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WiMAX: IEEE 802.16

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ABSTRACT

This thesis is related with the WiMAX (World Interoperability Microwave Access) technology and the standard elaborated by the Institute of Electrical and Electronic Engineers (IEEE) under the 802.16 family of standards.

Nowadays, the demand of broadband access is growing exponentially every year. Users demand a good-quality connection at anytime in everywhere, whereas countries look for an economic, fast-to-deploy and high performance broadband technology to provide access to every region. WiMAX can be a solution to this problem thanks to its technical advantages such as large coverage and low-cost, as for the strong support of the industry through the WiMAX Forum. In addition to, the Mobile WiMAX version can give the full mobility of cellular services at higher broadband speeds than other technologies such as Wi-Fi.

In this thesis, after a brief introduction about the broadband wireless technologies and the different IEEE 802.16 standards, an accurately explanation of WiMAX and its technical aspects is included. At the end, it is possible to examine the different applications implemented with WiMAX and a brief comparison with other wireless technologies.

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1. INTRODUCTION TO BROADBAND WIRELESS

The demand of broadband services is growing exponentially in the last years. There are several wired technologies that provide us a high-speed broadband access such as Digital Subscriber Line (DSL) over twisted-pair telephone or cable over fiber optics. The main problem of these wired access technologies is the difficulty and high cost of installation and maintenance, especially in remote and rural areas.

In the last years, Internet has developed from being only an academic tool to having hundreds of millions of users around the world. Besides, the demand of a high-speed connection has caused a huge development of the broadband technologies.

As Broadband Access, wireless mobile services have grown considerably in the last years, from 11 millions of subscribers worldwide in 1990 to more than 2 billion in 2005. This increase is due to the use of laptops, mobiles and PDAs. There is no doubt that at the end of the first decade of the 21st century, high-speed wireless data access will be largely deployed worldwide.

The main reason for the development of WiMAX ("World Interoperability Microwave Access") is the demand of higher data rates not only for faster downloading but also for the use of new applications like voice over Internet Protocol (VoIP), video streaming, multimedia conferencing, and interactive gaming. WiMAX will revolutionize broadband communications in developed countries and will allow the developing countries to be communicated to. With this technology the users will be able to have access to broadband networks anywhere and anytime. There are some competitive technologies such as third generation of mobile communications (3G) or HSPA but nowadays they only can provide high-data rates in small areas of coverage and under some specific conditions.

Two very different families of WiMAX systems exist and should be treated separately: Fixed and Mobile WiMAX.

1.1-EVOLUTION OF BROADBAND WIRELESS

Due to the development of telecom industry and the huge growth of Internet, the carriers were researching to find a new wireless technology to reach the new requirements. The evolution of WiMAX technology can be structured in four stages:

1) Narrowband wireless local-loop systems (WLL)
2) First-generation line-of-sight (NLOS)
3) Second-generation non-line-of-sight (NLOS)
4) Standards-based broadband wireless systems

1.1.1-Narrowband wireless local-loop systems (WLL)

The first use was obviously voice telephony; it was successful in developing countries as well as in rural regions in developed countries where the wired technology is not widely deployed and its deployment can be quite expensive.

The European Telecommunications Standards Institute (ETSI) published a WLL cordless system in 1992 named DECT (Digital Enhanced Cordless Telecommunications). The range of DECT equipments is up to a few hundred meters. DECT works in the 1.9 GHz bandwidth. This system uses digital TDMA (Time Division Multiple Access) and it has a great success nowadays.

In markets with a robust local-loop infrastructure installed, WLL had to offer more than voice telephony, so operators found an opportunity with the commercialization of Internet access services providing high-speed Internet access. In 1997, AT&T developed a wireless access system for the 1,900 MHz PCS (personal communications services) offering two voice lines and a 128 kbps data connection. This system was called “Project Angel”.

At the same time, other companies started to offer wireless Internet access using the license-exempt 900MHz and 2,4Ghz bands reaching speeds up to a few hundreds of kilobits. These connections required the installation of antennas on the rooftops.

1.1.2- First-generation line-of-sight (LOS)

The development of DSL and cable modems caused the evolution of wireless systems for supporting higher speeds to be competitive. Local Multipoint Distribution System (LMDS) started to be deployed using high frequency bands (24GHz and 39GHz) supporting several hundreds of megabits per second.

At the end of 1990s, multichannel multipoint distribution services (MMDS) began to be deployed using the 2, 5 GHz band that was used for the cable TV broadcasting in rural regions where cable TV was not available. Some operators started to offer one-way Internet access using the telephone line as the return path. In 1998, FCC regulated this band allowing two-ways communication.

This first generation with LOS coverage was deployed using the towers installed for wireless cable services. It was necessary to install antennas that were high enough and pointed towards the tower.

1.1.3- Second-generation Broadband Systems

This second generation solved the LOS problem and provided more capacity using a cellular architecture and techniques as Orthogonal Frequency Division Multiplexing (OFDM), Code Division Multiple Access (CDMA) and multiantenna processing. It was possible to reach speeds up to a few megabits per second.

1.1.4- Standard-based technology

The Institute of Electrical and Electronic Engineers (IEEE) formed a group in 1998 called 802.16. The aim of this group was develop a standard for the Wireless Metropolitan Area Network for regulating the 10GHz to 66GHz band.

From the first standard approved in December 2001 until now, several standards and amendments has been developed. All the standards and its corresponding features will be analyzed in the chapter 2.

It is important to know that 802.16 is only a collection of standards that includes a wide range of variations. The IEEE only developed the specifications but it is the industry and especially an industrial group (WiMAX Forum) who is in charge that has to convert it into an interoperable standard.

1.2.-FIXED BROADBAND WIRELESS

There are two different network topologies in fixed broadband wireless:

- Point-to-point applications include interbuilding communications within a campus and microwave backhaul.
- Point-to-multipoint is usually based in a base station mounted in a tower or in a building that communicates with the subscriber; the most common usages are:

1- Consumers and small business broadband:

The main usage of WiMAX in the near future is broadband services like high-speed Internet access, telephony over IP (VoIP) and a host of other Internet applications.

WiMAX presents some advantages over wired technologies like lower deployment costs, lower operational costs for the maintenance, faster realization and independence of the incumbent's carriers.

There are two types of deployment models, one of them requires the installation of an outdoor antenna at the costumer's building and the other one requires a all-in-one radio modem installed indoors. Using outdoor antenna improves the coverage and performance of the system; however it requires a truck-roll with a trained professional so it implies a higher cost in developed countries but in developing countries turns to be cheaper.

2- T1 services for business:

The other use of Fixed WiMAX is a solution for competitive T1, fractional T1 and higher-speed services for the business market. It will be successful due to the fact that not all the buildings have access to fiber and in business exists a demand of symmetrical T1 services that cable and DSL cannot reach.

3- Backhaul for Wi-Fi hotspots:

Wi-Fi hotspots are widely deployed in public areas in developed countries. The traditional solution is using wired broadband connections to connect the hotspots back to a network point. In this case, WiMAX can be a cheaper and faster alternative for WiFi backhaul and it can also be used for 3G backhaul.

WiMAX could be very successful in developing countries where a wired network is not installed. WiMAX will be a cheaper alternative to extend broadband access over the country.

1.3. - MOBILE BROADBAND WIRELESS

In a context where the users get familiarized with the use of high-speed broadband services, they will demand same services in nomadic or mobile situations. The first step is adding nomadic capabilities to fixed broadband connection, thus users can get connection moving within the service area with pedestrian-speed.

In the market, the cellular spectrum operating licenses are limited and very expensive so WiMAX could be a good opportunity to offer mobility services for some operators of fixed lines that do not offer mobile services. However, the existing mobile operators are more interested in the development of 3G than in adopting WiMAX.

WiMAX presents some important advantages that can be useful for its development such as the low latency that is fundamental for voice over IP services (VoIP). Other advantages are the flexible bandwidth and multiple levels of Quality of Services (QoS) that may allow the use of WiMAX for entertainment applications. Some examples of these applications could be interactive gaming, IP-TV and streaming audio services for MP3 players.

The main drawback is that the IEEE 802.16 standard only specifies an air interface so the core network has to be deployed.

1.4.-OTHER BROADBAND TECHNOLOGIES

There are several broadband wireless technologies which provide broadband wireless services, some of them are already being used and other are being developed. In this subchapter, we can see a brief mention of some of them, but in the subchapter 11 we will see a complete comparison between them.

Mobile operators are changing their networks to 3G technologies to deliver broadband applications to their subscribers. Mobile operators using GSM (global system for mobile communication) are deploying UMTS (Universal Mobile Telephone System) and HSDPA (High Speed Download Packet Access). Otherwise, CDMA operators are upgrading their networks to 1x EV-DO (1x evolution data optimized).

HSDPA is the downlink interface defined in the Third-generation Partnership Project (3GPP) and is capable of providing a peak user data rate of 14.4 Mbps in a 5MHz channel. The uplink interface defined by 3GPP is HSUPA (high-speed upload packet access) that supports peak data rates up to 5.8Mbps. HSDPA and HSUPA are

defined together as HSPA. 3GPP is developing the long-term evolution (LTE) of the standard that will be able to support a peak data rate of 100Mbps in the downlink and 50Mbps in the uplink.

In addition to 3G, Wi-Fi is another important providing system of broadband wireless and it has become the last-feet broadband connectivity at home, offices and public areas. Current Wi-Fi systems that are based in 802.11a/g standards support a typical throughput of 23/19 Mbps with an indoor coverage of about 35 meters. However, a new revision of the standard, 802.11n, support a throughput data-rate of 54 Mbps with coverage of about 70 meters using multiple-antenna spatial multiplexing.

WiMAX is a very flexible and scalable standard that may be adapted to different frequency bands. The standard is torn in two different goals. On the one hand, if the frequency and bandwidth are limited, the compatibility and development will be easier. On the other hand, the frequency and the bandwidth are standardized in different profiles and this flexibility allows the use of this technology in countries with different spectrum availability and regulations.

2.-WiMAX

2.1.-IEEE 802.16 STANDARDS

As mentioned in 1.1.4, WiMAX is not a standard, it is only a marketing trend trademarked by WiMAX Forum to describe the IEEE 802.16 based technology. WiMAX standard refers to a set of capabilities that are likely to experience widespread implementation.

In its short live, WiMAX has evolved from the market and technological perspective. The original IEEE 802.16 specification was to provide a high-data rate, point to point communication and with LOS (Line of Sight) conditions between fixed locations. This application was created to provide wireless bridging between fixed locations within the network infrastructure. The typical example of this usage is a tower that is wirelessly backhauled to a fixed location which is attached to a larger wired network.

After its first usage, the scope was expanded to offer direct support of end-user networks interconnecting end-users with network infrastructure. WiMAX can offer high-data rate over long distances so it is an adequate technology to solve the problem space of the Internet Service Provider (ISP) in wireless local loop where low-rate wired infrastructure often limits the capabilities of the connection for the costumers. This technology is explained in the standard IEEE 802.16a and in the IEEE 802.16d (or also 802.16-2004) which unified the original 802.16 and 802.16a. Although there are already other technologies in the market for solving this problem space, WiMAX can be very successful in regions without a good wired infrastructure like in developing regions or in rural regions in developed countries.

The big evolution of the WiMAX usage was to provide mobility support. WiMAX is the air-interface for the actual radio interface network, where both fixed and mobile users can have access to the network. The basis of mobile WiMAX is explained in the IEEE 802.16e (or 802.16-2005) standard.

In this context, existing incumbent Wireless Service Providers (WSP) in the market have invested big amounts of money to reach the current level of capabilities so now they will not adopt easily a new entry technology but it may be a good solution to a new-entry WSPs to offer wireless services. However, for a new WSP it would not be easy due to the high cost of the spectrum (to operate in licensed bands), of the infrastructure and the difficulty to reach the economy of scale required for driving down the equipment and service costs to a competitive level.

One advantage of this standard is the possibility to offer services in unlicensed frequency bands but the problem is that WiMAX Forum has no certification profiles for unlicensed (5.8 GHz) Mobile WiMAX. Other problems for the expansion are the lack of a kill-app for mobile usage and the evolution of other technologies such as HSDP (High Speed Download Packet Access).

The lack of a "killer app" that gives completely mobile data networking supposes a drawback for the development. In the market, there is an important demand of nomadic mobility services that allows moving from one place to another without losing the connection at pedestrian velocity. However it is not sure that the connection on motion at vehicular velocity would be successful for the costumers. It would be able to be useful in military networks and in some public transport scenarios like trains in order to provide network access to travelers.

The standards only specify the physical layer (PHY) and the media access control (MAC) of the air interface while the upper layers are not specified and the CN (Core Network) is not specified and has to be deployed and maintained. Bellow, one can find explained some characteristics of the different standards:

Most important standards:

IEEE 802.16 (Fixed SSs)

- Published in April 2002
- **Network Topology:** Point-to- fixed point (PTP) backhaul (dedicated link with only two nodes: BS and SS)
- **Frequency bands**: 10-66 GHz (licensed band but it is high frequency so there is less interference and more bandwidth available)
- **Modulation**: Single Carrier
- **Modulation schemes:** It uses Adaptive Modulation so the physical layer (PHY) can employ the following modulation schemes: QPSK, 16-QAM or 64-QAM modulation adaptively changing on the basis of channel conditions
- **Propagation conditions:** LOS(Line of Sight) is required in every communication (radio waves are too short to penetrate buildings)
- **Channel Bandwidth:** 25 MHz in USA and 28 MHz in Europe
- **Antennas:** directional antenna at both sides (outdoor mounting)
- **Duplexing:** it can employ TDD (Time Division Duplexing) or FDD (Frequency Division Duplexing). TDD requires only one channel that is shared by the uplink and downlink but separated by different time slots so it is only possible transmitting or receiving at the same time, it is perfect for data transmission. However, FDD uses two different channels for the uplink and downlink with the minimum delay, so it is suitable for voice communication.
- **Multiplexing:** TDM (Time Division Multiplexing) for downlink channel and TDMA (Time Division Multiple Access) for the uplink channel. In TDM, subscribers share the same frequency band but they are allocated in different time slots. In TDMA slots are assigned based on fixed or contention modes.
- **Data-rate**: high data-rate(32-134 Mbps with a channel of 28 MHz) using highly directional antennas and high power-levels
- **Cell radius:** 2-5 km
- **Security:** Rudimentary, reliance on antenna directivity to mitigate intrusions
- **Error correction**: Red-Solomon block with inner convutional code

IEEE 802.16a (Fixed SSs)

- Published in April 2003
- **Frequency bands:** 2-11 GHz (unlicensed and licensed bands)
- **Network Topology:** Point-to- fixed point (PTP) backhaul and two new modes: Point-to- multipoint (PMP) and mesh-topology. In PMP, a group of subscribers are connected to BS separately. However in mesh-topology the SSs are more intelligent and can perform as transmitter or receiver. Thus, one SSs do not have to connect only with the BS such as in PMP, so it can transmit to the neighbor and hence extends the network coverage and reduces the system failures
- **Propagation conditions:** NLOS (non-line of sight) because radio waves with these frequencies can penetrate in every building. NLOS has worse performance than LOS owing to attenuation when passing through obstacles and more interference
- **Antenna:** omni-directional antennas (indoor)
- **DFS (Dynamic Frequency Selection)** is used to avoid interference. It consists on switching the RF (radio frequency) channel on the basis of certain measurement criteria as SIR(Signal to Interference Ratio)
- **Flexible channel bandwidth:** from 1.25 to 28 MHz (for some devices is difficult to transmit in a wide bandwidth channel)
- **Modulation:** OFDM(Orthogonal Frequency Division Multiplexing) is used
- **Modulation scheme:** Adaptive modulation is also used
- **Data rate:** Medium data-rate up to 75Mbps
- **Cell radius:** 5-10 km (maximum distance of 50 km)

IEEE 802.16-2004 (Fixed SSs)

- Published in October 2004
- **Frequency bands**: both of them: 2-11 GHz and 10-66 GHz
- **Unifies** IEEE 802.16, 802.16a, 802.16b and 802.16c
- **Network Topology**: Point-to- fixed point (PTP) backhaul and Point-to- multipoint (PMP) and mesh topology
- **Modulation:** it provides three different air-interfaces:

  a) WirelessMAN-SC2: single carrier modulation
  b) WirelessMAN-OFDM: OFDM modulation with a 256-point Fast Fourier Transform (FFT) with TDMA channel access.
  c) WirelessMAN-OFDMA: OFDM is employed with a 2048-point FFT. Multiple-access is provided assigning a subset of subcarriers to each user.

  The physical layer can employ QPSK, 16-QAM or 64-QAM modulation adaptively changing on the basis of channel conditions

- **Propagation conditions:** non LOS propagation and LOS propagation
- **Channel Bandwidth:** 1.25 to 28 MHz
- **Data rate:** Medium data-rate(<75 Mbps with channels of 20MHz)
- **Cell radius:** 5-10 km (maximum coverage of 50 km)
- **Security:** includes two-way authentication
- **MAC enhancements:** supports “multihop” mesh networking to enable to retransmit one packet from one node to another one and extend the coverage area
- **Error Correction:** FEC and Automatic Retransmission Request(ARQ)

- **Antenna techniques:** it uses sectored omnidirectional antenna instead of directional. Thus decrease dependence on a precise antenna pointing and allows extending the coverage area. Moreover, adaptive antenna beam-forming allows the improvement of the resistance to interference and scability performance

IEEE 802.16-2005 or 802.16e (Fixed or Mobile SSs)

In this case, 802.16-2005 is not a standalone document. Sometimes it is called "Mobile WiMAX". It is strongly influenced by the Korean Standard "Wibro" that is unified with WiMAX in this standard. It is based on 802.16-2004 and it includes very important enhancements. The most important are:

- Published in February 2006
- **Frequency band:** 2- 6 GHz for mobility
- **Not backward compatible** with 802.16-2004 so software and hardware have to be updated
- **Modulation:** It employs scalable OFDMA (Orthogonal Frequency Division Multiplexing) Access that is highly robust to network congestion and to interference. With OFDM only one user can use the channel during one time slot, whereas in OFDMA multiple users can transmit at the same time
- OFDMA supports larger FFT size of 1024 so it a allows more flexible subchannel allocation
- **Adaptive:** Signal coding, modulation and amplitude are assigned separately to each subchannel depending on the channel conditions
- **Mobile Stations** appear and with them handover support
- **Security:** secure key exchange during authentication and encryption using AES(Advanced Encryption Standard) and DES(Data Encryption Standard) during data transfer
- **Antenna techniques:** includes MIMO(Multiple In Multiple Out) and enhancements and new implementations of Adaptive Antenna System (AAS)
- **Error Control:** includes advanced FEC coding schemes as turbo codes and low-density parity check codes. It also includes Hybrid Automatic Retransmission Request (HARQ).
- **Channel bandwidth:** 1.25 to 20MHz
- **Data rates:** Low-medium data-rate(<15 Mbps with channels of 5 MHz)
- **New Performance modes:** Power-save, sleep and idle-modes.
- **Number of users**: it supports more number of users than 802.16-2004
- **Cell radius:** 2- 5 km
- **QoS:** Better support for Quality of Service (QoS), a new QoS class appears

Other standards:

IEEE 802.16b (Fixed SSs)

- Published in October 2002
- Frequency bands: 5-6 GHz (license-exempt applications) providing QoS
- Replaced by 802.16-2004

IEEE 802.16c (Fixed SSs)

- Published in January 2003
- The goal was enable greater levels of interoperability
- Frequency bands: 10-66 GHz
- Replaced by 802.16-2004

IEEE 802.16.2-2001

- Published in September 2001
- Frequency bands: 10-66 GHz
- Replaced by 802.16-2004

IEEE 802.16.2-2004

- Published in March 2004
- Frequency bands: 10-66 GHz and 2-11 GHz
- Amendment of 802.16-2004 which includes enhancements to avoid interference

IEEE 802.16f-2005

- Published in September 2005
- Enhanced version of 802.16-2004 that includes Manager Information Base (MIB) for the MAC and PHY layers and management procedures.

Amendments in progress:

1) Active amendments

IEEE 802.16f-2005: It includes Management Information Base (MIB) and associated management procedures. It provides a management reference model for 802.16-2004 networks. The model consists on a Network Management System (NMS), managed nodes and service flow database. BS and managed nodes collect the information and

It is sent to NNS via management protocols as SNMP (System Network Management Protocol)

IEEE 802.16g-2007: It provides Management Plane Procedures and Services to 802.16-2004 and 802.16-2005 to enable interoperable and efficient management of network resources, mobility and spectrum. Other important goal is to standardize management plane behavior in 802.16 fixed and mobile devices.

The 802.16 devices can be part of a bigger network; they have to interface with other entities for management and control processes. Thus, a Network Control Management System (NCMS) is included that interface with the BS. 802.16g is based only in the management and control interactions between the NCMS and the PHY and MAC layers.

IEEE 802.16k-2007*:* It is working in the development of a series of standards as amendments to 802.16-2004 and 802.16D (IEEE MAC bridges standard) for 802.16 MAC layer bridging.

2) Amendments under development

IEEE 802.16h: The scope of this standard is improving the coexistence mechanism for License-Exempt Operation. That means to develop improved MAC mechanisms to enable coexistence between 802.16-2004 devices and other devices that are using the license-exempt band.

IEEE 802.16i: It will replace 802.16f providing mobility enhancements to MIB and associated management procedures

IEEE 802.16j*:* The goal of this group is to develop amendments to make possible that 802.16-2005 can support mobile multihop relay operation. It intends to improve the network's coverage, throughput and system capacity. It extends the network with three different types of relay nodes: fixed relays, nomadic relays and mobile relays

IEEE 802.16Rev2*:* Consolidate 802.16-2004, 802.16e, 802.16g and possibly 802.16i in a new document

3) Amendment at pre-draft stage

IEEE 802.16m*:* Advanced Air Interface. Data rates of 100 Mbps for mobile communications and 1Gbps for fixed applications. It will include cell, macro and micro cell coverage with no restrictions in the channel bandwidth. It is supposed to be approved at the end of 2008.

2.2. - PROTOCOL ARCHITECTURE

According to the OSI model, the 802.16 covers the two lowest levels: physical layer (PHY) and a sublayer of the data link level which is Media-Access Control layer (MAC). PHY layer provides an electrical, mechanical, and procedural interface to the transmission medium. MAC sublayer is the responsible of determining which subscriber stations (SSs) can access to the network and it is divided in three different sublayers:

- Convergence Sublayer (CS): its task is to map higher data units into proper service data units and it is also responsible for allowing bandwidth allocation and preserving/enabling QoS, as well as for header suppression and reconstruction. CS has two different services: ATM convergence sublayer and packet convergence sublayer.

- Common Part Sublayer (CPS): 802.16-2004 and 802.16-2005 is designed to support PMP (Point-to-multipoint) connection and mesh topology is left as optional. It is responsible for establishing and maintaining the connection, bandwidth allocation.

- Privacy Sublayer (PS): it provides secure key exchange and encryption. PS has two different protocols: 1) encapsulation to encrypt data across the network and authentication, 2) Privacy Key Management (PKM) to facilitate secure distribution of the keying data from the BS to SS.

PHY layer is responsible for data transmission and reception. It is specified depending on the frequency band, the propagation conditions (LOS or NLOS) and it also depends on the channel bandwidth. It supports adaptive modulation (BPSK, QPSK, 16-QAM and 64-QAM).

LLC is the upper sublayer of the level 2 of OSI (data link) responsible for multiplexing protocols transmitted over MAC (when transmitting) and de-multiplexing (when is receiving).

PHY and MAC will be explained accurately in the chapters 7 and 8 respectively. In the next figure, we can see the PHY and MAC layer and their respective sublayers.

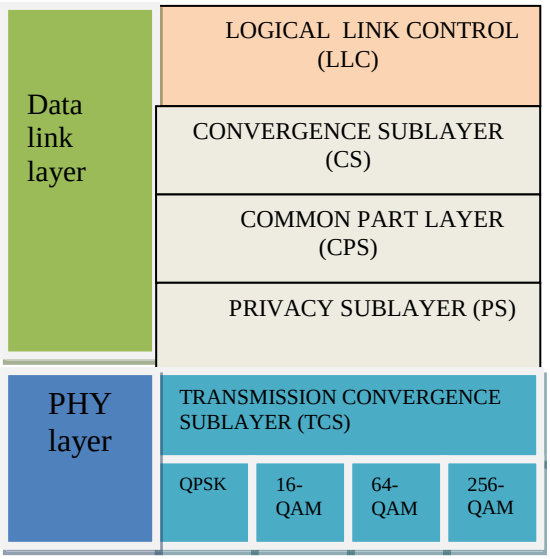

Figure 1: Protocol Stack

2.3.-WiMAX FORUM

WiMAX Forum was formed in April 2001 and it is an organization dedicated to certifying the interoperability of WiMAX products. It is composed by more than 522 (Intel, AT&T, Samsung, Nokia, Motorola, etc) members comprising the majority of operators, component and equipment companies in the communications ecosystem.

WiMAX is not a standard, it is a term trademarked by the WiMAX Forum to describe 802.16-based technology and ETSI HyperMAN (European Telecommunications Standard's Institute high performance radio MAN). The IEEE

elaborates the specifications and leaves to the industry the task of converting them into an interoperable standard that can be certified.

WiMAX Forum has eight different working groups: application, certification, global roaming, regulatory, networking, marketing, service provider and technical.

Certification Working Group (CWG): is responsible of certifying the product in a lab. This process includes two different tests:

- Conformance test to ensure that the products implement correctly the 802.16 and HyperMAN specifications
- Interoperability test to check if the products of the different vendors work correctly within the same network

WiMAX Forum defines two types of profiles to address different classes of products that use the same technology: system profiles and certification profiles.

One system profile is based on 802.16-2004 and it is optimized for fixed and nomadic access. On the other hand, the second system is based on 802.16-2005 and it is optimized for mobile access.

The certification profiles are defined by three characteristics: spectrum band, channel width and duplexing type. The WiMAX Forum has defined five fixed profiles and fourteen mobile profiles.

If the product passes the interoperability and conformance test, it will achieve the "WiMAX Forum Certified" designation. Some suppliers include in their products the "WiMAX-ready", "WiMAX-Compliant" or "PreWiMAX" but they are not officially certified.

In the following tables we can see the different WiMAX certification profiles for fixed and mobile WiMAX:

Fixed WiMAX

Frequency band	Channel Bandwidth(MHz)	Duplexing
3.5 GHz	3.5	TDD
	3.5	FDD
	7	TDD
	7	FDM
5.8 GHz	10	TDD

Mobile WiMAX

Frequency band	Channel Bandwidth(MHz)	Duplexing
2.3-2.4 GHz	5	TDD
	8.75	TDD
	10	TDD
2.305-2.320 GHz, 2.345-2.360 GHz	3.5	TDD
	5	TDD
	10	TDD
2.496-2.69 GHz	5	TDD
	10	TDD

3.3-3.4 GHz	5	TDD
	7	TDD
	10	TDD
3.4-3.8 GHz 3.4-3.6 GHz 3.6-3.8 GHz	5	TDD
	7	TDD
	10	TDD

Networking Working Group (NWG): Only with the PHY and MAC specifications is not enough to build an interoperable broadband wireless network and it is necessary to specify the end-to-end aspects of the network. NWG is in charge of elaborating these end-to-end aspects within the 802.16 specifications to support fixed, nomadic and mobile WiMAX systems.

Application Working Group (AWG): The Application Working Group promotes WiMAX by analyzing WiMAX applications with an engineering focus, developing recommendations at the application-network interface, and publishing the results.

Marketing Working Group (MWG): Promotes the WiMAX Forum, its brands and the standards.

Regulatory Working Group (RWG): RWG is the central authority within the WiMAX Forum on spectrum and regulatory matters. It influences worldwide regulatory agencies to promote WiMAX-friendly, globally harmonized spectrum allocations.

Service Provider Working Group (SPWG): It gives service providers a platform to influence BWA product and spectrum requirements to ensure that their individual market needs are fulfilled. SPWG is the single source for coordinated recommendations and requirements that drive the network and air interface specifications for WiMAX networks and products.

Technical Working Group (TWG): It develops technical product specifications and certification test suites for the air interface based on the OFDMA PHY, complementary to the IEEE 802.16 standards, primarily for the purpose of interoperability and certification of MS, BS and SS conforming to the IEEE 802.16 standards.

Global Roaming Working Group (GRWG): Assure availability of global roaming service for WiMAX networks in a timely manner as demanded by the market.

2.4.-SPECTRUM OPTIONS

As analyzed in the previous subchapters, the frequency range of frequencies where WiMAX can work is quite wide. However not all the frequencies are used, the operators usually use the licensed 2.3 GHz and 3.5 GHz bands and the unlicensed 5.725-5.825 GHz band, other frequencies within the frequency range of the standard can be used in the future. For instance, due to the upgrade from analog television to digital division, a large amount of spectrum could be available in the band UHF below 800MHz and it could be used by WiMAX.

In the next table, one can see the different frequency bands used depending on the region:

REGION	TYPICAL FREQUENCY BANDS FOR WIMAX
EUROPE	2.5, 3.5 and 5.8 GHz
USA	2.3, 2.5 and 5.8 GHz
CENTRAL AND SOUTH AMERICA	2.3, 2.5 and 5.8 GHz
SOUTH-EAST ASIA	2.3, 2.5, 3.3, 3.5 and 5.8 GHz
MIDDLE EAST AND AFRICA	3.5 and 5.8 GHz

3.-TECHNICAL FOUNDATIONS OF WiMAX

3.1.-WIRELESS CHANNEL: PATHLOSS AND SHADOWING

One of the main topics in a wireless communications system is the channel; and there are some factors to be considered. It is required to study all these factors of the channel to decide the amount of power necessary or the suitable modulation for a successful communication.

Path loss is the reduction of density or attenuation in an electromagnetic wave as it propagates through the space. It includes the propagation losses (effects caused by the expansion of the wave in the free space), absorption losses (when signal penetrates different not transparent media), diffraction losses (when the signal is obstructed by some object in its way), connection losses and others phenomena. Path loss is also influenced by environment (urban or rural), terrain relief, propagation medium, distance between transmitter and receptor and also the height of the antennas.

The study of these factors is always required in every wireless communications system and sometimes it could be difficult. Nowadays there are several programs that allow us to calculate easily all the conditions but the most important formulas in this chapter will be enunciated.

The free-space path loss formula or Friis formula is:

$$P_r = P_t \frac{\lambda^2 G_t G_r}{(4\pi d)^2}$$

where P_r and P_t are the received and transmitted power respectively, λ is the wavelength, G_r and G_t are the gains of the transmitter and receiver antennas and d is the distance between them. It is more usual to use this formula in decibels units:

$$PL = 32.45 + 20\log d(km) + 20logf(MHz) - G_r - G_t$$

However, the terrestrial propagation environment is not free space so other factors have to be considered due to the reflections that create interference. In wireless communications path loss can be represented by the path loss exponent n, whose valor is usually between 2(free space) and 4 (lossy environments or flat-earth model) and a constant C measured in a fixed distance.

$$PL = 10n\log(d) + C$$

Calculations of the path loss are usually called predictions. There are two different methods to predict the path loss. On the one hand, the statistical methods or empirical that are based in measured and averaged losses in different radio links, some examples are COST-231 or Okumura-Hata. On the other hand there are deterministic models based on the physical laws but they can offer more reliable predictions but requiring more computational effort.

There are many other factors than can degrade the signal strength, for example trees or buildings located between the transmitter and the receiver. Modeling all the locations and objects in the environment is impossible so the method consists in introducing a random effect called shadowing or scale-fading. Although shadowing can sometimes be beneficial, usually it modifies considerably the system performance because it requires a several dB margin to be built into the system.

The empirical path loss with shadowing is:

$$P_r = P_t P_o \chi \left(\frac{d_o}{d}\right)^{\alpha}$$

where α is the path loss exponent, P_o is the measured path loss at a reference distance of d_o and χ is a sample of shadowing process which is modeled as a lognormal random variable

$$\chi = 10^{\frac{x}{10}}, where\ x \sim N(0, {\sigma_s}^2)$$

and $N(0, {\sigma_s}^2)$ is a Gaussian distribution with mean 0 and variance ${\sigma_s}^2$.This standard deviation is formulated in dB and its usual values are in the range 6-12 dB.

3.2.-CELLULAR SYSTEMS

Due to the effects of shadowing and pathloss, it is known that with a given transmit power the distance of coverage is limited. It is only possible to cover a wide area with a high amount of power and by increasing the height of the antennas. So pathloss and short-range transmission allow to have isolated transmitters operating on the same frequency channel at the same time.

WiMAX systems are expected to work in cellular architecture. In this kind of systems, the service area is divided in smaller areas called cells and each one has its own base station. The main advantage is that the system capacity can be increased and the power consumption reduced but it implies also a higher inversion in equipments.

The increased capacity of the network comes to the fact that same frequency channels can be reused in different areas for a different transmission. When a cellular system is going to be built, a frequency planning is required to determine the frequency-reuse factor and a geographical-reuse pattern. The frequency-reuse factor (f) is the rate at which the same frequency can be used in the network. It is defined as 1/K where K is the numbers of cells that cannot use the same frequency channel for transmission. So if f=1 the same frequency can be used in all the cells but the most common values are 1/3, 1/4, 1/7, 1/9 and 1/12. A set of cells with different frequency channels is called cluster.

In a cellular distribution network it is simple to increase the overall system capacity only by making the cells smaller and turning down the power. Cellular systems support user mobility so that call transfers from one cell to another or “handoff” has to be provided.

The performance of a cellular system is affected by the cochannel interference that is caused by the users from the same cell and from the other cells. The other cells interference (OCI) is a function of the radius of the cell(R) and the distances to the centre of the neighboring cochannel cell to the radius of the cell (D) and it is independent from the transmitted power if the size of each cell is the same. The spatial isolation between cochannel cells is regulated by the parameter "cochannel-reuse ratio" (Q) which in hexagonal cells (the most usual pattern) is $Q = \frac{D}{R} = \sqrt{N}$ where N is the size of the cluster.

Since the interference in some parts of the cell is high and therefore the SIR (signal interference ratio) is low, the performance can be improved with the sectoring technique that consists of the use of directional antennas instead of an omnidirectional at the base station. In this way, if the cell is divided in six sectors, the amount of bandwidth used is six times less but the overall capacity of the cell is increased more than six times. The main problem is the requirement of more antennas and the increasing of the intersector handoffs. The structure of a cluster (six cells with different channel frequency in each one) is represented in the scheme bellow. The structure of a cellular system consists of several clusters.

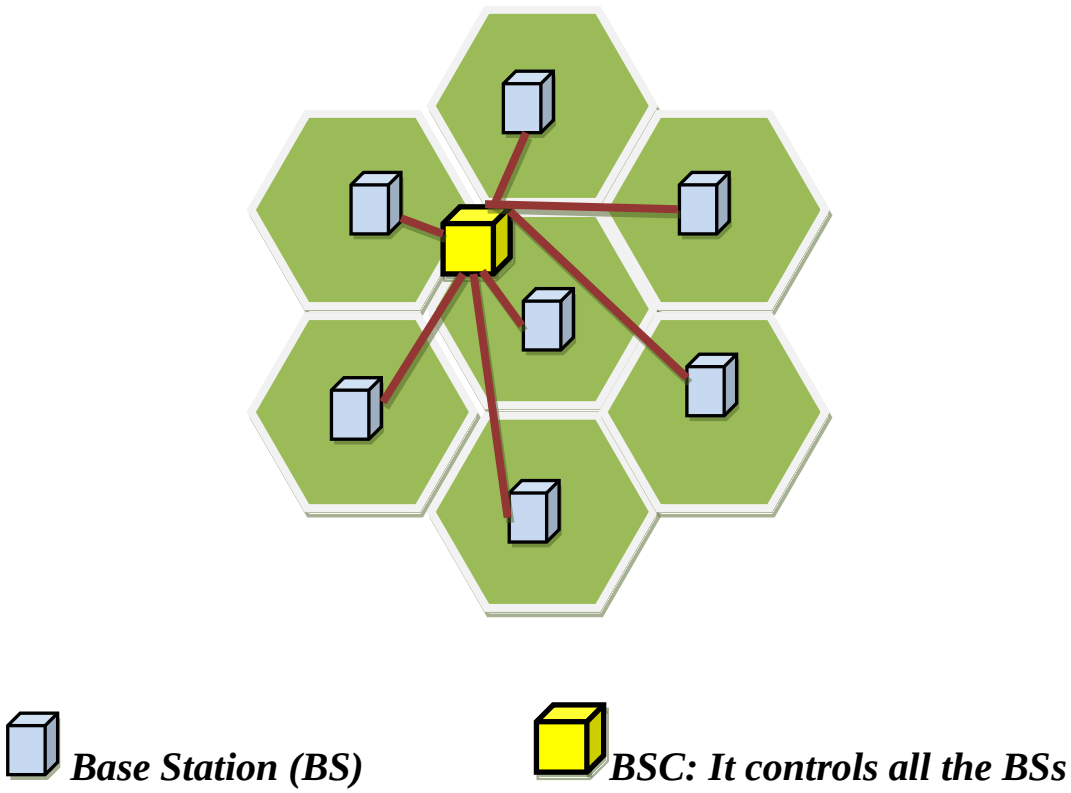

Figure 2: Cellular System

3.3.-FADING

Fading is caused by the reception of multiple versions of the same signal due to reflections in the path that are referred to as "multipath". In the receiver several signals with different attenuation, phase and delay arrive. The interference caused can be

constructive or destructive depending on the phase difference of the arriving signals. This effect can be dramatic even if only moving a very short distance the transmitter or the receiver. Fading is a very relevant effect in urban areas with high population density and indoors.

Doppler spread: is caused when a user or some of the reflectors in the path are moving and this user's velocity causes a shift in the frequency of the signal. Depending on the Doppler shift there are two kinds of fading; fast and slow fading. Doppler spread (fd) is determinate by the following formula dependent on the carrier frequency (fc), speed of the light(c) and the maximum speed between the transmitter and the receiver (v):

$$f_{d=\frac{vfc}{c}}$$

This measurement unit in the frequency domain is the coherence time($T_c = 1/f_d$) which is a measure of the minimum time required for the magnitude change of the channel to become decorrelated from its previous value. It has to be compared with the symbol time. The terms slow and fast fading refer to the rate at which the magnitude and phase change imposed by the channel on the signal changes

- Fast fading ($f_d \gg 1 \; or \; T_c \leq T$) consists of fast variations of the amplitude, phase and a Doppler shift while the transmitter or receiver is moving or the environment is changing. This fading is produced every fraction of wavelength (λ) of motion. It can be studied statistically with probability functions like Rayleigh, Rice and Nakagami.
- Slow fading ($f_d \leq 1$ or $T_c \gg T$) consists of the small changes in the amplitude of the signal caused by the motion of a transmitter or receiver when they are moving a distance of more than ten times the wavelength. It is also known as shadowing that is determinate by a statistical log-normal as it is explained in 3.1.

Delay spread: The carrier frequency of the signal is varied but also the amplitude will vary. The delay spread (τ) measures the amount of time that elapses between the first arriving path and the last arriving path. In the frequency domain the measurement unit is the coherence bandwidth ($B_c = 1/T$), which measures the minimum separation in frequency after which two signals will experience uncorrelated fading.

- Flat fading (τ>>T): the coherence bandwidth is larger than the original of the signals. All frequency components will have the same magnitude of fading.
- Frequency-selective fading ($\tau \leq T$): the coherence bandwidth is smaller than the original of the signal so the frequency components will experience different magnitudes of fading.

Mitigation: To mitigate the fading in the channels, these are classified in two groups depending on the type of fading that they present. The frequency-selective fading is more prominent in wideband channels (the channel's bandwidth is bigger than the coherence bandwidth and the delay spread is smaller than the symbol time). These kind of channels with time dispersion or frequency selectivity are known like "broadband fading". On the other hand, the channels with only frequency dispersion or time selectivity are "narrowband fading".

- In narrowband fading the most usual techniques are:

  - Time diversity (interleaving and adaptive modulation) that consists in introducing redundancy (forward error correction code) in the transmitted signal.
  - Spatial diversity consists of two receive antenna to select the stronger of the two signals receive.
  - Frequency diversity (the signal is transmitted using several frequency channels or spread over a wide spectrum).

- In broadband fading, frequency-selective fading causes dispersion in time or intersymbol interference (ISI), meaning that one symbol interferes with the following symbol.
  - The modulation OFDM (Orthogonal Frequency-Division Multiplexing) is the best method to overcome ISI and it is based on the multicarrier concept. It consists of rather than sending a single signal with data rate R and bandwidth B, sending L signals with data rate R/L and bandwidth B/L. OFDM will be explained in the next chapter.

  - Equalization is the other technique. The first type is linear equalization which consists of running the received signal through a filter that models the inverse of the channel. The other one is the nonlinear equalization that uses previous symbol decisions made by the receiver to cancel their subsequent interference.

4.-OFDM (Orthogonal Frequency Division Multiplexing)

4.1.-INTRODUCTION TO DIGITAL MODULATIONS

In telecommunications, modulation is the process of varying a periodic waveform in order to convey a message. It consists of modifying one of the three parameters: frequency, amplitude or phase.

Nowadays, all the telecommunications systems use digital modulations. It consists of modulating an analog signal by a digital bit stream in order to transport it through a given channel like fiber optics, radio link, wire, etc. It brings some advantages to analog modulations like better resistance to noise, more immunity to interference, better data rates, more security, etc. A unique pattern of binary bits is assigned to each frequency, phase or amplitude.

If the alphabet consists of M = 2^N alternative symbols, each symbol represents a message consisting of N bits. The symbol rate or baud rate is the number of symbol sent per second (B_d) and it is measured in bauds. The data rate is the number of bits sent per second or Nf_s (bits/sec). For example with an alphabet based in 64 symbols, each symbol is represented by 6 bits and the data rate is six times the symbol rate.

Many digital modulations can be used in telecommunications systems but in the IEEE 802.16 standard only four of them are supported: BPSK, QPSK, 16-QAM and 64-QAM.

1. BPSK or 2-PSK (Binary Phase Shift Keying)

BPSK is a digital modulation that conveys data by changing the phase of a reference signal. It is the simplest digital phase modulation and each symbol are separated by a phase of 180º, so the value of the modulated signal can be π or -π. BPSK is the most robust modulation but the major problem is that is only able to modulate at 1 bit/symbol so it is not suitable for high data rate communications when bandwidth is limited

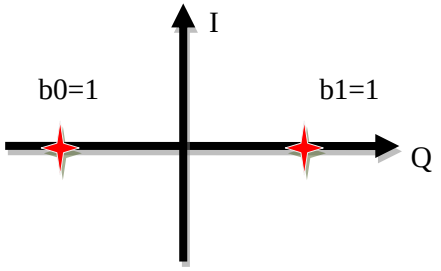

Figure 3: BPSK Constellation

2. QPSK or 4-PSK (Quadrature Phase Shift Keying)

QPSK is also a digital modulation that changes the phase of a reference signal. It considers two-bit modulation symbol. Many variations of QPSK can be used but all of them have 4-points constellation. The decision in the receiver is more difficult than in BPSK where the decision was between "1" and "0". Now, the system has to differ between 4 symbols with different phases ($\pi/4$, $3\pi/4$, $5\pi/4$ and $7\pi/4$). It is less resistant to noise and presents less immunity to interference but it is more spectral efficient.

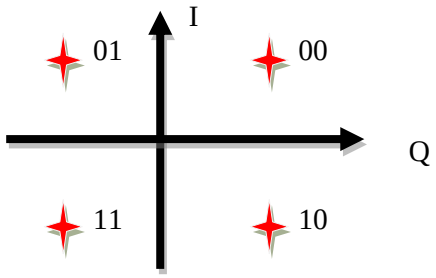

Figure 4: QPSK Constellation

3. Quadrature Amplitude Modulation(16-QAM and 64-QAM)

QAM is a digital modulation that conveys data by changing the amplitude of two carrier waves. These two waves are out of phase with each other by 90º. When a signal is transmitted with QAM is characterized by the following formula:

$$S(t) = I(t)\cos(2\pi f_o t) + Q(t)\sin(2\pi f_o t)$$

At the receiver this signal can be demodulated using a coherent demodulator.

It should be mentioned that QPSK and 4-QAM are the same modulation. 16-QAM and 64-QAM are the two amplitude modulations that can be used according to the IEEE 802.16 standard. The most spectral efficient modulation is 64-QAM (6 bits/symbol are transmitted).

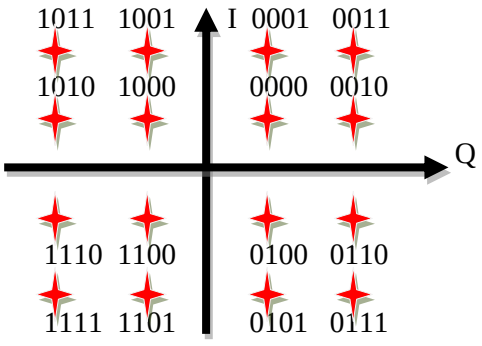

Figure 5: 16QAM Constellation

Finally, one has to consider that having more than one modulation could be interesting for the systems because it allows link adaptation. It means that depending on the channel conditions one or another modulation can be used. If the radio link is good a

high-level modulation can be used. Otherwise, a low-level and robust modulation can be used.

4.2.-MULTICARRIER MODULATION

The main goal of a multicarrier modulation is a high data rate communication and an ISI-free channel because a digital communication system cannot work in its presence. In order to have a channel without ISI the symbol time (T) has to be larger than the channel delay spread τ.

In wideband channels the desired symbol time is usually much smaller than the channel delay spread, so intersymbol interference is considerable. In order to solve this problem, the high data-rate bit stream is divided in L low-rate bit streams, which are sent over L different orthogonal-frequency subchannel. Each of these substreams has$T_s/L >> \tau$, so in this way the channel is ISI-free.

The number of the subcarriers chosen to ensure that each subchannel have a bandwidth less than the coherence bandwidth of the channel ($B/L \ll B_c$), which ensures flat fading.

However, multicarrier modulation has some problems such as a large bandwidth penalty will be imposed due to the fact that the subcarriers cannot have perfectly rectangular pulse shapes and they will be still time-limited. Moreover, this kind of modulation requires very high quality low-pass filters to maintain the orthogonality of the subcarriers at the receiver, as well as L independent RF units and demodulation paths.

4.3.-OFDM BASICS

OFDM is a frequency-division multiplexing digital multi-carrier modulation scheme, which popularity comes from the high data rates. It can reach that due to its efficient and flexible management of the intersymbol interference.

OFDM is based in the principle of transmitting simultaneously many narrow-band orthogonal frequencies called OFDM subcarriers which are designed not to interfere with each other and they can be separated using FFT (Fast Fourier Transform) algorithm. These frequencies are orthogonal with each other, allowing a high spectral efficiency. Each subcarrier can be modulated with one different conventional modulation scheme. These subcarriers have smaller bandwidth than a single carrier so they present a better resistance to multipath propagation.

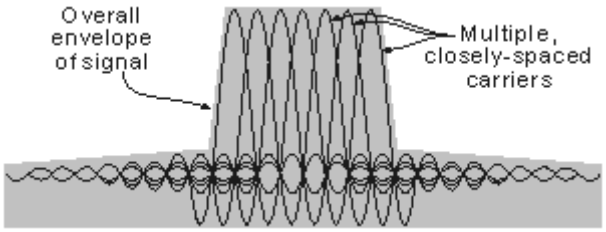

Figure 6: OFDM Spectrum(www.radio-electronics.com)

The OFDM baseband signal transmitted is determined by:

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

where $s[i]$ is the symbol carried in the ith subcarrier, B_c is the distance between two adjacent subcarriers or subcarrier bandwidth and Δf is the frequency of the first subcarrier and T is the useful symbol duration.

After a brief explanation of what OFDM is, some of the principles and characteristic will be explained:

- **Orthogonality**

In OFDM, the subcarrier frequencies are chosen in such a way that the interference between the subchannels or co-channel interference is eliminated. This fact simplifies the design of the transmitter and the receiver owing to only a filter is needed and not one for each subchannel.

OFDM requires very accurate frequency synchronization between the transmitter and the receiver. If there is some frequency deviation the subcarriers will not be orthogonal anymore. Frequency offsets are usually caused by mismatched transmitter and receiver oscillators and by Doppler shift due to motion. This fact can be solved at the receiver but if it is combined with multipath, the reflections will appear and it will be harder to correct. These problems become worse with vehicular –speed movements.

- **DFT (Discrete Fourier Transform) or FFT(Fast Fourier Transform)**

OFDM uses an efficient computational technical known as DFT or FFT (matrix computation that allows DFT to be computed). It allows us to relate events in time domain to frequency domain. This technique and its inverse IFFT (Inverse Fast Fourier Transform) are able to create a multitude of orthogonal subcarriers using only a single radio.

OFDM symbol can be recovered easily by simply computing. Although the usage the FFT the ISI has been mitigated, the symbol is imperfect due to cochannel interference, additive noise and other imperfections

- **Guard interval**

An OFDM symbol means a group of L data symbols (all the data symbols transmitted in parallel) and it lasts T seconds, where $T = LT_s$. As the spectrum of OFDM is not band limited (sinc(f) function), linear distortion caused by multipath can

cause ISI. In order to avoid this effect, it is important to transmit a guard interval between OFDM symbols. The duration of each guard interval (T_g) has to be longer than the delay spread (τ) of the channel to ensure that each symbol interferes only with itself. After its introduction the duration of each symbol is $T_{total} = T + T_g$. Its introduction also reduces the synchronization problems.

The ratio T_G/T_d is very often denoted *G* in WiMAX/802.16 documents. If the channel conditions are good a lighter value of G has to be used and if the multipath effect is important and the channel is bad a high value of G is required. For OFDM and OFDMA PHY layers, 802.16 defines the following values for *G:* 1/4, 1/8, 1/16 and 1/32. For the mobile WiMAX profiles defined, only the value 1/8 is mandatory.

- **Cyclic prefix**

One way to prevent ISI is the introduction of a cyclic prefix for the guard interval. It is transmitted during the guard interval and consists of a copy of the end of the OFDM symbol. For instance, if the maximum channel delay spread is v+1 samples, it will be necessary to add a sequence of v samples between each symbol in order to make independent from the precedent symbol and the next one.

The use of cyclic prefix supposes a power and bandwidth penalty. Since v redundant symbols are sent, the required bandwidth is increased from *B* to $\left(L + \frac{v}{L}\right) B$ and the power loss is determinate by $\frac{L}{L+v}$.

- **Types of subcarriers**

Not all the subcarriers convey useful data; there are different types of subcarriers depending on their function in the system:

1. Data subcarrier: useful data transmission
2. Pilot subcarrier: used for channel estimation and synchronization
3. Null subcarriers: no transmission and used in guard bands
4. Direct Current (DC) subcarrier: it is another null subcarrier but in OFDM is the carrier with the same frequency than the centre frequency of the transmitter.

- **Frequency equalization**

The performance of equalization in OFDM is simpler than in a conventional single-carrier modulation. Fading caused by the multipath propagation can be considered flat if the sub-channel is sufficiently narrow-banded and hence when the number of sub-channels is large.

The complex channel gains (the amplitude and the phase) for each subcarrier must be known in order to estimate the received symbols. After the FFT, the data symbols are estimated using a one-tap frequency-domain equalizer or FEQ (Frequency Domain Equalizator) whose function is determinate by $\hat{X} = \frac{Y_1}{H_1}$ where Y_1 is the received signal and H_1 is the response of the channel. Therefore, the FEQ corrects the phase and equalizes the amplitude before the decision device.

- **Timing and Frequency Synchronization**

The receiver has to perform two important actions to achieve a successful communication: timing and frequency synchronization. The first one consists on determining the timing offset of the symbol and the optimal timing instants; however the OFDM symbol structure allows a degree of error. The frequency synchronization, which can modify the orthogonality and hencemis more stringent, consists of aligning the carrier frequency as much as possible with the transmitted carrier frequency.

- **Peak-to-Average Ratio (PAR)**

OFDM signals have a higher peak-to-average-ratio than single-carriers signals do. The sum of all the narrow-band carriers in the time domain can be large sometimes and others can be small, so the peak value is larger than the average value. A high PAR represents a hard problem for the devices such as high-power (HPA) amplifiers or digital-to-analog converter (DAC), so this fact causes the requirement of more accurate and, hence expensive devices.

If a high peak signal is transmitted through a nonlinear device like HPA or DAC, it generates in-band distortion and out-of-band energy. One of the solutions for this problem is transmitting a waveform with high peak power in the linear region of the HPA in order to decrease the average power in the input signal. It is called input backoff (IBO) and results in an output backoff (OBO). A high backoff can reduce the battery life and the power efficiency. The IBO is defined as: $10log_{10}\frac{P_{insat}}{\overline{P_{in}}}$ where P_{insat} is the saturation power and $\overline{P_{in}}$ is the average input power. The typical value of IBO is similar to the PAR of the signal.

There are several techniques to reduce the PAR effect:

- Clipping: reduces the input power by an amount equal to the PAR and also truncates the amplitude of signals that exceed one determinate clipping level. It can be combined with filtering process.
- Tone reservation: adds power to unused carriers like null carriers
- Active constellation extension: based on extending the corner points of an M-QAM.

- **OFDM Symbol parameters used in WiMAX**

An OFDM symbol is characterized by four different parameters. In the next table, one can analyze these parameters and their possible values:

Parameter	Description	Possible Values
BW	Nominal channel bandwidth	In MHz: 1.25, 1.75, 3.5, 5, 7, 8.75(WiBro), 10, 14 , 15
N_s	Number of subcarriers, including the DC, pilot and guard subcarriers	OFDM: 256 SOFDMA: 128, 512, 1,024, 2,048
G	Ratio of Cyclic prefix (CP) time	1/4, 1/8, 1/16, 1/32
n	Sampling factor(dependent on BW)	OFDM: BW multiples of→n 1.25→144/125 1.5→86/75 1.75→8/7 2.0→57/50 2.75→316/275 Other→8/7 OFDMA: BW multiples of→ 1.75→8/7 1.25,1.5,2 or 2.75→28/25 Other→8/7

4.4.-OFDMA (Orthogonal Frequency Division Multiplexing Access)

The problem in the access to the network in WiMAX is that many users in the same geographic area require high data rates in a finite bandwidth and with low latency. To solve this problem WiMAX uses OFDMA, a multi-user version of OFDM. It is a technique that creates independent streams of data assigning subsets of subcarriers to users depending on the demand of each one. In the next figure, an OFDMA spectrum with 2 users and their corresponding subcarriers assigne:

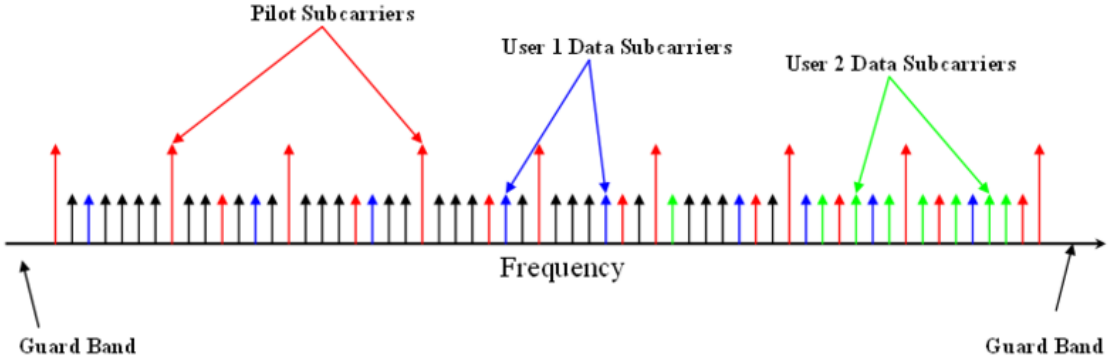

Figure 7: OFDMA subcarriers

Another important function of OFDM is the adaptive user-to-subcarrier assignment based on feedback information of the channel conditions. If the assignment is done fast, it can improve the resistance of OFDM to narrow-band co-channel interference and fast fading.

There are multiple-access strategies for OFDM to divide the available dimensions (frequency, time or code division multiplexing) among all the users. In FDMA (Frequency Division Multiplexing Access) eight frequency slots will be created, one for each user. In TDMA (Time Division Multiplexing Access), the user will use the eight time slot created but it is only possible transmitting one eight of the time. Finally, with CDMA (Code Division Multiplexing Access) each user will transmit all of the time over all the frequencies but would use one of the eight available orthogonal codes to avoid the interference with the other seven users.

The major problem of these strategies is that they only ensure the orthogonality among the users of the same cell.

OFDMA is a mix of FDMA and TDMA, it presents the same advantages than single-user OFDM like multipath resistance or frequency diversity but it can serve many different users with different data rates, QoS (Quality of Service) requirements or using different user's applications. However, OFDMA has more advantages with regard to OFDM like its potential to reduce the transmit power, to reduce the PAR problem and even better spectral efficiency.

One of the advantages of OFDMA is the multiuser diversity which demonstrates that as the number of user increases, the probability of getting a large channel gain improves. In WiMAX this gain will be reduced by effects like spatial diversity and the need to assign users contiguous blocks of subcarriers.

As it was said, WiMAX systems use adaptive modulation and coding based on feedback information, which means transmitting as high data rate as possible when the channel conditions are good and transmit a lower data rate when the channels conditions are poor. A high data rate can be achieved using large constellations such 64-QAM and less robust-error codes like 3/4 convolutional or turbo codes. On the opposite to this, to achieve a low data rate, a small or constellation such QPSK has to be used with a correction rate code of 1/2 or turbo codes. Feedback is critical to apply adaptive modulation and coding, in addition to the transmitter has to know the channel SINR (Signal to Interference plus Noise Ratio) to determine the optimum modulation and transmit power. In the next table, the different data rates depending on the channel bandwidth, modulation and code rate are presented assuming that the daa rate is shared among the users in the sector with a downlink-to-uplink bandwidth ratio of 3:1 in TDD mode:

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.

In WiMAX the feedback channel is protected with error correction but the main problem to its performance is the loss of data due to mobility with vehicular speeds (more than 20km/h) or carrier frequencies bigger than 2,100 MHz.

Resource-Allocation Techniques for OFDMA

WiMAX standard does not specify algorithms to determine which users to schedule, how to assign the subcarriers to them or how to determine the appropriate power level for each user on each subcarrier.

The resource allocation is usually used for two different optimizations: minimize the total transmit power with a fixed data rate or maximize the data rate with a forced transmit power. The different algorithms depending on the data rate are:

- **Maximum Sum Rate Algorithm (MSR):** It is used to maximize the sum rate of all users given a limited transmit power. It is optimal if the goal is to get as much data as possible through the system but the main problem is that only can work with excellent channels so it is only achievable for users close to the base station.
- **Maximum Fairness Algorithm (MF):** In a cellular system as WiMAX the path loss varies seriously between users due to the different distances of them from the BS, so it is known that with MSR algorithm, not all the users can be served. At least that allows the underserved users to get some throughput. MF's goal is to allocate the subcarriers and power such that the minimum user's data rate is maximized.
- **Proportional Rate Constraints Algorithm (PRC):** In the MF, the throughput is determined by the user with worst SINR so most of resources are assigned to that user. Its goal is to maximize the total throughput but with the additional

constraint that each user's data is proportional to a set of predetermined system parameters.

- **Proportional Fairness Scheduling (PFS):** The previous algorithms achieve different objectives such as the total sum throughput (MSR), maximum fairness (equal data rates among users) or set proportional rates for each user. In addition, other fact has to be considered: the latency. Latency is unacceptable so PFS is an algorithm that balances throughput and latency and achieves some degree of fairness.
- **Comparison:** Depending on the system conditions, one or another algorithm will be the most appropriated. In the next table there is a comparison of them:

Algorithm	**Sum Capacity**	**Fairness**	**Complexity**
Max Sum Rate	Best	Poor	Low
Max Fairness	Poor	Best	Medium
Proportional Rate Constraints	Good	Most flexible	High
Proportional Fairness	Good	Flexible	Low

5.-PHY LAYER

The physical layer (PHY) is based on the 802.16-2004 and 802.16e-2005 standards and it is strongly influenced by WiFi technology. In the standards we can distinguish four different formats of physical layer:

- WirelessMAN SC: a single carrier PHY layer to work in frequency bands bigger than 11GHz b and requires LOS propagation conditions
- WirelessMAN SCa: a single carrier PHY layer to work in 2-11 GHz frequency bands and requires NLOS propagation conditions and point-to-multipoint communications
- WirelessMAN OFDM: a 256-FFT-based OFDM PHY layer for point-to-multipoint communications in NLOS conditions and working at frequencies between 2 and 11 GHz.
- WirelessMAN OFDMA: a 2048-FFT-based OFDMA PHY layer for point-to-multipoint communications in NLOS conditions and working at frequencies between 2 and 11 GHz. In 802.16-2005 the specifications have been modified to SOFDMA (scalable OFDMA). Different sizes of FFT can be used: 128, 512, 1024, and 2048.

5.1- CHANNEL CODING

Figure 9: OFDMA transmission chain

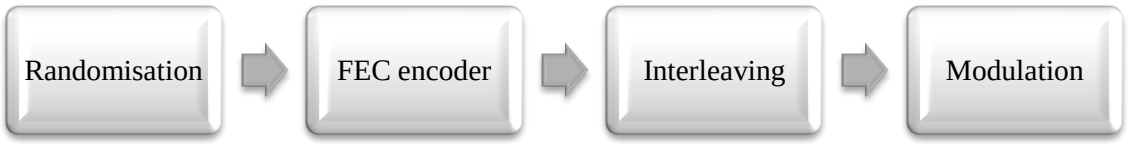

Figure 8: OFDM transmission chain

The radio link suffers a great variation from the interference. In order to prevent and to correct the errors caused, a good performance of the channel coding is required. The PHY transmission chains of OFDM and OFDMA are illustrated in the following figures, the only difference is that ODMA PHY includes a repetition block.

5.1.1- Randomization

It is performed in the uplink and in the downlink to all the blocks, except to the FEC (Frame Control Header) block, using the output of a length shift-register sequence that is initialized at the beginning of every FEC block. This shift-register sequence added with the data sequence creates the randomized data. If the amount of data to transmit does not fit exactly with the amount of data allocated, padding with only ones (0xFF) is added at the end of the block.

5.1.2- Forward Error Codes (FEC)

A FEC consisting of the concatenation of Red-Solomon outer code and an inner code has to be supported in the uplink and the downlink. It will be used always as the code mode to request access to the network and in the FCH burst.

In OFDM PHY there are three different FEC to be applied: Reed-Solomon Convolutional Code (RS-CC) which is mandatory, Convolutional Turbo Code (CTC) and Block Turbo Code (BTC) that are both optional.

In OFMA PHY there are four different FEC to be applied; Tail-biting Convolutional Code (CC) which is mandatory and three that are optional: Convolutional Code (CTC), Block Turbo Code (BTC) and Low Density Parity Check (LDPC).

- **Convolutional Codes**

For OFDM PHY layer, Reed-Solomon Convolutional Code **(**RS-CC) is performed by first passing the data in block format through the RS encoder and then passing it through a convolutional encoder. This code consists on adding some redundant bits to the digital sequence.

Reed-Solomon Code is defined by some parameters: RS (N=256, K=239) where N is the number of overall bytes after encoding and K is the number of data bytes before encoding and finally T= (N-K)/2=8 is the maximum number of data bytes with error that can be corrected. So the code rate of OFDM PHY is 239/256.

The convolution coding has an original rate of 1/2 and a single 0x00 tail byte is added at the end of the burst after randomization. In the RS encoder, the redundant bits are sent before the input bits keeping the 0x00 tail byte at the end of the allocation

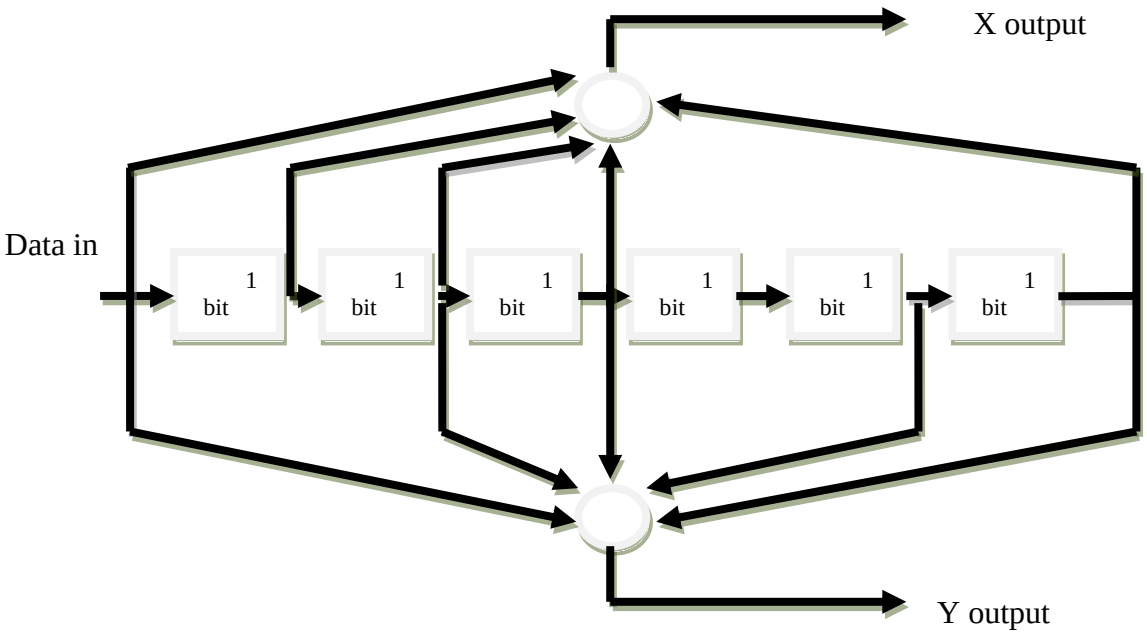

Figure 10: Convolutional Encoder

For OFDMA PHY the mandatory scheme used is also based on convolutional code (CC). The convolutional encoder uses an encoder with a constraint length 7 and native code rate ½. Tail-biting is used to initialize the encoder. The encoder memorizes the last 6 bits from the end of the data block and they are appended to the beginning, to be used as flush bits. These bits flush out the bits left in the encoder by the precious FEC block. The first 12 parity bits are generated by the convolutional encoder which depend on the 6 bits left of the previous block.

- **Turbo codes**

Convolutional Turbo Codes (CTC)

It is mandatory for mobile and optional for fixed WiMAX. WiMAX uses duobinary turbo codes with an encoder of constraint length 4. In this kind of encoders, two bits from the uncoded sequence are used simultaneously as input. The duobinary convolution encoder has two generating polynomials: $1 + D^2 + D^3$ and $1 + D^3$. Thus, the encoder has four possible transitions compared the two transitions of a binary turbo encoder.

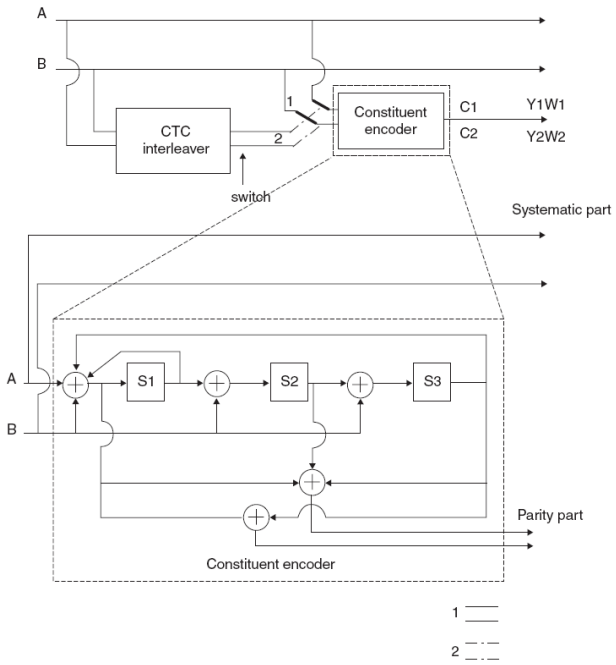

Figure 6.8 OFDMA PHY Convolutional Turbo Code (CTC) encoder. (From IEEE Std 802.16-2004 [1]. Copyright IEEE 2004, IEEE. All rights reserved.)

Figure 11: OFDMA PHY Convolutional Turbo Code (CTC) Encoder

The output of the native 1/3 coding rate encoder is first separated in six different blocks(A,B, Y1, Y2, W1 and W2) where A and B contain the system bits, Y1 and W1 contain the parity bits of the encoded sequence in natural order, and Y2 and W2 contain the parity bits of the interleaved sequence. Each of the blocks is independently interleaved and the subblocks that contain the parity bits are punctured (remove some of the parity bits after encoding) to achieve the target code rate.

Block Turbo Codes and Low-Density Parity Check

Although these codes are defined in the standards as optional channel coding schemes, they are unlikely to be employed in WiMAX. The reason is that most equipment manufacturers decided to use Convolutional Turbo Codes (CTC) for their superior performance and advantages.

5.1.3.-Interleaving

After channel coding, the next step is interleaving. It is used to protect the communication against long sequence of consecutive errors. These errors may affect a lot of bits in a row and therefore disable the communication. The encoded data bits are interleaved with a block of the size of coded bits. Interleaving is applied independently on each FEC block and is based on two steps:

1- Ensures that adjacent coded bits are allocated in nonadjacent subcarriers. The distance between the subcarriers to which two adjacent bits are mapped on, depends on the subcarrier permutation schemes used.
2- Adjacent bits are alternately mapped onto less and more significant bits of the modulation constellation.

5.1.4.-Repetition

Repetition was added in the standard 802.16e-2005 for OFDMA PHY. It can be used to increase the margin more than using only FEC mechanisms.

This process is characterized by the repetition factor (R) that can be 2, 4 or 6. Thus, for the uplink, the number of allocated slots Ns will be a whole multiple of the repetition factor. However, for the downlink, the number of allocated slots Ns will be in the range of [R x K, R x K + (R-1)] where K is the number of required slots before the repetition. For instance, if R=4 the number of the allocated slots (Ns) will be in the range of 40 and 43 for the burst.

The binary data that can fit in a region that is repetition coded is reduced by a factor R compared to non repeated region with the same size and same FEC technique used.

The repetition scheme can be used only with QPSK modulation with every type of coding schemes except applying HARQ with CTC.

5.2.-HYBRID-ARQ

The Hybrid-ARQ uses an additional error code to ensure a more reliable transmission of data. There are two different types of HARQ that are supported by WiMAX.

In HARQ Type I or “chase combining”, the redundancy bits are not changed from one transmission to the next. When the coded data block is received, the receiver first checks the error-correction code, if the channel quality is good enough all the errors should be detected and it will be possible to obtain the correct data block. However, if the channel quality is not good, the receiver requests a retransmission of the data block. The current data block is combined with the previous discarded data blocks stored at the receiver to decode correctly the information. This process continues until either the block is decoded without error or the maximum number of allowed transmissions is reached.

In HARQ Type II or also referred to as “incremental redundancy”, the redundancy version of the encoded bits is changed from one transmission to the next. Thus, it consists on increasing the redundancy bits in each transmission. The first transmission contains only data and error detection and if the reception is error free, the data block is decoded. However, if data is

received in error, the second transmission will contain FEC parities and error detection, so the code rate is reduced. If the data block is received with error, error correction can be attempted by combining the information received from both transmissions. Type II allows a lower bit error rate (BER) and block error rate (BLER) than Type I.

5.3.-TRANSMISSION CONVERGENCE SUBLAYER (TCS)

It is an option in WiMAX that is located between MAC and PHY layer. If TCS is enabled, it converts the variable-length MAC PDUs into fixed-length FEC blocks, called TC PDU. A pointer is added at the beginning of each TC PDU to indicate the header of the first MAC PDU.

5.4.-SUBCHANNEL AND SUBCARRIER PERMUTATION

In OFDMA, a subchannel is defined as a subset of subcarriers that are assigned to the users. Subcarriers of a subchannel can be adjacent to each other or distributed through the entire frequency band depending on the subcarrier permutation mode. A distributed subcarrier permutation provides better frequency diversity, while an adjacent subcarrier distribution is better for beamforming and for the exploitation of the multiuser diversity. The number of subchannel allocated to transmit a data block depends on the size of the data block, coding rate used and modulation format.

The contiguous sets of subchannels assigned to a single user or group of users is defined as "data region" and is always transmitted with the same burst profile (one of the 52 different combinations of modulation format, code rate and type of FEC allowed in WiMAX). The various permutations schemes allowed are:

5.4.1.-Downlink Full Usage of Subcarriers (DL FUSC)

All the data subcarriers are used to create various subchannels. Each subchannel is made up of 48 data subcarriers, which are distributed evenly throughout the entire frequency band to counter the effects of fading channels. The pilot subcarriers are allocated first and the rest of the subcarriers are mapped on the various subchannels. The set of the pilot subcarriers is divided in two constant sets and two variable sets. The variable sets are used to estimate the channel response across the entire frequency band and the constant sets are just based on the OFDM symbol duration and subcarriers spacing.

5.4.2.-Downlink Partial Usage of Subcarriers (DL PUSC)

The main difference between FUSC and PUSC is that in PUSC all the subcarriers are divided in six groups. The first step is arranging all the subcarriers except null subcarriers in a cluster which is formed by 14 adjacent subcarriers over 2 OFDM symbols. In each cluster, subcarriers are divided in 24 data subcarriers and 4 pilot subcarriers. After that, the different clusters are renumbered with a pseudorandom

scheme and divided in 6 groups. A subchannel will be formed of two clusters of the same group.

It is possible to allocate all or only one subset of the six groups to a transmitter but it is useful to allocate separated subsets to neighboring transmitters in order to separate their signals in the subcarrier space. Thus, it is possible to use a segmentation scheme and all the sectors in a BS can use the same RF channel maintaining orthogonality among the subcarriers.

5.4.3.-Uplink Partial Usage of Subcarriers (UL PUSC)

The subcarriers are first divided in tiles and each tile consists of 4 subcarriers over three OFDM symbols. The subcarriers of a tile are divided in eight data subcarrier and four pilot subcarriers (the ones of the corners).

There is another optional UL PUSC where each tile is composed by three subcarriers over three OFDM symbols. Each tile is formed by eight data subcarrier and one pilot subcarrier.

After that, the tiles are renumbered using a pseudorandom numbering sequence and they are divided in six groups. Each subchannel is created using six tiles from a single group.

5.4.4.-Band Adaptive Modulation and Coding (AMC)

All subcarriers constituting a subchannel are adjacent to each other. In this way, it is easier the exploitation of multiuser diversity, although frequency diversity is lost.

In this permutation (the same for the uplink and downlink), nine adjacent subcarriers with eight data subcarriers and one pilot subcarrier are used to form a bin. A group of four rows of bins is called a physical band. An AMC subchannel consists of six contiguous bins within the same logical band (group of physical bands). Thus, an AMC subchannel can be formed of one bin over six consecutive symbols, two consecutive bins over three consecutive symbols or three consecutive bins over two consecutive symbols.

5.5.-RANGING

In 802.16e-2005, ranging is an uplink physical layer procedure to maintain the quality of the radio-link communication between the MS and BS. The BS receives the ranging information from the SS and it processes the signal to determine some parameters such SINR and time of arrival which allows the BS to indicate the MS adjustments in the transmit power level or the timing offset.

The ranging procedure involves the transmission of the ranging code repeated over two OFDM symbols using the ranging channel. This ranging code is a PN sequence of length 144 and chosen from a set of 256 codes. There are four different types of code and each one has a determined function. The group N is used for initial ranging, M for

periodic ranging, O for bandwidth request and S for handover ranging. This sequence is modulated in BPSK.

5.6.-SLOT AND FRAME STRUCTURE

The smallest unit of PHY layer resource that can be allocated to a single user in time or frequency domain is a slot.

In 802.16, both FDD (frequency division duplexing) and TDD (time division duplexing) are allowed. In FDD, the uplink and downlink subframes are transmitted simultaneously on different carrier frequencies and a fixed duration of the frame is established. For mobile stations, there is an additional duplexing mode called H-FDD (Half-duplex FDD) with the restriction that the MS cannot transmit and receive at the same time. In full duplex the SS is continuously listening the channel downlink, while in half-duplex only can listen when it is not transmitting. However, in TDD the uplink and downlink subframes are transmitted on the same carrier frequencies but at different times. A frame contains the uplink and downlink subframe and has a fixed duration but the bandwidth does not have to be divided in two equal parts.

Comparing the two techniques, FDD has a fixed duration for the uplink and downlink, while TDD is adaptive. Thus it is more suitable for asymmetrical traffic like Internet. The frame structure of TDD and FDD is the same, except that in FDD, the UL and DL subframes are multiplexed on different carrier frequencies.

5.6.1.-OFDM PHY Downlink Subframe

It consists of only one PHY PDU that can be shared by several SSs. It starts with one preamble that allows timing and frequency synchronization to listen to the SSs and also initial channel estimation, noise estimation and interference estimation. It is modulated in BPSK (the most robust modulation allowed).

The downlink preamble is followed by a frame control header (FCH) that contains the Downlink Frame Prefix (DLFP), which provides frame configuration information, such as the MAP message length, the modulation, and coding scheme, and the utilizable subcarriers. It is coded with BPSK and a code rate of 1/2.

If DL-MAP or UL-MAP is transmitted (a case where they are not necessary: the DLFP indicates all the burst profiles of the downlink subframe), it will be allocated in the first MAC PDU after the FCH and it will indicate the data regions of the various users in the DL and UL. MAP messages include the burst profile for each user, which defines the modulation and coding scheme used in that link. As 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. Using these messages, the SS can identify which subchannels are for its use.

Periodically, the downlink channel descriptor (DCD) and the uplink channel descriptor (UCD) are transmitted following the UL-MAP or DL-MAP message with

additional control information to the description of channel structure and the burst profiles allowed by the BS.

FCH is followed by one or more downlink burst. The same burst profile can be used one or more times but these burst profiles are transmitted in order of decreasing robustness of their burst profiles.

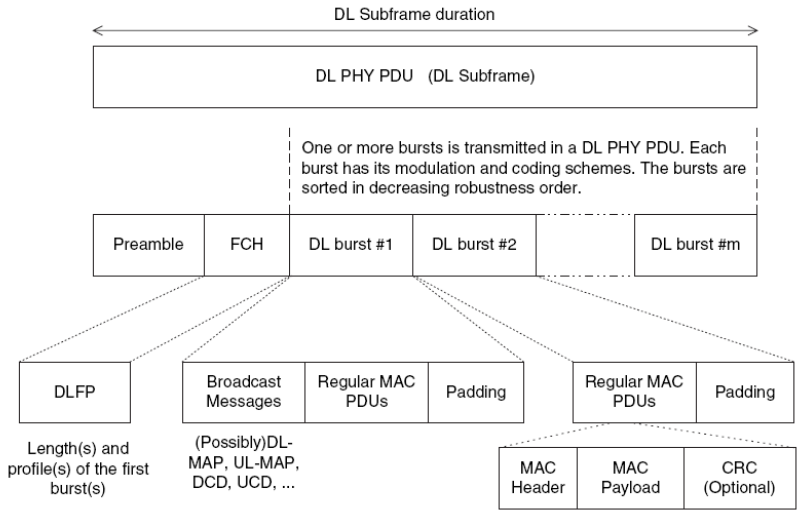

Figure 9.4 Details of the OFDM PHY downlink subframe. Each downlink burst may be sent to one (unicast) or more SSs (multicast or broadcast).

Figure 12: OFDM PHY DL subframe

5.6.2.-OFDM PHY Uplink Subframe

An OFDM Uplink Subframe consists of three different parts, with this order:

- Contention slots allowing initial ranging: the BS specifies an interval in which new stations can join the network
- Contention slots allowing bandwidth requests: the BS specifies an uplink interval in which requesting bandwidth for uplink data transmission is possible
- One or many uplink PHY PDU and each one transmitted on a burst. Each PDU is an uplink subframe transmitted from a different SS

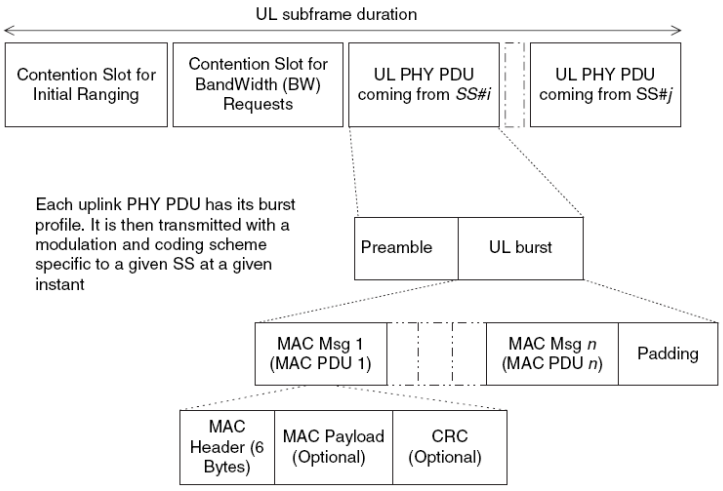

Figure 9.5 Details of the OFDM PHY uplink subframe.

Figure 13: OFDM PHY UL subframe

5.6.3-OFDMA PHY Frame

In OFDMA, the frame structure is different due to the subcarriers distribution. There are some non-mandatory elements present in the frame structure, so it is possible to find different distributions.

Each DL and UL is divided into various zones, each of these using different subcarrier permutation modes. Some of the zones as DL PUSC are mandatory and the rest are optional. The size of the slot is dependent on the permutation scheme used:

- FUSC: Each slot is 48 subcarriers by one OFDM symbols
- DL PUSC: Each slot is 24 subcarriers by two OFDM symbols
- UL PUSC: Each slot is 16 subcarriers by three OFDM symbols
- Band AMC: Each slot is 8,16,24 subcarriers by 6,3, or 2 OFDM symbols

The first OFDM symbol in the DL is used as preamble for timing and frequency synchronization, initial channel estimation and noise and interference estimation. BPSK is used to create the preamble in the frequency domain.

The interval between two consecutive DL frame preambles is defined as frame length; it is variable between 2msec and 20 msec.

After the DL frame preamble, the initial subchannels are used to allocate the frame control header (FCH). It contains the DL_Frame_Prefix which contains information about the DL-MAP duration, ranging subchannels and system control information. FCH is transmitted with QPSK rate 1/2 and with four repetitions. DL-MAP and UL-MAP are transmitted after FCH to specify the data regions and the different transitions between zones of the various users in the DL and UL subframes of the current frame. Periodically DCD and UCD are transmitted like in OFDM PHY uplink.

The uplink subframe includes:

- Allocation for ranging
- Allocation for data transmission
- Fast feedback slot and it also contents some performance information such as handover operation. BS can include a Channel Quality Information Channel for periodic CINR (Carrier Interference Noise Ratio) reports.
- Other optional signaling data allocation and subchannels

In the next figure the TDD frame structure for Mobile WiMAX is represented:

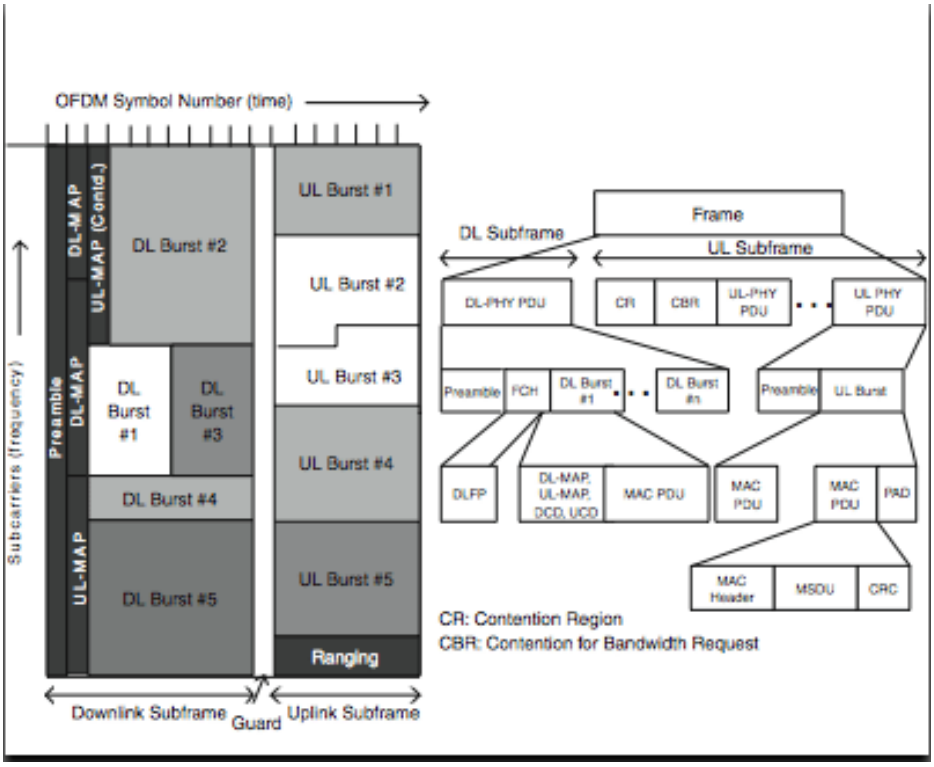

Figure 14: TDD frame structure for Mobile WiMAX

5.7.-POWER CONTROL

The BS uses the ranging channel transmissions of various MSs to estimate the initial and periodic adjustments for power control in order to maintain the quality of the communication between BS and MS and to reduce the interference. The BS uses the MAC management messages to indicate the correction in the power-level to the MS. The requirements of this mechanism are:

- Supporting power attenuation due to distance loss or power fluctuations at rates of 30dB/s with depths of at least 10 dB
- Taking into account the interaction of the power amplifier and the different burst profile. PAR depends on modulation.
- The SS should maintain the same transmitted power density unless the maximum power level is reached. If the subchannels allocated to a SS are

increased or decreased, the power level has to be increased or decreased in the same proportion.

The MS reports to the BS the maximum available power and the transmitted power and the BS has to adjust to these parameters for an optimal assignment of the subchannels and an optimal burst profile.

5.8.-CHANNEL-QUALITY MEASUREMENTS

The downlink power-control process, adaptive modulation and adaptive code rate are based on the measurements of the channel quality. These measurements are RSSI (Received Signal Strength Indicator) and SINR (Signal to Interference plus Noise Ratio) and they are transmitted to the BS by the SS. Based on this information provided, the BS can change the burst profile or change the power level of the DL transmissions.

6.-MAC LAYER

MAC (Media Access Control) is a part of the layer 2 (Data Link) of OSI (Open System Interconnect) stack. It is responsible for controlling and multiplexing various such links over the same physical medium. As mentioned in section 2.2, MAC is composed by three different sublayers: MAC Convergence Sublayer (CS), MAC Common Part Sublayer (CPS) and MAC Security Sublayer.

6.1.-MAC CONVERGENCE SUBLAYER

MAC Convergence Sublayer or often referred as CS, is the top sublayer of the MAC layer and the interface with the layer 3. It provides mapping of external data, received from the higher layers through the CS service access point (SAP), into MAC Service Data Unit (SDU). These SDUs are transmitted to the MAC CPS where the MAC procedures are applied. It is also responsible for packet header suppression.

WiMAX MAC Layer is connection oriented and the logical connection between the BS and MS is identified by CID (unidirectional connection identifier). SDUs of a specific destination address can be carried over different connections, depending on the QoS requirements, and the CS has to determine the corresponding CID.

One of the functions of CS is removing the repetitive part of each SDU to improve the efficiency of the network. For instance, if the SDUs are IP packets, the address contained will not change from one packet to next one so, they can be deleted. There are different packet header suppression rules depending on the service provided. Thus, the CS determines the part of the header to be suppressed (PHS field) using the PHS mask. Moreover, there is another function known as PHS verify, if it is enabled the CS compares the bits of the PHS field with the ones expected. After that, if the new PHS field matched with the PHS field cached, the header is deleted, whereas if PHS is not used, CS suppresses all the SDU's header.

The PHS rules have to be known by the transmitter and the receiver so, the BS sends a dynamic service allocation (DSA) or a dynamic service change (DSC) with all of the parameters required in the PHS rule in order to synchronize.

6.2.-MAC PDU OR MAC FRAME

Each MAC PDU or MAC frame consists of one fixed-length header followed by a payload and a cyclic redundancy check (CRC) which is calculated in all the PDU (header and payload). The payload can be formed by: zero or more subheaders included in the payload, zero or more SDUs or a fragment of a SDU.

Regarding to the MAC PDU header, in WiMAX there are two different types of PDUs:

- Generic PDU: used to carry data and MAC-layer signaling messages. It consists of a generic header followed by payload and CRC. It is the only one used in the downlink.
- Bandwidth request PDU: used by the MS to indicate to the BS that more bandwidth is required in the uplink. It consists only of a bandwidth-request header, with no payload or CRC.

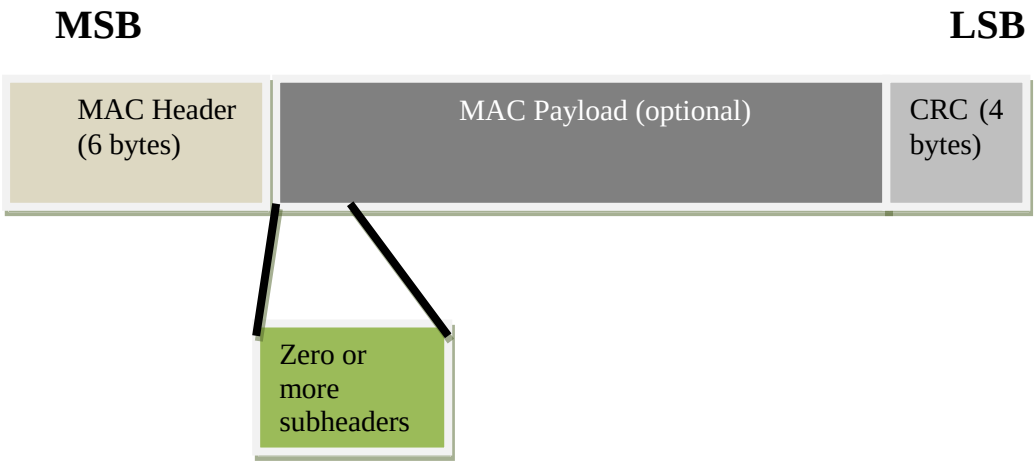

Figure 15: MAC Frame Structure

Generic Header: is composed of the following fields with its corresponding length:

Field	Length	Field	Length
Header type(HT) set to 0	1	Encryption subheader field (EKS)	2
Encryption Control(EC) 1=encrypted	1	Reserverd (Rsv)	1
Type	6	Length of MAC PDU in bytes with the header included	11
Extended subheader field (ESF) 1=present	1	Connection identifier on which the payload is to be sent (CID)	16
CRC indicator(CI) 1=enabled	1	Header check sequence (HCS)	8

Bandwidth request header: has a different frame structure and it is transmitted without payload:

Field	Length	Field	Length
Header type(HT) set to 1	1	Bandwidth request (BR) number of bytes requested by SS for a given CID	19
Encryption Control(EC) set to 0	1	Connection identifier on which the payload is to be sent (CID)	16
Type	3	Header check sequence (HCS)	8

In a generic MAC PDU, apart from the previous headers, there are five different types of subheaders which can be included in the payload. It is indicated in the type field (6 bits) of the header where each bit position indicates:

0. (LSB) Fast-Feedback allocation subheader: contains feedback from the MS about DL channel state information
1. Packing subheader: indicates that multiple SDUs are packed into a single PDU
2. Fragmentation subheader: indicates that the SDU is fragmented over multiple MAC PDUs
3. Extended type: indicates if the packing or fragmentation subheader is extended. If its value is 1
4. ARQ feedback payload: indicates that it is enable with value 1
5. (MSB) Grant-management subheader: management bandwidth messages such as polling or additional-bandwidth request

When the channel conditions are bad, it could be interesting to fragment one SDU in more than one PDU in order to have a more efficient use of the bandwidth. On the contrary, when the channel is good, it is more interesting to pack more than one SDU in only one MAC PDU to have a better use of the available resources.

Another technique included in 802.16 is concatenation which consists of concatenating more than one PDU in a single transmission.

6.3.-QUALITY OF SERVICE (QoS)

Quality of service is the guarantee of the service-level performance for a data stream from a source to destination. It determines the mechanism used by the network to allocate UL and DL transmission opportunities for the PDUs. Thus, a better sharing of the bandwidth available among the users is possible. The principal purpose is to define a transmission ordering and scheduling in the air interface. For instance, a user sending a mail does not need real-time transmission

The 802.16 standard provides five different QoS classes or scheduling services for the different applications that might work over WiMAX networks:

1. The unsolicited grant service (UGS): supports real-time data streams and it consists of fixed-size data packets issued at periodic intervals. It guarantees the throughput and latency for the system. It is suitable for VoIP and T1/E1.
2. The real-time polling services (rtPS): supports real-time services that generate variable-size data packets issued at periodic intervals. It is the case of MPEG transmission. The BS provides unicast polling opportunities to the SS at a fixed interval (in order to ensure latency) to request bandwidth.
3. The non-real-time polling services (nrtPS): support nonreal-time applications and it consists of variable size data packets ensuring a minimum data rate. Like in rtPS, there are unicast polling opportunities but in this case the duration between them is about few seconds (much larger). All the SSs belonging to the group can also request resources, so sometimes collisions are produced. It is suitable for FTP traffic.

4. The best-effort service (BE): supports data streams for which no minimum service guarantees are required. Data is sent whenever resources are available; the MS only uses contention-based polling to request bandwidth. If request is not successful, the SS will try again later.
5. The extended real-time polling service (ertPS): supports variable data rate real-time applications. It is based in the efficiency of UGS and rtPS. The BS works in the same way that UGS; however, whereas in UGS allocations are fixed in time, ertPS allocations are dynamic. It is suitable for VoIP without silence suppression.

To provide QoS, a unidirectional flow of packets known as service flow is transmitted. A service flow is a MAC transport service provided for transmission of uplink or downlink traffic and it is identified by a 32-bit SFID (identifier). It is defined by a set of QoS parameters such as latency, jitter (maximum delay variation for the connection) and throughput assurances. A service flow has the following components:

- Service Flow ID: an identifier for the service flow
- Connection ID: an identifier of the logical connection used to carry the service flow. The primary CID is used to transport the MAC messages.
- Provisioned QoS parameter set (initial state): the recommended QoS parameters to be used for the service flow.
- Admitted QoS parameter set (intermediate state): defines a set of QoS parameters for which the BS is reserving resources. It can be a subset of provisioned QoS parameter set used when the BS is not able to admit the service with the provisioned QoS parameter set.
- Active QoS parameter set (final state): QoS parameters being provided at a given time
- Authorization module: logical BS function that approves or denies every change of QoS parameters.

The various service flows admitted by WiMAX network are usually grouped into service flow classes and each one identified by a unique set of QoS requirements. These classes are not specified by WiMAX and it is the service provider who has to define them.

To enable the dynamic setup and configuration of the services flow, the standard defines a set of MAC management messages known as dynamic service messages (DSx messages) used to negotiate all the QoS parameters related to a service flow. These messages are dynamic service addition (DSA), dynamic service change (DSC), dynamic service deletion (DSS).

6.4.-BANDWIDTH REQUEST

Bandwidth request refers to the mechanism used by the SS to indicate the BS the necessity of bandwidth allocation.

In the downlink, the allocation of bandwidth to various MS is made by the BS on a per CID basis without MS's action. MAC PDUs arrive for each CID, the BS schedules them for the PHY resources based on QoS requirements. After the allocation of the PHY resources, the BS indicates it to MS with the transmission of DL-MAP.

In the uplink, a grant is the right for a SS to transmit during a determinate interval, so the SS requests resources from the BS. The burst profile changes dynamically, all the requests are made in terms of number of bytes required to carry the MAC header and the payload, but not the PHY overhead. These bandwidth requests can be transmitted during any interval except initial ranging interval.

A request may come as a stand-alone bandwidth request header or piggyback request.

In a standalone request bandwidth, the MAC PDU is transmitted in a dedicated MAC having a header format without payload type I. There are two different types of grant-request indicated by the field type:

- Incremental: when the BS adds the quantity of bandwidth requested to its perception of the bandwidth needs for the connection.
- Aggregate bandwidth: it is made for a particular CID; the BS replaces its perception of the bandwidth need with the amount of bandwidth requested.

Piggybacked bandwidth request uses the grant management subheader included in a generic MAC PDU and it can be only incremental.

The 802.16 standard defines two main grant-request methods:

- Unicast polling or polling: the BS allocates bandwidth to the SS in order to make bandwidth requests. If a MS is polled individually, the process is called unicast polling. The BS indicates the UL allocations to the MS to send bandwidth-request PDU by the UL-MAP message of the DL subframe.

- Multicast or contention-based polling: if there is not sufficient bandwidth to poll a MS individually, multicast or broadcast polling is used. It consists of polling a group of MSs and it is allocated in the bandwidth request contention slot of the uplink frame (TDD mode) or subframe (FDD mode). Every SS can have access to the network by asking to the SS for a UL slot. The BS evaluates the service-level agreement, radio network state and the scheduling algorithm and after the evaluation may assign an UL slot for transmitting data. If a bandwidth allocation is not assigned to a SS after a number of retries, the MAC PDU is discarded.

6.5.-NETWORK ENTRY

When a new SS wants to connect to the WiMAX network, it has to follow a set of steps to establish correctly the communication with the BS. As it can be seen in the figure below, the procedure is composed by different steps:

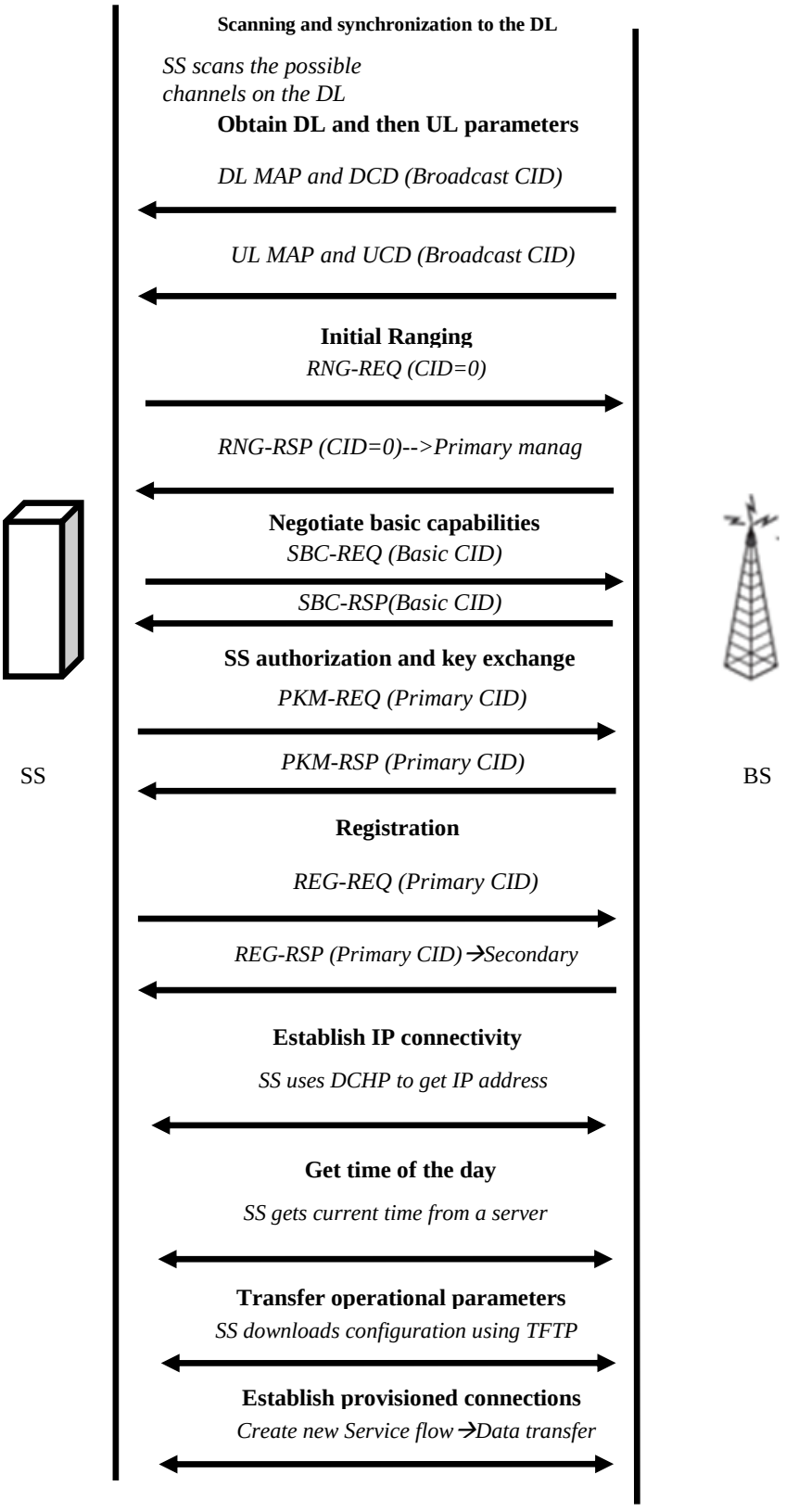

Figure 16: Network Entry procedure

Following this figure, a brief explanation step by step of the procedure:

1- Scan for downlink channel and establish synchronization with the BS: each SS stores a nonvolatile list of all operational parameters such as the previous frequency used in the DL. If the synchronization with the stored frequency fails, it will try to obtain another downlink channel.

2- Obtain transmit parameters: the SS searches for the DL-MAP message in order to obtain synchronization. It remains in synchronization state while it receives periodically DL-MAP and DCD. Once it reaches synchronization, it will wait for the UCD and UL-MAP in order to obtain the transmit parameters for the UL channel.

3- Perform ranging: the SS performs the initial ranging with the purpose of obtaining the timing and power-level requirements to maintain the UL connection with the BS. The SS sends a RNG-REQ in a contention-based initial interval. The process continues until the SS receives a RNG-RSP with status complete. After that, the SS can start the UL transmission.

4- Negotiate basic capabilities: in this step, the SS informs the BS of its capabilities transmitting SBC-REQ (SS Basic Capabilities Request). This capabilities refers to:

   1. Bandwidth allocation: support for half-duplex and full duplex if FDD is used.
   2. PHY related parameters: maximum transmit power, current transmit power, FFT size, 64 QAM support, HARQ support, STC and MIMO support, AAS private MAP support, transmission gap, subcarrier permutation support, uplink power.-control support.

   The BS responds to the SS through a SBC-RSP in which the intersection of the SS and SS capabilities is transmitted.

5- Authorize SS and perform key exchange: within the authentication mechanism which will be explained in the security chapter, the SS and BS have to exchange secure keys. SS sends a PKM-REQ (Private Key Management Request) to the BS and this responds with a PKM-RSP.

6- Perform registration: registration is the process in which the SS obtains a secondary CID and therefore access to the network. Although the basic connections between the BS and the SS are established during the initial ranging, these are not secure; a secure connection is established after the authorization and registration process. The SS sends a REG-REQ with a hashed message authentication code (HMAC) used to validate the authenticity of the message by the BS.

7- Establish IP connectivity: the established secondary connection is used to establish the IP connectivity; the IP version is established through REG messages and if it is omitted, it is interpreted as version 4. The SS uses the Dynamic Host Configuration Control (DHCP) server in order to obtain the IP address.

8- Establish time of the day: it is required for time-stamping logged events. It is transmitted by UDP (User Datagram protocol). It receives from the UTC (Universal Coordinated Time) and it is combined with the offset of the DHCP server to obtain the local time.

9- Transfer operational parameters: after the DCHP procedure is done, the SS download its configuration with many useful information from the server using the Trivial File Transfer Protocol (TFTP)

10- Set up connections: After transfer operational parameters (managed SS) or after registration (unmanaged SS), the BS sends DSA-REQ messages to the SS to set up connection for provisioned service flows of the SS and the SS responds with DSA-RES.

Each SS has a universal and unique 48-bit address which is used to identify the stations in the servers. They also include some security information to authenticate the SS to the security server and authenticate the responses from the security and provisioning servers.

6.6.-CONNECTION MAINTENANCE

Once the communication is established between the SS and the BS, in order to maintain the quality of this, a periodic ranging is performed.

In downlink, if CINR (Carrier to Interference-plus-Noise Ratio) goes outside an allowed operating region, the SS requests for a change in the burst profile. If the SS has been granted an uplink bandwidth, it sends a DBPC-REQ (Downlink Burst Profile Change Request) message and the BS responds with a DBPC-RSP. Whereas if a grant is not available and the SS requires a new burst profile (based on link adaptation), it sends and RNG-REQ messages in the initial ranging interval and follows the same procedure than in initial ranging. Both messages are sent using the primary CID.

In the uplink, for each uplink burst grant in which signal is detected, the BS analyzes the quality and compares it with certain limits. If the quality is not good enough, the BS sends a RNG-RSP indicating some correction for the physical layer and the status “continue”. After a specified number of repetitions of this process, if the quality is not good, the BS sends a RNG-RSP with the status “abort” and the management of the link is stopped.

In the SS, when the status received in the RNG-RSP is “continue”, the RNG-REQ has to be included in the allocated transmitted burst. If the BS determines that the quality is good enough and the sent status is “success”, the SS uses the grant to service for its pending uplink data queues.

6.7.-PMP vs. MESH MODE

In PMP, a centralized BS with a sectorized antenna is the only transmitter operating in a given direction and a given frequency channel, so all the stations within the sector receive the same transmission. Due to be the only transmitter, the BS does not have to coordinate with the other BSs, only for TDD in which the time has to be divided for the uplink and downlink. The downlink is usually broadcast; it is usually specified in the DL-MAP the portion of downlink subframe which is for a specific SS. If it is not specified in the DL-MAP, the SS checks the CID of the received PDUs and saves those destined to it. Related to uplink, it is shared by the SSs on a demand basis. Depending on the service class, the SS can have the right to transmit continuously or granted by the BS after the reception of a request from the user.

The main difference between PMP mode and mesh mode is that in PMP mode, traffic only occurs between BS and SSs, whereas in mesh mode the traffic can be routed through other SSs, so can occur directly between SSs.

In Mesh networks, the stations are known as nodes and the one that has a direct connection to backhaul services outside the mesh network is known as Mesh BS. Within a Mesh network, uplink and downlink are defined as traffic in direction of Mesh BS and traffic away from the Mesh BS, respectively.

Some other important concepts in Mesh mode are: neighbor, neighborhood and extended neighborhood. The nodes with which a node has direct links are called neighbors. Neighbors of a node form a neighborhood and all the neighbors of a node form an extended neighborhood.

In a Mesh system, the SS and even the BS have to coordinate with others to transmit. Thus, using distributed scheduling, all the SS and Mesh BS shall coordinate their transmission in the two-hop neighborhood and shall transmit their schedules (grants, requests and available resources) to all the other neighbors. In this distribution the Mesh BS, using the request from the Mesh SSs in a certain hop range, has to determine the amount of granted resources for each link in the downlink and uplink and after that communicates these grants to all the Mesh SSs within the hop range. Each SS has a physical neighborhood list.

Nowadays, there is not a WiMAX profile using mesh topology although it appears in the 802.16 standard.

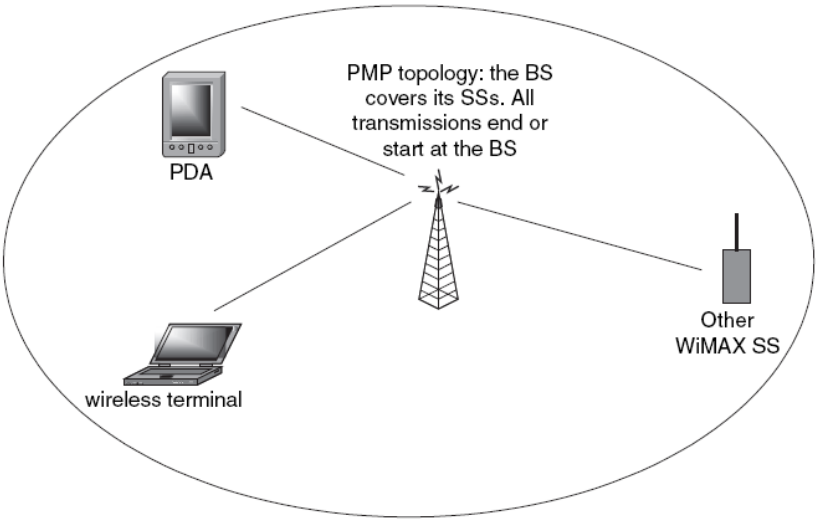

Figure 17: PMP Topology

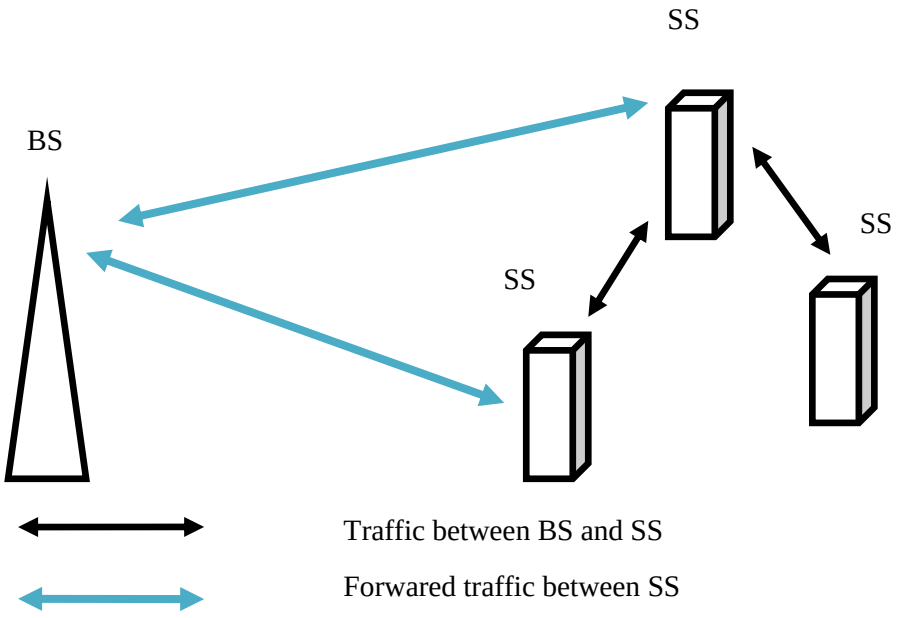

Figure 18: Mesh Topology

6.8.-MAC FUNCTIONS FOR MESH TOPOLOGY

Although most of the MAC functions for Mesh topology are the same already explained for PMP topology, there are some different MAC functions to be considered:

1. Addressing and connections:

When a node is authorized in a network, it will receive a 16-bit Node ID from the Mesh BS transmitted in the mesh subheader of the MAC PDU.

In order to address the nodes in the local neighborhood, an 8-bit link identifier known as link-ID will be used to identify each link the node establish with its neighbors in distributed scheduling. The link-ID is communicated when a new link is established transmitted inside the CID, specifically in the generic MAC header in unicast messages.

Since the messages are broadcasted, the receiver node can determine the schedule using the node ID of the transmitter in the mesh subheader of the MAC PDU and the link-ID inside the payload in the in the mesh mode schedule with MSH-DSCH (Mesh Mode Schedule with Distributed Scheduling) message.

2. Bandwidth allocation:

1. Distributed Scheduling mode:

In this distribution every station shall coordinate their transmission in the two-hop extended neighborhood. In this mode, some part of the control portion of the frame is used by a node to transmit its own schedule and proposed schedule changes to its neighbors. All the stations within a network shall use the same frequency channel to transmit schedule information (MSH-DSCH messages) regularly during the control period of the frame.

A SS that has a direct link to the BS shall synchronize to the BS, while a SS that is at least two-hop from the BS shall synchronize to the neighbor SSs that are closer to the BS.

There are two different types: coordinate distributed scheduling which ensures that transmissions are scheduled without being necessary the action of the BS; whereas in uncoordinated scheduling transmissions are established by directed grants and requests between two nodes and it is necessary the scheduling to ensure that no collision with data and control traffic is produced.

2. Centralized Scheduling mode:

In this mode, the Mesh BS acts in similar manner than a BS in PMP topology with the difference that not all the SSs have to be directly connected to the BS, however the BS provides schedule configuration (MSH-CSCF) and assignments (MSCH-CSCH) to all the SSs of the network.

3. Mesh Network Synchronization:

Network configuration (MSH-NCFG) and network entry (MSH-NENT) packets provide a basic level of communication among nodes of nearby networks. These packets are used to synchronize with the nearby networks, communication and coordination of channel usage between nearby networks, and to notify the entrance of a new node in the network.

7.-MOBILITY

The 802.16-2005 standards introduce new concepts related to mobility management and power management. Power management enables the MS to preserve its battery resources, an important factor in mobile devices. On the other hand, mobility management enables the MS to move from the coverage area of one BS to the next without losing connection.

7.1.-POWER-SAVING MODES

7.1.1.-Sleep Mode

In WiMAX, sleep mode is optional for the MS and mandatory for the BS. A MS with active connections negotiates with the BS to interrupt its connection over the air interface for an established period of time called "sleep window". During this period the MS will not transmit but it will listen to the channel to maintain the connectivity. It is followed by a "listen window", during which the MS restores its connection. The goals of the sleep mode are to minimize MS power usage and to minimize the use of the serving base station air interface resources.

The period of time during which all the MS are in sleep-mode and they cannot receive any DL transmission or send any UL transmission is known as "unavailability interval". During this period the BS does not transmit to the MS, so the MS may power down or can scan neighbor BS to collect information for handover process. During the "availability interval", the MS shall operate in the same way as in the state of normal operation.

Sleep-mode takes place in one of the three power-saving classes depending on the procedures of activation and deactivation, parameter sets and policies of MS availability for data transmission. The MAC messages used to establish a sleep-mode are MOB_SLP-REQ (Sleep Request Message sent by MS) and MOB_SLP-RSP (Sleep Response Message sent by MS).

7.1.2.-Idle mode

In mobile WiMAX, idle mode is an optional mechanism that allows a MS to receive broadcast transmission without being registered in the network. For a MS, it eliminates the need of handoff when there is not an active data session for a given time. It is also beneficial for the BS to conserve PHY and MAC resources because it does not need to perform any hand-off procedures or signaling to the MS that is in idle mode. Idle mode also includes a fast method (paging) to alert to the MS of the existence of pending downlink traffic.

The BS coverage area is divided in smaller areas called paging groups. The MS are continuously monitoring the DL transmission of the network to determine the paging group of its location. If the MS detects that it is in a new paging group, it performs a

"paging group update" to inform of its current paging group to the BS. Thus, with this mechanism, when a BS needs to establish connection with a MS, it only has to page the ones belonging to the same paging group instead of paging all the BS of the network.

During its operation, the MS can be in "paging-unavailable interval" or in "paging-listen interval". When it is in "paging-unavailable interval", it is not available for paging and can power down, conduct ranging with a neighbor BS or scan the neighbor BSs for the CINR (Carrier to Interference-plus-Noise Ratio) and SINR (Signal to Interference-plus-Noise). In the "paging-listen interval", MS listens to DCD and DL-MAP message of the serving BS to determine when the paging message is scheduled. When a MS is paged, it terminates its idle-mode operation and re-enters to the network. A MOB_PAG-ADV message is broadcasted during the paging interval to request an update of its location or a re-entry to the network.

7.2.-HANDOVER

This process known as handover or handoff, is similar in all the cellular systems, it requires support from layers 1, 2 and 3. The ultimate decision is determined by layer 3 but PHY and MAC layer have to provide information to it.

The BS allocates time for each MS to measure the radio condition of the neighbors BSs (scanning). During this scanning interval, the MS measures the received signal strength indicator (RSSI) and the signal-to-interference-plus noise ratio (SINR). This process is based in the following MAC messages: MOB_SCN-REQ (scanning interval request), MOB_SCN-RSP (scanning interval allocation) and MOB_SCN-REP (scanning report).

The hand-off process is performed following a set of stages:

1. Cell reselection: MS performs scanning and association with one or more neighboring BSs in order to determine its suitability as target BS.

2. Handoff decision and initiation: handover is initialized when a MS decides to migrate its connections from one BS to another. The MS sends a MOB_MSHO-REQ to a BS indicating one or more BSs as handoff target and the BS responds indicating the suitable BS to be used for the handoff by a MOB_MSHO-RSP message. After that, the MS sends a MOB_MSHO-IND indicating the BS selected for the handoff from the ones specified in the MOB_MSHO-RSP.

   This process can also be initialized by the BS sending a MOB_BSHO-REQ to the MS indicating one or more BSs for the handoff target. After that, the MS responds indicating its choice through a MOB_BSHO-IND.

3. Synchronization to the target BS: After the target BS determination, the MS analyzes the DL frame preamble to obtain time and frequency synchronization. After that, it analyzes the DL-MAP, DCD and UL-MAP to obtain information about the ranging channel.

4. Ranging with target BS: This process is similar to the initial ranging in network entry process. The MS synchronizes its UL transmission with the BS.

5. Termination of context with previous BS: after the establishment of the connection with the target BS, the MS terminates the connection with the serving BS, sending a MOB_HO-IND message to the BS.

Apart from the conventional handoff process previously explained, WiMAX defines two optional handoff procedures: macro diversity handover (MDHO) and fast base station switching (FBSS). In the first case, the MS is allowed to transmit and receive using the air interface of more than one BS at the same time. The BS of the diversity set which controls the UL MAP and DL MAP is known as anchor BS.

In the case of FBSS, each BS has a diversity set of all the BSs with which the MS has an active connection (one or more CID established and periodic ranging with all the BSs). The difference related to MDHO is that the MS only communicates in the uplink and downlink with one BS, the anchor BS.

8.-WiMAX NETWORK ARCHITECTURE

As mentioned, the IEEE 802.16 standards only specify the PHY and MAC of the radio link and that is not enough to build an interoperable wireless network. WiMAX Forum's Network Working Group (NWG) is in charge of developing and standardizing the end-to-end network aspects such as network architecture that are beyond the IEEE 802.16 standards. On the other hand, WiMAX Forum's Service Provide Group (SPWG) helps to define requirements and priorities.

The specifications are collected in three different documents elaborated by WiMAX Forum:

- Stage 1: scenarios and services requirements (elaborated by SPWG)
- Stage 2: network reference model according to the requirements
- Stage 3: protocols associated with the network architecture

8.1.-NETWORK REFERENCE MODEL

The WiMAX reference model is composed by three different components interconnected by reference points. These components are: Mobile Station (MS), Access Service Network (ASN) and Connectivity Service Network (CSN). The figure bellow illustrates the network reference model with its components and reference points.

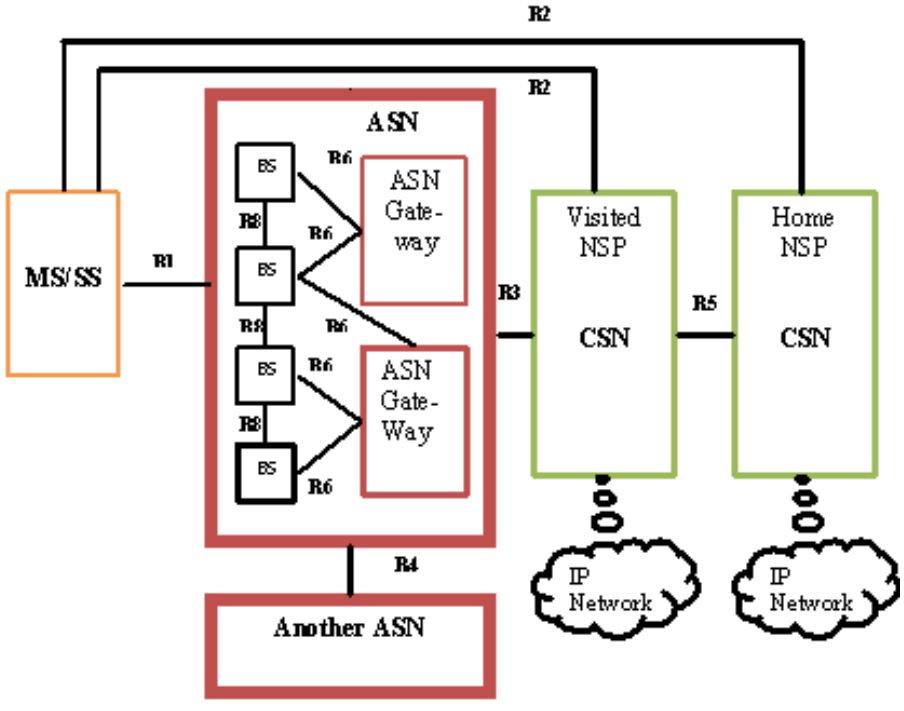

Figure 19 : Network Reference Level

The ASN can be composed by one or more BSs and one or more ASN gateways. It includes the capabilities which will provide radio access connection to the network to the user with a MS. One ASN or several ASNs (interconnected through R4) which are owned by a NAP (Network Access Provider) may be used by one or more business

entities called as NSP (Network Service Provider). Each NSP has a Connectivity Service Network (CSN) which provides IP connectivity and all the IP core functions. The subscriber may be served by a Home NSP or by a Visited NSP, a NSP with which the home NSP has a roaming agreement.

8.1.1. - Access Service Network (ASN)

The ASN has the following functions in the network:

- Layer 2 connectivity with the subscribers (MS)
- Radio Resource Management (RRM) mechanism such as handover control and execution
- Mobility functions such paging within the ASN or location management
- Network discovery and selection of the favorite CSN/NSP
- Relay function to establish connectivity in layer (IP) between the MS and the CSN

There are three different profiles for ASN and depending on which one; some functions are performed by BS and others by ASN-Gateway. For instance, profile B combines BS and ASN-GW in a single entity, whereas profiles A and C divide the functions between the two entities. The main differences between profile A and C are:

- In profile C, the handover function is in the ASN-GW and in profile C is in the BS and the ASN-GW only performs the handover relay function.
- In profile A, the radio resource controller (RRC) is located in ASN-GW, whereas in profile C this function is in the BS.

The BS implements the functions related to PHY and MAC layers described in the 802.16 standards and it is defined by a sector and frequency assignment. In the case of multiple frequencies assigned, the ASN will have as number of BS as frequencies assigned. It is responsible for scheduling the uplink and downlink, traffic classification, signaling messages exchanged with the ASN-GW, relaying authentication messages between the MS and the ASN-GW, reception and delivery of the traffic encryption key and key encryption key to the MS, and DCHP proxy functionality.

The ASN-GW is a logical entity which includes control function entities paired with a corresponding function in the ASN, in the CSN or in another ASN and bearer plane routing or bridging. Some of its functions are: to provide ASN location management and paging, to act as a server for network session and mobility management, the admission control and temporary caching of subscriber profiles and encryption keys, provides mobility tunnel establishment and management with the BS; to act as a client for session/mobility management; and to perform routing to the CSN. ASN-GW can be divided in two groups: enforcement point for bearer plane functions (EP) and decision point for no-bearer plane functions (DP).

8.1.2.-Connectivity Service Network (CSN)

CSN is the logical entity which provides all the functions that enables IP connectivity to the WiMAX subscriber. To support all the functions some equipment is needed such as routers, AAA proxy servers, DCHP servers, firewall, interworking

gateways to interoperability and user data-base. Some of the important provided functions are:

- Authentication, authorization and accounting (AAA) server
- IP address allocation to the MS
- Subscriber billing
- Inter-CSN tunneling to support roaming between NSPs
- Inter-ASN mobility management
- Connectivity infrastructure and policy control for services such as IP networks and Internet
- Mobility based on Mobile IP home agent (HA) where the MS's location is registered

8.1.3.-Reference Points

- R1 (MS-ASN): implements air-interface specifications. It needs to include protocols related to the management plane.
- R2 (MS-CSN): includes protocols related to authentication, authorization, IP host configuration management. It is a logical and not direct protocol interface between MS and CSN.
- R3 (ASN-CSN): transports control plane messages (AAA, mobility-management capabilities and data plane messages tunneling between the ASN and the CSN).
- R4 (ASN-ASN): transports control and data plane messages especially during the handover of a WiMAX user between two ASNs.
- R5 (CSN-CSN): consists of a set of bearer and control plane protocols for interworking between the home and the visited network.
- R6 (BS-ASN Gateway): consists of a set of control plane protocols (mobility tunnel management based on MS mobility) and bearer plane protocols (intra-ASN data path or inter-ASN tunnels between the BS and the ASN-GW)
- R7 (ASN GW DP-ASN GW EP): coordination between the two groups of functions
- R8 (BS-BS): transports control plane message flow (inter-BS communication protocol and additional protocols to control the efficient data transfer between BSs in a handover process) to reach a fast handover between BSs. It also can transport bearer plane messages (protocols that allow the data transfer between BSs during HO process).

8.2.-NETWORK FUNCTIONALITIES

8.2.1.-Network Discovery and Selection

It is common that one SS may operate in an environment where more than one network is available and multiple service providers are offering services over these networks. WiMAX implements a solution to discover and select the networks, composed of four stages:

- NAP discovery: using this process, the SS can discover all available NAPs within a coverage area. MS decodes the DCD message in the DL-MAP and identifies the "operator ID" in the BSID field.
- NSP discovery: using this process, the MS will discover all the NSPs that are providing service over a given ASN. It uses the list NSP ID broadcasted by the ASN.
- NSP enumeration and selection: the MS will select one of the available NSPs using an algorithm. The selection can be automatic or manual.
- ASN attachment: after the NSP selection, the MS indicates its selection and attaches to an ASN providing its identity and home NSP domain by sending a NAI (Network Access Identifier) message.

8.2.2.-Mobility Management

The mobility procedures are divided in two different levels:

- Micromobility or ASN-anchored mobility: it refers to intra-ASN mobility where a CoA (Care of Address) address update is necessary and the MS maintains the same anchor foreign agent. The handover is between R6 or R8 reference points.

- Macromobility or CSN-anchored mobility: it refers to inter-ASN mobility where the MS changes to a new anchor foreign agent. The handover is produced in the R3 interface with tunneling over R4 to transport undelivered packets. WiMAX systems must support one of the following mobile IP schemes: proxy-MIP(MS is unaware and there is not signaling over the air to communicate the CSN change) and the other scheme is Client-MIP (client participates in inter-ASN mobility)

8.2.3.-IP Address Assignment

WiMAX networks support two addressing mechanism: IPv4 and IPv6. The Dynamic Host Control Protocol (DHCP) is used to allocate a dynamic point of attachment (PoA) IP address to the MS. The home CSN may allocate IP address to the ASN via AAA. The DHCP proxy will be allocated in the ASN, whereas the DHCP server will be in the CSN.

To support IPv6, the ASN includes an IPv6 access router functionality to assign a globally routable IP address to the MS. In mobile IPv6, the MS obtains the care-of address (CoA), which is a temporary IP address, from the ASN of the visited network and the home address (HoA) from the home CSN.

In the next table, there is a classification of the different PoA methods used depending on the IP version and the type of service:

Service type	PoA IP address scheme IPv4	PoA IP address scheme IPv6
Fixed	Static or dynamic	Static or stateful
Nomadic	Dynamic	Stateful or stateless
Mobile	DHCP for P-Mobile IP terminals	Stateful or stateless
	MIP mode for C-Mobile IP terminals	

- Stateful: Host obtains address from a server that keeps track of which addresses have been assigned to which hosts.
- Stateless: The stateless mechanism allows a host to generate its own addresses using a combination of locally available information and information advertised by routers
- Static: fixed address assigned by a server
- Dynamic: temporary address that changes every connection

8.2.4.-AAA Framework

WiMAX architecture is designed to support all the IEEE 802.16e services based on IETF (Internet Engineering Task Force)-EAP (Extensible Authentication Protocol) specifications. The following services are included:

- Authentication: device authentication in the network
- Authorization: user profile information used for mobility or QoS management
- Accounting: information for pre-paid or post- paid services

Security will be explained accurately in the chapter 9.

8.2.5.-Quality-of-Service Architecture

WiMAX Forum defines the various functional entities to provision and manage the service flows. It enables different flexible support of simultaneous use of a diverse set of IP services. The architecture supports differentiated levels of QoS, bandwidth management and admission control. It calls for an extensive use of standard IETF (Internet Engineering Task Force) mechanisms for managing policy decision and policy enforcements between operators.

The important functional entities are:

- Policy function (PF): evaluates a service request against policy database located in the home NSP. Service request to the PF may come from the SFA or from an AF.

- AAA server: it stores the user QoS profiles and the associated policy rules. User QoS is downloaded to a SFA at network entry within the authentication and authorization process.

- Service Flow Management (SFM): it is located in the BS and manages local resource information and performs administration control that determines, based on available radio resource and other local information, whether a radio link can be created.

- Service Flow Authorization (SFA): this logical entity is located in the ASN and evaluates the incoming service request against the QoS profile, after that the SFA will decide whether to allow the flow or not. If the QoS profiles are not with the SFA, it forwards the service flow to the PF for decision making. For each MS, one SFA is assigned as anchor SF for a given session and it is responsible for the communication with the PF. The relay SFA that directly communicates with the SFM is called serving SFA. The SFAs will perform ASN-level policy enforcement using a Local Policy Database (LPD)

- Application function: it can initiate service flow creation on behalf of a user.

9.-SECURITY

A secure wireless architecture should support the following basic requirements:

- Data integrity: ensure data are protected from being tampered by someone during the path
- Authentication: ensure that the user/device is the one that says to be
- Privacy: protection against spy network
- Authorization: verify that the user/device is authorized to receive a specific service of a network
- Access control: ensure that only authorized users can access to the network

Security is handled in various layers of the OSI reference model. Thus, the security sublayer specified in the 802.16 standard deals with the link layer for authentication, authorization and encryption processes. In this layer the most used techniques are AES, X.509 and PKI.

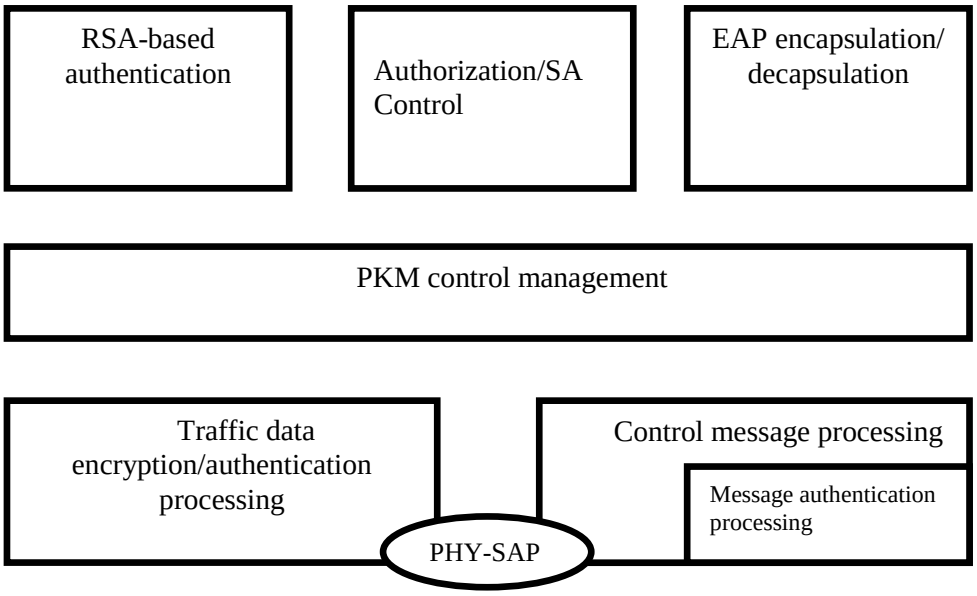

Figure 20 : Protocol stack of the security sublayer

In the network layer, firewalls and AAA servers are used in order to avoid malicious attacks. In this case, RADIUS and DIAMETER are the deployed techniques for AAA interaction.

Transport layer (through Transfer Layer Security (TLS)) and application layer (through certificates, end-to-end security and digital signatures) present additional security measures.

9.1.-AUTHENTICATION AND ACCESS CONTROL

The data-link layer security functions perform most of the functions related to authentication, authorization and encryption between the user and the base station. An access control system is composed of three elements: supplicant (entity that wants to access to the network), authenticator (entity which controls the access) and authentication server (entity which decides based on some factors if a user can get access).

9.1.1.-Authentication

Authentication can come in two different ways:

- Unilateral authentication: where the BS identifies the MS
- Mutual authentication: where BS authenticates the MS and the MS authenticates the BS

Authentication procedure is made using a private key interchange protocol that allows authentication and also the establishment of the encryption key. In WiMAX, the Privacy Key Infrastructure (PKI) is built based on symmetric key encryption which is composed by two different keys: public key and private key. The public key is known widely, whereas the private key is kept as secret.

PKM establishes an Authentication Key (AK) of 160 bits between the MS and the SS, after that the Key Encryption Key (KEK) of 128 bits is derived from the AK. KEK is not used for encryption of traffic data, for this purpose the Traffic Encryption Key (TEK) is required. TEK is generated in the BS with a TEK encryption algorithm where KEK is used as encryption key.

The IEEE 802.16e standard defines a Privacy Key Management (PKM) version 2 whose main difference respect to PKMv1 is the usage of mutual authentication, so the BS is also authenticated in order to prevent connection to a false BS. It allows three types of authentication options:

- RSA based authentication: A BS identifies the SS through a X.509 digital certificate issued by the SS manufacturer which contains the MS's Public Key (PK) and MAC address. After that, the BS uses the PK to encrypt an AK which is then sent to the MS.

- EAP (Extensible Authentication Protocol) based authentication: specifies a set of request messages that the supplicant (SS) sends to the authentication server located on the BS; based on the responses, the access to the network is possible or not. Some rules to authenticate a user or a device are defined as EAP methods such as certificates, credentials, passwords and smart cards. In WiMAX, the choice of the authentication method depends on the operator. Thus, there are three different methods: EAP-AKA (for SIM cards), EAP-TLS (for X.509 digital certificate) and EAP-TTLS (for MS-Chapv2 (Microsoft –Challenge Handshake Authentication Protocol)).

- RSA based authentication followed by EAP authentication.

Once the authorization is done, a Security Association (SA), which is a set of security information managed by the BS and shared between the BS and some MSs, is established to support secure communications. This set of security information consists of methods for data encryption, data authentication and TEK exchange.

There are three types of SA: primary, dynamic and static. Primary SAs consists of an initial TEK exchange during the MS initialization phase, whereas static SAs are performed within the BS. After the SA establishment, the BS periodically will refresh the keying elements in response to the creation and termination of service flows. This process is known as dynamic SAs.

9.1.2- Authorization

After authentication, the MS requests authorization (request for an AK and SA identity (SAID)) to the BS through X.509 certificates, encryption algorithms and cryptographic IDs. The BS interacts with the AAA server and responses with the AK encrypted with the MS's public key and also with a lifetime key (from 30 minutes to 7 days) and a SAID. After the initial authorization, the AAA server reauthorizes periodically the SS through the BS.

The X.509 digital certificate version 3 used in WiMAX provides a public key infrastructure used for authentication. Each SS carries a unique X.509 certificate which has been issued by a Certification Authority and installed by the SS manufacturer. This certificate includes the SS MAC address and the SS RSA public key.

9.1.3.-Security in the Network Layer

The authentication and authorization methods mentioned previously run over PHY and MAC layer and between the client and the authentication server. However, there are other mechanisms that run over network layer between the authenticator and the authenticator server: RADIUS and DIAMETER.

RADIUS is a client/server UDP application that runs over IP where the authentication server is the RADIUS server and the authenticator is the RADIUS client. It supports AAA functions and also provides some other function measuring session volume and duration. The name of DIAMETER comes from the fact that is twice better than RADIUS. It corrects some deficiencies of RADIUS protocol.

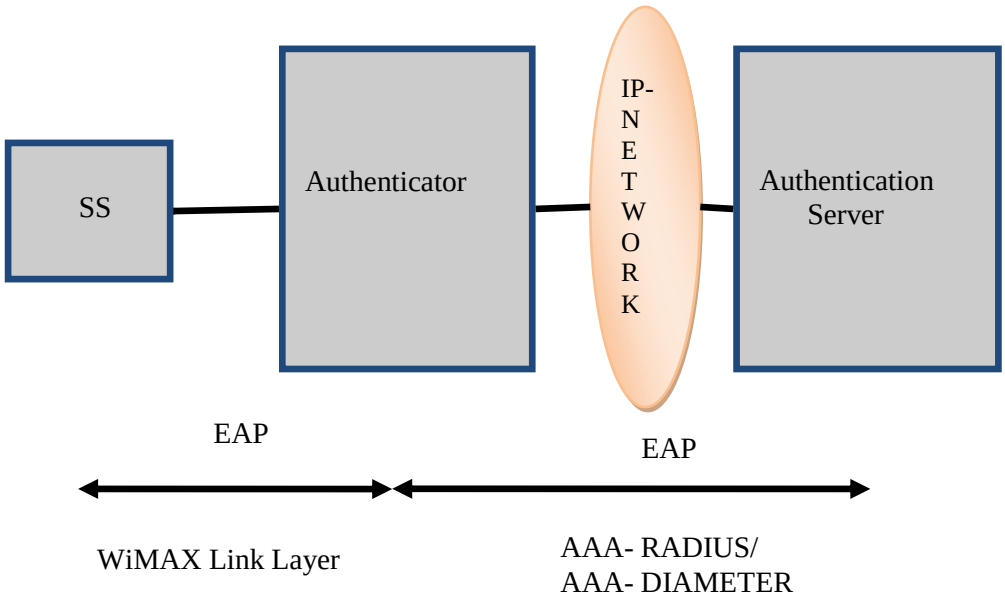

Figure 21: WiMAX Access-Control Structure

9.2.-DATA ENCRYPTION

Encryption is the process used to protect the confidentiality of data from the transmitter to the receiver. For this purpose, a block of data to encrypt known as plaintext is taken and combined with another block of data known as encryption key to perform a reversible mathematical operation in order to generate the ciphertext. In the receiver, an inverse operation, decryption, is performed in order to extract the plaintext of the block of data. If the same code is used for encryption and decryption, the process is known as symmetric key encryption. If different codes are used it is an asymmetric encryption.

In the 802.16 standard, two different encryption methods can be used: AES (Advanced Encryption Standard) and DES (Data Encryption Standard). DES has several security holes and it is considered insecure so the link-layer encryption method widely adopted in wireless telecommunications such as WiMAX is AES. It offers strong encryption and AES is also fast, easy to implement in hardware and software, and requires less memory than other encryption schemes.

In the 802.16e standard, four different implementations of AES are considered: AES in CBC (Cipherblock Chaining Code) mode, AES in CBCM mode (CBC-MAC), AES in Counter (CMC) mode, AES KeyWrap with a 128-bit key. Both Wi-Fi and WiMAX

systems specify the use of AES in counter mode with cipher-block chaining message-authentication mode (CBC-MAC or CCM).

In the next figure, the MAC PDU using AES-CCM is represented. First, a 4-bytes packet data number (PN) is added before the encrypted data. It will be followed by the plaintext of L-bytes which is encrypted using the current TEK and followed by the cyphertext Message Authentication Code (MAC) or Integrity Check Value (ICV) of 8-bytes. PN is linked to the SA and incremented in each PDU transmitted and this PN is not encrypted but it is included for the MAC calculation.

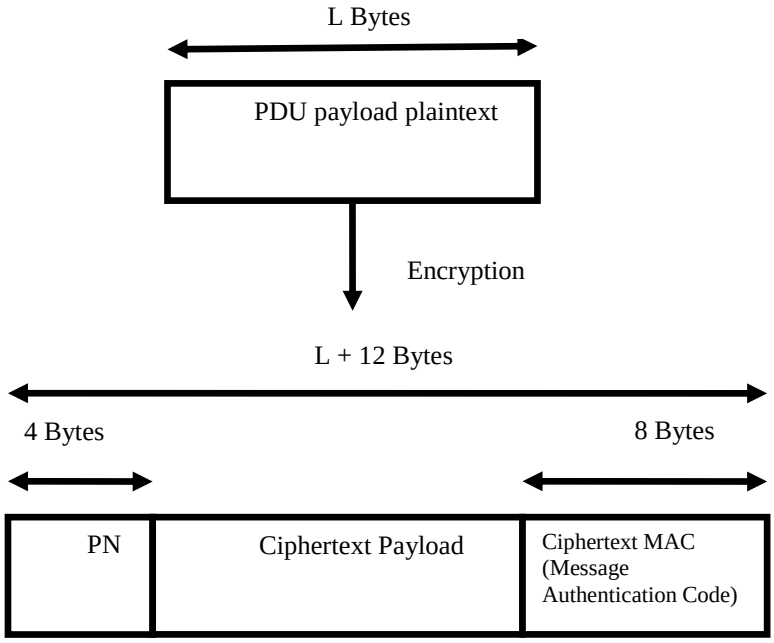

Figure 22: Encrypted payload format in AES-CCM

10.-APPLICATIONS

WiMAX has some advantages to wired connections: low-operational cost, cheaper implementation costs, less maintenance costs, less impact on environment, quicker and easier setup and more flexibility.

WiMAX can have a range up to 50 km at data rates of 75 Mbps using both unlicensed and licensed frequency bands. It can be used for large area coverage and also for last-mile and backhauling. In this chapter, some of the applications will be explained. In the next figure the main usages of WiMAX are represented:

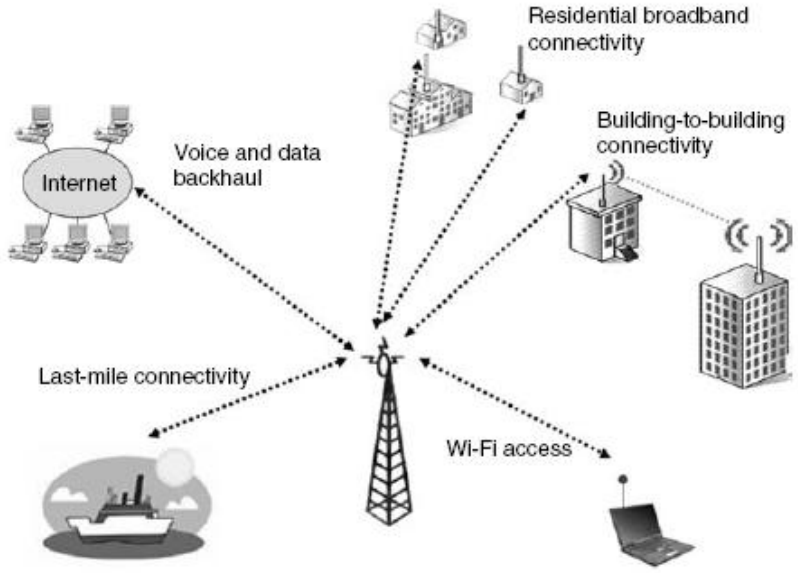

Figure 23 : Main usages of WiMAX

10.1.-WMAN (WIRELESS METROPOLITAN AREA NETWORK)

WiMAX can provide wireless broadband access to metropolitan areas with the same result as traditional MAN (Metropolitan Access Network) technologies but without the necessity of maintaining the physical transmission medium (fiber, copper). Another drawback of wired connections is the limitation due to distance and the quality of wiring.

With a WMAN based on WiMAX is possible to provide broadband access for services as internet or multimedia applications up to several kilometers using PMP (point-to-multipoint) topology. However, this WMAN based in WiMAX is limited by frequency ability, transmit power and receiver sensitivity.

Usually a group of users is connected to the network through a BS in NLOS conditions and each BS is backhauled to the core network via fiber or through a PTP (point-to-point) microwave link. In the next figure the typical structure is represented:

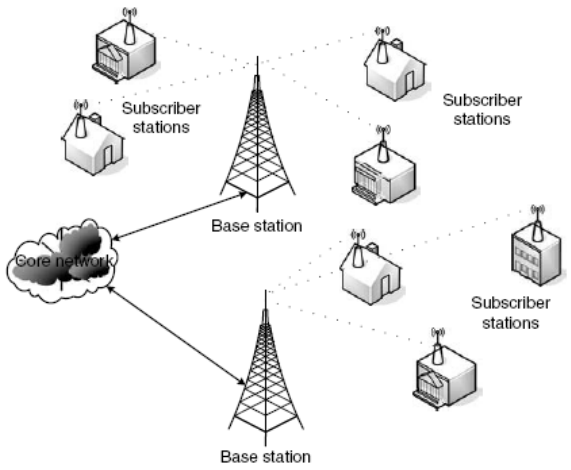

Figure 24: WMAN Network

10.2.-WiMAX MILITARY APPLICATIONS

WiMAX is a suitable technology for military applications because it uses frequency bands higher than commercial and military frequency bands, so it does not interfere in the current communications services.

With WiMAX is possible to exchange information from different sources and it is ideal for tactical defense operations. From the commander center it is possible to transmit information to the soldiers (through the antenna attached on their vehicles) in a wide area.

10.3.-RURAL AREA BROADBAND SERVICES

Providing a good quality and high-speed connection to all the areas in a country is one of the challenges that every government has to overcome. In the big cities is not a problem due to the existence of a wired infrastructure via fiber or copper, whereas in the rural areas is not as easy. There are rural areas where the broadband services are limited by low-speed dial-up connections or without any connection to Internet at all.

For the operators extend the wired infrastructure can result so expensive and without economic-sense due to the low-density of population of these rural areas and the long distance from the urban areas. Although satellites can be used to serve these areas, it has some disadvantages such as limited upstream bandwidth, spectrum unavailability and high-delay. However, WiMAX can be a perfect solution due to its low cost of installation and maintenance, its scalability that allows adding a new cell easily and also it can provide high-speed access.

10.4.-WIRELESS BACKHAUL

The backhaul is the connection from the access point to the provider and also the connection from the provider to the core network. For instance, for cellular systems, the

backhaul is done by leasing T1 services for a third-provider and it can be really expensive. However, WiMAX can provide high-capacity backhaul serving multiple cells and with the possibility of expansion to more cell with a low cost.

Due to the expansion of Wi-Fi hotspots, WiMAX can be used as backhaul for them. WiMAX can combine multiple Wi-Fi access points together into a cluster and fill the gap between their coverage areas. For this implementation, the radio link is established in LOS conditions and usually with PTP topology, although in some cases PMP is used to provide a complete solution. In the next figure, the backhaul for a cellular network is represented:

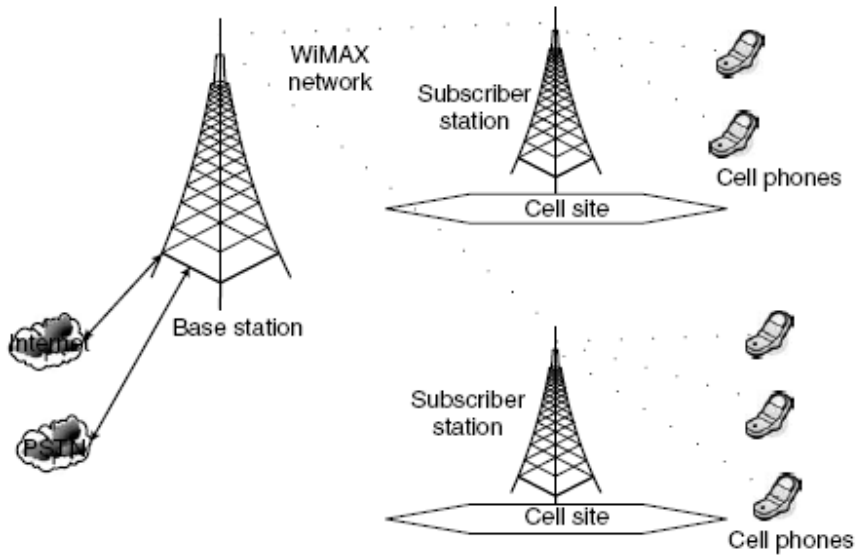

Figure 25 : Cellular Backhaul

10.5.-LAST-MILE ACCESS TO THE BUILDINGS

Sometimes, the last-mile connection to the buildings can be a problem to provide high-speed access to subscribers, SOHO (Small Office Home Office) or businesses. The installation of DSL and cable solutions can result expensive, laborious and also requires a long-time. WiMAX can be used for this last-mile link with a lower cost and offering a comparable speed. The topology used is PMP linking a central station to a group of users.

10.6.-PRIVATE NETWORKS

For some big companies or government departments can be useful to connect the central office with the remote offices through a high-speed connection. For this purpose, WiMAX is an alternative to wired connections which can result expensive. Using a PMP topology it will be possible to link the central office with the others.

10.7.-SECURITY APPLICATIONS

Wireless video surveillance combines IP technology and WiMAX technology for the surveillance of public places such as cities or private places such as shops, military bases or buildings. Using WiMAX is possible to cover a wide area and also hard-to-reach locations without the necessity of installing wired infrastructure. Through the use of IP networks, it is possible to transmit the videos via secure and private IP.

10.8.-MEDICAL APPLICATIONS

In some cases, WiMAX technology can be used as the foundation of a mobile hospital and a platform for e-health. A doctor can diagnose his patient from the distance connecting the doctor's computer with the patient's computer through WiMAX. For example a report of blood pressure can be send to the doctor and he can give a diagnostic.

WiMAX can also be useful to connect the mobile hospital vans and communicate some data and instructions within a disaster zone where the wired infrastructure is broken down.

10.9.-OTHER APPLICATIONS

After the explanation of the most common usages of WiMAX, some other applications will be mentioned in this section:

- Expansion of ATM to rural and remote areas connecting them to the central office through WiMAX
- WiMAX allows a video conferencing to its subscribers
- Real-time monitoring for dangerous works and sensor networks to monitor temperature, air-quality and other factors
- WiMAX can provide vehicular data voice services to allow the logistic providers to contact their vehicles in real-time
- Backup/ redundancy to wired networks
- Though WiMAX, public safety agencies can be connected with each other
- In disaster zones where the wired infrastructure break down, WiMAX can be a solution for the communications
- Telephone's services using VoIP technology
- Communications and Internet access in the sea

11. – COMPARISONS

11.1.-COMPARISON BETWEEN FIXED AND MOBILE WiMAX

At the moment, Fixed WiMAX is more developed and has more certified products in the market. It could be a suitable solution to provide broadband wireless technology in rural places or developing countries where the wired infrastructure is not deployed. However, in developed countries with a well wired infrastructure deployed, Fixed WiMAX does not offer any advantage in speed to high data-rate technologies such as cable or DSL. The main advantage that WiMAX can offer is to provide a cheaper broadband wireless access allowing nomadicity (connection works everywhere in the city although can be necessary to restart session) or mobility (connection works everywhere without the necessity of restarting session).

Another advantage of WiMAX is that Fixed WiMAX can use the same infrastructure than Mobile WiMAX. Thus, for an operator can be useful to start covering a small area with Fixed WiMAX and obtaining a leading position before the final deployment of Mobile WiMAX.

The principal advantages that Mobile WiMAX presents respect to Fixed WiMAX are:

- Support for mobility (even at vehicular velocities) and robust support for nomadicity, non-line of sight (NLOS)
- It offers also Mobile VoIP, so it can be also an alternative to cellular phones
- Mobile WiMAX can become an alternative to 3G mobile communications for data applications
- It can be a good alternative for new operators to offer mobile services without the necessity of an expensive infrastructure and with low operational cost

The main drawback is that Mobile WiMAX is a more complex technology, so that means a higher cost for the network operator, especially if Multiple Input Multiple Output (MIMO) or Adaptive Antenna System (AAS) are used.

11.2.-COMPARISON BETWEEN WiMAX AND Wi-Fi

The main difference is that WiMAX has much longer coverage distance than WiFi and can also allow mobility between cells. These two technologies are complementary and WiMAX can be used as backhaul for Wi-Fi hotspots. Due to the short coverage range of Wi-Fi hotspots, it is necessary the installation of several access points to cover an area, however with WiMAX one user can move around a city without disconnection. Besides, the use of the inefficient CSMA/CA and the interference constraints of operating in license-exempt band reduce the capacity of outdoor Wi-Fi. Another additional drawback is that Wi-Fi cannot offer broadband access at vehicular velocity.

Although WiMAX has a better performance than Wi-Fi, the cost and complexity of the equipment and the high cost of the frequency license, can make difficult the replacement of Wi-Fi by WiMAX for some applications. The main advantage of Wi-Fi

is the wide availability of terminal with Wi-Fi interface such as PDAs, laptops, cellular phones, cameras or media players.

Other important advantage is that WiMAX can serve many user per channels (100 or more), whereas in Wi-Fi, only one user can be served in a channel. Another advantage is the five QoS that WiMAX offers instead of only one QoS class (based on best effort) in Wi-Fi.

11.3.-COMPARISON BETWEEEN WiMAX AND 3G

Although 3G is currently deployed and 3G terminals are already in the market, there is space on the market for both. Thus, in a few years depending on the application, country and on the market, 3G or WiMAX will be more suitable. In this subchapter the principal advantages of both will be explained:

Advantages of 3G:

- This technology is already in use in many countries, so 3G presents and advance of three years respect to WiMAX
- The spectrum used in WiMAX can change from one country to another, so it is possible that not all equipments can be used worldwide and it will be needed multifrequency equipments. On the contrary, most of the 3G terminals can work in other countries.
- WiMAX uses higher frequencies than 3G and usually when frequency increases received power decreases. It is usual that transmitted power is limited at these frequencies due to environmental and regulatory requirements.
- Operators with license and manufacturer companies developing 3G terminals are more interested in 3G than in developing a new technology
- In roaming and high-speed mobility, WiMAX capabilities are unproven comparing to 3G

Advantages of WiMAX:

- High amounts of money were paid in some countries for 3G license, however WiMAX spectrum should be cheaper
- The WiMAX physical layer is based on OFDM, that is high spectral-efficient. New upgrades of 3G including OFDM and MIMO in it are being developed. This evolution is called LTE (Long-Term Evolution)
- WiMAX is an all-IP technology, whereas 3G systems use some protocols developed for the first version of 3G that are not all-IP. Using this IP architecture simplifies the core network whereas 3G has a complex and separate core network for voice and data. IP also allows a better integration with application developers and an easier convergence with other networks.
- WiMAX has a strong support of important industry companies (WiMAX Forum)
- WiMAX is an open system where many algorithms are left to the vendor so it allows optimization. On the other hand, it could cause some interoperability problems
- WiMAX offers higher data-rates, greater flexibility, higher average throughputs and system capacity

- WiMAX has the ability of supporting more symmetrical links for T1 replacement and flexible adjustment of uplink-downlink data-rate ratio, whereas 3G has fixed data rate for uplink and downlink

11.4.-OTHER COMPARABLE SYSTEMS

Two other standards can emerge in the future and compete with WiMAX, at the moment are under development: IEEE 802.20 and IEEE 802.22.

The IEEE 802.20 standard is aimed to provide broadband access at vehicular velocities up to 250 kmph in frequency lower than 3.5 GHz with downlink data-rate of 4 Mbps and uplink data-rate of 1.2 Mbps.

The IEEE 802.22 standard is aimed to provide wireless broadband access in rural and remote regions using the frequency bands of unused TV channels that were operating in VHF and UHF bands. FCC plans to allow the use of this spectrum without licenses.

11.5.-COMPARISON TABLE

In the next table, the different parameters of Fixed WiMAX, Mobile WiMAX, 3G and Wi-Fi are presented:

Parameter	**Fixed WiMAX**	**Mobile WiMAX**	**Wi-Fi**	**3G (HSPA)**
Standards	IEEE 802.16-2004	IEEE 802.16e-2005	IEEE 802.11a/g/n	3GPP Release 6
Frequency	3.5 and 5.8 GHz initially	2.3 GHz, 2.5 GHz and 3.5 GHz	2.4 GHz, 5 GHz	800/900/1,800 /1,900 MHz
Bandwidth	3.5MHz and 7MHz in 3.5GHz band ; 10 MHz in 5.8GHz	3.5 MHz, 7MHz, 5MHz, 10MHz and 8.75MHz initially	20MHz for 802.11a/g; 20/40MHZ for 802.11n	5MHz
Peak DL data rate	9.4Mbps in 3.5 MHz with 3:1 DL-to-UL ratio TDD;6.1Mbps with 1:1	46Mbps with 3:1 DL-to-UL ratio TDD; 32Mbps with 1:1	54 Mbps shared using 802.11a/g; more than 100Mbps peak layer 2 through-put using 802.11n	14.4 Mbps using all 15 codes; 7.2Mbps with 10 codes
Peak UL data rate	3.3 Mbps in 3.5Mhz using 3:1 DL-to-UL ratio;6.5Mbps with1:1	7Mbps in 10 MHz using 3:1 DL-to-UL ratio; 4 Mbps using 1:1		1.4 Mbps initially; 5.8Mbps later
Modulation	QPSK, 16QAM,64QAM	QPSK, 16QAM,64QAM	BPSK, QPSK,16QAM, 64QAM	QPSK, 16QAM
Duplexing	TDD, FDD	TDD initially	TDD	FDD
Multiplexing	TDM	TDM/OFDMA	CSMA	TDM/CDMA
Cell coverage	5-10 km (up to 50 km)	2-5 km	Indoor : 30 m Outdoor: 300 m	1.5-5 km

12.-SUMMARY AND CONCLUSION

12.1.-SUMMARY

During this thesis WiMAX and the IEEE 802.16 standard were explained. In this section, a brief summary with the main aspects of WiMAX is included:

- WiMAX is based on a flexible and robust air interface defined by the IEEE 802.16 standard (only PHY and MAC layers are specified)
- The IEEE elaborates the specifications and leaves to WiMAX Forum (group of industries) the task of converting them into an interoperable standard that can be certified
- The physical layer is based in OFDM, specifically OFDMA a multi-user version of OFDM, which allows overcome the multipath distortion and intersymbol interference. For increasing the reliability of the link layer, some techniques such as hybrid ARQ or error correction coding are used
- WiMAX uses adaptive modulation and coding, multiuser diversity and spatial multiplexing. These techniques allow to improve the overall capacity of the system
- Flexible MAC layer can accommodate different types of traffic such as video, voice or multimedia
- WiMAX specifies security functions such as strong encryption and authentication
- Two versions of WiMAX are specified: Fixed WiMAX (802.16-2004) and Mobile WiMAX (802.16-2005). Mobile WiMAX will allow mobility up to vehicular velocities without losing the connection
- To support mobility, WiMAX incorporates mechanisms for location management and handoff management
- WiMAX an all-IP-based network architecture that allows all the advantages of IP
- Advantages: lower deployment and maintenance cost than wired infrastructure, mobility support, high-data rates, strongly secure communications, possibility of using unlicensed frequency bands and wide coverage up to 50 km

12.2.-FINAL CONCLUSION

WiMAX has generated a tremendous amount of interest in the wireless community and it can be one of the most deployed technologies in the future. The main reason for its success is the strong support of the industry and the strong base of standardization. IEEE 802.16 has evolved considerably from the first standard approved in 2002 and it will evolve more due to the new standards under development. At the moment, in 2008, it is deployed for some applications such as providing broadband access in rural areas, backhaul for Wi-Fi hotspots or video surveillance in the cities. Moreover, the combination of Wi-Fi (indoor) at home and WiMAX (outdoor) can be a really competitive technology.

In the market there are already a wide variety of certified products for Fixed WiMAX. However, as mentioned, in places with a well developed telecommunications infrastructure, Fixed WiMAX does not present any advantage to technologies such as DSL or cable.

In the future, Mobile WiMAX is expected to offer broadband full mobility for all kind of services such as voice, data and video and therefore offer 4G services. In April 2008, the first eight Mobile WiMAX products for 2.3 GHz were certified by WiMAX Forum and it is expected that more than 100 products (also for 2.5 GHz profiles) will be certified at the end of 2008.

WiMAX Forum projects that in 2012, WiMAX will have 133 millions of worldwide users (70 per cent of them will use mobile and portable devices).

Nowadays, Korea is one of the most important markets for WiMAX, there are 140,000 of subscribers and expects at least 420,000 at the end of 2008 covering the 40 per cent of the country. In Europe, in almost every country there are operators offering broadband services, especially in rural regions, through WiMAX. For instance, in Finland, there are 15 WiMAX operators with coverage especially in rural areas of Lapland. The expansion of WiMAX can be helped by the action of governments which can be interested in providing a high-speed broadband access to every user in every area.

It is clear that year after year users demand higher speed access and have the necessity of mobility and to be connected in everywhere at anytime. No one knows which technology will be more successful in the future but WiMAX can achieve success thanks to the IEEE 802.16 group mainly, which is continuously adapting the standard to the new requirements, and the strong support of the industry.

13.- REFERENCES

1. Jeffrey G.Andrews, Arunabha Gosh and Rias Muhamed; *Fundamentals of WiMAX, understanding broadband Wireless Networking*; Prentice Hall, 2007

2. Loutfi Nuaymi; *WiMAX technology for broadband access,* John Viley & Sons, 2007

3. IEEE; *The 802.16-2005 standard*

4. IEEE; *The 802.16-2004 standard*

5. Syed Ahson and Mohammad Ilyas; *WiMAX Applications,*CRC Press, 2008

6. Syed Ahson and Mohammad Ilyas; *WiMAX Technologies, Performance Analysis and QoS,* CRC Press, 2008

7. Syed Ahson and Mohammad Ilyas; *WiMAX Standards and Security,* CRC Press, 2008

8. Yang Xiao; *WiMAX MobileFi: Advanced Research and Technology,* Auerbach Publications, 2008

9. Clint Smith and John Meyer; *3G Wireless with WiMAX and Wi-Fi,*McGraw-Hill Professional Engineering, 2004

10. Daniel Sweeney; *WiMAX Operator's Manual: Building 802.16 Wireless Networks,* Apress, 2006

11. Louis Litwin and Michael Pugel; *The principles of WiMAX,* www.rfdesign.com, 2001

12. WiMAX Forum: Senza Fili Consulting; *Fixed, nomadic, portable and mobile applications for 802.16-2004 and 802.16e WiMAX networks,* WiMAX Forum , November 2005

13. WiMAX Forum*; Mobile WiMAX Part I: A technical overview and Performance Evaluation,* WiMAX Forum, August 2006

14. WiMAX Forum; Documents of www.wimaxforum.org

15. Parviz Yegani; *WiMAX Overview*, Cisco Systems, 2005

16. Rohde & Schwarz; *WiMAX: General Information about the standard 802.16*

17. Michael Richardson and Patrick Ryan; *WiMAX: opportunity or hype?,* University of Colorado, 2006

18. AirSpan Networks Inc, *Mobile WiMAX Security,* 2007

19. Documents of IEEE: www.ieee802.org

20. Rafael Herradón Diez, *Comunicaciones móviles digitales*, DIAC- Polytehnic Universtity of Madrid, 2007

21. WiMAX 360; *WiMAX Know-How from Engineers, Technicians and WiMAX Professionals*, www.wimax360.com

22. Dictionary Spanish- English: www.wordreference.com

Table of figures: