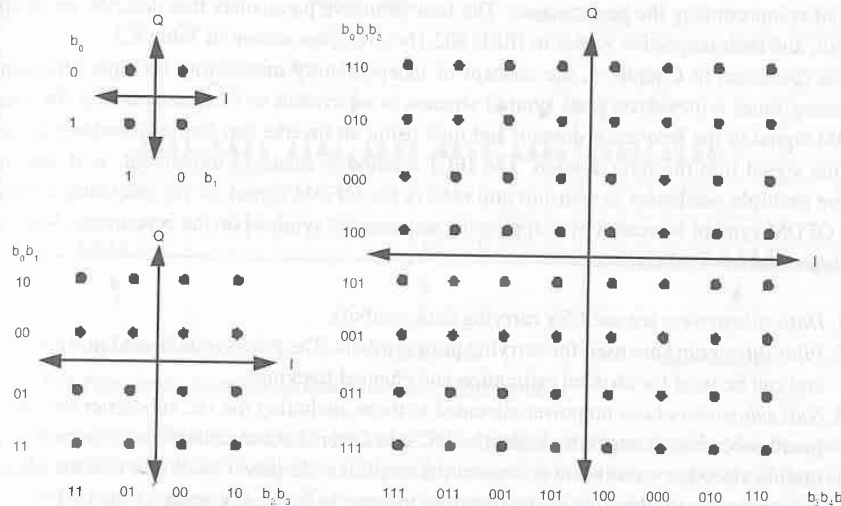


Figure 8.7 QPSK, 16 QAM, and 64 QAM modulation constellations

$$x(t) = \sum_{i=0}^{L-1} s[i] e^{-2\pi j(\Delta f + iB_c)t} \quad 0 \leq t \leq T, \quad (8.4)$$

where $s[i]$ is the symbol carried on the i th subcarrier; B_c is the frequency separation between two adjacent subcarriers, also referred to as the subcarrier bandwidth; Δf is the frequency of the first subcarrier; and T is the total useful symbol duration (without the cyclic prefix). At the receiver, the symbol sent on a specific subcarrier is retrieved by integrating the received signal with a complex conjugate of the tone signal over the entire symbol duration T . If the time and the frequency synchronization between the receiver and the transmitter is perfect, the orthogonality between the subcarriers is preserved at the receiver. When the time and/or frequency synchronization between the transmitter and the receiver is not perfect,³ the orthogonality between the subcarriers is lost, resulting in *intercarrier interference* (ICI). Timing mismatch can occur due to misalignment of the clocks at the transmitter and the receiver and propagation delay of the channel. Frequency mismatch can occur owing to relative drift between the oscillators at the transmitter and the receiver and nonlinear channel effects, such as Doppler shift. The flexibility of the WiMAX PHY layer allows one to make an optimum choice of various PHY layer parameters, such as cyclic prefix length, number of subcarriers, subcarrier separation, and preamble interval, such that the performance degradation owing to ICI and ISI (intersymbol interference) is minimal.

3. Time synchronization is not as critical as frequency synchronization, as long as it is within the cyclic prefix window.

without compromising the performance. The four primitive parameters that describe an OFDM symbol, and their respective values in IEEE 802.16e-2005, are shown in Table 8.3.

As discussed in Chapter 4, the concept of independently modulating multiple orthogonal frequency tones with narrowband symbol streams is equivalent to first constructing the entire OFDM signal in the frequency domain and then using an inverse fast fourier transform to convert the signal into the time domain. The IFFT method is easier to implement, as it does not require multiple oscillators to transmit and receive the OFDM signal. In the frequency domain, each OFDM symbol is created by mapping the sequence of symbols on the subcarriers. WiMAX has three classes of subcarriers.

1. *Data subcarriers* are used for carrying data symbols.
2. *Pilot subcarriers* are used for carrying pilot symbols. The pilot symbols are known a priori and can be used for channel estimation and channel tracking.
3. *Null subcarriers* have no power allocated to them, including the DC subcarrier and the guard subcarriers toward the edge. The DC subcarrier is not modulated, to prevent any saturation effects or excess power draw at the amplifier. No power is allocated to the guard subcarrier toward the edge of the spectrum in order to fit the spectrum, of the OFDM symbol within the allocated bandwidth and thus reduce the interference between adjacent channels.

Figure 8.8 shows a typical frequency domain representation of an IEEE 802.16e-2005 OFDM symbol containing the data subcarriers, pilot subcarriers, and null subcarriers. The power in the pilot subcarriers, as shown here, is boosted by 2.5 dB, allowing reliable channel tracking even at low-SNR conditions.

Table 8.3 Primitive Parameters for OFDM Symbol^a

Parameter	Value (MHz)	Definition
B	Variable (1.25, 1.75, 3.5, 5, 7, 8.75, 10, 14, 15 ^b)	Nominal channel bandwidth
L	256 for OFDM; 128, 512, 1,024, 2,048 for SOFDMA	Number of subcarriers, including the DC subcarrier pilot subcarriers and the guard subcarriers
n	8/7, 28/25	Oversampling factor
G	1/4, 1/8, 1/16, and 1/32	Ratio of cyclic prefix time to useful symbol time

a. Not all values are part of the initial WiMAX profile.

b. The 8.75MHz channel bandwidth is for WiBro.

8.6 Subchannel and Subcarrier Permutations

In order to create the OFDM symbol in the frequency domain, the modulated symbols are mapped on to the subchannels that have been allocated for the transmission of the data block.

8.7 Slot and Frame Structure

The MAC layer allocates the time/frequency resources to various users in units of *slots*, which is the smallest quanta of PHY layer resource that can be allocated to a single user in the time/frequency domain. The size of a slot is dependent on the subcarrier permutation mode.

- FUSC: Each slot is 48 subcarriers by one OFDM symbol.
- Downlink PUSC: Each slot is 24 subcarriers by two OFDM symbols.
- Uplink PUSC and TUSC: Each slot is 16 subcarriers by three OFDM symbols.
- Band AMC: Each slot is 8, 16, or 24 subcarriers by 6, 3, or 2 OFDM symbols.

In the time/frequency domain, the contiguous collections of slots that are allocated for a single user from the *data region* of the given user. It should be noted that the scheduling algorithm used for allocating data regions to various users is critical to the overall performance of a WiMAX system. A smart scheduling algorithm should adapt itself to not only the required QoS but also the instantaneous channel and load conditions. Scheduling algorithms and their various advantages and disadvantages are discussed in Chapter 6.

In IEEE 802.16e-2005, both frequency division duplexing and time division duplexing are allowed. In the case of FDD, the uplink and downlink subframes are transmitted simultaneously on different carrier frequencies; in the case of TDD, the uplink and downlink subframes are transmitted on the same carrier frequency at different times. Figure 8.14 shows the frame structure for TDD. The frame structure for the FDD mode is identical except that the UL and DL subframes are multiplexed on different carrier frequencies. For mobile stations, (MS) an additional duplexing mode, known as H-FDD (half-duplex FDD) is defined. H-FDD is a basic FDD duplexing scheme with the restriction that the MS cannot transmit and receive at the same time. From a cost and implementation perspective, an H-FDD MS is cheaper and less complex than its FDD counterpart, but the UL and DL peak data rate of, an H-FDD MS are less, owing to its inability to receive and transmit simultaneously.

Each DL subframe and UL subframe in IEEE 802.16e-2005 is divided into various zones, each using a different subcarrier permutation scheme. Some of the zones, such as DL PUSC, are mandatory; other zones, such as FUSC, AMC, UL PUSC, and TUSC, are optional. The relevant information about the starting position and the duration of the various zones being used in a UL and DL subframe is provided by control messages in the beginning of each DL subframe.

The first OFDM symbol in the downlink subframe is used for transmitting the DL preamble. The preamble can be used for a variety of PHY layer procedures, such as time and frequency synchronization, initial channel estimation, and noise and interference estimation. The subcarriers in the preamble symbol are divided into a group of three carrier sets. The indices of subcarriers associated with a given carrier set are given by

$$Carrier_{n,k} = k + 3n, \quad (8.5)$$

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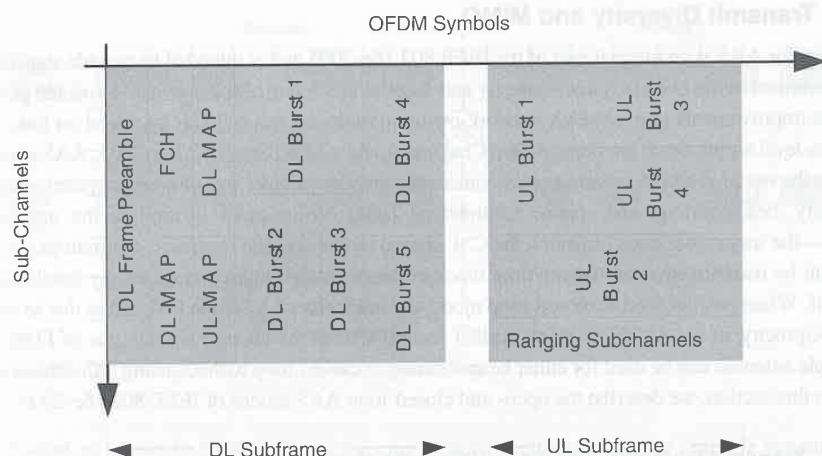


Figure 8.14 TDD frame structure

where the carrier set index, k , runs from 0 to 2, and the subcarrier index runs from 0 to $(N_{used}-3)/3$. Each segment (sector), as defined in the PUSC subcarrier permutation section, uses a preamble composed of only one of the three allowed carrier sets, thus modulating every third subcarrier. A cell-ID-specific PN (pseudonoise) sequence is modulated, using BPSK to create the preamble in the frequency domain. The power of the subcarriers belonging to the carrier set of the preamble is boosted by $2\sqrt{2}$. The frame length, which is defined by the interval between two consecutive DL frame preambles, is variable in WiMAX and can be anywhere between 2msec and 20msec.

In the OFDM symbol following the DL frame preamble, the initial subchannels are allocated for the frame correction header. The FCH is used for carrying system control information, such as the subcarriers used (in case of segmentation), the ranging subchannels, and the length of the DL-MAP message. This information is carried on the DL_Frame_Prefix message contained within the FCH. The FCH is always coded with the BPSK R1/2 mode to ensure maximum robustness and reliable performance, even at the cell edge.

Following the FCH are the DL-MAP and the UL-MAP messages, respectively, which specify the data regions of the various users in the DL and UL subframes of the current frame. By listening to these messages, each MS can identify the subchannels and the OFDM symbols allocated in the DL and UL for its use. Periodically, the BS also transmits the downlink channel descriptor (DCD) and the uplink channel descriptor (UCD) following the UL-MAP message, which contains additional control information pertaining to the description of channel structure and the various burst profiles⁴ that are allowed within the given BS. In order to conserve resources, the DCD and the UCD are not transmitted every DL frame.

4. As defined previously, a *burst profile* is the combination of modulation constellation, code rate, and the FEC used.

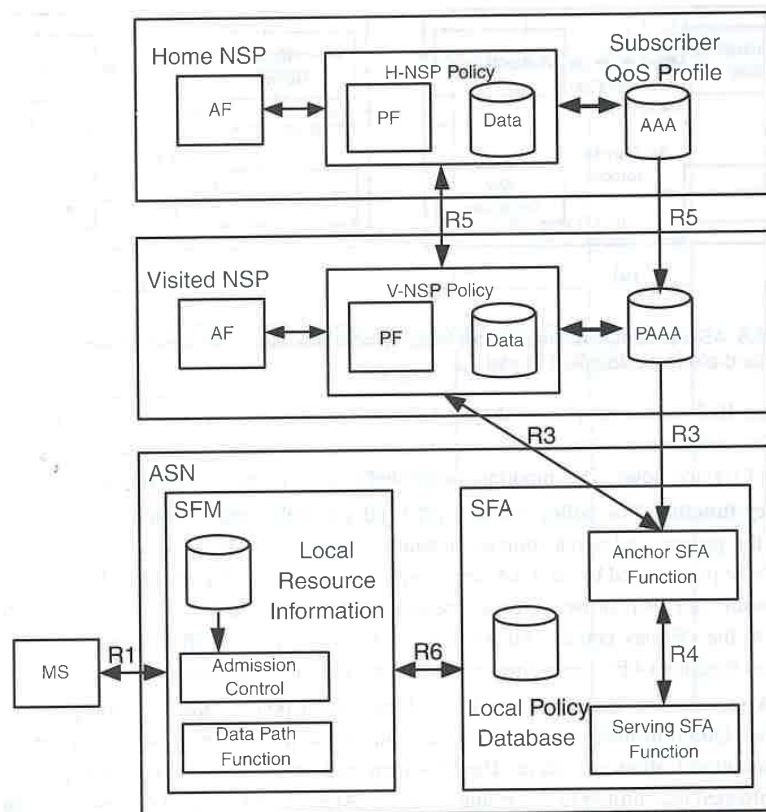


Figure 10.9 QoS functional architecture

the SFM is called the *serving SFA*. The SFAs may also perform ASN-level policy enforcement, using a local policy function (LPF) and database. The LPF may also be used for local admission control enforcement.

Application function. The AF is an entity that can initiate service flow creation on behalf of a user. An example of an AF is a SIP proxy client.

10.8 Mobility Management

The WiMAX mobility-management architecture was designed to

- Minimize packet loss and handoff latency and maintain packet ordering to support seamless handover even at vehicular speeds

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- Comply with the security and trust architecture of IEEE 802.16 and IETF EAP RFCs during mobility events
- Supporting macro diversity handover (MOHO) as well as fast base station switching (FBSS)⁷
- Minimize the number of round-trips of signaling to execute handover
- Keep handover control and data path control separate
- Support multiple deployment scenarios and be agnostic to ASN decomposition
- Support both IPv4- and IPv6-based mobility management and accommodate mobiles with multiple IP addresses and simultaneous IPv4 and IPv6 connections
- Maintain the possibility of vertical or intertechnology handovers and roaming between NSPs
- Allow a single NAP to serve multiple MSs using different private and public IP domains owned by different NSPs
- Support both static and dynamic home address configuration
- Allow for policy-based and dynamic assignment of home agents to facilitate such features as route optimization and load balancing

The WiMAX network supports two types of mobility: (1) *ASN-anchored mobility* and (2) *CSN-anchored mobility*. ASN-anchored mobility is also referred to as intra-ASN mobility, or micromobility. In this case, the MS moves between two data paths while maintaining the same anchor foreign agent at the northbound edge of the ASN network. The handover in this case happens across the R8 and/or R6 reference points. ASN-anchored handover typically involves migration of R6, with R8 used for transferring undelivered packets after handover. It is also possible to keep the layer 3 connection to the same BS (anchor BS) through the handover and have data traverse from the anchor BS to the serving BS throughout the session. CSN-anchored mobility is also referred to as inter-ASN mobility, or macromobility. In this case, the MS changes to a new anchor FA—this is called FA migration—and the new FA and CSN exchange signaling messages to establish data-forwarding paths. The handover in this case happens across the R3 reference point, with tunneling over R4 to transfer undelivered packets. Figure 10.10 illustrates the various possible handover scenarios supported in WiMAX.

Mobility management is typically triggered when the MS moves across base stations based on radio conditions. It may also be triggered when an MS wakes up from idle mode at a different ASN or when the network decides to transfer R3 end points for an MS from the serving FA to a new FA for resource optimization.

In many cases, both ASN- and CSN-anchored mobility may be triggered. When this happens, it is simpler and preferable to initiate the CSN-anchored mobility after successfully completing the ASN-anchored mobility.

7. Note that the initial WiMAX system profiles do not support MDH and FBSS.

1 UNITED STATES PATENT AND TRADEMARK OFFICE

2
3
4 BEFORE THE PATENT TRIAL AND APPEAL BOARD

5
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7 INTEL CORPORATION,

8 Petitioner

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10 v.

11
12 UNM RAINFOREST INNOVATION,

13 Patent Owner

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15
16 U.S. Patent No. 8,265,096

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18
19 **DECLARATION OF KAREN WHITNEY**
20 **UNDER 28 U.S.C. § 1746**
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1 I, Karen Whitney, declare:

2 1. I make this declaration on behalf of Intel Corporation in the matter of the
3 *inter partes* review of U.S. Patent No. 8,265,096 (“the Patent Proceeding”). Unless
4 otherwise stated, the facts stated in this declaration are based on my personal
5 knowledge.

6 2. I am the Collection & Digital Services Manager at Perkins Coie, 1201
7 Third Ave., Suite 4900, Seattle, Washington 98101. I have been the Collection &
8 Digital Services Manager since July 2019. I joined Perkins Coie in July 2013 and
9 worked as a library technician until July 2016. Between April 2018 and July 2019, I
10 was the Library Operations Supervisor and prior to that I was a librarian from July
11 2016 to March 2018. I previously worked as a Library Technician at Dorsey &
12 Whitney LLP from 2001 to 2012. I received a B.S. in Business-IT Management from
13 WGU in 2014 and a Masters in Library and Information Science from San Jose State
14 University in 2016. I am over the age of majority and make this declaration of my
15 own personal knowledge.

16 3. I am knowledgeable of the practices of the Perkins Coie Law Library
17 system, including with library procedures for seeking, entering, and indexing print and
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19 4. I am knowledgeable of online marketplaces, including Amazon.com,
20 which I have used to locate and purchase print and electronic sources for the Perkins
21 Coie Library.

22 5. On February 23, 2007, the Perkins Coie Law Library was contacted by
23 Chun Ng, an attorney at Perkins Coie. Mr. Ng requested that we locate and purchase a
24 copy of J. Andrews et al., *Fundamentals of WiMAX Understanding Broadband*
25 *Wireless Networking* (2007). That same day Perkins Coie Library staff accessed
26 Amazon.com and located the requested book and ordered it.

27 6. On March 14, 2007, Perkins Coie Library staff received and processed
28 the copy of *Fundamentals of WiMAX*. The inside title page was stamped by Perkins
ZyXEL Communications Corporation Ex. 1005

1 Coie Law Library staff when processed. The stamp bares the date “Mar 14 2007.” It
2 was hand delivered to Mr. Ng later that same day.

3 7. Exhibit [1005] in the Patent Proceeding accurately depicts scanned pages
4 from the original copy of Fundamentals of WiMAX that the Perkins Coie Law Library
5 received on March 14, 2007 and which was publicly available for purchase at least on
6 February 23, 2007.

7 8. I declare under penalty of perjury under the laws of the United States of
8 America that this declaration is true, complete, and accurate to the best of my
9 knowledge. I further acknowledge that willful false statements and the like are
10 punishable by fine or imprisonment, or both (18 U.S.C. § 1001).

11 Executed at Seattle, Washington, this 8th day of September, 2020.

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14 Karen Whitney
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