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Fundamentals of WiMAX:

A Technology Primer

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1 WiMAX Overview

WiMAX in the IEEE and WiMAX Forum

WiMAX (worldwide interoperability for microwave access) is the commercial name for products based on the IEEE 802.16 standard as trade marked by the WiMAX Forum, an association of companies representing the ecosystem of the WiMAX technology.

The Institute of Electrical and Electronics Engineers (IEEE) is the main body responsible for defining the protocol on which the WiMAX technology is based. IEEE 802 LAN/WAN Standard Committee develops Local Area Network and Metropolitan Area Network standards. The IEEE has designated the number 802.16 for broadband wireless access on which WiMAX is based.

While the IEEE standard defines the air interface, the WiMAX Forum has undertaken the task of defining the complete end-to-end network architecture and specifying the system profile to ensure worldwide interoperability of WiMAX equipment. The WiMAX Forum also undertakes the task of certifying vendor equipment as compliant with standard specifications in conjunctions with selected test and certification laboratories.

At the current moment, there are two commercial versions of WiMAX: Fixed WiMAX based on IEEE 802.16d (or 802.16-2004, approved in June 2004) and Mobile WiMAX based on IEEE 802.16e-2005 (ratified in December 2005). Mobile WiMAX can be used in both fixed and mobile scenarios while Fixed WiMAX does not support mobility features.

Mobile WiMAX is a feature rich technology with many aspects for improvements. The current Mobile WiMAX systems are based on so called “Release 1.0 system profile.” There is also a follow on release “Release 1.5 system profile” which includes additional features not available in Release 1.0 such as Frequency Domain Duplexing (FDD) and uplink MIMO (multiple input multiple output) functionality. Release 2.0 system profile is based on a new iteration of the IEEE standard – 802.16m – which is planned to be completed by the end of 2010.

Mobile WiMAX is the mainstream technology adopted by numerous wireless access service providers and supported by equipment vendors whereas the Fixed WiMAX standard has limited deployment and support within the larger WiMAX ecosystem.

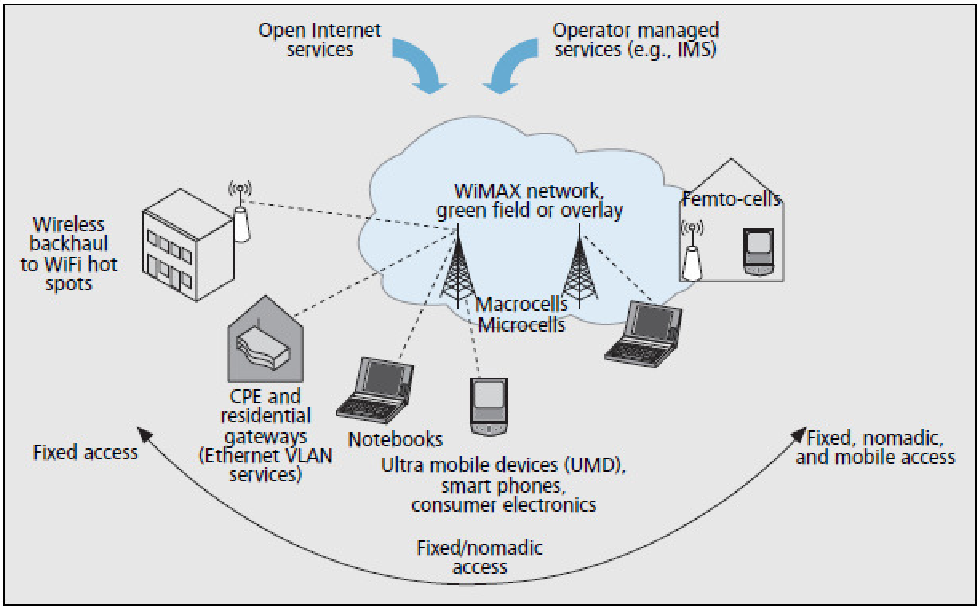


Figure 1 WiMAX enables a variety of applications and usage scenarios in the same network.

WiMAX Technology Overview

WiMAX is generally considered a fourth generation (4G) wireless access technology that provides significant advancement in throughput over existing wireless access technologies. These advancements are made possible because WiMAX implements the following technologies which are common with other 4G wireless access systems (most notably Long Term Evolution – LTE):

1- Orthogonal Frequency Division Multiple Access (OFDMA): WiMAX uses a side frequency channel to transmit and receive information, typically 3.5 – 10 MHz wide, depending on the frequency band and system profile. The signal is transmitted over multiple frequency-domain orthogonal carriers which make up the frequency channel. Mobile WiMAX uses 512 or 1024 carriers, depending on the channel. The carriers are orthogonal in the frequency domain as to limit intersymbol interference: time domain representation allows constraining interference to a short guard interval at the beginning of each symbol resulting which increases the robustness of time-dispersive radio channels. Advancements in OFDMA technology are made possible by the ability to perform inverse Fourier Transform operation at low cost (small size and low power consumption) by modern microelectronic processors. Hence, advancements in silicon technologies and the ability to condense higher processing power in ever smaller die at lower power consumptions made possible the implementation of modulation techniques known as early as the 1960's. In WiMAX, users share the frequency domain by allocating different carriers to different users. Users also share the time domain as they are scheduled for transmit and receive functions in their order during a 5 msec frame. Mobile WiMAX is based on Time Domain Duplex where the same frequency is used for transmit and receive operation. Other advantages of the OFDM technology include low-complexity receiver design which does not require frequency-domain equalization and simple combining of multiple signals from multiple transmitters.

2- Advanced Antenna Systems: Multiple Input Multiple Output (MIMO) techniques were invented in the 1990's and came to maturity during the past decade. These techniques take advantage of signal multipath in wireless communication to increase the capacity of the transmission channel. In theory, channel capacity is linearly proportional to the minimum number of transmit and receive antennas (i.e. Channel Capacity ∝ min (N_{Tx}, M_{Rx}), where N_{Tx} is the number of transmit antennas and M_{Rx} is the number of receive antennas). Hence a 2 transmit and 2 receive antenna system as common in Mobile WiMAX would show a maximum doubling of the channel throughput (or capacity). In practice, up to 1.5x capacity gain is achieved. Furthermore, in propagation environments where multipath is absent, MIMO would have limited to no capacity gain. In this case, as well as in cases where signal quality is low, a technique called "Space Time Coding" is used to transmit versions of the same symbol on multiple antennas thereby increasing signal robustness. This technique is often referred to as MIMO A in Mobile WiMAX whereas the former, capacity enhancing MIMO mode based on "Spatial Multiplexing" techniques is referred to as MIMO B. The MIMO techniques are made easier to implement in WiMAX because of its TDD nature where "channel reciprocity" allows estimating downlink propagation channel coefficients based on knowledge of the uplink channel (or vice versa). This facilitates implementation of MIMO and other advanced antenna system techniques and limits the requirement for calibration and feedback of received signal coefficients to the transmitter.

3- Flat-IP Architecture: WiMAX is based on all IP-platform with no legacy circuit-switched component as in 3G systems (where data is IP based and voice is circuit switched) as shown in Figure 2. The IEEE standard only defines layers one and two (physical and medium access control layers) leaving the higher layers of the protocol stack open to relay on other bodies like the Internet Engineering Task Force (IETF) to set the standards (e.g. TCP/IP, SIP, IPSec). This is different from 3G systems where 3GPP (Third Generation Partnership Project) sets the standard for a wide range of interfaces to ensure inter-vendor and inter-network interoperability. The WiMAX Forum has setup a Network Working Group (NWG) to address the issue of standardization over the higher-level networking protocols nevertheless. The flat-IP architecture reduces the total cost of ownership of the network and reduces the deployment cycle to allow for faster time-to-market (or time-to-operation) of the network. These are very compelling features for traditional uses of wireless technologies (e.g. wireless network operators) as well as emerging uses of broadband systems (e.g. industrial applications) as expensive dedicated core equipment (e.g. switches) are eliminated in favor of standard off the shelf routers and switches thereby enabling the tighter integration of the mobile network with the Internet and other corporate networks.

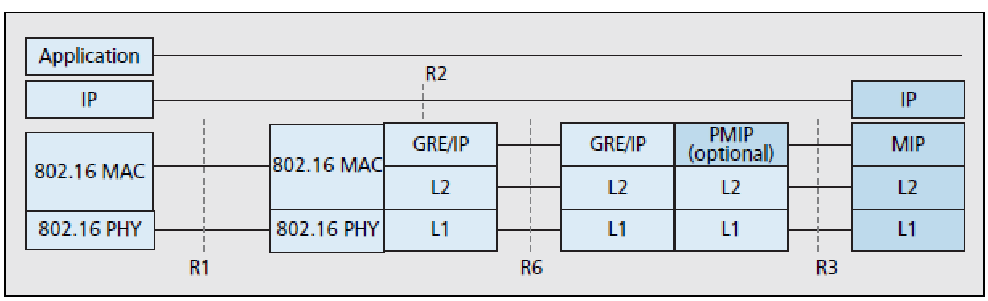


Figure 2 WiMAX flat, all-IP architecture.

In addition to the three main reasons above, there are a number of key differentiators that enhance the appeal of WiMAX. Quality of Service mechanisms that support different types of user applications like Voice over Internet Protocol (VoIP), video transmission and web browsing are but a few examples. Privacy and Key Management Protocol version 2 (PKMv2) is the basis of WiMAX security. Authentication is accomplished through different types of Extensible Authentication Protocol (EAP) such as EAP-TLS (Transport Layer Security) and EAP-SIM (Subscriber Identity

Module). User data is encrypted with AES-CCM cipher (Advanced Encryption Standard / Counter with CBC-MAC mode of authentication) with 128 bit keys generated from EAP authentication. These and other features differentiate WiMAX from 3G technologies as well as from unlicensed band wireless standards such as WiFi.

Certification Naming Conventions

The WiMAX Forum Certification Working Group (CWG) is responsible for coordinating certification activities for the WiMAX ecosystem which includes developing the test requirement, cases and plans, and signing test lab as well as setting the procedures and rules of certification testing. The CWG in conjunction with the WiMAX Forum Board of Directors and input from the WiMAX vendor and user community decides on the certification profiles which describe the frequency bands of operation as well as the channel bandwidth.

Table 1 details the defined certification profiles and naming conventions. As of the present, not all of these profiles are being certified – only a few are which include MP05 and MP09. Other certification profiles will follow in the future depending on market demand for such systems.

Table 1 WiMAX Certification profiles and naming conventions.

Marketing Working Group ID	Frequency (GHz)	Bandwidth (MHz)	Duplex	ID Mark 1	ID Mark 2
M2300T-01	2.3-2.4	8.75	TDD	1A	MP01
M2300T-02	2.3-2.4	5 & 10	TDD	1B	MP02
M2300T-03	2.305-2.320, 2.345-2.360	3.5	TDD	2A	
M2300T-04	2.305-2.320, 2.345-2.360	5	TDD	2B	MP03
M2300T-05	2.305-2.320, 2.345-2.360	10	TDD	2C	MP04
M2300T-06	2.305-2.320, 2.345-2.360	5 & 10	TDD		
M2300F-07	2.345-2.360, 2.305-2.320	2x3.5	FDD	2D	
M2300F-08	2.345-2.360, 2.305-2.320	2x5	FDD	2E	
M2300F-09	2.345-2.360, 2.305-2.320	2x10	FDD	2F	
M2300F-10	2.345-2.360, 2.305-2.320	TBD	FDD		
M2500T-01	2.496 - 2.690	5 & 10	TDD	3A	MP05
M2500F-02	2.496-2.572, 2.614-2.690	2x5 or 2x10	FDD	3B	
M3300T-01	3.3 - 3.4	5	TDD	4A	MP06
M3300T-02	3.3 - 3.4	7	TDD	4B	MP07
M3300T-03	3.3 - 3.4	10	TDD	4C	
M3500T-01	3.4 - 3.8	5	TDD	5A	MP08
M3700T-01	3.6 - 3.8	5	TDD	5AH	
M3500T-02	3.4 - 3.6	5	TDD	5AL	MP09
M3700T-02	3.4 - 3.8	7	TDD	5B	
M3700T-03	3.6 - 3.8	7	TDD	5BH	
M3500T-03	3.4 - 3.6	7	TDD	5BL	MP10
M3500T-04	3.4 - 3.8	10	TDD	5C	MP11
M3700T-04	3.6 - 3.8	10	TDD	5CH	
M3500T-05	3.4 - 3.6	10	TDD	5CL	MP12
M1700F-01	1.710 1.755 , 2.110-2.155	2x5 or 2x10	FDD	6A	
M0700F-01	.776-.787 .746-.757	2x5 or 2x10	FDD	7A	

M0700F-02	.788-.793 and .793-.798 .758-.763 and .763-.768	2x5	FDD	7B	
M0700F-03	.788-.798 , .758-.768	2x10	FDD	7C	
M0700F-04	"700 MHz"	2x5 / 2x7 / 2x10	FDD		
M0700T-04	.698-.746	5 / 10	TDD	7D	
M0700T-05	.746-.806	5 / 10	TDD	7E	
M0700T-06	.790-.862	5 / 10	TDD	7F	
M0700T-07	"700 MHz"	7	TDD		
M0700T-08	"700 MHz"	5 / 7 / 10	TDD		

2 Mobile WiMAX Reference Architecture

The Network Working Group of the WiMAX Forum has developed the Network Reference Model (NRM) which identifies the functional entities and reference points over which interoperability is achieved between the functional entities.

The NRM is divided into three functional entities: the mobile station (MS), the Access Service Network (ASN) and the Connectivity Service Network (CSN). The Access Service Network includes the set of functions allowing a WiMAX subscriber access to the radio network. The Connectivity Service Network is defined as the set of network functions that provide IP connectivity services to a WiMAX subscriber. Figure 3 shows the network reference model.

The grouping and distribution of functions into physical devices within the functional entities is left to the equipment vendor to decide as long as the implementation meets the functional and interoperability requirements. This is leads to different profiles defined by the particular mapping of the functions to network elements. In one network architecture, the functions are mapped onto two network elements: The base station (BS) and the ASN Gateway (ASN-GW). Other functional mappings and network architectures are possible as well.

The base station performs the radio related functions of the ASN: it includes the WiMAX physical (PHY; Layer 1) and medium access control (MAC; Layer 2) layers. The ASN-GW performs control functions as well as other functions related to subscriber data such as routing and bridging.

The CSN typically includes the Authentication Authorization and Accounting (AAA) Server, Policy Control Server, Mobile IP Home Agent (HA), Dynamic Host Configuration Protocol (DHCP) Server, and other servers and interworking gateways.

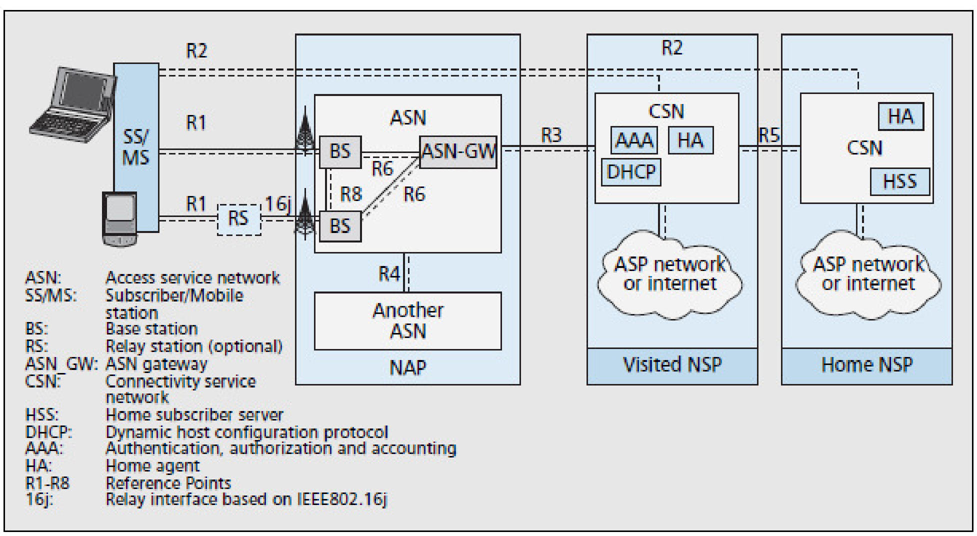


Figure 3 Mobile WiMAX Network Reference Model.

Network Architecture Reference Points

The reference points represent the interface between different functional entities of the WiMAX Network Reference Model. Protocols run between functional entities across the reference points which are used as anchors for interoperability testing. There are two types of reference points: Inter-ASN reference points and Intra-ASN reference points.

Inter-ASN Reference Points

R1: consists mainly of the IEEE 802.16 protocol between the MS and the BS (Layers 1 & 2).

R2: consists of the protocols and procedures between the MS and the CSN mainly associated with Authentication, Ser-vices Authorization and IP Host Configuration management.

R3: consists of control plane protocols as well as the IP data plane between the ASN and the CSN.

R4: consists of control and data plane procedures between ASNs and ASN Gateways particularly to support mobility ser-vices.

R5: consists of control and data plane protocols needed to support roaming between the CSN operated by a home Net-work Service Provider (NSP) and that operated by a visited NSP.

Intra-ASN Reference Points

Decomposing the ASN into base station and ASN GW entities give rise to the following reference points:

R6: consists of control (e.g. QoS, security, paging and other mobility related protocols) and data plane protocols between the base station and the ASN-GW.

R7: an optional reference point resulting from the decomposition of the ASN-GW itself into a decision point and enforcement point functions. The enforcement point includes all data plane functions while the decision point includes all the non-data plane functions.

R8: an optional reference point that consists of the set of control plane messages between base stations for handover purposes.

Access Service Network Profiles

An ASN profile defines a particular mapping of functions into base station and ASN GW and exposes reference points over which protocols and messages are defined. Three basic profiles have been defined by the WiMAX Forum NWG: Profile A, B, and C. Figure 4 shows a high-level functional description of these profiles particularly noting the placement of the handover (HO) and Radio Resource Control (RRC) functions in the network.

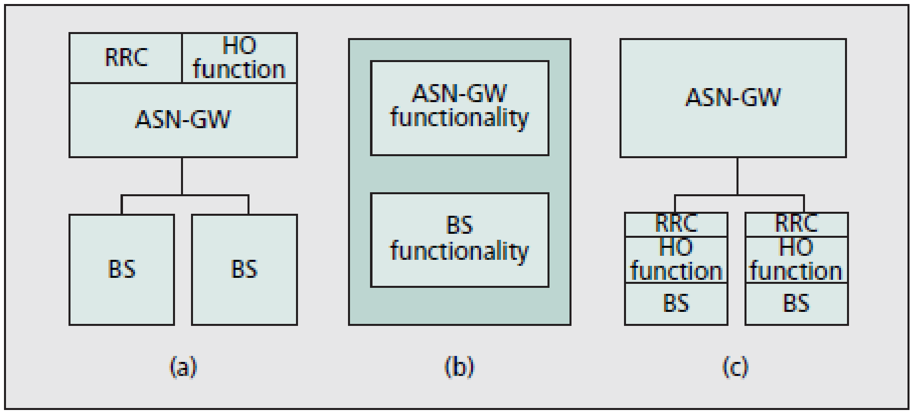


Figure 4 Description of WiMAX access service network profiles.

Profile A

Profile A is essentially a centralized profile where the ASN GW includes both radio dependent and independent functions. The key features of this profile include the following:

- Handover (HO) Control function is in the ASN GW.
- Radio Resource Control (RRC) function is in the ASN GW that allows Radio Resource Management (RRM) among multiple base stations.
- ASN Anchored mobility among base stations is achieved by utilizing R6 and R4 physical connections.

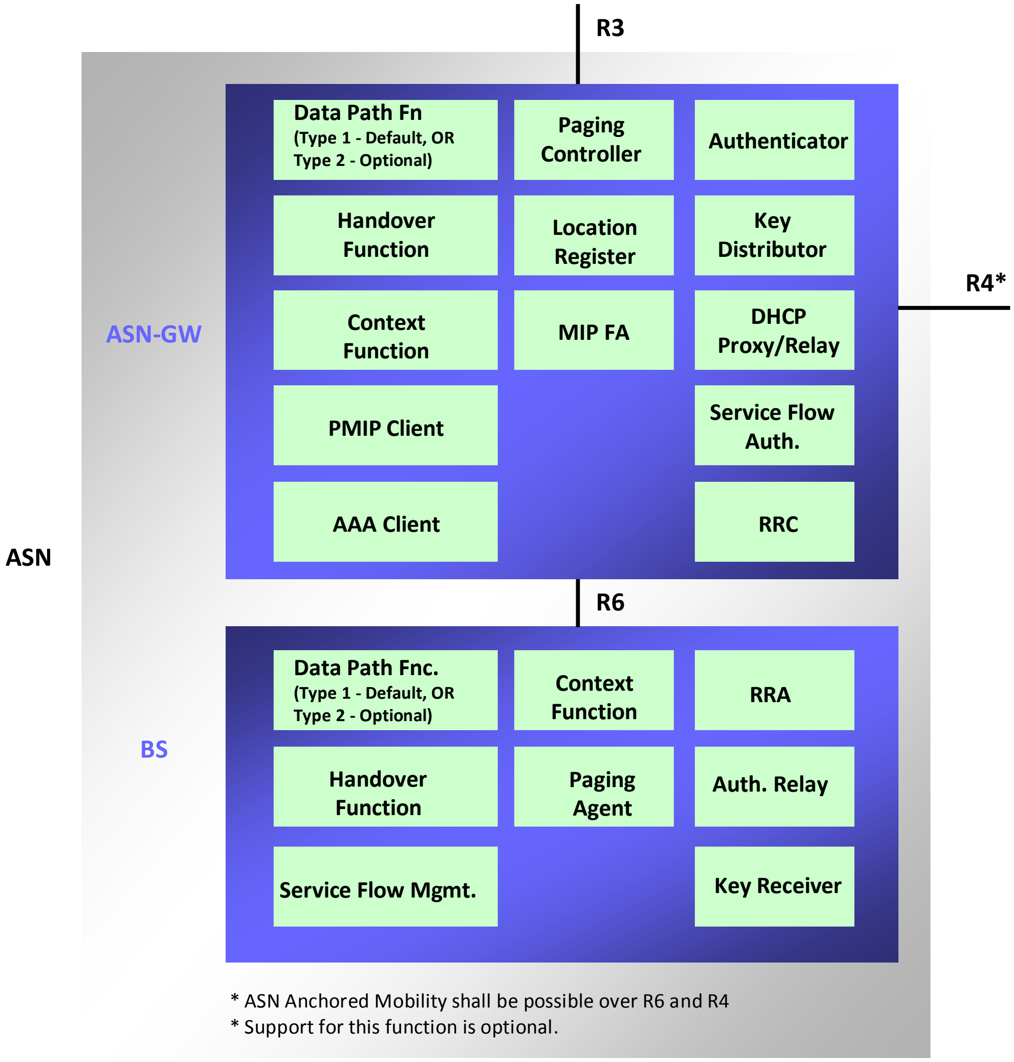
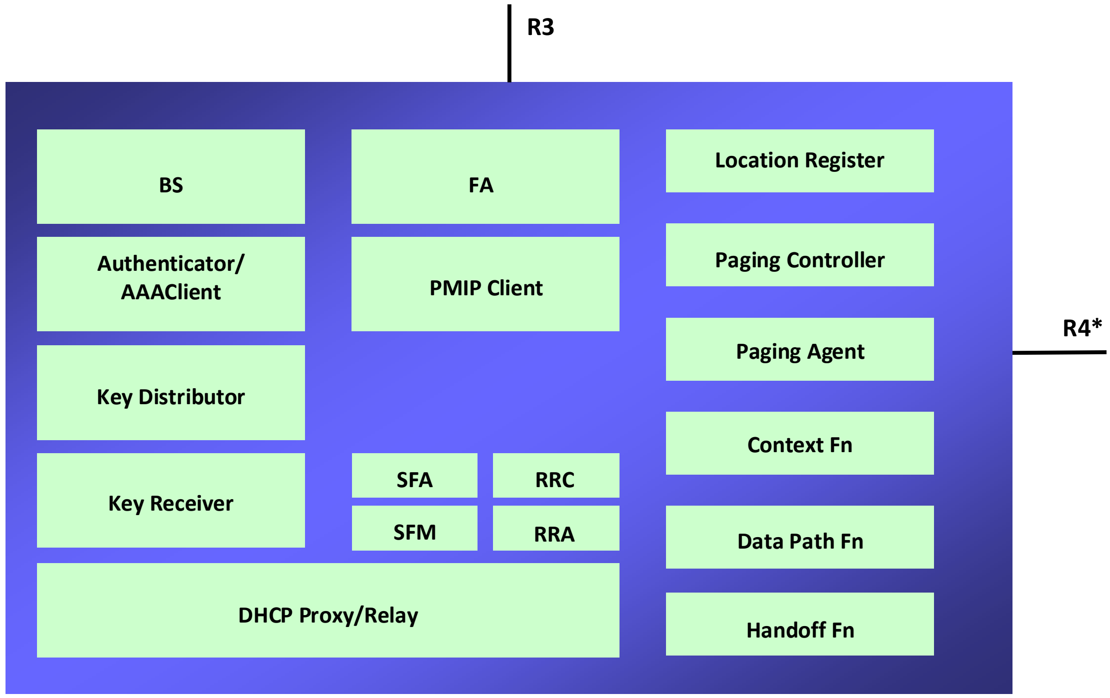


Figure 5 Profile A Functional Decomposition.

Profile B

Profile B can be qualified as an ASN with unexposed (i.e. proprietary) intra-ASN interfaces: The ASN is a black-box where intra-ASN interoperability is not specified. Furthermore, mapping of the ASN functions is not specified which results in different realizations of Profile B implementation. Hence, it is possible to arrive at an implementation where all the ASN functions are located within a single physical device (namely the base station) or an implementation where the functions are spread over multiple physical devices.

Profile B ASNs must be capable of interoperating with other ASNs of any profile over the R3 and R4 reference points to enable multi-ASN networks.



Notes:

1. No assumption made on physical co-location of functions within an ASN.
2. Allows centralized, distributed or hybrid implementations. Intra ASN interfaces are not exposed in this profile..

Figure 6 Profile B Functional Overview.

Profile C

Profile C features a base station that contains radio dependent functions and an ASN GW that includes radio independent functions. The key features of this profile include the following:

- Handover Control is in the Base Station.
- RRC is in the base station that would allow RRM within the base station. A "RRC Relay" is in the ASN GW to re-lay the RRM messages sent between base stations via R6.
- As in Profile A, ASN Anchored mobility among base stations is achieved by utilizing R6 and R4 physical connections.

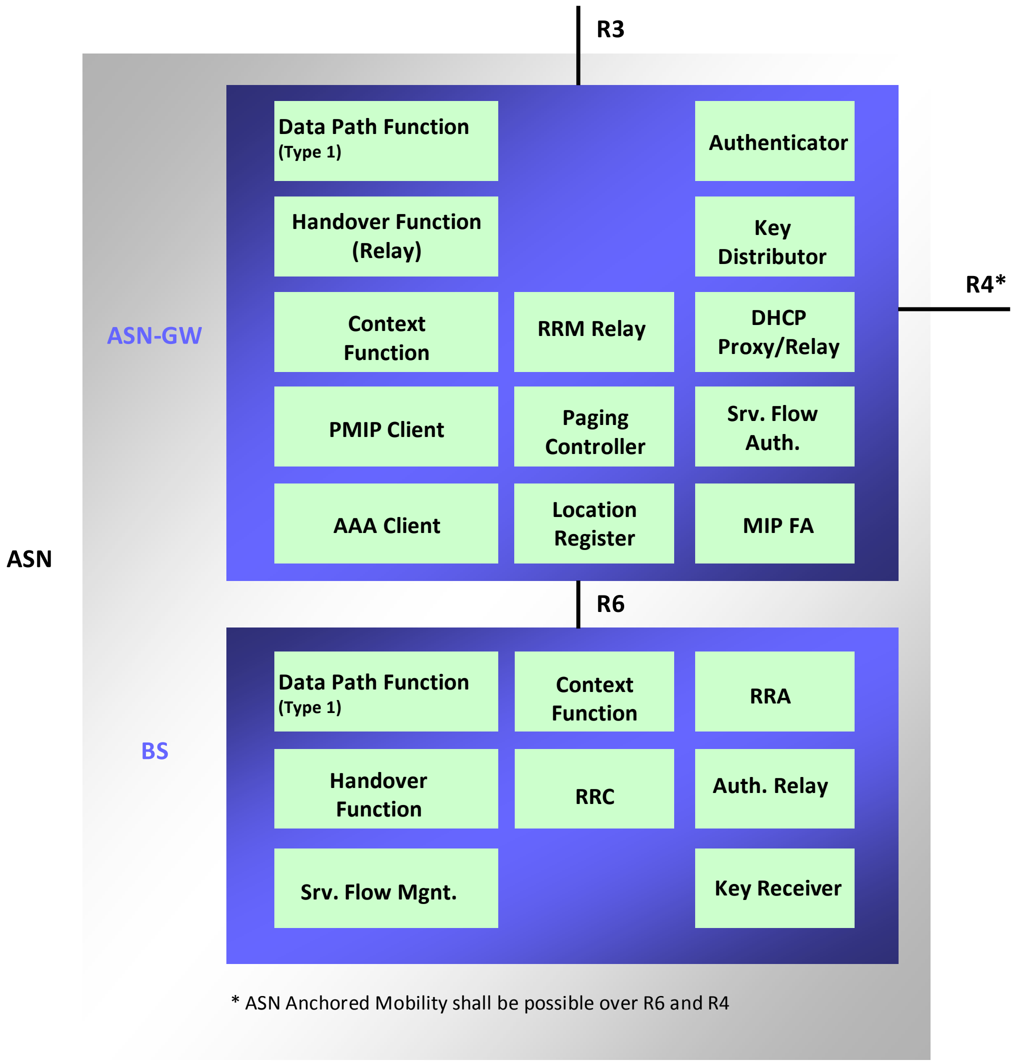


Figure 7 Profile C Functional Decomposition.

Table 2 Profile A & C Functional Comparison.

Function Category	Function	Profile A ASN Entity		Profile C ASN Entity	
		Base Station	ASN Gateway	Base Station	ASN Gateway
Security	Authenticator		✓		✓
	Authentication Relay	✓		✓	
	Key Distributor		✓		✓
	Key Receiver	✓		✓	
Intra-ASN Mobility	Data Path	✓	✓	✓	✓
	Handover	✓	✓		
	Context Server & Client	✓	✓	✓	✓
L3 Mobility	Mobile IP Foreign Agent		✓		✓
Radio Resource Management	Radio Resource Control		✓	✓	
	Radio Resource Agent	✓		✓	
	Radio Resource Control Relay	n/a	n/a		✓
Paging	Paging Agent	✓		✓	
	Paging Controller		✓		✓
QoS	Service Flow Authorization	✓		✓	
	Service Flow Management		✓		✓

3 Throughput Performance of Mobile WiMAX

Physical Layer (PHY) Throughput Performance

The PHY layer throughput indicates the aggregate data rate transferred over the air which includes overhead from higher layers. The PHY throughput is an upper limit on the expected throughput of a system.

Throughput for Mobile WiMAX which is based on the Scalable OFDMA (S-OFDMA) PHY of the IEEE 802.16e-2005 standard will depend on the permutation mode (PUSC, FUSC, AMC, etc.). Here, we focus on the PUSC mode which is the standard profile.

OFDMA divides the channel bandwidth into a number of sub-carriers. In S-OFDMA, the carrier spacing is constant, therefore, the number of carriers increase the wider the channel bandwidth. S-OFDMA supports 128, 512, 1024 or 2048 carriers, of which 512 and 1024 are most common as they are part of the Mobile WiMAX system profile.

Figure 8 shows a description of the sub-carrier space constituting a frequency channel. Sub-carriers include null sub-carriers at the edges of the channel for guard band purpose, pilot carriers used for channel estimation and corrections resulting from mobility (e.g. phase noise), and data sub-carriers used to carry management and traffic data. Table 3 shows the utilization of carriers in Mobile WiMAX. Note that 3.5 MHz channel bandwidth is not part of the IEEE 802.16e-2005 standard for the S-OFDMA PHY, but may be supported by some base station vendors. Also, there are a higher number of pilot sub-carriers for the uplink (mobile to base station) path which is designed to provide better correction for effects of mobility on the uplink communication channel.

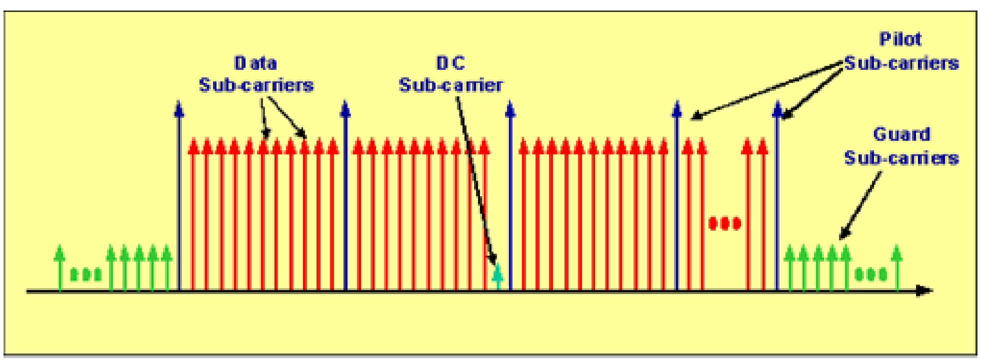


Figure 8 Scalable-OFDMA Sub-carrier structure.

Based on the sub-carrier space, a number of parameters for the S-OFDMA PHY can be derived. These parameters are shown in Table 4 for a frame of 5 msec and cyclic prefix of 1/8 as per the Mobile WiMAX System Profile.

Table 3 Utilization of carriers in Mobile WiMAX.

Bandwidth (MHz)	3.5		7		5		10	
Total Sub-Carriers	512		1024		512		1024	
Path	DL	UL	DL	UL	DL	UL	DL	UL
Used Carriers	420	408	840	840	420	408	840	840
Data Carriers	360	272	720	560	360	272	720	560
Pilot Carriers	60	136	120	280	60	136	120	280
Null Carriers	92	104	184	184	92	104	184	184
Sub-channels	15	17	30	35	15	17	30	35

Table 4 also shows the total number of symbols available for control and data traffic in an S-OFDMA frame. These symbols are assigned to the downlink (base station to mobile) or uplink path. The maximum number of symbols for 3.5 and 7 MHz channels is 33, while for 5 and 10 MHz channels it is 47. We have already accounted for the transition gaps between the downlink and uplink symbols in RTG and TTG. Figure 9 shows the frame structure for Mobile WiMAX.

Table 4 Key parameters for the S-OFDMA PHY in PUSC mode.

Mode	802.16e S-OFDMA PHY; PUSC Permutation			
Bandwidth (MHz)	3.5	7	5	10
Sampling Factor	8/7	8/7	28/25	28/25
FFT Size	512	1024	512	1024
Sampling Frequency (MHz)	4	8	5.6	11.2
Sample Time (msec)	250	125	178.6	89.3
Sub-carrier Frequency Spacing (kHz)	7.8	7.8	10.9	10.9
Useful Symbol Time (msec)	128	128	91.4	91.4
Cyclic Prefix	1/8	1/8	1/8	1/8
Guard Time (msec)	16	16	11.4	11.4
OFDMA Symbol Time (msec)	144	144	102.9	102.9
Frame Length (msec)	5	5	5	5
Symbols/Frame	33	33	47	47
RTG (msec)	60	60	60	60
TTG (msec)	188	188	106	106

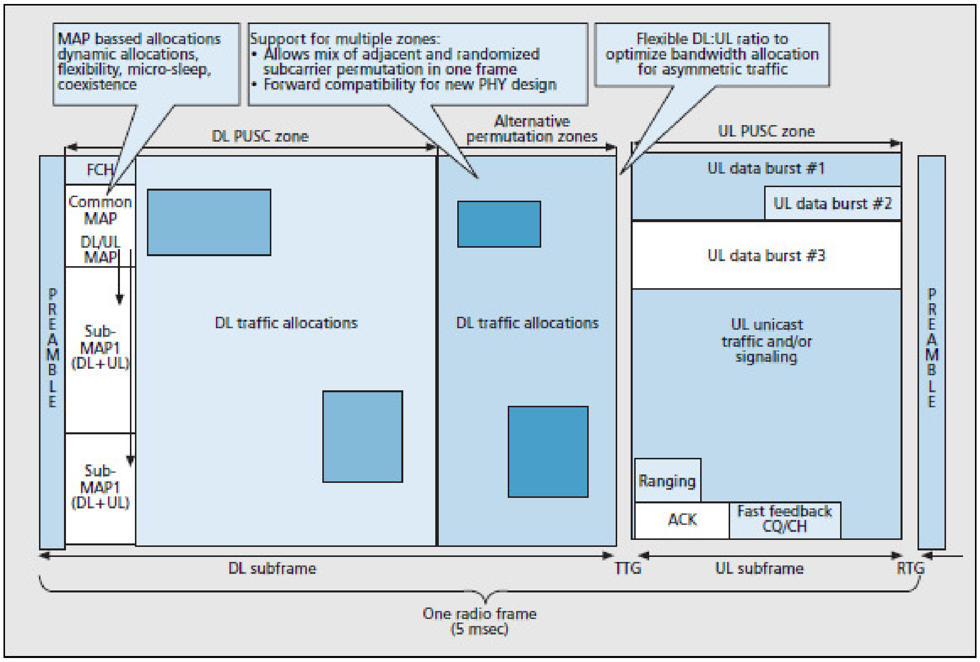


Figure 9 Mobile WiMAX Scalable OFDMA frame structure and channelization (Release 1.0).

The throughput rates can be calculated from the number of available data carriers and the number of symbols in each sub-frame. Table 5 shows the throughput rate per modulation coding scheme (MCS) for a 60:40 traffic ratio (20:13 and 28:19 DL:UL symbols for 3.5/7 MHz and 5/10 MHz channels, respectively). Note that 64QAM is not part of the Mobile WiMAX System Profile but may be supported by certain base station vendors.

Table 5 Physical layer throughput (Mbps) for PUSC mode assuming 60:40 traffic ratio.

Bandwidth (MHz)	3.5		7		5		10	
Modulation \ Path	DL	UL	DL	UL	DL	UL	DL	UL
BPSK ½	0.7	0.4	1.4	0.7	1	0.5	2	1.1
QPSK ½	1.4	0.7	2.9	1.5	2	1	4	2.1
QPSK ¾	2.2	1.1	4.3	2.2	3	1.6	6	3.2
16QAM 1/2	2.9	1.4	5.8	2.9	4	2.1	8.1	4.3
16QAM 3/4	4.3	2.1	8.6	4.4	6	3.1	12.1	6.4
64QAM 2/3	5.8	2.8	11.5	5.8	8.1	4.1	16.1	8.5
64QAM 3/4	6.5	3.2	13	6.6	9.1	4.7	18.1	9.6
64QAM 5/6	7.2	3.5	14.4	7.3	10.1	5.2	20.2	10.6

We can add the downlink and uplink rates to find the total throughput supported by Mobile WiMAX physical layer.

Layer 2 (MAC) Throughput Performance

Medium Access Control (MAC) layer rate factor control overhead into the throughput performance. From Figure 9, each frame starts with a preamble symbol used for synchronization and downlink channel estimation. This is followed by a frame control header (FCH) which provides information to decode the MAP messages that follow (e.g. sub-channels used by the sector in the current frame, coding and length of the subsequent DL-MAP message, etc. The MAP messages indicate the resource allocation (user data bursts) for the downlink and uplink sub-frames.

UL sub-frame starts with the uplink control channels: CQICH, ACKCH and Ranging Channels. The CQICH and ACK channels is used for transmitting channel state information and ACK information from mobile stations to the base station, respectively. The ranging channel is used for various types of ranging (initial, refresh, and reentry).

The control overhead consists of fixed and variable parts. The fixed part includes the preamble, FCH, and control channels. The variable part includes the DL-MAP and UL-MAP which also consist of a fixed and a variable part. The DL-MAP and UL-MAP contain as many Information Elements (IE) as the number of data bursts. Each IE has a one-to-one correspondence to a user data burst. Table 6 shows an accounting of the size of the fixed allocation for DL-MAP and UL-MAP. Table 7 shows the accounting for the DL-MAP-IE and UL-MAP-IE.

Table 6 Fixed allocation of DL-MAP and UL-MAP.

DL-MAP	**Bits**
Management Message Type	8
PHY SYNC. Field	32
DCD Count	8
Base Station ID	48
Number of OFDMA Symbol	8
Nibble Padding (if needed)	4
Total DL-MAP	**104**
UL-MAP	
Management Message Type	8
Uplink Channel ID	8
UCD Count	8
Alloc. Start Time	32
No. of OFDMA Symbol	8
Nibble Padding	4
Total UL-MAP	**64**

The CID is the connection identifier that uniquely determines a connection between a base station and a mobile station in one direction. The N_CID is the number of CIDs in the corresponding burst (N_CID = 1 in the example above). Each burst can contain more than one CIDs. DIUC/UIUC (Downlink/Uplink Interval Usage Code) indicates the usage information of the corresponding burst (e.g., modulation and coding schemes used). The OFDMA Symbol offset is the offset for the symbol at which the burst starts (measured in symbols). The sub-channel offset is the lowest index OFDMA sub-channel used for carrying the burst, starting from sub-channel 0. The boosting field indicates whether the sub-carriers for this allocation are power boosted. For example, 000 means no power boost, 001 means +6dB, etc. The number of OFDMA symbols is the number of symbols that are used to carry the burst. Similarly, the number of sub-channels is the number of sub-channels that are used to carry the burst. The repetition coding indicates how many times the code is repeated. For example, 00 means no repetition, 01 means two, 10 means 4, and 11 means 6 repetitions.

Table 7 Size of DL-MAP-IE and UL-MAP-IE.

DL-MAP_IE	**Bits**
CID	16
N_CID	8
DIUC	4
OFDMA Symbols Offset	8
Sub-channel Offset	6
Boosting	3
Number of OFDMA Symbols	7
Number of sub-channels	6
Repetition Coding Indicator	2
Total DL-MAP_IE	**60**
UL-MAP_IE	
CID	**16**
UIUC	**4**
Duration	**10**
Repetition Coding Indicator	**2**
Total UL-MAP_IE	**32**

Based on the above, the size of the MAP messages depends on the number of users active on a sector and the size will be as follows:

DL-MAP: 104 + N * DL-MAP_IE bits

UL-MAP: 64 + N* UL-MAP_IE bits

Since the MAPs carry critical information, all the mobile stations in the cell are supposed to decode them correctly. To make sure that even the mobile stations near the cell boundary decode the MAPs correctly, the coding overhead is rather high for the MAP data. In case of Mobile WiMAX, these parts are encoded with MCS QPSK 1/2 with 4 repetitions. Therefore, effective data rate is 1/8. Depending on the frequency reuse, repetition 6 may have to be used (e.g. frequency reuse of 1). Because of this, the MAP overhead can be quite a big portion of a WiMAX frame. For an effective coding rate of 1/8 over QPSK (2 bits) coding, each symbol can carry only 90 or 180 bits for 3.5/5 MHz and 7/10 MHz channels, respectively (360 or 720 carriers * 2 bits * 1/8).

In all, common estimates for MAC layer overhead are at 8 symbols for the downlink sub-frame and 3 symbols for the uplink sub-frame.

Table 8 shows an example of MAC layer throughput considering 8 symbols of overhead for the downlink sub-frame and 3 symbols for Mobile WiMAX in PUSC mode with 60:40 traffic ratio (including CP of 1/8 and frame length if 5 msec).

Table 8 MAC layer throughput for Mobile WiMAX (SISO/MIMO A mode) assuming 8 DL and 3 UL symbol overhead.

Bandwidth (MHz)	3.5		7		5		10	
Modulation / Path	DL	UL	DL	UL	DL	UL	DL	UL
BPSK ½	0.4	0.3	0.9	0.6	0.7	0.4	1.4	0.9
QPSK ½	0.9	0.5	1.7	1.1	1.4	0.9	2.9	1.8
QPSK ¾	1.3	0.8	2.6	1.7	2.2	1.3	4.3	2.7
16QAM ½	1.7	1.1	3.5	2.2	2.9	1.7	5.8	3.6
16QAM ¾	2.6	1.6	5.2	3.4	4.3	2.6	8.6	5.4
64QAM 2/3	3.5	2.2	6.9	4.5	5.8	3.5	11.5	7.2
64QAM ¾	3.9	2.4	7.8	5	6.5	3.9	13	8.1
64QAM 5/6	4.3	2.7	8.6	5.6	7.2	4.4	14.4	9

4 WiMAX System Gain and Link Budget

WiMAX System Parameters

System gain for WiMAX varies depending on the vendor equipment and is affected by several parameters of the base station and subscriber equipment such as output power of the transmitter, receiver sensitivity, and antenna gain among other parameters. An example of system parameters is provided in Table 9 to derive the link budget for WiMAX. These parameters are applicable to a system in 5 GHz band. Mobile WiMAX systems are more prevalent in 2.3, 2.5-2.6 and 3.4-3.6 GHz. The base station features an outdoor radio unit which is common to WiMAX systems. This allows placing the RF unit close to the antenna thereby eliminating long feeder cable runs and avoiding high losses. The subscriber station is of an indoor desktop form-factor with omni-directional antenna.

Table 9 Mobile WiMAX system parameters (outdoor subscriber station).

Base Station Parameters	
Transmitter Mean Output Power (dBm)	36
RF Feeder Cable / connector Loss (dB)	0.5
Antenna Gain (dBi)	15
Subscriber Station Parameters	
Transmitter Mean Output Power (dBm)	27
RF Feeder Cable / Connector Loss (dB)	0.1
Antenna Gain (dBi)	5
Frequency Band and Channelization	
Frequency Band (GHz)	2.5
Bandwidth (MHz)	10
Traffic Ratio	
Number of Downlink Symbols	26
Number of Uplink Symbols	21
Cell Edge Modulation	
Downlink Modulation	QPSK 1/2
Uplink Modulation	QPSK 1/2
Number of Allocated Uplink Sub-Channels	2
Path Loss Model Parameters	
Base Station Height (AGL, m)	30
Subscriber Station Height (AGL, m)	1.5
Propagation Model	Erceg B
Area Reliability	90%
Contour Reliability	75%
In building Penetration Loss (dB)	15

WiMAX Link Budget

Table 10 shows the link budget calculations for a typical mobile network deployment scenario corresponding to the system parameters shown in Table 9. The link budget is calculated for uplink and downlink user traffic as well as for control information sent as a part of DL/UL-MAP. UL/DL MAP carries information about sub-channel allocation and other control information for the UL and DL sub-frames.

When transmitting MAP information BTS uses fixed coding and modulation (QPSK ½ with repetition factor of 4), unlike during traffic transmission when adaptive coding and modulation mechanism is employed.

Table 10 Link Budget for Mobile WiMAX.

Transmitter	MAP	DL Traffic	UL Traffic	Units
Tx Power per Antenna Element	36	36	27	dBm
Number of Tx Antenna Elements	2*	2	1	
TX Feeder Loss	0.5	0.5	0.1	dB
Tx Antenna Gain	15	15	5	dBi
EIRP	53.5	53.5	31.9	dBm
Available Sub-Carriers	840	840	840	
Allocated Sub-Channels	30.0	30.0	2	
Allocated Sub-Carriers	840.0	840.0	48	
Power per Occupied Sub-Carrier	24.3	24.3	15.1	dBm
Receiver				
Rx Antenna Gain	5	5	15	dBi
Rx Feeder Loss	0.1	0.1	0.5	dB
Diversity Gain	5	6	5	dB
HARQ Gain	0	3	3	dB
Rx Noise Figure	5	5	4	dB
Margins				
Log Normal Fade Margin	6.5	6.5	6.5	dB
Interference Margin	3	3	3	dB
Penetration Loss	15	15	15	dB
Total Margin	**24.5**	**24.5**	**24.5**	**dB**
RX Sensitivity				
Thermal Noise	-174	-174	-174	dBm/Hz
Sub-Carrier Spacing	10.94	10.94	10.94	Hz
Modulation	**QPSK 1/8**	**QPSK 1/2**	**QPSK 1/2**	
SNR Required	4	10	10	dB
Rx Sensitivity (per sub-carrier)	-124.6	-118.6	-119.6	dBm
Rx Sensitivity (composite)	-95.4	-89.4	-102.8	dBm
System gain	**158.8**	**156.8**	**157.2**	**dB**
Maximum Allowable Path Loss	**134.3**	**132.3**	**132.7**	**dB**

* Assumes cyclic delay diversity (CDD) is implemented.

The following explains some of the key measures in the link budget calculations shown in Table 10:

Effective Isotropic Radiated Power (EiRP): The radiated power in dBm referenced to an isotropic radiator. EiRP is the sum of the transmitter mean power, the losses in the feeder cable and the antenna gain.

For the downlink, we note that placing the radio close to the antenna eliminates much of the feeder cable losses. This is one key advantage of all-outdoor, zero-footprint base stations as well as base stations implementing split baseband-RF design with a remote radio module. The benefit, in addition to eliminating feeder cable losses include using lower power radios (since most feeder cable losses have been eliminated), cutting down on power consumption by using convection cooled radios, savings on space as the radios are much smaller in size and weight. This allows for a versatile compact design suited for quick network roll out.

Sub-carriers and sub-channels: Total number of subcarriers and number of sub-carriers per sub-channel is function of FFT size and hence the bandwidth used for a particular deployment. Mobile WiMAX implements "uplink sub-channelization" which allows the user to transmit over a limited number of sub-carriers (48) thereby boosting the transmit power as the power spectral density is focused on a limited set of sub-carriers.

Diversity gain: Diversity schemes are used to take advantage of multi-path that occurs when system operates in non-LOS conditions. Mobile WiMAX base station offers diversity in both the transmitter and receiver. Mobile WiMAX transmit diversity option uses space time coding (STC) for traffic data transmission. For receive diversity, maximum ratio combining (MRC) takes advantage of two separate receive chains to help overcome fading and reduce path loss. Both of these diversity techniques reduces the fade margin requirement and this is captured in link budget calculation throughout diversity gain number.

HARQ Gain: HARQ is an advanced retransmission strategy, which in the case of packet error allows retransmissions directly at physical/MAC layer. This provides additional gain and reduces SNR requirements.

Fade Margin: The amount of fade margin *s* added to the path loss is determined based on the desired 'area reliability' parameter. The area reliability parameter represents the confidence interval for service in the coverage area of the cell. The fade margin is determined from the inverse of the normal cumulative distribution function for a contour confidence interval that corresponds to the selected area reliability factor. Table 11 shows the translation between contour and area reliability.

Table 11 Contour to area reliability translation.

Area Reliability	Contour Reliability	
	Category A & B	Category C
95%	86%	85%
90%	75%	73%
85%	65%	63%
80%	56%	54%

Receiver Sensitivity per sub-carrier: Receiver sensitivity per sub-carrier is calculated as

$$N_T + NF + SNR_{Rx} + 10\log(\text{Sub-Carrier Spacing}) \qquad (1)$$

where,

N_T is the thermal noise density (-174 dB/Hz)

SNR_{Rx} is the receiver signal to noise ratio as per Table 12, which are based on SISO modem performance in ITU Pedestrian B channel and for BER of 10^{-3}.

NF is the noise figure of the receiver which is taken to be 5 dB.

Sub-Carrier Spacing is function of BW and FFT size.

Composite Receiver Sensitivity: Composite receiver sensitivity is calculated as

Rss = Receiver Sensitivity per sub-carrier + 10log(Allocated Sub-Carriers) (2)

Table 12 SNR Requirements for BER of 10^{-3} with CTC in Pedestrian B channel.

Modulation	Code Rate	Repetition	SNR (dB)
QPSK	1/2	6	0.2
QPSK	1/2	4	2.0
QPSK	1/2	2	5.0
QPSK	1/2	1	8.0
QPSK	3/4	1	14.0
16QAM	1/2	1	15.0
16QAM	3/4	1	22.0
64QAM	2/3	1	28.0
64QAM	3/4	1	30.0

System Gain: System gain is given by the following equation

System Gain = $EiRP - R_{SS} + G_{Rx}$ (3)

where G_{Rx} is any additional gain and loss on the receiver path such as antenna gain, cable loss, diversity gain (STC, MRC) and hybrid ARQ gain. System gain is a key metric that shows the ability of a system to overcome path loss. Both base station and mobile station parameters impact the system gain. Hence, when comparing one system gain to another, it is important to base the comparison on similar scenarios (e.g. mobile handsets, desktop laptops, similar modulation schemes, etc.).

Maximum Allowable Path Loss (*MAPL*): The system gain is adjusted for the shadow as well as for other parameters such as the wall penetration loss, subscriber height adjustment and interference margin resulting from the particular reuse plan for the network. The coverage radius of a cell is calculated based on this figure. To ensure a balanced path, the lower of the downlink and uplink path loss is used to arrive at a final figure for the coverage radius.

Erceg Path Loss Model

Using a propagation path loss model we can estimate the coverage area and range for WiMAX. This is shown in Table 13 suing the Erceg path loss model which is commonly used in broadband fixed wireless access applications.

Table 13 Cell coverage for Mobile WiMAX system.

Minimum Cell Radius (km)	1.35
MAP Cell Radius (km)	1.5
Downlink Cell Radius (km)	1.35
Uplink Cell Radius (km)	1.4

The Erceg model is used to determine the distance according to the maximum allowable path loss calculated by the link budget. The median path loss is expressed by the following equation:

$$PL = A + 10\gamma log_{10}(d/d_0) + s \qquad (5)$$

where $A = 20log_{10}(4\pi d_0/\lambda)$ (λ being the wavelength in m), γ is the path-loss exponent with $\gamma = (a - bh_b + c/h_b)$ for h_b between 10 m and 80 m (h_b is the height of the base station in m), d_0 = 100m and a, b, c are constants dependent on the terrain category shown in Table 14.

Table 14 Erceg propagation model parameters.

Terrain Type	Category A	Category B	Category C
Description	Hilly terrain with moderate to heavy tree density	Hilly terrain with light tree density or flay terrain with moderate to heavy tree density	Flat terrain with light tree density
A	4.6	4	3.6
B	0.0075	0.0065	0.005
C	12.6	17.1	20
m_s	10.6	9.6	8.2
s_s	2.3	3	1.6

The shadow fading, s, follows a normal distribution with a mean standard distribution (μ_s) between 8.2 and 10.6 dB and standard deviation (σ_s) between 1.6 and 2.3.

The path loss model is based on data collected at frequencies close to 2 GHz for a receiver antenna at 2 m above ground. In order to use other frequencies and subscriber station height, corrections are applied to the model:

$$PL_{modified} = PL + \Delta PL_f + \Delta PL_h \qquad (6)$$

where PL is the path loss given above, ΔPL_f (in dB) is the frequency correction term given by

$$\Delta PL_f = 6\ log_{10}(f/1900) \qquad (7)$$

where f is the frequency in MHz, and ΔPL_h (in dB) is the receive antenna height correction term given by

$$\Delta PL_h = -10.8 log_{10}(h/2);\ \text{for Categories A and B} \qquad (8)$$

$$\Delta PL_h = -20\ log_{10}(h/2);\ \text{for Category C} \qquad (9)$$

where h is the receive antenna height between 2 m and 10 m.

5 Quality of Service in WiMAX Networks

To enable a wide variety of data services and applications, WiMAX is equipped with a number of mechanisms to ensure Quality of Service (QoS) over the wireless interface. This is done primarily at the Medium Access Control layer (MAC) which is responsible for ensuring QoS over the wireless interface. However, a holistic view of a WiMAX network comprises a greater scope than the wireless interface to include the backbone network elements (e.g. routers, switches and gateways) responsible for providing user demanded services (e.g. voice, video, gaming, etc.).

As a broadband wireless access network, WiMAX has been designed to accommodate different types of services such as voice, video and data. Each of these services has their own requirements in terms of performance. These performance metrics can be summarized into the following four parameters:

- Throughput: indicates the requirements of the services in terms of bandwidth measures in bits/second.
- Latency: indicates the delay time for the information to travel from source to destination.
- Jitter: indicates the variations in latency.
- Loss: indicates the percentage of packet loss the service can tolerate.

The air interface in a wireless networks presents a particular challenge to ensuring quality of service. This is because the propagation channel changes continuously thereby introducing impairments onto the wireless signal. The physical layer of WiMAX implements a number of techniques to correct for these errors such as convolutional turbo codes. Furthermore, WiMAX implements repetitive transmission techniques such as Hybrid-ARQ (Automatic Repeat Request) to further improve the robustness of the air link. The focus here is, however, on higher-level network aspects of ensuring quality of service.

WiMAX Medium Access Control Layer – A QoS Perspective

The WiMAX MAC is the interface between higher layers of network protocols (e.g. IP) and the physical layer which is responsible to transmitting data over the wireless interface. The MAC can be divided into three sublayers: Convergence Sublayer (CS), Common Parts Sublayer (CPS) and Security Sublayer as shown in Figure 10. Of the three, we will expand on the Convergence (classification) and Common Parts Sublayers (scheduling) as they have most impact on ensuring QoS over the WiMAX network.

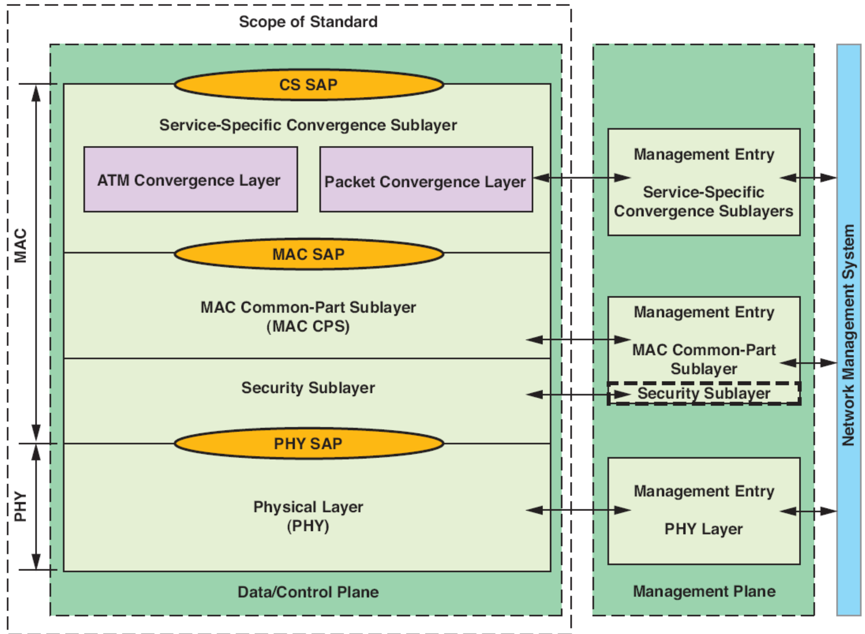


Figure 10 802.16 protocol stack.

Connections and Service Flows

The WiMAX MAC is connection-based where all services and traffic (even connection-less traffic) are mapped to a connection. Each logical connection between the peer MAC layer of the base station and the subscriber station is identified by a 16-bit unidirectional identifier (Connection ID - CID). The CID is unique for a given Base Station/Subscriber Station pairing and changes when a Subscriber Station moves from one base station to another. The CID is used to identify all information exchanged between the base station and subscriber station after the initial registration and authentication. This reduces overhead associated with using the longer MAC address (48 bits) for identification and allows traffic differentiation. There are also two types of connections: transport (data) and management.

Another important concept of the WiMAX MAC is that of a service flow which defines a connection through a set of QoS parameters. A 32-bit service flow ID (SFID) is mapped to a unique CID and the base station maintains the association between the two identifiers. Multiple service flows per subscriber station are possible. The SFID remains constant as the Subscriber Station moves between Base Stations, but may not necessarily stay constant if the base stations belong to different ASN gateways. Service flows in both the UL and DL direction may exist without actually being activated to carry traffic; however, a CID corresponds to an active flow.

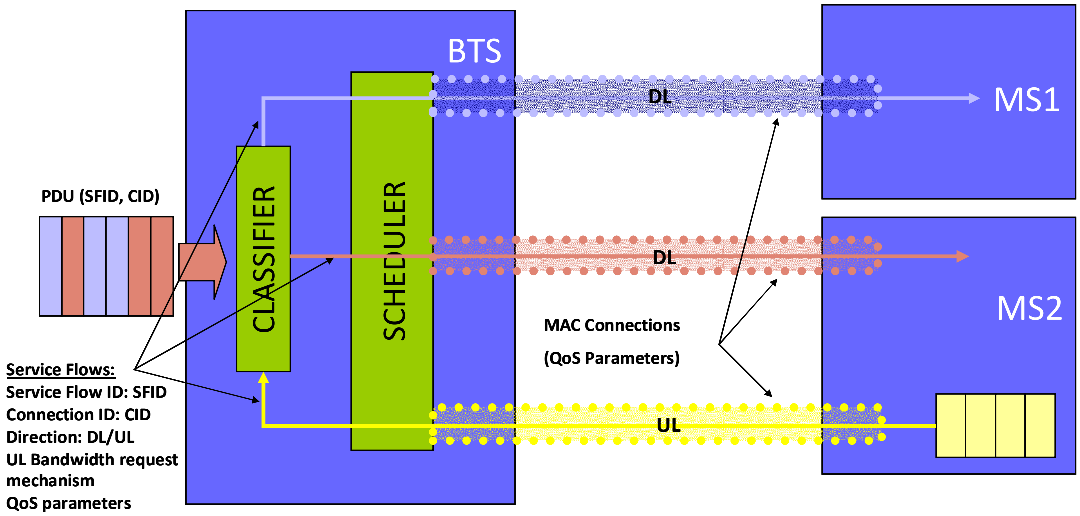


Figure 11 Mobile WiMAX QoS support.

Each Subscriber Station has a unique 48 bit MAC address. In addition to the MAC address, a Network Access Identifier (NAI) identifies a particular user subscription. The NAI is used as a user identifier for interactions between the ASN gateway and AAA servers and between ASN gateway and Home Agents. The ASN gateway maintains the mapping between NAI and MAC address (Profile C).

Three management connections are assigned in each direction (uplink/downlink) upon network entry, each with a different QoS requirement.

- Basic: used for short, time critical messaging (MAC & radio control).
- Primary: used for longer, more delay tolerant messages (authentication & connection setup)
- Secondary: used to transfer standards-based management messages (DHCP, TFTP, SNMP).

MAC Convergence Sublayer

The convergence sublayer is akin to an adaptation layer that separates the higher level network protocols from the rest of the WiMAX MAC and physical layers. Incoming packets at the base station from the core network (know as Service Data Units – SDU) are classified (i.e. mapped) to connections between MAC peers at the base station and subscriber station according to a set of rules (e.g. source or destination IP address, ToS/ DCSP code point, etc.). Classification creates the association to a service flow where a set of parameters are defined to ensure QoS. The convergence sublayer is also responsible for other operations such as packet header suppression and reconstruction.

Several convergence sublayers are specified in the IEEE standard, but Mobile WiMAX has adopted the IP CS as standard with Ethernet CS being optional.

MAC Common Parts Sublayer

The classified SDUs arrive at the MAC CPS where they are assembled into Packet Data Units (PDU) which is the basic payload unit of the WiMAX MAC. Several SDUs may be packed into a single PDU or alternatively, a single SDU is fragmented into several PDUs. The MAC CPS at the receiver does the opposite operation to extract the SDUs which are delivered to the higher layers.

The MAC PDUs are then scheduled for transmission over the air interface which is done sequentially in time. The scheduler is responsible for determining the priority of PDU transmission and for allocating bandwidth to different communication streams between the base station and the subscribers it serves. It also instructs the subscriber stations of their allocated transmission time and bandwidth. The function of the scheduler becomes more complex as the quality of the propagation channel changes continuously resulting in intervals of good and poor transmission opportunities to each subscriber.

There are two methods to allocate bandwidth to the subscriber station. The first is Grant Per Connection (GPC) where, as the name implies, bandwidth is granted by the base station to the SS on a connection by connection basis explicitly. The subscriber station transmits in the order specified by the base station. The second is Grant Per Subscriber Station where granted bandwidth by the base station is aggregated into a single grant to the subscriber station to accommodate all the connections at the SS. The Scheduler in the SS then allocates the granted bandwidth to the different connections. This allows more flexibility in the system since the SS has the ability to change bandwidth allocation between connections to account for changes in the QoS situation since the last bandwidth request was made. (Example: if the QoS situation at the SS has changed since the last request, the SS has the option of sending the higher QoS data along with a request to replace this bandwidth stolen from a lower QoS connection. The SS could also use some of the bandwidth to react more quickly to changing environmental conditions.)

GPC is a simpler technique to grant bandwidth but is less efficient and scalable than GPSS (particularly where there is more than one connection per SS). GPC leads to multiple entries in the UL-MAP message creating higher overhead whenever a subscriber with multiple connections is polled or granted transmission opportunities. GPSS is scalable to a higher number of subscriber stations and connections. GPSS allows the subscriber station to react quicker to the status of the physical layer and the requirements of the connection and applications running on the SS. This enhances system performance.

WiMAX uses a self correcting protocol as opposed to an acknowledged protocol which increases efficiency and decreases delay. In case a bandwidth requested by a SS is not granted, the SS will initiate another request after a time-out period. The bandwidth request is incremental where the SS asks for more bandwidth for a connection.

The subscriber uses the Range Request (RNG-REQ) message to request a change in the downlink burst profile. Another message is the Downlink Burst Profile Change Request (DBPC-REQ). The Downlink Burst Profile Change Response (DBPC-RSP) message confirms or denies the change.

Because the quality of the propagation channel changes continuously, messages between the base station and subscriber station may be lost. This requires different order of burst profile change when transitioning from to a more robust profile than when transitioning to a less robust one.

Scheduling Services

A scheduling service is used to determine the mechanism to allocate transmission opportunity for MAC PDUs. Mobile WiMAX defines five scheduling services as summarized in Table 15:

1. Unsolicited Grant Service (UGS) offers fixed-size grants on a real-time periodic basis and does not need the subscriber station to explicitly request bandwidth. This eliminates the overhead and latency associated with bandwidth request. UGS is appropriate for real-time service flows that generate fixed-size data packets on a periodic basis, such as T1/E1.

2. Real-time Polling Services (rtPS) is designed to support real-time services that generate variable-size data packets on a periodic basis, such as MPEG (Motion Pictures Experts Group) video. In this service class, the base station provides unicast polling opportunities for the subscriber station to request bandwidth. The unicast polling opportunities are frequent enough to ensure that latency requirements of real-time services are met. This service requires more request overhead than UGS does but is more efficient for service that generates variable-size data packets or has a duty cycle less than 100 percent.

Table 15 Scheduling services in Mobile WiMAX.

QoS Class	Applications	Mandatory QoS Parameters
UGS Unsolicited Grant Service	E1/T1, VoIP (without silence suppression)	• Maximum Sustained Traffic Rate (= minimum reserved traffic rate) • Maximum Latency Tolerance • Jitter Tolerance
rtPS Real-Time Packet Service	Streaming Audio or Video (e.g. MPEG)	• Minimum Reserved Traffic Rate • Maximum Sustained Traffic Rate • Maximum Latency Tolerance • Traffic Priority
ertPS Extended Real-Time Packet Service	Voice with Activity Detection (VoIP)	• Minimum Reserved Traffic Rate • Maximum Sustained Traffic Rate • Maximum Latency Tolerance • Jitter Tolerance • Traffic Priority
nrtPS Non-Real-Time Packet Service	File Transfer Protocol (FTP)	• Minimum Reserved Traffic Rate • Maximum Sustained Traffic Rate • Traffic Priority
BE Best-Effort Service	Data Transfer, Web Browsing, etc.	• Maximum Sustained Traffic Rate • Traffic Priority

3. Non-real-time Polling Services (nrtPS) is very similar to rtPS except that the subscriber station can also use contention-based polling in the uplink to request bandwidth. In nrtPS, it is allowable to have unicast polling opportunities, but the average duration between two such opportunities is in the order of few seconds, which is large compared to rtPS. All the subscriber stations belonging to the group can also request resources during the contention-based polling opportunity, which can often result in collisions and additional attempts.

4. Extended Real-time Polling Service (ertPS) is a new scheduling service introduced with the IEEE 802.16e standard and adopted in the Mobile WiMAX system profile. In this class, periodic UL allocations provided for a particular subscriber station can be used either for data transmission or for requesting additional bandwidth. This feature allows ertPS to accommodate data services whose bandwidth requirements change with time such as VoIP with activity detection (silence suppression).

5. Best-effort Service (BE) provides very little QoS support and is applicable only for services that do not have strict QoS requirements. Data is sent whenever resources are available and not required by any other scheduling-service classes. The subscriber station uses only the contention-based polling opportunity to request bandwidth.

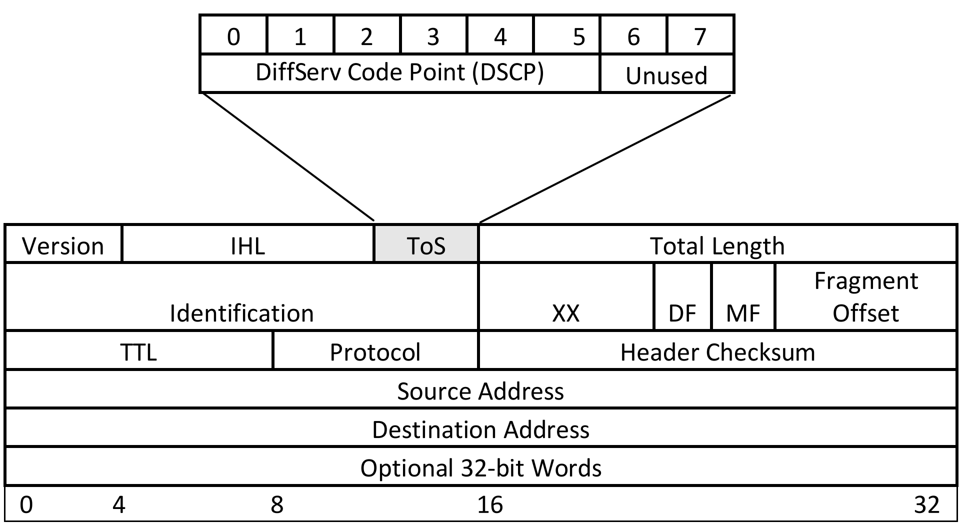
End-to-End Quality of Service

End-to-end Quality of Service is available with WiMAX access network using the IEEE and IETF standards. The WiMAX network follows the IEEE 802.16 standard that specifies five scheduling service classes which facilitate priority access to the wireless medium. These scheduling classes are mapped into the IETF’s Diffserv (Differentiated Services) Expedited Forwarding (EF) and Assured Forwarding (AF) classes.

Diffserv makes use of the IPv4 Type of Service (TOS) field (and the equivalent IPv6 Traffic Class field) to specify the Differentiated Services Code Point (DCSP). Each DSCP is mapped to a particular forwarding type, known as Per-Hop Behavior (PHB), according to the policy set for the network. Diffserv defines two types of PHB: expedited forwarding (EF) and assured forwarding (AF).

Table 16 Differentiated services code point.

ToS	P2	P1	P0	T3	T2	T1	T0	Zero
DS	DS5	DS4	DS3	DS2	D1	DS0	ECN1	ECN0
Octet	Class Selector			Drop Precedence				



Expedited forwarding PHB can be used to build a low-loss, low-latency, low-jitter, assured bandwidth, end-to-end service through Differential Service domains. Such a service appears to the endpoints like a point-to-point connection or a “virtual circuit”. EF is provided by ensuring that queuing delays at each transit node are removed. This is done by assigning to a given traffic stream a minimum departure rate from each transit node that is greater than the pre-agreed maximum arrival rate.

Assured forwarding PHB is a service in which packets from a given source are forwarded with a given probability, provided that the traffic from that source does not exceed some pre-agreed maximum. There are four AF classes. Each class is allocated a certain amount of forwarding resources (buffer space and bandwidth) in each transit node. Within each AF class, IP packets are marked with one of three possible drop precedence values. In case of congestion, the drop precedence of a packet determines the relative importance of the packet within the class. A congested transit node tries to protect packets with a lower drop precedence value from being lost by preferably discarding packets with a higher drop precedence value.

IP QoS flows are simply mapped to an appropriate DiffServ per-hop behavior (PHB) over the flash-OFDMA air link.

6 WiMAX Usage Scenarios and Applications

WiMAX Usage Scenarios

WiMAX is suited to support a large number of usage scenarios based on its technical features and commercial cost points. These scenarios and their key requirements are shown in Table 17.

Table 17 WiMAX Usage Scenarios.

Usage Scenario	Flexible Architecture	High Security	WiMAX QoS	Quick Deployment	Multi-Level Service	Interoperability	Portability	Mobility	Cost-Effective	Wider Coverage	NLOS	High Capacity
Banking Networks	✓	✓	✓						✓		✓	
Education Networks	✓		✓						✓	✓		
Public Safety	✓	✓	✓	✓			✓	✓			✓	
Offshore Communications	✓		✓				✓	✓		✓	✓	
Campus Connectivity	✓	✓	✓									✓
Temporary Construction			✓	✓			✓				✓	
Theme Parks	✓		✓				✓	✓			✓	
WSP Access Network		✓	✓		✓	✓			✓		✓	✓
Rural Connectivity			✓			✓			✓	✓		
Military Applications	✓	✓		✓			✓	✓				

Private Networks

Private networks are used exclusively by a single organization, institution or business to offer dedicated communication links for voice, data and video applications. Private networks generally need to be quick and easy to install.

Banking Networks

Large banks can connect branches and ATM (Automated Teller Machine) sites to their regional office through a private WiMAX network carrying voice, data and video traffic. Banks typically require high security and bandwidth to handle the traffic load. WiMAX data encryption offers over-the-air link security, however, banks will most likely also need end-to-end security, such as that provided by SSL or IPSec, to protect against interception and manipulation of sensitive banking data.

WiMAX networks also offer a high degree of scalability, so that low-data-rate traffic between the regional office and ATM machines can co-exist with the high levels of traffic needed to support branch-to-regional office communications. This is made possible by the WiMAX QoS, which is used to prioritize voice (telephony among branches), data (financial transactions, email, Internet, and intranet) and video (surveillance, CCTV) traffic.

Education Networks

School boards can use WiMAX networks to connect schools and school board offices within a district. Some of the key requirements for a school system are NLOS, high bandwidth (>15 Mbps), Point-to-Point and Point-to-Multipoint capability, and a large coverage footprint. WiMAX-based education networks, using QoS, can deliver the full range of communication requirements, including telephony voice, operating data (such as student records), email, Internet and intranet access (data), and distance education (video) between the school board office and all of the schools in the school district, and between the schools themselves.

The WiMAX solution provides broad coverage, making it very cost-effective, particularly for rural schools, which may have little or no communications infrastructure, and which are widely dispersed.

Public Safety

Government public safety agencies, such as police, fire, and search and rescue, can use WiMAX networks to support response to medical and other emergency situations. In addition to providing two-way voice communications between the dispatch center and on-site emergency response teams, the network relays video images and data from the site of the accident or disaster to the control center. This data can be relayed to expert teams of medical or emergency staff, who can analyze the situation in real-time, as if they were on site.

WiMAX QoS allows the network to handle these diverse types of traffic. WiMAX solutions are highly deployable, so the initial response team can set up a temporary wireless network at the site of the accident, event, or natural disaster, in a matter of minutes. They can also relay traffic from this network back to a control or dispatch center, over an existing WiMAX network.

As well, there may be a requirement for mobility, such as, for example, a policeman having to access a database from a moving vehicle, or a fireman having to download information about the best route to a fire scene or the architecture of the building on fire. A video camera in the ambulance can offer advance information about the condition of a patient, before the ambulance reaches the hospital.

Offshore Communications

Oil and gas producers can use WiMAX equipment to provide communication links from and-based facilities to oilrigs and platforms, to support remote operations, security, and basic communications. Remote operations include remote troubleshooting of complex equipment problems, site monitoring, and database access. For example, video clips of malfunctioning components or subassemblies can be transmitted to a land-based team of experts for analysis. Security includes alarm monitoring and video surveillance. Basic communications includes voice telephony, email, Internet access, and video conferencing.

Campus Connectivity

Government agencies, large enterprises, industrial campuses, transportation hubs, universities, and colleges, can use WiMAX networks to connect multiple locations, sites and offices within their campus. Campus systems require high data capacity, low latency, a large coverage footprint, and high security. Like other usage scenarios, campus networks carry a mix of voice, data, and video, which the WiMAX QoS helps prioritize and optimize.

Temporary Construction Communications

Construction companies can use WiMAX networks to establish communication links between the company head office, construction sites, offices of other project participants, such as architectural and engineering firms, and storage facilities. The fast deployment of WiMAX networks is also important in this scenario, since it allows for quick provision of communications to the construction site, including voice (telephony) and data (emails, engineering drawings, and Internet access). Surveillance video can also be carried over the network, to support monitoring of the site or areas of the site that are otherwise difficult to access. A local Hotspot can also be set up at the construction site, allowing personnel at the site to communicate and exchange data and schedule information.

Like the other usage scenarios, the WiMAX built-in QoS will prioritize network traffic and optimize the communications channel. Construction sites include, but are not limited to, office buildings, residential land development, and oil and gas facilities.

Theme Parks

Theme park operators can use WiMAX to deliver a broad range of communication services for their amusement parks, expositions, hospitality and operation centers, and buses and service vehicles. The above network can support a wide range of communications traffic, including two-way dispatch from a control center, video surveillance throughout the park, reservation data, inventory database access and update, site status monitoring, video on demand, and voice telephony. Some of the key requirements for a system like this are support for fixed and mobile operations, high security, scalable architecture and low latency.

WiMAX mobility capability will support two-way voice and data communications to the theme park's tour buses and service vehicles. Real-time video can be broadcast to tour buses, providing tourist information, promotions, and weather to passengers.

Public Networks

In public network, resources are accessed and shared by different users, including both businesses and private individuals. Public networks generally require a cost-effective means of providing ubiquitous coverage, since the location of the users is neither predictable nor fixed. The main applications of public networks are voice and data communication, although video communication is becoming increasingly popular. Security is a critical requirement, since many users share the network. A few usage scenarios involving public networks are shown below.

Wireless Service Provider Access Network

Wireless Service Providers (WSPs) use WiMAX networks to provide connectivity to both residential (voice, data and video) and business (primarily voice and Internet) customers. The WSP could be a CLEC (Competitive Local Exchange Carriers) that is starting its business with little or no installed infrastructure. Since WiMAX is easy to deploy, the CLEC can quickly install its network and be in position to compete with the ILEC (Incumbent Local Exchange Carrier). The WiMAX built-in QoS mechanism is highly suited for the mix of traffic carried by the CLEC. The QoS MAC also offers multi-level service to address the variety of customer service needs. A common network platform, offering voice, data and video, is highly attractive to end customers, because it presents a one-stop shop and a single monthly bill. Support for multiple service types allows for different revenue streams, yet it reduces customer acquisition cost, and increases ARPU (Average Revenue per User). The WSP needs only one billing system and one customer database.

Rural Connectivity

Service providers use WiMAX networks to deliver service to underserved markets in rural areas and the suburban outskirts of cities. The delivery of rural connectivity is critical in many developing countries and underserved areas of developed countries, where little or no infrastructure is available.

Rural connectivity delivers much-needed voice telephony and Internet service. Since the WiMAX solution provides extended coverage, it is a much more cost-effective solution than wired technology in areas with lower population densities.

Application Requirements

The availability of different classes of scheduling services in WiMAX enables multiple services and applications. This is a key advantage of WiMAX (and 4G technologies) over current 3G wireless technologies.

Applications can be characterized according to key requirements for throughput, delay, jitter, and information loss. Table 18 shows such classifications of applications over five different "Services Classes." This helps in the future planning of WiMAX networks to ensure that the offered applications are properly supported.

Table 18 Application QoS Requirements.

Service Class	Service Class	Application Layer Throughput	End-to-End Transport Layer One-Way Delay	End-to-End Transport Layer One-Way Delay Variation	Transport Layer Information Loss Rate
1	Real-time Games	50-85 Kbps	< 60 ms preferred	< 30 ms preferred	< 3%
2	Conversational (e.g., VoIP and Video Phone)	4-384 Kbps	< 60 ms preferred < 200 ms limit	< 20 msec	< 1%
3	Real-time Streaming (e.g., IPTV, Video Clips and Live Music)	>384 Kbps	< 60 ms preferred	< 20 ms preferred	< 0.5%
4	Interactive Applications (e.g., Web Browsing and Email Server Access, IM)	>384 Kbps	< 90 ms preferred	N/A	Zero*
5	Non-Real-time Download (e.g., Bulk Data, Movie Download and P2P)	>384 Kbps	< 90 ms preferred	N/A	Zero*

**Represents loss rate after retransmissions (i.e. post-TCP)*

About Telesystem Innovations Inc.

Telesystem Innovations is a management and technical consulting firm providing expert strategic advice on 4G wireless technologies (LTE, WiMAX) including technology evaluation; spectrum pricing; business plan and financial modeling; and product and technology roadmap. Our clients include major network operators, original equipment manufacturers/system vendors and venture capital firms.

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