CHAPTER 2

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 IFEEE 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 Wireless-MAN-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).

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 architecture	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 bandwidths	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

<table>
<tr><th>Band Index</th><th>Frequency Band</th><th>Channel Bandwidth</th><th>OFDM FFT Size</th><th>Duplexing</th><th>Notes</th></tr>
<tr><td colspan="6">Fixed WiMAX Profiles</td></tr>
<tr><td rowspan="4">1</td><td rowspan="4">3.5 GHz</td><td>3.5MHz</td><td>256</td><td>FDD</td><td rowspan="2">Products already certified</td></tr>
<tr><td>3.5MHz</td><td>256</td><td>TDD</td></tr>
<tr><td>7MHz</td><td>256</td><td>FDD</td><td></td></tr>
<tr><td>7MHz</td><td>256</td><td>TDD</td><td></td></tr>
<tr><td>2</td><td>5.8GHz</td><td>10MHz</td><td>256</td><td>TDD</td><td></td></tr>
<tr><td colspan="6">Mobile WiMAX Profiles</td></tr>
<tr><td rowspan="3">1</td><td rowspan="3">2.3GHz–2.4GHz</td><td>5MHz</td><td>512</td><td>TDD</td><td rowspan="2">Both bandwidths must be supported by mobile station (MS)</td></tr>
<tr><td>10MHz</td><td>1,024</td><td>TDD</td></tr>
<tr><td>8.75MHz</td><td>1,024</td><td>TDD</td><td></td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">2.305GHz–2.320GHz,
2.345GHz–2.360GHz</td><td>3.5MHz</td><td>512</td><td>TDD</td><td></td></tr>
<tr><td>5MHz</td><td>512</td><td>TDD</td><td></td></tr>
<tr><td>10MHz</td><td>1,024</td><td>TDD</td><td></td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">2.496GHz–2.69GHz</td><td>5MHz</td><td>512</td><td>TDD</td><td rowspan="2">Both bandwidths must be supported by mobile station (MS)</td></tr>
<tr><td>10MHz</td><td>1,024</td><td>TDD</td></tr>
<tr><td rowspan="3">4</td><td rowspan="3">3.3GHz–3.4GHz</td><td>5MHz</td><td>512</td><td>TDD</td><td></td></tr>
<tr><td>7MHz</td><td>1,024</td><td>TDD</td><td></td></tr>
<tr><td>10MHz</td><td>1,024</td><td>TDD</td><td></td></tr>
<tr><td rowspan="3">5</td><td rowspan="3">3.4GHz–3.8GHz,
3.4GHz–3.6GHz,
3.6GHz–3.8GHz</td><td>5MHz</td><td>512</td><td>TDD</td><td></td></tr>
<tr><td>7MHz</td><td>1,024</td><td>TDD</td><td></td></tr>
<tr><td>10MHz</td><td>1,024</td><td>TDD</td><td></td></tr>
</table>

With the completion of the IEEE 802.16e-2005 standard, interest within the WiMAX group has shifted sharply toward developing and certifying mobile WiMAX[1] 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.

For the reminder 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 20MHz[2] 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

2. 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 costcurves 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 channels[3]—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 $O(B\mathbf{log}BT_m)$, 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 $O(B^2T_m)$.
- **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).

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 narrowband 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-2005[5] 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 μs when operating in a 3.5MHz channel and up to 8 μs 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 (Tg/Tb)	1/32, 1/16, **1/8**, 1/4				
Oversampling rate (Fs/BW)	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 (μs)	64	**91.4**			
Guard time assuming 12.5% (μs)	8	**11.4**			
OFDM symbol duration (μs)	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.

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 10.94kHz. 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 10.94kHz 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 μs and vehicular mobility up to 125 kmph when operating in 3.5GHz. A subcarrier spacing of 10.94kHz implies that 128, 512, 1,024, and 2,048 FFT are used when the channel bandwidth is 1.25MHz, 5MHz, 10MHz, and 20MHz, 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 8.75MHz 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 pseudorandomly 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 5MHz bandwidth. For 10MHz 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.

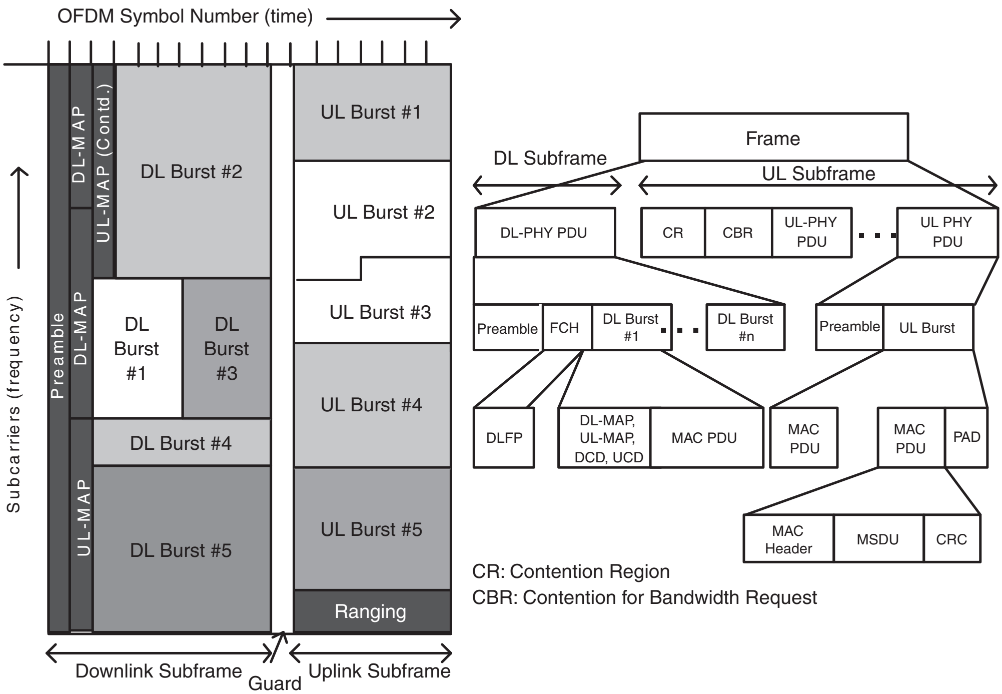

Figure 2.1 A sample TDD frame structure for mobile WiMAX

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.

Table 2.4 Modulation and Coding Supported in WiMAX

	Downlink	Uplink
Modulation	BPSK, QPSK, 16 QAM, 64 QAM; BPSK optional for OFDMA-PHY	BPSK, QPSK, 16 QAM; 64 QAM optional
Coding	Mandatory: convolutional codes at rate 1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6; repetition codes at rate 1/2, 1/3, 1/6, LDPC, RS-Codes for OFDM-PHY	Mandatory: convolutional codes at rate 1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6; repetition codes at rate 1/2, 1/3, 1/6, LDPC

Table 2.5 PHY-Layer Data Rate at Various Channel Bandwidths

Channel bandwidth	3.5MHz		1.25MHz		5MHz		10MHz		**8.75MHz**[a]	
PHY mode	256 OFDM		128 OFDMA		512 OFDMA		1,024 OFDMA		1,024 OFDMA	
Oversampling	8/7		28/25		28/25		28/25		28/25	
Modulation and Code Rate	**PHY-Layer Data Rate (kbps)**									
	DL	UL	DL	UL	DL	UL	DL	UL	DL	UL
BPSK, 1/2	946	326	**Not applicable**							
QPSK, 1/2	1,882	653	504	154	2,520	653	5,040	1,344	4,464	1,120
QPSK, 3/4	2,822	979	756	230	3,780	979	7,560	2,016	6,696	1,680
16 QAM, 1/2	3,763	1,306	1,008	307	5,040	1,306	10,080	2,688	8,928	2,240
16 QAM, 3/4	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 1/2	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 2/3	7,526	2,611	2,016	614	10,080	2,611	20,160	5,376	17,856	4,480
64 QAM, 3/4	8,467	2,938	2,268	691	11,340	2,938	22,680	6,048	20,088	5,040
64 QAM, 5/6	9,408	3,264	2,520	768	12,600	3,264	25,200	6,720	22,320	**5,600**

a. The version deployed as WiBro in South Korea.

2.4 MAC-Layer Overview

The primary task of the WiMAX MAC layer is to provide an interface between the higher transport layers and the physical layer. The MAC layer takes packets from the upper layer—these packets are called *MAC service data units* (MSDUs)—and organizes them into *MAC protocol data units* (MPDUs) for transmission over the air. For received transmissions, the MAC layer does the reverse. The IEEE 802.16-2004 and IEEE 802.16e-2005 MAC design includes a *convergence sublayer* that can interface with a variety of higher-layer protocols, such as ATM, TDM Voice, Ethernet, IP, and any unknown future protocol. Given the predominance of IP and Ethernet in the industry, the WiMAX Forum has decided to support only IP and Ethernet at this time. Besides providing a mapping to and from the higher layers, the convergence sublayer supports MSDU header suppression to reduce the higher layer overheads on each packet.

The WiMAX MAC is designed from the ground up to support very high peak bit rates while delivering quality of service similar to that of ATM and DOCSIS. The WiMAX MAC uses a variable-length MPDU and offers a lot of flexibility to allow for their efficient transmission. For example, multiple MPDUs of same or different lengths may be aggregated into a single burst to save PHY overhead. Similarly, multiple MSDUs from the same higher-layer service may be concatenated into a single MPDU to save MAC header overhead. Conversely, large MSDUs may be fragmented into smaller MPDUs and sent across multiple frames.

Figure 2.2 shows examples of various MAC PDU (packet data unit) frames. Each MAC frame is prefixed with a generic MAC header (GMH) that contains a connection identifier[8] (CID), the length of frame, and bits to qualify the presence of CRC, subheaders, and whether the payload is encrypted and if so, with which key. The MAC payload is either a transport or a management message. Besides MSDUs, the transport payload may contain bandwidth requests or retransmission requests. The type of transport payload is identified by the subheader that immediately precedes it. Examples of subheaders are packing subheaders and fragmentation subheaders. WiMAX MAC also supports ARQ, which can be used to request the retransmission of unfragmented MSDUs and fragments of MSDUs. The maximum frame length is 2,047 bytes, which is represented by 11 bits in the GMH.

2.4.1 Channel-Access Mechanisms

In WiMAX, the MAC layer at the base station is fully responsible for allocating bandwidth to all users, in both the uplink and the downlink. The only time the MS has some control over bandwidth allocation is when it has multiple sessions or connections with the BS. In that case, the BS allocates bandwidth to the MS in the aggregate, and it is up to the MS to apportion it among the multiple connections. All other scheduling on the downlink *and* uplink is done by the BS. For the downlink, the BS can allocate bandwidth to each MS, based on the needs of the incoming traffic, without involving the MS. For the uplink, allocations have to be based on requests from the MS.

The WiMAX standard supports several mechanisms by which an MS can request and obtain uplink bandwidth. Depending on the particular QoS and traffic parameters associated with a service, one or more of these mechanisms may be used by the MS. The BS allocates dedicated or shared resources periodically to each MS, which it can use to request bandwidth. This process is called *polling*. Polling may be done either individually (unicast) or in groups (multicast). Multicast polling is done when there is insufficient bandwidth to poll each MS individually. When polling is done in multicast, the allocated slot for making bandwidth requests is a shared slot,

8. See Section 2.4.2 for the definition of a connection identifier.

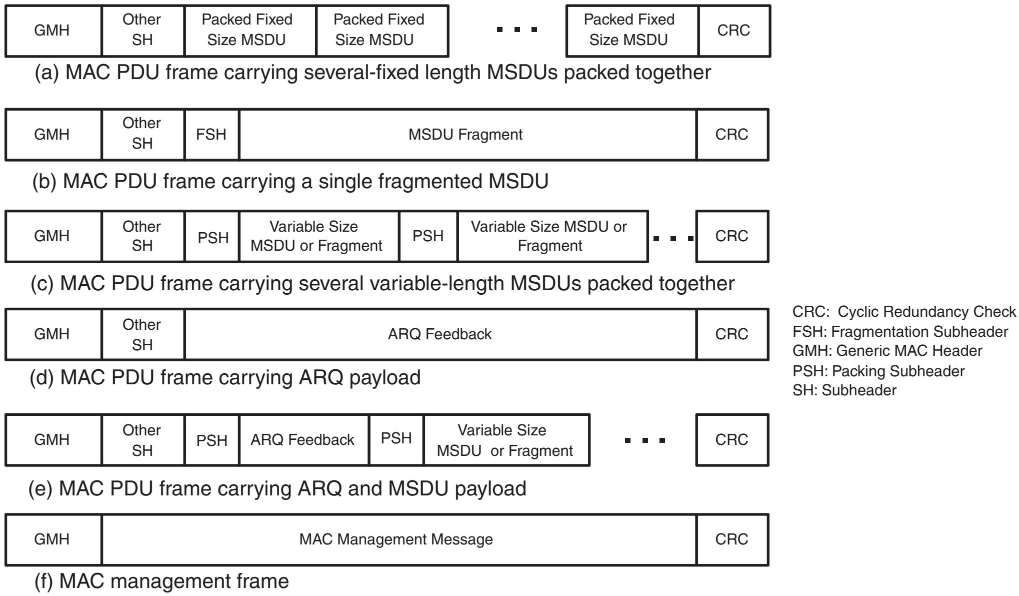

Figure 2.2 Examples of various MAC PDU frames

which every polled MS attempts to use. WiMAX defines a contention access and resolution mechanism for the case when more than one MS attempts to use the shared slot. If it already has an allocation for sending traffic, the MS is not polled. Instead, it is allowed to request more bandwidth by (1) transmitting a stand-alone bandwidth request MPDU, (2) sending a bandwidth request using the ranging channel, or (3) piggybacking a bandwidth request on generic MAC packets.

2.4.2 Quality of Service

Support for QoS is a fundamental part of the WiMAX MAC-layer design. WiMAX borrows some of the basic ideas behind its QoS design from the DOCSIS cable modem standard. Strong QoS control is achieved by using a connection-oriented MAC architecture, where all downlink and uplink connections are controlled by the serving BS. Before any data transmission happens, the BS and the MS establish a unidirectional logical link, called a *connection,* between the two MAC-layer peers. Each connection is identified by a *connection identifier* (CID), which serves as a temporary address for data transmissions over the particular link. In addition to connections for transferring user data, the WiMAX MAC defines three management connections—the basic, primary, and secondary connections—that are used for such functions as ranging.

WiMAX also defines a concept of a service flow. A *service flow* is a unidirectional flow of packets with a particular set of QoS parameters and is identified by a *service flow identifier* (SFID). The QoS parameters could include traffic priority, maximum sustained traffic rate, maximum burst rate, minimum tolerable rate, scheduling type, ARQ type, maximum delay, tolerated jitter, service data unit type and size, bandwidth request mechanism to be used, transmission PDU formation rules, and so on. Service flows may be provisioned through a network management system or created dynamically through defined signaling mechanisms in the standard. The base station is responsible for issuing the SFID and mapping it to unique CIDs. Service flows can also be mapped to DiffServ code points or MPLS flow labels to enable end-to-end IP-based QoS.

To support a wide variety of applications, WiMAX defines five scheduling services (Table 2.6) that should be supported by the base station MAC scheduler for data transport over a connection:

1. **Unsolicited grant services (UGS):** This is designed to support fixed-size data packets at a constant bit rate (CBR). Examples of applications that may use this service are T1/E1 emulation and VoIP without silence suppression. The mandatory service flow parameters that define this service are maximum sustained traffic rate, maximum latency, tolerated jitter, and request/transmission policy.[9]
2. **Real-time polling services (rtPS):** This service is designed to support real-time service flows, such as MPEG video, that generate variable-size data packets on a periodic basis. The mandatory service flow parameters that define this service are minimum reserved traffic rate, maximum sustained traffic rate, maximum latency, and request/transmission policy.
3. **Non-real-time polling service (nrtPS):** This service is designed to support delay-tolerant data streams, such as an FTP, that require variable-size data grants at a minimum guaranteed rate. The mandatory service flow parameters to define this service are minimum reserved traffic rate, maximum sustained traffic rate, traffic priority, and request/transmission policy.
4. **Best-effort (BE) service:** This service is designed to support data streams, such as Web browsing, that do not require a minimum service-level guarantee. The mandatory service flow parameters to define this service are maximum sustained traffic rate, traffic priority, and request/transmission policy.
5. **Extended real-time variable rate (ERT-VR) service:** This service is designed to support real-time applications, such as VoIP with silence suppression, that have variable data rates but require guaranteed data rate and delay. This service is defined only in IEEE 802.16e-2005, not in IEEE 802.16-2004. This is also referred to as extended real-time polling service (ErtPS).

Although it does not define the scheduler per se, WiMAX does define several parameters and features that facilitate the implementation of an effective scheduler:

- Support for a detailed parametric definition of QoS requirements and a variety of mechanisms to effectively signal traffic conditions and detailed QoS requirements in the uplink.

9. This policy includes how to request for bandwidth and the rules around PDU formation, such as whether fragmentation is allowed.

Table 2.6 Service Flows Supported in WiMAX

Service Flow Designation	Defining QoS Parameters	Application Examples
Unsolicited grant services (UGS)	Maximum sustained rate Maximum latency tolerance Jitter tolerance	Voice over IP (VoIP) without silence suppression
Real-time Polling service (rtPS)	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Traffic priority	Streaming audio and video, MPEG (Motion Picture Experts Group) encoded
Non-real-time Polling service (nrtPS)	Minimum reserved rate Maximum sustained rate Traffic priority	File Transfer Protocol (FTP)
Best-effort service (BE)	Maximum sustained rate Traffic priority	Web browsing, data transfer
Extended real-time Polling service (ErtPS)	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Jitter tolerance Traffic priority	VoIP with silence suppression

- Support for three-dimensional dynamic resource allocation in the MAC layer. Resources can be allocated in time (time slots), frequency (subcarriers), and space (multiple antennas) on a frame-by-frame basis.
- Support for fast channel-quality information feedback to enable the scheduler to select the appropriate coding and modulation (burst profile) for each allocation.
- Support for contiguous subcarrier permutations, such as AMC, that allow the scheduler to exploit multiuser diversity by allocating each subscriber to its corresponding strongest subchannel.

It should be noted that the implementation of an effective scheduler is critical to the overall capacity and performance of a WiMAX system.

2.4.3 Power-Saving Features

To support battery-operated portable devices, mobile WiMAX has power-saving features that allow portable subscriber stations to operate for longer durations without having to recharge. Power saving is achieved by turning off parts of the MS in a controlled manner when it is not actively transmitting or receiving data. Mobile WiMAX defines signaling methods that allow the MS to retreat into a sleep mode or idle mode when inactive. *Sleep mode* is a state in which the MS effectively turns itself off and becomes unavailable for predetermined periods. The periods 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.

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 FBHH and MDHO in WiMAX networks is not fully developed yet and is not part of WiMAX Forum Release 1 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

(FIPS) and is easier to implement.[10] The 128-bit or 256-bit key used for deriving the cipher is generated during the authentication phase and is periodically refreshed for additional protection.

Device/user authentication: WiMAX provides a flexible means for authenticating subscriber stations and users to prevent unauthorized use. The authentication framework is based on the Internet Engineering Task Force (IETF) EAP, which supports a variety of credentials, such as username/password, digital certificates, and smart cards. WiMAX terminal devices come with built-in X.509 digital certificates that contain their public key and MAC address. WiMAX operators can use the certificates for device authentication and use a username/password or smart card authentication on top of it for user authentication.

Flexible key-management protocol: The Privacy and Key Management Protocol Version 2 (PKMv2) is used for securely transferring keying material from the base station to the mobile station, periodically reauthorizing and refreshing the keys. PKM is a client-server protocol: The MS acts as the client; the BS, the server. PKM uses X.509 digital certificates and RSA (Rivest-Shamer-Adleman) public-key encryption algorithms to securely perform key exchanges between the BS and the MS.

Protection of control messages: The integrity of over-the-air control messages is protected by using message digest schemes, such as AES-based CMAC or MD5-based HMAC.[11]

Support for fast handover: To support fast handovers, WiMAX allows the MS to use preauthentication with a particular target BS to facilitate accelerated reentry. A three-way handshake scheme is supported to optimize the reauthentication mechanisms for supporting fast handovers, while simultaneously preventing any man-in-the-middle attacks.

2.4.6 Multicast and Broadcast Services

The mobile WiMAX MAC layer has support for multicast and broadcast services (MBS). MBS-related functions and features supported in the standard include

- Signaling mechanisms for MS to request and establish MBS
- Subscriber station access to MBS over a single or multiple BS, depending on its capability and desire
- MBS associated QoS and encryption using a globally defined traffic encryption key
- A separate zone within the MAC frame with its own MAP information for MBS traffic
- Methods for delivering MBS traffic to idle-mode subscriber stations
- Support for macro diversity to enhance the delivery performance of MBS traffic

10. See Chapter 7 for more details on encryption.
11. CMAC (cipher-based message authentication code); HMAC (hash-based message authentication codes); MD5 (Message-Digest 5 Algorithm). All protocols are standardized within the IETF.

2.5 Advanced Features for Performance Enhancements

WiMAX defines a number of optional advanced features for improving the performance. Among the more important of these advanced features are support for multiple-antenna techniques, hybrid-ARQ, and enhanced frequency reuse.

2.5.1 Advanced Antenna Systems

The WiMAX standard provides extensive support for implementing advanced multiantenna solutions to improve system performance. Significant gains in overall system *capacity and spectral* efficiency can be achieved by deploying the optional *advanced antenna systems* (AAS) defined in WiMAX. AAS includes support for a variety of multiantenna solutions, including transmit diversity, beamforming, and spatial multiplexing.

Transmit diversity: WiMAX defines a number of space-time block coding schemes that can be used to provide transmit diversity in the downlink. For transmit diversity, there could be two or more transmit antennas and one or more receive antennas. The space-time block code (STBC) used for the 2×1 antenna case is the Alamouti codes, which are orthogonal and amenable to maximum likelihood detection. The Alamouti STBC is quite easy to implement and offers the same diversity gain as a 1×2 receiver diversity with maximum ratio combining, albeit with a 3 dB penalty owing to redundant transmissions. But transmit diversity offers the advantage that the complexity is shifted to the base station, which helps to keep the MS cost low. In addition to the 2×1 case, WiMAX also defines STBCs for the three- and four-antenna cases.

Beamforming: Multiple antennas in WiMAX may also be used to transmit the same signal appropriately weighted for each antenna element such that the effect is to focus the transmitted beam in the direction of the receiver and away from interference, thereby improving the received SINR. Beamforming can provide significant improvement in the coverage range, capacity, and reliability. To perform transmit beamforming, the transmitter needs to have accurate knowledge of the channel, which in the case of TDD is easily available owing to channel reciprocity but for FDD requires a feedback channel to learn the channel characteristics. WiMAX supports beamforming in both the uplink and the downlink. For the uplink, this often takes the form of receive beamforming.

Spatial multiplexing: WiMAX also supports spatial multiplexing, where multiple independent streams are transmitted across multiple antennas. If the receiver also has multiple antennas, the streams can be separated out using space-time processing. Instead of increasing diversity, multiple antennas in this case are used to increase the data rate or capacity of the system. Assuming a rich multipath environment, the capacity of the system can be increased linearly with the number of antennas when performing spatial multiplexing. A 2×2 MIMO system therefore doubles the peak throughput capability of WiMAX. If the mobile station has only one antenna, WiMAX can still support spatial multiplexing by coding across multiple users in the uplink. This is called multiuser collaborative spatial multiplexing. Unlike transmit diversity and beamforming, spatial multiplexing works only under good SINR conditions.

2.5.2 Hybrid-ARQ

Hybrid-ARQ is an ARQ system that is implemented at the physical layer together with FEC, providing improved link performance over traditional ARQ at the cost of increased implementation complexity. The simplest version of H-ARQ is a simple combination of FEC and ARQ, where blocks of data, along with a CRC code, are encoded using an FEC coder before transmission; retransmission is requested if the decoder is unable to correctly decode the received block. When a retransmitted coded block is received, it is combined with the previously detected coded block and fed to the input of the FEC decoder. Combining the two received versions of the code block improves the chances of correctly decoding. This type of H-ARQ is often called type I *chase combining*.

The WiMAX standard supports this by combining an *N*-channel *stop and wait ARQ* along with a variety of supported FEC codes. Doing multiple parallel channels of H-ARQ at a time can improve the throughput, since when one H-ARQ process is waiting for an acknowledgment, another process can use the channel to send some more data. WiMAX supports signaling mechanisms to allow asynchronous operation of H-ARQ and supports a dedicated acknowledgment channel in the uplink for ACK/NACK signaling. Asynchronous operations allow variable delay between retransmissions, which provides greater flexibility for the scheduler.

To further improve the reliability of retransmission, WiMAX also optionally supports type II H-ARQ, which is also called *incremental redundancy*. Here, unlike in type I H-ARQ, each (re)transmission is coded differently to gain improved performance. Typically, the code rate is effectively decreased every retransmission. That is, additional parity bits are sent every iteration, equivalent to coding across retransmissions.

2.5.3 Improved Frequency Reuse

Although it is possible to operate WiMAX systems with a universal frequency reuse plan,[12] doing so can cause severe outage owing to interference, particularly along the intercell and intersector edges. To mitigate this, WiMAX allows for coordination of subchannel allocation to users at the cell edges such that there is minimal overlap. This allows for a more dynamic frequency allocation across sectors, based on loading and interference conditions, as opposed to traditional fixed frequency planning. Those users under good SINR conditions will have access to the full channel bandwidth and operate under a frequency reuse of 1. Those in poor SINR conditions will be allocated nonoverlapping subchannels such that they operate under a frequency reuse of 2, 3, or 4, depending on the number of nonoverlapping subchannel groups that are allocated to be shared among these users. This type of subchannel allocation leads to the effective reuse factor taking fractional values greater than 1. The variety of subchannelization schemes supported by WiMAX makes it possible to do this in a very flexible manner. Obviously, the downside is that cell edge users cannot have access to the full bandwidth of the channel, and hence their peak rates will be reduced.

12. This corresponds to all sectors and cells using the same frequency. Reuse factor is equal to 1.

2.6 Reference Network Architecture

The IEEE 802.16e-2005 standard provides the air interface for WiMAX but does not define the full end-to-end WiMAX network. The WiMAX Forum's Network Working Group, is responsible for developing the end-to-end network requirements, architecture, and protocols for WiMAX, using IEEE 802.16e-2005 as the air interface.

The WiMAX NWG has developed a network reference model to serve as an architecture framework for WiMAX deployments and to ensure interoperability among various WiMAX equipment and operators. The network reference model envisions a unified network architecture for supporting fixed, nomadic, and mobile deployments and is based on an IP service model. Figure 2.3 shows a simplified illustration of an IP-based WiMAX network architecture. The overall network may be logically divided into three parts: (1) mobile stations used by the end user to access the network, (2) the access service network (ASN), which comprises one or more base stations and one or more ASN gateways that form the radio access network at the edge, and (3) the connectivity service network (CSN), which provides IP connectivity and all the IP core network functions.

The architecture framework is defined such that the multiple players can be part of the WiMAX service value chain. More specifically, the architecture allows for three separate business entities: (1) network access provider (NAP), which owns and operates the ASN; (2) network services provider (NSP), which provides IP connectivity and WiMAX services to subscribers using the ASN infrastructure provided by one or more NAPs; and (3) application service provider (ASP), which can provide value-added services such as multimedia applications using IMS (IP multimedia subsystem) and corporate VPN (virtual private networks) that run on top of IP. This separation between NAP, NSP, and ASP is designed to enable a richer ecosystem for WiMAX service business, leading to more competition and hence better services.

The network reference model developed by the WiMAX Forum NWG defines a number of functional entities and interfaces between those entities. (The interfaces are referred to as reference points.) Figure 2.3 shows some of the more important functional entities.

Base station (BS): The BS is responsible for providing the air interface to the MS. Additional functions that may be part of the BS are micromobility management functions, such as handoff triggering and tunnel establishment, radio resource management, QoS policy enforcement, traffic classification, DHCP (Dynamic Host Control Protocol) proxy, key management, session management, and multicast group management.

Access service network gateway (ASN-GW): The ASN gateway typically acts as a layer 2 traffic aggregation point within an ASN. Additional functions that may be part of the ASN gateway include intra-ASN location management and paging, radio resource management and admission control, caching of subscriber profiles and encryption keys, AAA client functionality, establishment and management of mobility tunnel with base stations, QoS and policy enforcement, foreign agent functionality for mobile IP, and routing to the selected CSN.

Connectivity service network (CSN): The CSN provides connectivity to the Internet, ASP, other public networks, and corporate networks. The CSN is owned by the NSP and includes

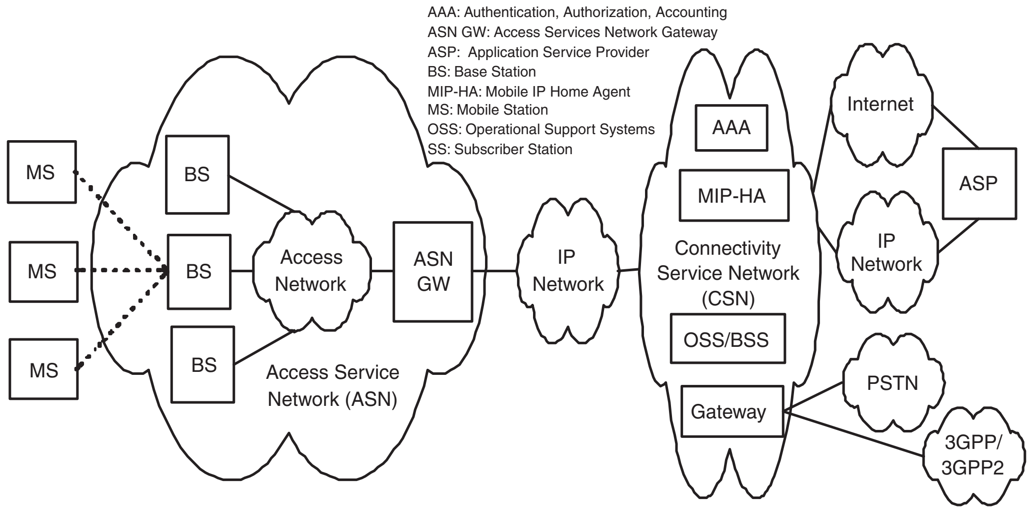

Figure 2.3 IP-Based WiMAX Network Architecture

AAA servers that support authentication for the devices, users, and specific services. The CSN also provides per user policy management of QoS and security. The CSN is also responsible for IP address management, support for roaming between different NSPs, location management between ASNs, and mobility and roaming between ASNs. Further, CSN can also provide gateways and interworking with other networks, such as PSTN (public switched telephone network), 3GPP, and 3GPP2.

The WiMAX architecture framework allows for the flexible decomposition and/or combination of functional entities when building the physical entities. For example, the ASN may be decomposed into base station transceivers (BST), base station controllers (BSC), and an ASN-GW analogous to the GSM model of BTS, BSC, and Serving GPRS Support Node (SGSN). It is also possible to collapse the BS and ASN-GW into a single unit, which could be thought of as a WiMAX router. Such a design is often referred to as a distributed, or flat, architecture. By not mandating a single physical ASN or CSN topology, the reference architecture allows for vendor/operator differentiation.

In addition to functional entities, the reference architecture defines interfaces, called *reference points*, between function entities. The interfaces carry control and management protocols—mostly IETF-developed network and transport-layer protocols—in support of several functions, such as mobility, security, and QoS, in addition to bearer data. Figure 2.4 shows an example.

The WiMAX network reference model defines reference points between: (1) MS and the ASN, called R1, which in addition to the air interface includes protocols in the management plane, (2) MS and CSN, called R2, which provides authentication, service authorization, IP configuration, and mobility management, (3) ASN and CSN, called R3, to support policy enforcement and mobility management, (4) ASN and ASN, called R4, to support inter-ASN mobility, (5) CSN and CSN, called R5, to support roaming across multiple NSPs, (6) BS and ASN-GW,

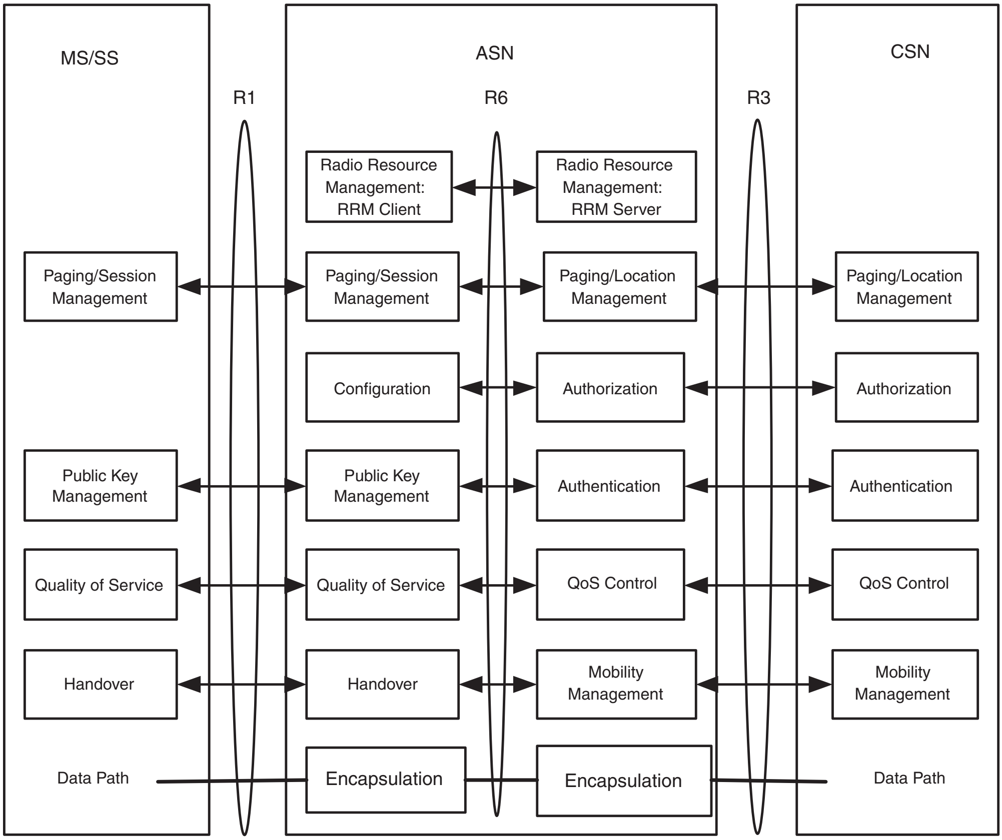

Figure 2.4 Functions performed across reference points

called R6, which consists of intra-ASN bearer paths and IP tunnels for mobility events, and (7) BS to BS, called R7, to facilitate fast, seamless handover.

A more detailed description of the WiMAX network architecture is provided in Chapter 10.

2.7 Performance Characterization

So far in this chapter, we have provided an overview description of the WiMAX broadband wireless standard, focusing on the various features, functions, and protocols. We now briefly turn to the system performance of WiMAX networks. As discussed in Chapter 1, a number of trade-offs are involved in designing a wireless system, and WiMAX offers a broad and flexible set of design choices that can be used to optimize the system for the desired service requirements. In this section, we present only a brief summary of the throughput performance and coverage range of WiMAX for a few specific deployment scenarios. Chapters 11 and 12 explore the link-and system-level performance of WiMAX is greater detail.

2.7.1 Throughput and Spectral Efficiency

Table 2.7 shows a small sampling of some the results of a simulation-based system performance study we performed. It shows the per sector average throughput achievable in a WiMAX system using a variety of antenna configurations: from an open-loop MIMO antenna system with two transmit antennas and two receiver antennas to a closed-loop MIMO system with linear precoding using four transmit antennas and two receive antennas.

The results shown are for a 1,024 FFT OFDMA-PHY using a 10MHz TDD channel and band AMC subcarrier permutation with a 1:3 uplink-to-downlink ratio. The results assume a multicellular deployment with three sectored base stations using a (1,1)[13] frequency reuse. This is an interference-limited design, with adjacent base stations assumed to be 2 km apart. A multipath environment modeled using the International Telecommunications Union (ITU) pedestrian B channel[14] is assumed. Results for both the fixed case where an indoor desktop CPE is assumed and the mobile case where a portable handset is assumed are shown in Table 2.7.

The average per sector downlink throughput for the baseline case—assuming a fixed desktop CPE deployment—is 16.3Mbps and can be increased to over 35Mbps by using a 4 × 2 closed-loop MIMO scheme with linear precoding. The mobile-handset case also shows comparable performance, albeit slightly less. The combination of OFDM, OFDMA, and MIMO provides WiMAX with a tremendous throughput performance advantage. It should be noted that early mobile WiMAX systems will use mostly open-loop 2 × 2 MIMO, with higher-order MIMO systems likely to follow within a few years. Also note that there may be fixed WiMAX systems deployed that do not use MIMO, although we have not provided simulated performance results for those systems.

Table 2.7 also shows the performance in terms of spectral efficiency, one of the key metrics used to quantify the performance of a wireless network. The results indicate that WiMAX, especially with MIMO implementations, can achieve significantly higher spectral efficiencies than what is offered by current 3G systems, such as HSDPA and 1xEV-DO.

It should be noted, however, that the high spectral efficiency obtained through the use of (1,1,) frequency reuse does entail an increased outage probability. As discussed in Chapter 12, the outage can be higher than 10 percent in many cases unless a 4 × 2 closed-loop MIMO scheme is used.

2.7.2 Sample Link Budgets and Coverage Range

Table 2.8 shows a sample link budget for a WiMAX system for two deployment scenarios. In the first scenario, the mobile WiMAX case, service is provided to a portable mobile handset located outdoors; in the second case, service is provided to a fixed desktop subscriber station placed indoors. The fixed desktop subscriber is assumed to have a switched directional antenna that provides 6 dBi gain. For both cases, MIMO spatial multiplexing is not assumed; only diversity

13. This implies that frequencies are reused in every sector.
14. See Section 12.1 for more details.

Table 2.7 Throughput and Spectral Efficiency of WiMAX

Parameter			Antenna Configuration			
			2 × 2 Open-Loop MIMO	2 × 4 Open-Loop MIMO	4 × 2 Open-Loop MIMO	4 × 2 Closed-Loop MIMO
Per sector average throughput (Mbps) in a 10MHz channel	Fixed indoor desktop CPE	DL	16.31	27.25	23.25	35.11
		UL	2.62	2.50	3.74	5.64
	Mobile handset	DL	14.61	26.31	22.25	34.11
		UL	2.34	2.34	3.58	5.48
Spectral efficiency (bps/Hertz)	Fixed indoor desktop CPE	DL	2.17	3.63	3.10	4.68
		UL	1.05	1.00	1.50	2.26
	Mobile handset	DL	1.95	3.51	2.97	4.55
		UL	0.94	0.94	1.43	2.19

reception and transmission are assumed at the base station. The numbers shown are therefore for a basic WiMAX system.

The link budget assumes a QPSK rate 1/2 modulation and coding operating at a 10 percent block error rate (BLER) for subscribers at the edge of the cell. This corresponds to a cell edge physical-layer throughput of about 150kbps in the downlink and 35kbps on the uplink, assuming a 3:1 downlink-to-uplink ratio. Table 2.8 shows that the system offers a link margin in excess of 140 dB at this data rate. Assuming 2,300MHz carrier frequency, a base station antenna height of 30 m, and a mobile station height of 1 m, this translates to a coverage range of about 1 km using the COST-231 Hata model discussed in Chapter 12. Table 2.8 shows results for both the urban and suburban models. The pathloss for the urban model is 3 dB higher than for the suburban model.

2.8 Summary and Conclusions

This chapter presented an overview of WiMAX and set the stage for more detailed exploration in subsequent chapters.

- WiMAX is based on a very flexible and robust air interface defined by the IEEE 802.16 group.
- The WiMAX physical layer is based on OFDM, which is an elegant and effective technique for overcoming multipath distortion.
- The physical layer supports several advanced techniques for increasing the reliability of the link layer. These techniques include powerful error correction coding, including turbo coding and LDPC, hybrid-ARQ, and antenna arrays.

Table 2.8 Sample Link Budgets for a WiMAX System

Parameter	Mobile Handheld in Outdoor Scenario		Fixed Desktop in Indoor Scenario		Notes
	Downlink	**Uplink**	**Downlink**	**Uplink**	
Power amplifier output power	43.0 dB	27.0 dB	43.0 dB	27.0 dB	A1
Number of tx antennas	2.0	1.0	2.0	1.0	A2
Power amplifier backoff	0 dB	0 dB	0 dB	0 dB	A3; assumes that amplifier has sufficient linearity for QPSK operation without backoff
Transmit antenna gain	18 dBi	0 dBi	18 dBi	6 dBi	A4; assumes 6 dBi antenna for desktop SS
Transmitter losses	3.0 dB	0 dB	3.0 dB	0 dB	A5
Effective isotropic radiated power	61 dBm	27 dBm	61 dBm	33 dBm	A6 = A1 + $10\log_{10}$(A2) – A3 + A4 – A5
Channel bandwidth	10MHz	10MHz	10MHz	10MHz	A7
Number of subchannels	16	16	16	16	A8
Receiver noise level	–104 dBm	–104 dBm	–104 dBm	–104 dBm	A9 = –174 + $10\log_{10}$(A7*1e6)
Receiver noise figure	8 dB	4 dB	8 dB	4 dB	A10
Required SNR	0.8 dB	1.8 dB	0.8 dB	1.8 dB	A11; for QPSK, R1/2 at 10% BLER in ITU Ped. B channel
Macro diversity gain	0 dB	0 dB	0 dB	0 dB	A12; No macro diversity assumed
Subchannelization gain	0 dB	12 dB	0 dB	12 dB	A13 = $10\log_{10}$(A8)
Data rate per subchannel (kbps)	151.2	34.6	151.2	34.6	A14; using QPSK, R1/2 at 10% BLER
Receiver sensitivity (dBm)	–95.2	–110.2	–95.2	–110.2	A15 = A9 + A10 + A11 + A12 – A13
Receiver antenna gain	0 dBi	18 dBi	6 dBi	18 dBi	A16
System gain	156.2 dB	155.2 dB	162.2 dB	161.2 dB	A17 = A6 – A15 + A16
Shadow-fade margin	10 dB	10 dB	10 dB	10 dB	A18
Building penetration loss	0 dB	0 dB	10 dB	10 dB	A19; assumes single wall
Link margin	146.2 dB	145.2 dB	142.2 dB	141.2 dB	A20 = A17 – A18 – A19
Coverage range	1.06 km (0.66 miles)		0.81 km (0.51 miles)		Assuming COST-231 Hata urban model
Coverage range	1.29 km (0.80 miles)		0.99 km (0.62 miles)		Assuming the suburban model

- WiMAX supports a number of advanced signal-processing techniques to improve overall system capacity. These techniques include adaptive modulation and coding, spatial multiplexing, and multiuser diversity.
- WiMAX has a very flexible MAC layer that can accommodate a variety of traffic types, including voice, video, and multimedia, and provide strong QoS.
- Robust security functions, such as strong encryption and mutual authentication, are built into the WiMAX standard.
- WiMAX has several features to enhance mobility-related functions such as seamless handover and low power consumption for portable devices.
- WiMAX defines a flexible all-IP-based network architecture that allows for the exploitation of all the benefits of IP. The reference network model calls for the use of IP-based protocols to deliver end-to-end functions, such as QoS, security, and mobility management.
- WiMAX offers very high spectral efficiency, particularly when using higher-order MIMO solutions.

2.9 Bibliography

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