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Comparison between UMTS/HSDPA and WiMAX/IEEE 802.16e in Mobility Scenarios

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To my brother and my parents

“Pedras no caminho? Guardo todas, um dia vou construir um castelo…”

(Fernando Pessoa)

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Abstract

The purpose of this thesis was to compare the performance of UMTS/HSDPA and Mobile WiMAX. Two scenarios were considered: single and multiple users. In the single user scenario, only one user is placed in the network requesting a certain throughput, and then the maximum distance to the base station for a given throughput is calculated. Regarding the multiple user scenario, it has the objective of studying a realistic approach, where several users perform different services. A simulator was developed to study the multiple user scenario, enabling the analysis of network performance by varying several parameters.

For the single user scenario, it is observed that the cell radius for UMTS/HSDPA is higher than the one for Mobile WiMAX, due to the frequencies considered, up to 8.46 Mbps, but beyond this value Mobile WiMAX is more favourable, up until 15.09 Mbps.

Considering the multiple user scenario, Mobile WiMAX presents better results than UMTS/HSDPA, regarding average network throughput and number of served users, because of its higher capacity. As for the network radius, results are similar.

Keywords

UMTS/HSDPA, Mobile WiMAX, Capacity, Coverage, Multi-Service.

Resumo

O objectivo desta tese foi fazer a comparação de UMTS/HSDPA com Mobile WiMAX em termos de desempenho. Foram elaborados dois cenários: o de utilizador único e o de vários utilizadores na rede. No caso do utilizador único, é calculada a distância para a qual o utilizador consiga receber o ritmo de transmissão. Relativamente ao cenário de vários utilizadores na rede, o objectivo foi analisar um caso realista onde vários utilizadores estão a realizar serviços diferentes. Para testar o desempenho de vários utilizadores foi desenvolvido um simulador que permite a análise dos dois sistemas a determinado instante, variando certos parâmetros.

Para um único utilizador, observou-se que o raio da célula para UMTS/HSDPA é maior que o do Mobile WiMAX, até 8.46 Mbps, mas para além deste valor o Mobile WiMAX é mais favorável até 15.09 Mbps.

Quanto ao cenário de vários utilizadores na rede, Mobile WiMAX apresentou melhores resultados que UMTS/HSDPA relativamente aos ritmos de transmissão médios na rede e ao número de utilizadores servidos, devido à sua maior capacidade. Quanto ao raio da célula, os resultados obtidos são semelhantes.

Palavras-chave

UMTS/HSDPA, Mobile WiMAX, Capacidade, Cobertura, Multi-Serviço.

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List of Acronyms

2G	2nd Generation
3G	3rd Generation
16QAM	16 Quadrature Amplitude Modulation
3GPP	3rd Generation Partnership Project
64QAM	64 Quadrature Amplitude Modulation
AAA	Authentication Authorisation and Accounting
AMC	Adaptive Modulation and Coding
AMR	Adaptive Multi-Rate
AP	Access Point
ARQ	Automatic Repeat Request
ASN	Access Service Network
ASN-GW	ASN Gateway
BCH	Broadcast Channel
BE	Best Effort
BPSK	Binary Phase Shift Keying
BS	Base Station
BWA	Broadband Wireless Access
CDMA	Code Division Multiple Access
CN	Core Network
CPCH	Common Packet Channel
CPE	Consumer Premises Equipment
CPICH	Common Pilot Channel
CQI	Channel Quality Information
CS	Circuit Switch
CSN	Connectivity Service Network
DCH	Dedicated Transport Channel
DL	Downlink
DSCH	Downlink Shared Channel
DSL	Digital Subscriber Line
DTX	Discontinuous Transmission
ertPS	Extended Real-time Polling Service
FACH	Forward Access Channel
FDD	Frequency Division Duplex
FTP	File Transfer Protocol

GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile Switching Centre
GPRS	General Packet Radio System
GSM	Global System for Mobile Communications
H-NSP	Home-NSP
HARQ	Hybrid Automatic Repeat Request
HHO	Hard Handover
HLR	Home Location Register
HS-DPCCH	High-Speed Dedicated Physical Control Channel
HS-DSCH	High-Speed Downlink Shared Channel
HS-PDSCH	High-Speed Physical Downlink Shared Channel
HS-SCCH	High-Speed Shared Control Channel
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
IAO	Interactive Oriented
IBB	Interactive Background Balanced
IEEE	Institute of Electrical and Electronics Engineers
IMS	IP Multimedia Sub-system
IMT-2000	International Mobile Telecommunications-2000
IP	Internet Protocol
LBS	Location-Based Services
LoS	Line of Sight
MAC	Medium Access Control
MAC-hs	MAC-high speed
MAP	Medium Access Protocol
ME	Mobile Equipment
MIMO	Multiple Input Multiple Output
MMS	Multimedia Messaging Service
MSC	Mobile Services Switching Centre
MT	Mobile Terminal
nrtPS	Non-real-time Polling Service
NAP	Network Access Provider
NLoS	Non Line of Sight
NSP	Network Service Provider
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OVSF	Orthogonal Variable Spreading Factor
P-CPICH	Primary CPICH
PCH	Paging Channel

PHY	Physical Layer
PLMN	Public Land Mobile Network
PMP	Point-to-Multipoint
PS	Packet Switch
PUSC	Partially Used Sub-Carrier
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
rtPS	Real-time Polling Service
RACH	Random Access Channel
RLC	Radio Link Control
RNC	Radio Network Controller
RRC	Radio Resource Control
RRM	Radio Resource Management
SC	Single Carrier
SCCPCH	Secondary Common Control Physical Channel
SF	Spreading Factor
SGSN	Serving GPRS Support Node
SHO	Soft Handover
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SIP	Session Initiation Protocol
SIR	Signal-to-Interference Ratio
SMS	Short Messaging Service
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
SRNC	Serving RNC
SS	Subscriber Station
SSHO	Softer Handover
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UGS	Unsolicited Grant Service
UL	Uplink
UMTS	Universal Mobile Telecommunications System
USIM	UMTS Subscriber Identity Module
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
V-NSP	Visited-NSP
VLR	Visitor Location Register
VoIP	Voice over IP

WCDMA	Wideband Code Division Multiple Access
WiBRO	Wireless Broadband
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WWAN	Wireless Wide Area Network

List of Symbols

α	DL orthogonality factor
β	Effective code rate
Δf_c	Channel bandwidth
Δt_G	Guard time factor
η	Load factor
η_{DL}	DL load factor
η_{UL}	UL load factor
ρ	Application throughput
ρ_P	Physical layer throughput
ρ_{pilot}	P-CPICH E_c/N_0 when HSDPA is active
v	Activity factor
χ	Maximum interference margin
d	Distance
C_u	Number of codes per user
E_b	Energy per bit
E_c	Energy per chip
G_P	Processing gain
i	Other-cell interference ratio
I_0	Interference
I_M	Implementation margin
L	Path loss
L_{tm}	Approximation for the multi-screen diffraction loss
L_{tt}	Rooftop-to-street diffraction loss
M	Total margin
M_I	Interference margin
M_R	Modulation rate
n	Constant depending on the channel bandwidth
N_0	Noise spectral density

N_b	Number of bits
N_{DS}	Number of OFDM data symbols
N_{DSC}	Number of sub-carriers that carry data
N_F	Noise figure
N_{rf}	Noise spectral density of the receiver
N_{TSC}	Number of total sub-carriers
N_u	Number of users
$N_{uBS_{\max}}$	Number of users in the most populated BS
$P_{HS-DSCH}$	Power of the HS-DSCH summing over all active HS-PDSCH codes
P_{pilot}	P-CPICH transmit power
P_{HSDPA}	HSDPA transmit power
P_{noise}	Noise Power
P_{inter}	Inter-cell interference power
P_{intra}	Intra-cell interference power
P_{total}	Total BS transmit power
P_{Tx}	Transmitted power
r	Cell radius
R_b	Bit rate
R_c	Chip rate
SF_{16}	HS-PDSCH spreading factor of 16
T_F	Frame duration
T_s	OFDM symbol duration

List of Software

Borland C++ Builder 6

MapInfo

MapBasic

Microsoft Excel

Microsoft Word

Matlab

Microsoft PowerPoint

Microsoft Visio

Chapter 1

Introduction

This introductory chapter gives a brief overview of the work. It provides the scope and motivations of the thesis. At the end of the chapter, the work structure is presented.

1.1 Overview

Mobile Communications Systems revolutionised the way people interact with each other. With the way that society is evolving, it became necessary to develop systems that could enable people to communicate anytime, anywhere [LaWN06].

First Generation systems had the objective of providing analogue voice communications. Later, probably the greatest leap in Mobile Communications was achieved with the introduction of the so-called Second Generation (2G) systems, e.g., the Global System for Mobile Communications (GSM). It allowed not only digital voice communications, but other types of services, such as short messaging and access to data networks, with the introduction of General Packet Radio Service (GPRS) [HoTo04].

The increase in the demand of data-based services and higher data rates was the main purpose of the launch of 3rd Generation Partnership Project (3GPP) Release 99 Third Generation (3G) systems, e.g., the Universal Mobile Telecommunications System (UMTS). As the need for high data rates increased, High Speed Downlink Packet Access (HSDPA), which may be considered an enhancement of UMTS, was developed and launched in 2002 as part of the 3GPP Release 5. The first UMTS/HSDPA networks became available in 2005 providing 1.8 Mbps, increasing to 3.6 Mbps in 2006, and achieving 7.2 Mbps during 2007, for downlink (DL) [HoTo04]. HSDPA, along with its uplink (UL) version, High Speed Uplink Packet Access (HSUPA), are commonly referred to as High Speed Packet Access (HSPA). Figure 1.1 shows the new services that are available with the introduction of HSPA.

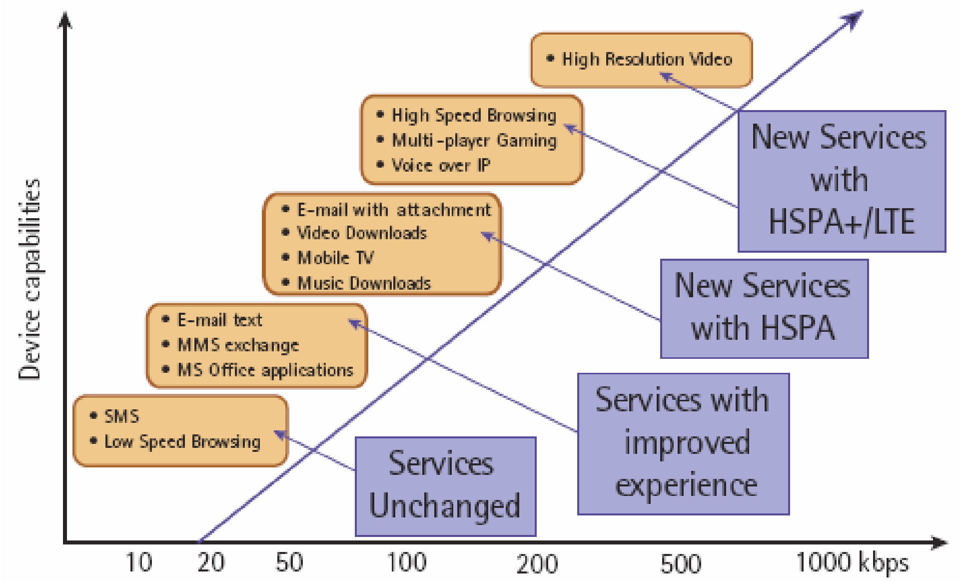


Figure 1.1. New services offered by HSPA (extracted from [UMFO08]).

UMTS/HSDPA is a technique that presents several enhancements compared to UMTS, such as Adaptive Modulation and Coding (AMC), which adapts the data rate according to the conditions and quality of the channel, and Hybrid Automatic Repeat Request (HARQ), responsible for retransmitting packets at the physical layer.

UMTS/HSDPA is based on Frequency Division Duplex (FDD), as the previous UMTS version, therefore, implementing Time Division Duplex (TDD) in UMTS/HSDPA would have higher costs than maintaining the previous transmission mode. UMTS/HSDPA is currently commercially available, proving data rates up to 7.2 Mbps. Nowadays, almost 74 countries offer HSDPA, and 60 additional networks are expected to be launched in a near future [3GAM08].

Worldwide Interoperability for Microwave Access (WiMAX) is, nowadays, one of the most promising telecommunication systems. It is a Broadband Wireless Access (BWA) system based on Institute of Electrical and Electronics Engineers (IEEE) 802.16 standard released in 2001 [Nuay07], [EkMa06]. In October 2007, the Radiocommunication Sector of the International Telecommunication Union (ITU-R) included WiMAX technology in International Mobile Telecommunications-2000 (IMT-2000) standards. This decision allows WiMAX's global deployment in the 2.5-2.69 GHz band, and to offer services to both rural and urban networks [BUSI08].

WiMAX is characterised by providing high data rates, of the order of Mbps, to a large area network, usually covering several kilometres, like a Wireless Metropolitan Area Network (WMAN) or a Wireless Wide Area Network (WWAN). WiMAX is capable of offering data rates higher than some of the already deployed technologies, such as UMTS and its enhancement HSDPA, as seen in Figure 1.2

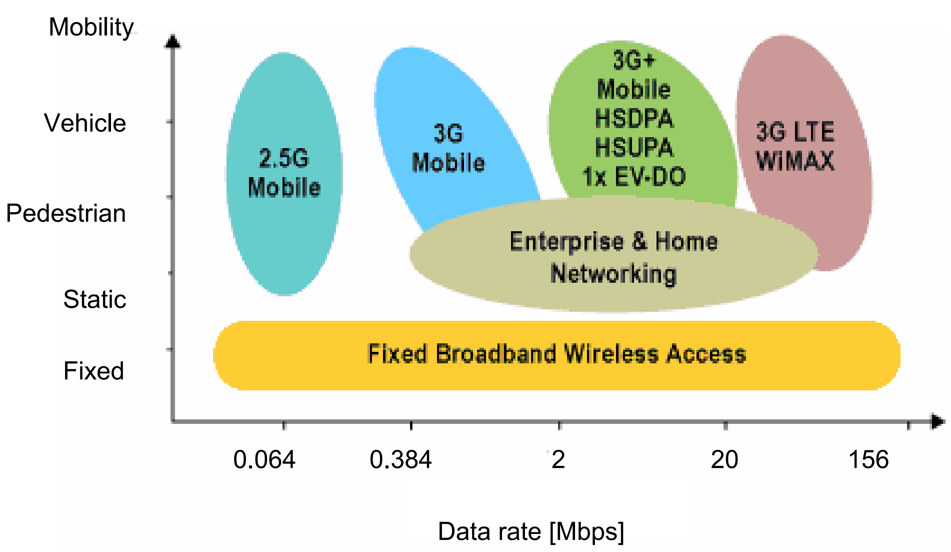


Figure 1.2. Data rates for the different systems (extracted from [ALTER08]).

The main applications of WiMAX as a BWA system are:

- Broadband fixed wireless access,
- Wireless Fidelity (WiFi) backhauling,
- Nomadic Internet Access,
- Mobile high data rate access (WiMAX/IEEE 802.16e).

The objective of WiMAX is to enable a wireless connection between the core infrastructure and the user's equipment, at a high data rate, therefore, the target of WiMAX is to be the wireless version of a Digital Subscriber Line (DSL), i.e., an alternative to cable.

Another possible application of WiMAX is WiFi backhauling, i.e., transport of data between the core network and Access Points (APs). Before reaching a Wireless Local Area Network (WLAN), dominated by WiFi technology, data would reach APs through WiMAX, responsible for carrying information between Internet Backbone and APs, Figure 1.3.

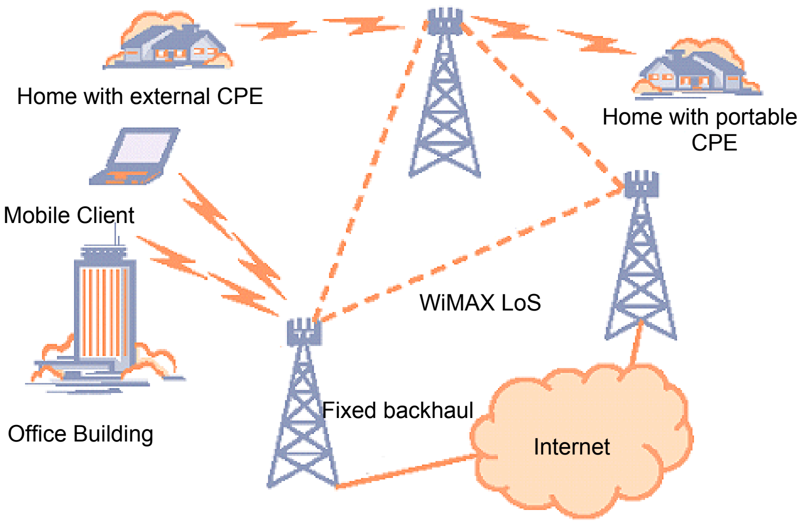


Figure 1.3. WiMAX system applications (adapted from [Nuay07], [PECF05]).

The link between the Base Station (BS) and the user's terminal is performed by the Consumer Premises Equipment (CPE). After the fixed wireless access, Nomadic Internet Access enables another kind of connection. A nomadic access happens when a user may move in a limited area covered by one BS, without breaking the connection. It is very useful when used in apartments, campuses and company areas

WiMAX range can be up to 20 km for outdoor connections, and a little less when dealing with indoor equipment. A reasonable throughput offered by WiMAX is approximately 10 Mbps, although some optimistic approaches state that it can be 70, or even 100 Mbps, in excellent radio channel conditions. WiMAX is based on Orthogonal Frequency Division Multiple Access (OFDMA) mode.

The next step regarding WiMAX/IEEE 802.16 is to provide high data rates for users moving from one BS to another, without breaking the connection, i.e., handover. Consequently, a new amendment had to be done to the previous standard, to enable continuous transmission to a Mobile Terminal (MT), IEEE 802.16e, which was approved in December of 2005. However, a WiMAX handover is not expected to perform at a speed higher than 100km/h [Nuay07]. Mobile WiMAX can offer data rates up to 31 Mbps [WiMF06a]. Other improvements brought by IEEE 802.16e are related to MIMO, beamforming, broadcast and sub-channelisation.

There is also the Korean version of Mobile WiMAX, called Wireless Broadband (WiBro), being completely compatible with IEEE 802.16e.

1.2 Motivation and Contents

The main scope of this thesis is to compare a system that is widely deployed, UMTS/HSDPA, with WiMAX and its mobile version, a new system that is currently in a phase of entering the market of Mobile Communications. Therefore, performing this type of analysis regarding network radius and capacity has the objective of studying, in a way, each one of the systems and providing a comparison between them, taking different parameters into account, such as the cell radius and the average data rate that each system can provide. The main contribution of this thesis is the development of a simulator that enables the analysis of UMTS/HSPDA and Mobile WiMAX in a real network, being capable of producing results according to several parameters.

The present work was performed in partnership with Optimus, a Portuguese mobile operator. This collaboration had an important role regarding some technical advice and insight view of the technologies, as well as some parameters' values used throughout this thesis.

The present thesis is composed of four chapters, besides the current one.

In Chapter 2, UMTS and WiMAX basic concepts are explained. First, the services and applications of each system are shown, and then the architecture, the radio interface and the performance analysis for UMTS/HSDPA and Mobile WiMAX are analysed. At the end of this chapter, a comparison between the two systems is presented.

Chapter 3 presents the description of the single service radius model, explaining its procedure. Also in this chapter the description of the simulator is shown, as well as the modifications introduced to the previous version. Later in the chapter, the input and output files and the simulator assessment are detailed.

Chapter 4 begins with the description of the default scenario and the analysis of the number of users considered during the simulations. UMTS/HSPDA and Mobile WiMAX results' analysis for both the single service radius model and the simulator are presented, explaining the influence of several parameters. Later in the Chapter, a comparison between UMTS/HSPDA and Mobile WiMAX regarding coverage and capacity is presented.

Finally, in Chapter 5, the conclusions of this thesis are presented, along with future work suggestions.

Chapter 2

UMTS and WiMAX Basic Concepts

The basic fundamentals of UMTS and WiMAX are presented in this chapter. Services and applications of both systems are addressed in Section 2.1. UMTS network structure is presented in detail in Section 2.2, followed by the radio interface, channels, system capacity, and interference. In Section 2.3, UMTS/HSDPA is explained concerning its architecture and performance. Sections 2.4 and 2.5 provide an overview of WiMAX and its mobile version in terms of its basic aspects, performance, capacity, and architecture. In Section 2.6, a brief comparison between the two systems is presented, together with a view regarding the current state of the art on this matter.

2.1 Services and Applications

The number of services and applications provided by mobile telecommunications systems has increased tremendously. UMTS is an evolution in terms of bit rate and capacity, therefore, new opportunities of services that require high quality, high bandwidth and high bit rates are open. The introduction of IP Multimedia Sub-system (IMS) along with Session Initiation Protocol (SIP) enables the entrance of new services based on Internet applications [HoTo04].

In order to manage the access to the different services, 3GPP defined different classes of services, essentially based on their Quality of Service (QoS) requirements and how delay-sensitive they are, Table2.1: Conversational, Streaming, Interactive, and Background, [3GPP01] and [3GPP02a].

Table 2.1. UMTS Services and applications (adapted from [3GPP01] and [3GPP02a]).

Service Class	Conversational	Streaming	Interactive	Background
Real Time	Yes	Yes	No	No
Symmetric	Yes	No	No	No
Switching	CS/PS	CS/PS	PS	PS
Guaranteed bit rate	Yes	Yes	No	No
Delay	Minimum Fixed	Minimum Variable	Moderate Variable	High Variable
Buffer	No	Yes	Yes	Yes
Example	Speech	Video-Clip	Web-browsing	E-mail

The Conversational class is the most demanding one. Its main purpose is for real-time conversation on both Circuit Switch (CS) and Packet Switch (PS). This class requires the maximum end-to-end delay given by the human perception for both audio and video conversation, i.e., below 400 ms. The technique applied for the CS speech service is Adaptive Multi-Rate (AMR), which has eight source data rates that can vary every 20 ms frame. As voice traffic is almost symmetric, both users occupy each link, on average, 50 % of the time, therefore Discontinuous Transmission (DTX) is used, which leads to a reduced bit rate, allowing for lower interference, thus, increasing network capacity. This class is characterised by preserving time relation among information entities of the stream.

Streaming class services are based on the multimedia streaming technique, in which the user can access data while it is being transferred. It is not necessary to complete the transmission, because the information is transferred in a continuous stream, which is accomplished with the use of buffers in the final terminal. Examples of these types of services are video and audio streaming, not being as delay-sensitive as the ones from the Conversational class. The Streaming class also preserves time relation among information entities of the stream.

The Interactive class is one with a very asymmetric traffic, being very tolerant in terms of delay. This class includes web browsing, online multiplayer games, Location-Based Services (LBS) and push-totalk applications, being based on PS connections. It is defined by requesting response patterns and preservation of payload contents. To be able to provide a good service, delay should be lower than 4 to 7 s [3GPP03].

Finally, the Background class is the least delay-sensitive of all, since practically there are no delay requirements. The delay can be higher, because the user is not expecting data within a certain time. Services in this class are e-mail or Multimedia Messaging Service (MMS). The delay can range between a few seconds to several minutes. One thing that must be assured is that the information must be error free.

For WiMAX, there are five scheduling services or QoS classes defined by the IEEE 802.16 standard [Nuay07]. The classification into scheduling service classes allows a more efficient bandwidth sharing between different users. Therefore, the BS allocates the necessary amount of bandwidth required for a certain application. The types of classes in WiMAX are Unsolicited Grant Service (UGS), Real-time Polling Service (rtPS), Non-real-time Polling Service (nrtPS), Best Effort (BE) and Extended Real-time Polling Service (ertPS) (added in 802.16e standard).

Each one of these classes has a set of QoS parameters that must be taken into account when the scheduling service is enabled, Table 2.2. The mandatory parameters are:

- Maximum sustained traffic rate,
- Minimum reserved traffic rate,
- Request/transmission policy,
- Tolerated jitter,
- Maximum latency,
- Traffic priority,

Table 2.2. Mandatory parameters present in QoS classes for WiMAX (adapted from [Nuay07]).

Scheduling Service	Maximum sustained traffic rate	Minimum reserved traffic rate	Request/ transmission policy	Tolerated jitter	Maximum latency	Traffic priority
UGS	Yes	Yes	Yes	Yes	Yes	No
rtPS	Yes	Yes	Yes	No	Yes	No
nrtPS	Yes	Yes	Yes	No	No	Yes
BE	Yes	No	Yes	No	No	Yes
ertPS	Yes	Yes	Yes	No	Yes	No

The UGS class is intended to support real-time data streams of fixed-size data packets issued at periodic intervals. VoIP without silence suppression is one example of this type of service. In UGS, overhead and latency are eliminated due to the fixed-size data packets, which are enough to hold the fixed-length data associated with a certain service. For UGS, minimum reserved traffic rate should be the same as the maximum sustained traffic rate.

The rtPS is designed to support real-time data streams of variable-sized data packets delivered at periodic intervals. This service requires more overhead than UGS but as the packet size is variable, guarantees good real-time data transport efficiency. Example of this type of service is video transmission. For rtPS, the minimum reserved traffic rate can be lower than the maximum sustained traffic rate.

The nrtPS class is similar to rtPS but it also supports delay, i.e., data streams are delay-tolerant, because the service is not intended to provide real-time contents. File Transfer Protocol (FTP) and web browsing are two examples of this type of service. A minimum data rate must be assured in this type of service.

The BE service is the least demanding one, since there are no minimum service guarantees, as the user is not expecting data within a certain time. Therefore, transmission can only occur if the network is not congested, as there is no obligation for the transmitter to grant the user request opportunities. One type of BE service is e-mail.

Finally, the ertPS class is a scheduling mechanism suitable for variable rate real-time applications that have data rate and delay requirements, such as VoIP without silence suppression. It is built on the efficiency of UGS and rtPS, because it provides data in an unsolicited manner like UGS but data packets are variable, as in rtPS.

It is observed that both UMTS and WiMAX offer a variety of services that are grouped into classes, defined by a set of parameters that are fundamental to acquire if the network is capable of providing or not the requested service at a certain time. Both standards defined priority classes, as the ones responsible for providing real-time services, and least demanding ones, as the ones responsible for delay-tolerant applications. Table 2.3 shows the parallelism between the different classes of each system.

Table 2.3.Correspondence between the different services of UMTS/HSDPA and WiMAX.

UMTS/HSDPA	Mobile WiMAX
Conversational	UGS
Streaming	rtPS
Interactive	nrtPs
Background	BE

2.2 UMTS Basic Aspects

2.2.1 Architecture and Radio Interface

The UMTS architecture is composed of three functional areas, Figure 2.1, UMTS Terrestrial Radio Access Network (UTRAN), User Equipment (UE) and Core Network (CN) [HoTo04], [3GPP02b]:

UTRAN can be defined as a block that is responsible for all radio related functionalities, CN is responsible for switching and routing calls to external networks, and UE is responsible for user and network radio communications. UTRAN consists of two main elements: the Node B, i.e., the Base Station (BS), and the Radio Network Controller (RNC). The function of the BS is to convert the data flow between Iub (interface between BS and RNC) and Uu (interface between UE and the BS) interfaces. RNC has an important role in Radio Resource Management (RRM), as it is responsible for controlling the radio resources in UTRAN.

The UE, i.e., the MT, consists of two parts: the Mobile Equipment (ME), which is used for communications over the Uu interface, and the UMTS Subscriber Identity Module (USIM), which is a card that carries information about the subscriber identity, as well as authentication and encryption.

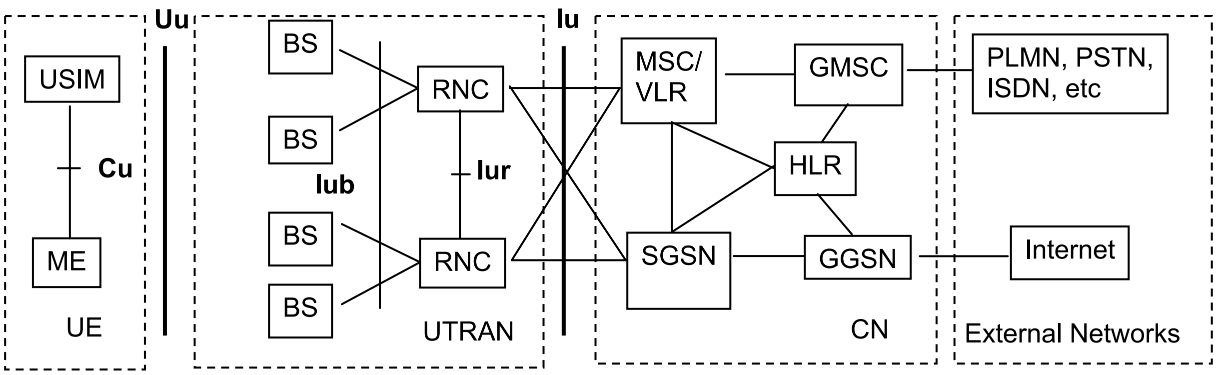


Figure 2.1. UMTS system architecture (extracted from [HoTo04]).

Regarding CN, one has mainly the typical GSM / GPRS components, such as Home Location Register (HLR), Visitor Location Register (VLR), Mobile Services Switching Centre (MSC), Gateway Mobile Switching Centre (GMSC), Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN).

HLR is where all the information related to each of the operators' clients is saved, VLR has the information on all the network active users at a certain moment (users can belong to the network, or to another one using the roaming service), and MSC is responsible for the voice and data transport management in CS inside the network. GMSC is the switch at the point where UMTS/Public Land Mobile Network (PLMN) is connected to external CS networks. All CS connections (incoming and outgoing) go through GMSC. The functionality of SGSN is similar to MSC/VLR, but for PS services. The GGSN is close to the GMSC functionality, but in this case regarding PS services.

The transition from GSM to UMTS is easy at the CN level, because UMTS' CN is an adaptation of the equivalent element of GSM. On the other hand, the air interface implies that a new set of protocols must be implemented, because multiple access is done on Wideband Code Division Multiple Access (WCDMA) and not on Time Division Multiple Access (TDMA). Also, UMTS was built to serve PS and CS, which was not initially the case of GSM.

In UMTS there are three types of handover: hard handover (HHO), soft handover (SHO) and softer handover (SSHO). In the hard handover, the link is transferred from one cell to another without being simultaneously connected to both, while in soft/softer handover, the simultaneous connection exists. In SSHO, an MT is in the overlapping cell coverage of two adjacent sectors of the same BS, having two different air interface channels. The combining is done in the BS. In SHO, the two sectors are associated with different BSs and the combining is performed by the RNC.

UMTS uses WCDMA on two modes, the FDD and the TDD ones. Throughout this work, only the FDD mode is considered [HoTo04], [3GPP05]. The frequency bands in UMTS Terrestrial Radio Access (UTRA)-FDD are [1920, 1980] MHz for UL and [2110, 2170] MHz for DL.

WCDMA has a chip rate of 3.84 Mcps, and the transmit-to-receive frequency separation is typically 190 MHz (the minimum transmit-to-receive interval is 134.8 MHz and the maximum is 245.2 MHz). The channel bandwidth is 4.4 MHz, with a spacing of 5 MHz, and it can be adjusted in 200 kHz steps. The frame length is 10 ms.

Two operations are used to differentiate signals: spreading and scrambling. Spreading is used to separate the physical data and control channel in UL, and to distinguish the connections to different users within one cell in DL [Corr06]. The spreading originates a wideband signal by multiplying the user's data by a sequence of chips, called channelisation. In order to do this, the Orthogonal Variable Spreading Factor (OVSF) is used, to maintain different codes orthogonal to each other. It also allows changing the Spreading Factor (SF) and maintaining orthogonality among codes.

The scrambling operation does not modify the bandwidth. In UL, it is used to separate MTs, and in DL, it is used to differentiate sectors. The scrambling operation can use long and short codes: UL uses both and DL only uses long codes.

UMTS has four types of channels [3GPP02c]: radio, logical, physical and transport. Radio channels are related to the frequency of the carrier. Logical channels are responsible for transferring specific information.

Transport channels are divided into two groups: common channels, shared by all users in the cell, and dedicated channels, which are meant to be used by just one user. There is only one Dedicated transport Channel (DCH). The channel carries the user's information from the higher layers of the network. Common transport channels are Broadcast Channel (BCH), Forward Access Channel (FACH), Paging Channel (PCH), Random Access Channel (RACH), Common Packet Channel (CPCH) for UL and the Downlink Shared Channel (DSCH) for DL. The most important and essential channels for the basic operations are FACH, PCH and RACH: FACH carries control information for the MT within the cell coverage area, and may also be used for packet data communications. It is mapped onto the Secondary Common Control Physical Channel (SCCPCH). PCH is responsible for the information regarding the initiation of a connection between the network and an MT, and RACH carries the necessary control information from the MT. Finally, there are the physical channels, which main purpose is to map the transport channels and carry information of the physical layer procedures.

One critical matter in UMTS is how power can be managed. Power management consists of two operations: power allocation and power control. Power control is used when several radio links are set between the MT and one or more BSs, the goal being to configure or reconfigure the power of the traffic channels in UL or DL; with no power control, a whole cell could be blocked by an overpowered MT. The types of power control are open and closed-loops. The open-loop power control is used to supply power to an MT when a connection is initiated; this is also called outer-loop power control. It sets a Signal-to-Interference Ratio (SIR) that is going to be compared with the estimated received SIR at the BS, in which the BS will command the MT to increase or decrease the power. The closed-loop power control, also called inner-loop power control, has an update rate of almost 1500 Hz, avoiding the near-far problem, where an MT situated near the BS receives less power than an MT located near the cell edge, the latter being more suitable to suffer inter-cell interference.

2.2.2 Capacity and Interference

In UMTS, capacity depends on the number and type of users that are connected to a BS. Three factors are responsible for the limitation on this number of users: the number of channelisation codes which may not be enough for all users; the power transmitted from the BS, which is obviously restricted; the system load, affecting cell coverage [HoTo04]. Regarding the system load, the interference margin must be taken into account:

$$M_{I[\mathrm{dB}]} = -10 \cdot \log(1-\eta) \tag{2.1}$$

where:

- η: load factor.

The load factor is important so that the cell capacity and interference margin can be estimated, specifying the traffic that can be supported by a BS. Obviously, if the load factor increases, the interference margin also increases, and the cell coverage is worse. The UL factor for a given user can be calculated by:

$$\eta_{UL} = (1+i_{UL}) \cdot \sum_{j=1}^{N_u} \frac{1}{1+\dfrac{G_{P\,j}}{\left(E_b/N_0\right)_j \cdot v_j}} \tag{2.2}$$

where:

- N_u: number of users per cell,
- v_j: activity factor of user j,
- $G_{P\,j}$: processing gain of user j, given by R_c / R_{bj},
- i_{UL}: inter- to intra-cell interferences ratio for UL,
- E_b: bit energy,

- N_0 : spectral noise density,
- R_b : bit rate of user j ,
- R_c : WCDMA chip rate,

while the DL load factor is:

$$\eta_{DL} = \sum_{j=1}^{N_u} v_j \cdot \frac{\left(E_b/N_0\right)_j}{G_{Pj}} \cdot \left[\left(1-\alpha_j\right) + i_{DL}\right] \tag{2.3}$$

where:

- α_j : orthogonality factor (between 0.4 and 0.9 in multipath channels)
- i_{DL} : inter to intra-cell interferences ratio for DL

Multipath must be considered in this case, because it is responsible for the loss of orthogonality among codes, contributing to interference.

One aspect that is important in terms of capacity and interference is the power transmitted by the BS:

$$P^{BS}_{Tx\ [\mathrm{W}]} = \frac{N_{rf} \cdot R_c \cdot \sum_{j=1}^{N_u} L_j \cdot v_j \cdot \frac{\left(E_b/N_0\right)_j}{G_{Pj}}}{1-\eta_{DL}} \tag{2.4}$$

where:

- N_{rf} : noise spectral density of the receiver (between -169 and -165 dBm)
- L_j : path loss between BS and user j

The BS transmission power is usually 43 dBm, approximately 20 W, per cell. When dealing with a multi-carrier system like UMTS, some suppliers offer 40 W, just to allow for the usage of two different carriers in the same device. The available power is shared among all connections in the cell. The common control channels take some of the power available, and the remaining power goes to the dedicated channels used by the users in the cell coverage area.

2.3 UMTS/HSDPA

2.3.1 Main Characteristics

UMTS/HSDPA introduced new characteristics in the system in order to increase its performance, such as AMC, which allows adjustable bit rate according to the quality of the channel, HARQ, which is responsible for retransmitting packets with errors, and a layer in the BS for Medium Access Control

(MAC-hs), [HoTo04].

One of the main features of UMTS/HSDPA was the implementation of new channels, Figure 2.2, which operate in parallel with DCH from Release 99. Three new channels were introduced:

- High-Speed Downlink Shared Channel (HS-DSCH): shared transport channel that carries the user's information in DL. One of its main characteristics is a Transmission Time Interval (TTI) of 2 ms, shorter than in Release 99 (10 ms), which allows the system to react quickly and efficiently to the channel variation. The channel also supports 16 Quadrature Amplitude Modulation (16QAM) modulation, besides Quadrature Phase Shift Keying (QPSK). Another characteristic is the fixed SF of 16.
- High-Speed Shared Control Channel (HS-SCCH): logical channel responsible for carrying the signalling and control information, regarding codes to de-spread and modulation used.
- High-Speed Dedicated Physical Control Channel (HS-DPCCH): physical channel responsible for control information for UL. Carries HARQ information and also the Channel Quality Information (CQI).

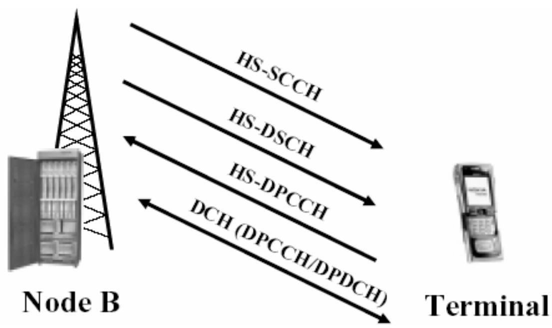


Figure 2.2. Channels required for UMTS/HSDPA operation (extracted from [HoTo06]).

The fixed spreading factor of 16 used in UMTS/HSDPA allows for 15 codes to be used for data transmission, because one code has to be used for HS-SCCH. Although the 15 codes can be allocated by the BS, from the MT point of view, they can vary from 5, 10 or 15 codes, depending on the MT.

Compared with Release 99, RRM for UMTS/HSDPA has suffered some changes. The architecture encompasses is the same, the main changes being mostly regarding the functionalities of each of the elements of the architecture. In Release 99, the RNC is responsible for the scheduling control, and the BS is mainly responsible for power control. With the introduction of UMTS/HSDPA, the BS is now responsible for scheduling control, among other functionalities, Table 2.4.

As scheduling has been moved to the BS, the overall RRM has been re-arranged. The Serving RNC (SRNC), the one being connected to the core network for a certain connection, maintains the control of hard handovers only and the QoS parameters mapping.

Besides the air interface, there are differences regarding other interfaces with the introduction of

UMTS/HSDPA. In Release 99, every interface between SGSN and MT has a bit rate varying from 0 to 384 kbps, but with Release 5 the several interfaces have different bit rates, the maximum being the interface between the BS and MT, reaching values up to 7.2 Mbps, when considering 10 codes.

Table 2.4. Comparison between Release 99 and Release 5 regarding RRM (adapted from [HoTo06]).

Elements	Release 99	Release 5
BS	Power Control	Scheduling Resource Allocation QoS provision Load and overload control
Drift RNC	Admission Control Initial power and SIR setting Radio Resource Reservation Scheduling for common channels Load and overload control	Admission Control Radio Resource Reservation Load and overload control
Serving RNC	QoS parameters mapping Scheduling for dedicated channels Handover control Outer loop power control	QoS parameters mapping Handover control

The higher bit rate in the interfaces and a better resource management is due to new functionalities introduced in network elements. The BS now handles Automatic Repeat Request (ARQ) and scheduling, and supports 16QAM modulation and data buffering. RNC is responsible for UMTS/HSDPA radio resources, mobility and Iub traffic management, and supports larger data volumes. MT handles ARQ with soft value buffer, and supports 16QAM demodulation.

2.3.2 Performance Analysis

It is important to evaluate UMTS/HSDPA performance in different scenarios, analysing the system through several parameters, like capacity, coverage area and bit rate. One fundamental feature of UMTS/HSDPA is AMC, which allows adapting the type of modulation and codes to be used according to the conditions of the channel.

One difference between Release 5 and Release 99 is the metric used to analyse network performance. In Release 99, the metric used is the received energy-per-user-bit-to-noise ratio $\left(E_b / N_0\right)$. However, this is not appropriate for UMTS/HSDPA, as the bit rate may change every TTI, therefore, the average HS-DSCH Signal-to-Interference-plus-Noise Ratio (SINR) after de-spreading the High-Speed Physical Downlink Shared Channel (HS-PDSCH) is the one being used, which is given by:

$$SINR = SF_{16} \frac{P_{HS-DSCH}}{(1-\alpha)\cdot P_{intra} + P_{inter} + P_{noise}} \tag{2.5}$$

where:

- SF_{16} : HS-PDSCH spreading factor of 16,

- $P_{HS-DSCH}$: received power of the HS-DSCH summing over all active HS-PDSCH codes,
- P_{intra} : received intra-cell interference power,
- P_{inter} : received inter-cell interference power,
- P_{noise} : received power noise,
- α : DL orthogonality factor.

HS-DSCH SINR is an essential measure when it comes to network dimensioning and link budget planning. Single user performance analysis is important when evaluating UMTS/HSDPA. Some aspects, like link adaptation, performance of control channels, and throughput are topics to be taken into account.

Link adaptation relates to the modulation and coding scheme selected for a certain connection regarding the channel quality. It determines the instantaneous SINR with the purpose of optimising throughput and delay. QPSK modulation is the most suitable for a low SINR and 16QAM is the most appropriate for a high one, which is necessary to provide higher data rates. Figure 2.3 illustrates this fact for a single user that supports 5 HS-PDSCH codes, independently of the user's profile.

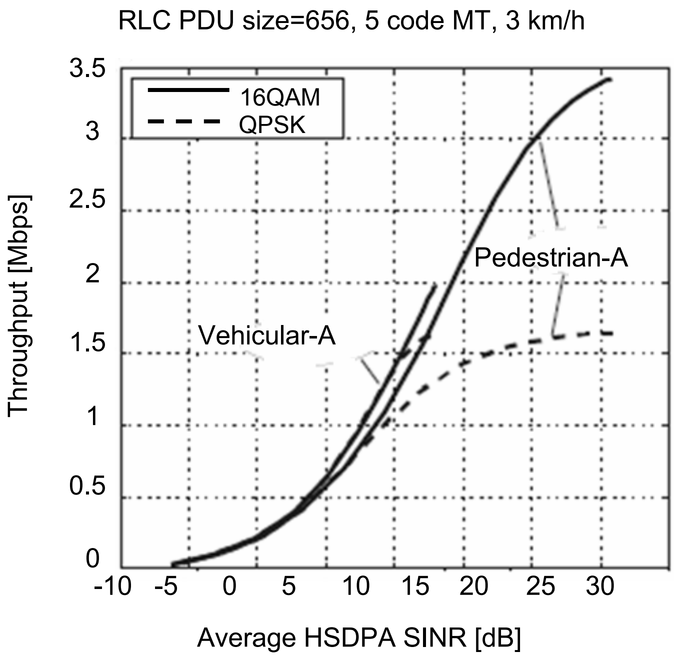


Figure 2.3. Single user performance with 16QAM/QPSK and with QPSK-only (extracted from [HoTo06]).

When dealing with a 5-code transmission, the SINR is higher than in the case of using 10 or 15 codes. This is due to the reduced amount of channel coding, leading to a lower spectral efficiency when using a 5-code transmission. HS-DSCH SINR for different users in the cell should be within the HS-DSCH dynamic range, which is between -3 and 17 dB.

UMTS/HSDPA performance can also be evaluated by the pilot (E_c / I_o), standing for energy per chip to interference ratio. The estimation of the single user throughput is possible via use of the average Primary-Common Pilot Channel (P-CPICH) (E_c / I_o) by first calculating the average HS-DSCH SINR for the case where 5, 10 or 15 codes are supported. The average HS-DSCH is given by:

$$SINR = SF_{16} \frac{P_{HSDPA}}{\frac{P_{pilot}}{\rho_{pilot}} - \alpha P_{total}} \quad (2.6)$$

where:

- P_{HSDPA} : UMTS/HSDPA transmit power,
- P_{pilot} : P-CPICH transmit power,
- P_{total} : total BS transmit power,
- ρ_{pilot} : P-CPICH (E_c / I_o) when UMTS/HSDPA power is on.

One important parameter of UMTS/HSDPA is cell coverage. Assuming a typical macro-cellular scenario with a BS three-sector topology with 65º half power beam width antennas, a COST 231 Hata Okumura [DaCo99] path loss model, and a transmit power of 12 W, it is possible to estimate the average throughput according to the cell coverage, Figure 2.4. The results in Figure 2.4 are for 7 W and 3 W of UMTS/HSDPA power, using 5 HS-PDSCH codes for a single user. The remaining power is for Release 99 channels on the same carrier. As seen in Figure 2.4, the average throughput for a single user decreases as the minimum cell coverage area increases. This is valid for both presented profiles, even though for 7 W and 5 HS-PDSCH codes, a user with a Pedestrian A profile can be served with 1.6 Mbps in 50% of the cell coverage area. A Vehicular A profile user can only be served with 1.1 Mbps for the same cell coverage.

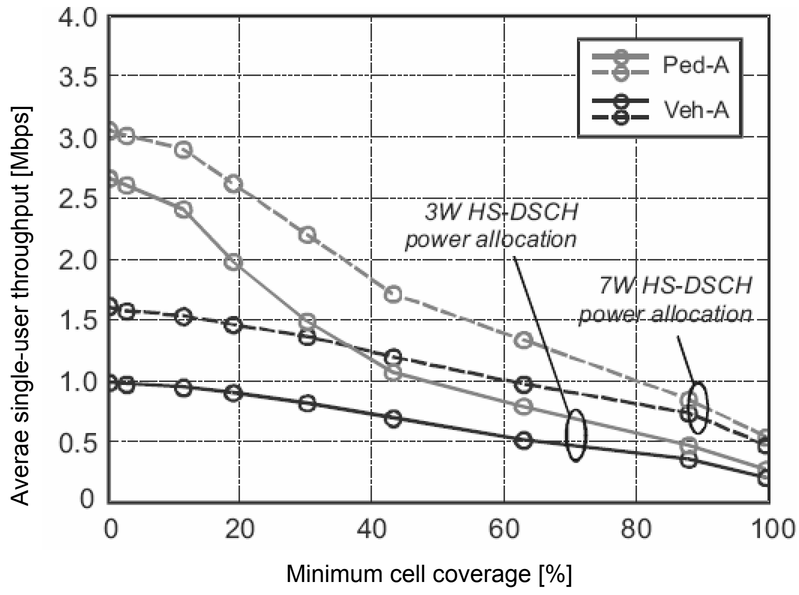


Figure 2.4. Average single-user throughput as a function of cell coverage area (extracted from [HoTo06]).

The Pedestrian A profile is typically used for micro-cells, where BS antennas are located below rooftop level, having less temporal dispersion than the Vehicular A one. The latter is usually applied for a macro-cellular scenario, where BS antennas are located above rooftops. It has a higher temporal dispersion, therefore, a worse DL orthogonality factor than the Pedestrian A profile. This leads to a larger multi-user diversity gain for the Pedestrian A profile, which is one of the factors responsible for having higher throughputs in this case, compared to the other profile.

As the number of UMTS/HSDPA users increase, multi-user diversity gain also increases for both profiles. On the other hand, the average throughput for a single user decreases. With the increase of the number of HS-PDSCH codes from 5 to 10, the average cell throughput raises approximately 50%. This is caused by the fact that it is more spectrally efficient to increase first the number of codes rather than starting first to raise the effective code rate, or the modulation order.

Considering a case where there is only UMTS/HSDPA traffic, there is a difference regarding throughput for UMTS/HSDPA users, with or without code-multiplexing. Using 10 HS-PDSCH codes in a UMTS/HSDPA–only cell for one user is slightly better than using the same 10 codes for two users with code-multiplexing, each one capable of receiving 5 HS-PDSCH codes. This is due to the higher overhead caused by having two HS-SCCHs in a cell, and to the additional problems of scheduling two users per TTI.

The total cell throughput is a sum of throughput on UMTS/HSDPA and DCH. As the power allocated for UMTS/HSDPA increases, throughput on UMTS/HSDPA becomes higher and on lower DCH. When UMTS/HSDPA is introduced, there is a gain in terms of capacity of almost 70% over Release 99. This is caused by fast link adaptation and HARQ offered by UMTS/HSDPA.

2.4 WiMAX Basic Aspects

2.4.1 Architecture and Radio Interface

The architecture for a BWA system like WiMAX aims mostly at supplying a framework for an efficient and high-performance end-to-end IP connection [Nuay07].

Some architecture requirements had to be taken into account so that WiMAX could provide several services and applications. The main requirements were basically oriented to create a high-performance packet-based network, which could support a variety of services, roaming, and also interconnection with other fixed or mobile networks.

Regarding services, the WiMAX architecture is able to provide voice and multimedia contents, as well as emergency calls, and access to a collection of other applications. In terms of dealing with other networks and operators, interconnection is assured, along with user authentication methods. The main components of the WiMAX, and its mobile version architecture are shown in Figure 2.5.

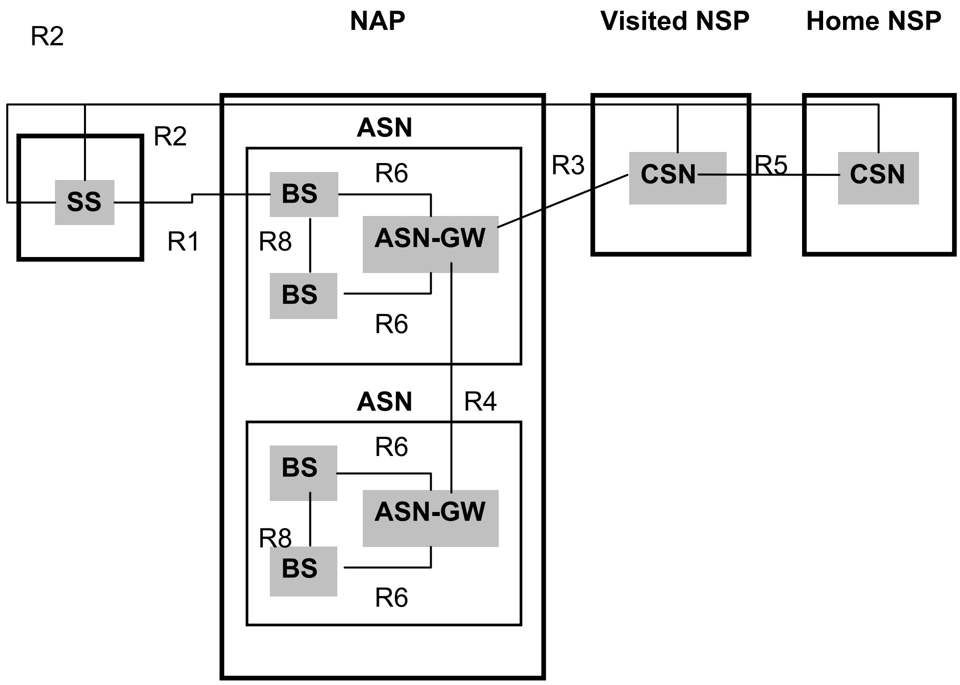


Figure 2.5. Mobile WiMAX architecture (adapted from [Nuay07]).

The three most important areas of the architecture are the SS (the commonly known MT), Access Service Network (ASN), and Connectivity Service Network (CSN), interconnected by interfaces or reference points R1 to R8.

The MT connects the subscriber to the BS: it connects to ASN through R1, and to CSN through R2. The ASN has the responsibility of controlling and providing radio access connection to subscribers. One or several ASNs interconnected by reference points R4 are deployed by the Network Access Provider (NAP). The NAP supplies radio access infrastructure and connects through R3 to one or several Network Service Providers (NSPs), which is an entity responsible for providing services. It deploys CSN, which has the purpose of establishing IP connectivity to subscribers. Roaming services are dealt with NSP, therefore, a subscriber may be located in a Home-NSP (H-NSP) or in a Visited-NSP (V-NSP), the latter having a roaming agreement with H-NSP.

The ASN includes several functionalities related to supplying radio connectivity to subscribers, being responsible for RRM mechanisms. The ASN consists of one or more BSs connected to several ASN Gateways (ASN-GWs). The connection among BSs is assured by reference point R8, and between BSs and ASN-GW by R6. The link among several ASN-GWs is done by R4. The BS has the purpose of scheduling users and signalling messages with ASN-GW through R6.

There are three different types for ASN implementation, based on the functionalities that each of the components has. In Profile A, ASN-GW is responsible for handover control and Radio Resource Control (RRC); Profile C is basically the same, but in this case the BS has more functionalities than in Profile A, such as handover control and RRC; Profile B is not specific about any distribution of functions to BS or ASN-GW, being left to the vendor to decide its best option.

CSN represents the core network, providing IP connectivity to subscribers. The main functions of CSN are: user connection authorisation, IP address allocation and Authentication Authorisation and Accounting (AAA) servers, QoS management, link with other equipment or network based on IP protocols, subscriber billing and provide services, such as Internet access, LBS and Peer-to-Peer connection

The frequency bands assigned for WiMAX are the 3.5 and 5.8 GHz bands in Europe and the 2.3, 2.5 and 5.8 GHz bands in the United States of America. It is foreseen that it will possible to operate in the 2.5 GHz band in Europe. The channel bandwidth can be 3.5, 5, 10, 20, 25 and 28 MHz. WiMAX has suffered some upgrades since its first release, new features being introduced. The first release allowed only for Line of Sight (LOS) transmission, operating with frequencies ranging from 10 to 66 GHz, the second version already allowed Non Line of Sight (NLoS) transmission, with frequencies varying from 2 to 11 GHz.

WiMAX achieves high data rates in part via the use of OFDM. It increases capacity and bandwidth efficiency compared to Single Carrier (SC) system. This is obtained by having sub-carriers very close to each other, but avoiding interference because neighbouring sub-carriers are orthogonal to each other. This leads to a high spectral efficiency of 3.5 to 5 bit/s/Hz, which is a little bit higher than the one presented by Code Division Multiple Access (CDMA) for 3G. WiMAX supports TDD and FDD modes, but only TDD mode is considered throughout this work, as most of the existing products use TDD. The TDD splits considered throughout this work are 1:0, 1:1, 2:1 and 3:1; the different splits for TDD represent the portion of data symbols responsible for DL and UL transmission in one TDD frame. OFDM transmission was originally conceived for a single user, therefore, it had to be associated to a multiple user access scheme so that several users could be served; Orthogonal Frequency Division Multiple Access (OFDMA) is the scheme to be used.

2.4.2 Performance Analysis

WiMAX throughput depends mostly on the following factors:

- Channel spacing,
- Number of sub-carriers inside a channel,
- Sub-carriers used as pilot carriers,
- Sub-carriers used as guard carriers,
- Symbol duration,
- Modulation Rates,
- Effective Code Rates.

For a 3.5 MHz channel, it is assumed that there are 256 sub-carriers inside a channel, the latter being limited on the left and on the right by sub-carriers that do not carry any data, in order to avoid interference with other radio channels, the guard carriers. There are 56 guard carriers, 28 being the lower-frequency guard and 27 the higher ones. Besides guard carriers, there are also 8 pilot carriers responsible for control and synchronisation. Each one of the remaining 192 sub-carriers is used to carry data. Therefore, it is possible to estimate throughput knowing the number of bits per OFDM symbol, and the duration of the symbol. The latter can be calculated by:

$$T_{s[\mu s]} = \left[N_{TSC} / (n \cdot \Delta f_c) \right] \cdot (1 + \Delta t_G) \tag{2.7}$$

where:

- N_{TSC} : number of total sub-carriers,
- n : sampling factor depending on the channel bandwidth,
- Δf_c : channel bandwidth,
- Δt_G : guard time factor.

The possible values for n are: 8/7, 86/75, 144/125, 316/275 and 57/50. The possible values for Δt_G are: 1/32, 1/16, 1/8 and 1/4. The number of information bits per OFDM symbol is given by:

$$N_b = N_{DSC} \cdot M_R \cdot \beta \tag{2.8}$$

where:

- N_{DSC} : number of sub-carriers that carry data,
- M_R : modulation rate,
- β : effective code rate.

The modulation rate is related to the number of bits that are carried in a symbol using a certain modulation scheme. The four modulations supported by WiMAX are: BPSK, QPSK, 16QAM and 64QAM. Throughput is obtained dividing (2.8) by (2.7), resulting:

$$\rho_{[bps]} = \frac{N_{DSC} \cdot M_R \cdot \beta}{\left[N_{TSC} / (n \cdot \Delta f_c) \right] \cdot (1 + \Delta t_G)} \tag{2.9}$$

The possibility of using several modulations has the advantage of link adaptation, i.e., adapting modulation according to radio channel conditions. A high-level modulation is used for a good radio link, while a low-level modulation is the most suited for bad radio link conditions.

2.5 Mobile WiMAX/IEEE 802.16e

IEEE 802.16e is an amendment of the standard 802.16-2004, approved in December 2005. It adds to the previous standard the features and attributes that are necessary to support mobility [WIMF06a]. There are some differences between the two standards, the major ones being the existence of mobile terminals, handover procedures, power management, and the use of Scalable Orthogonal Frequency Division Multiple Access (SOFDMA)

Mobility is based mostly on handover, which is an essential operation in every cellular network. For Mobile WiMAX, the types of handover are HHO and SHO, but only HHO is mandatory. Handover requirements are basically regarding security and time. The latter is due to the fact that handover must be fast enough, in the order of 50 or 150 ms. The procedure for handover in Mobile WiMAX is basically the same as the one used for UMTS/HSDPA, where there is a cell reselection by scanning neighbouring BSs, after which there is the process of synchronisation with the selected BS and consequent cell ranging. Handover may also be accomplished according to radio channel conditions or cell capacity considerations. In the WiMAX architecture, the components responsible for handling handover functionality are located in the ASN.

Power management is supported by Mobile WiMAX, two modes being available: Sleep and Idle. Sleep Mode is when the MT establishes periods of absence with the BS, in which the MT is unavailable for UL or DL traffic, allowing a better resource management for the BS, and decreasing the power usage by the MT. The Idle Mode is when the MT becomes periodically available for DL traffic without prior registration to a serving BS, occurring when the MT crosses an area populated by numerous BSs; it is beneficial as handover requirements are no longer needed, whether for MT or BS.

Mobile WiMAX air interface adopts SOFDMA to improve multi-path performance in NLoS scenarios. The use of SOFDMA enables the change of the number of used sub-carriers, therefore, providing adaptation to the occupied frequency bandwidth and consequently adapting data rate. SOFDMA supports a range of bandwidths from 5 to 10 MHz, to flexibly adjust the need for spectrum allocation. Supported sub-carriers numbers are 128, 512, 1024 and 2048. Only 512 and 1024 are mandatory for Mobile WiMAX, Table 2.5, where the channels bandwidths considered are 5 and 10 MHz. Only DL transmission is considered throughout this work, regarding simulations and results analysis.

Table 2.5. SOFDMA parameters for Mobile WiMAX (extracted from [WIMF06a]).

Parameters	Values			
	DL	UL	DL	UL
System Channel Bandwidth [MHz]	5		10	
Number of Sub-Carriers	512		1024	
Sub-Carrier Frequency Spacing [kHz]	10.94			
Null Sub-Carriers	92	104	184	184
Pilot Sub-Carriers	60	136	120	280
Data Sub-Carriers	360	272	720	560
Sub-Channels	15	17	30	35
OFDM Symbol Duration [μs]	102.9			
Frame Duration [ms]	5			
Number of OFDM Symbols (per 5 ms frame)	48			
Number of Data OFDM Symbols	44			

A sub-channel is an entity defined in the frequency domain, therefore, it is a group of sub-carriers. For each sub-channel, there are 24 data sub-carriers, along with pilot sub-carriers. This is used with the Partially Used Sub-Carrier (PUSC) technique, which is mandatory for Mobile WiMAX. According to the used channel bandwidth, there are 15 sub-channels for DL and 17 for UL in the 5 MHz channel, and

30 sub-channels for DL and 35 for UL in the 10 MHz one. This allows serving 15 users for 5 MHz channels, or 30 users for 10 MHz ones, in the same period of time. It is also possible to dynamically allocate the number of sub-channels for a single user concerning the throughput requested by the user. All sub-channels can be addressed to one single user in the limit situation. Table 2.6 shows the data rates achieved for 5 MHz and 10 MHz channels, using different modulation schemes.

Table 2.6. PHY Data Rates for 5 MHz and 10 MHz channels using several modulation schemes and code rates for TDD split 1:0 (extracted from [WIMF06a]).

Modulation	**Code Rate**	**5 MHz channel**		**10 MHz channel**	
		DL Data Rate [Mbps]	**UL Data Rate [Mbps]**	**DL Data Rate [Mbps]**	**UL Data Rate [Mbps]**
QPSK	1/2	3.17	2.28	6.34	4.70
	3/4	4.75	3.43	9.50	7.06
16 QAM	1/2	6.34	4.57	12.07	9.41
	3/4	9.50	6.85	19.01	14.11
64 QAM	1/2	9.50	6.85	19.01	14.11
	2/3	12.67	9.14	26.34	18.82
	3/4	14.26	10.28	28.51	21.17
	5/6	15.84	11.42	31.68	23.52

Data rate values for the Physical Layer (PHY) are obtained by [WIMF06a]:

$$\rho_{p[\text{bps}]} = \frac{N_{DSC} \cdot M_r \cdot \beta \cdot N_{DS}}{T_F} \tag{2.10}$$

where:

- ρ_p : physical layer throughput
- N_{DS} : number of data symbols
- T_F : frame duration

These results were obtained and published by the WiMAX Forum, so they may be optimistic. Mobile WiMAX can achieve physical data rates up to 15 Mbps using 5 MHz channel spacing and a range of almost 5 km. It is also possible to have NLoS transmission.

2.6 Systems Comparison

UMTS/HSDPA is an enhancement of the previously deployed UMTS system, therefore, offering new data services in addition to the ones already provided by UMTS. On the other hand, WiMAX was originally conceived to provide fixed wireless access, and recently evolved to new concepts to support mobility.

UMTS/HSDPA and Mobile WiMAX are both systems able to provide high data rates to several users. Although the main purpose is the same, there are some differences regarding technical issues used by each one of the systems. Table 2.7 summarises the main differences between them and shows some fundamental features.

Table 2.7. Comparison between UMTS/HSDPA and Mobile WiMAX.

Attributes	UMTS/HSDPA	Mobile WiMAX
Standard	WCDMA	IEEE 802.16e
Duplex Method	FDD	TDD
Multiple Access	CDMA	SOFDMA
Channel Bandwidth [MHz]	5	5, 7, 8.75, 10
Frequency [GHz]	2	2.5, 3.5, 5.8
Frame Size [ms]	2	5
Modulation	QPSK / 16QAM	QPSK / 16QAM / 64QAM
DL PHY Peak Data Rate [Mbps]	14.4	31.68 (for a 10 MHz channel)
Coverage [km]	Typically 2 to 5	Up to 5
HARQ	Yes	Yes
Fast Scheduling	Yes	Yes
AMC	Yes	Yes

UMTS/HSDPA and Mobile WiMAX adopted advanced techniques to improve data rates. Some of them are employed in both systems like HARQ, Fast Scheduling and AMC. However, Mobile WiMAX adopts OFDMA, allowing better spectral efficiency, QoS and robustness. Also, by supporting 64QAM, it enables data rates higher than UMTS/HSDPA. The use of TDD allows Mobile WiMAX to dynamically adjust DL/UL traffic. Regarding cell radius, there are typical values for UMTS/HSDPA that range from 2 to 5 km, being the latter an optimistic approach. As for Mobile WiMAX, cell radius can go up to 5 km.

In terms of architecture, the main structure is the same for both systems, i.e., there are three major areas that are responsible for establishing a connection. Table 2.8 shows the correspondence between the two architectures.

Table 2.8. Architecture correspondence of the main components between UMTS/HSDPA and WiMAX

UMTS/HSDPA	WiMAX
UTRAN	ASN
RNC	ASN-GW
BS	SS
CN	CSN
VLR	V-NSP
HLR	H-NSP

All the radio related functionalities are dealt in UTRAN in UMTS/HSDPA and in ASN in Mobile WiMAX. Handover is one important issue when dealing with mobile services. This feature is located in the RNC in the case of UMTS/HSDPA and located in ASN-GW or in the BS, depending on the profile chosen, in Mobile WiMAX. Several functionalities related to RRC, such as scheduling, are handled in the BS in UMTS/HSDPA and in ASN-GW or in the BS, again depending on the profile chosen, in Mobile WiMAX. In UMTS/HSDPA, CN is responsible for providing connectivity to subscribers and switching data to external networks. In Mobile WiMAX, this feature is assured by CSN. Roaming services are handled in VLR in UMTS/HSDPA and in Mobile WiMAX is guaranteed by V-NSP. The block that is closer to the end user is called SS in Mobile WiMAX and UE in UMTS/HSDPA.

UMTS/HSDPA uses the frequency band of 2 GHz previously established for UMTS, while Mobile WiMAX uses the 2.5, 3.5 and 5.8 GHz frequency bands. The different used frequencies make a difference regarding the cell radius for each system, since the frequency has some influence in the path loss, determining the distance that the user must be to receive a certain throughput.

In [SKKO05], the performance of WiBro and UMTS/HSDPA is evaluated and compared. Strengths and weaknesses of each technology are shown in this work. The comparison is basically regarding coverage and capacity that each of the technologies can offer. For coverage comparison, a model was used to evaluate both technologies, and UMTS/HSDPA was the one presenting better results, as WiBro's thermal noise is 3.4 dB higher than UMTS/HSDPA, which results in approximately 19% coverage shrinkage. Concerning capacity, WiBro presents better results, due to its robustness in multipath fading channel, since OFDMA and cyclic prefix are powerful tools for better robustness. As UMTS/HSDPA presents a TTI of 2 ms, which is shorter than WIBro's time frame of 5 ms, UMTS/HSDPA performs better when dealing with dynamic channel variation. Overall, the performance of WiBro is slightly better than UMTS/HSDPA.

In [WIMF06b], there is a detailed discussion on the comparison of Mobile WiMAX and the other 3G technologies, namely UMTS/HSDPA. The comparison is mainly focused on spectral efficiency and throughput, considering system's specifications and requirements. For Mobile WIMAX, a 10 MHz channel bandwidth in TDD mode is considered, and for UMTS/HSDPA two channels of 5 MHz of channel bandwidth are considered. Also, for Mobile WiMAX, Multiple Input Multiple Output (MIMO) was considered; Mobile WiMAX with MIMO offers a higher spectral efficiency than the one presented by UMTS/HSDPA, which is due to the use of OFDM and OFDMA, as it provides a high resource allocation and supports a wide range of antenna technologies. Regarding throughput, simulations results show that Mobile WiMAX presents results more than two times higher than the ones obtained for UMTS/HSDPA, both for DL and UL. One thing that should be considered is that this paper was prepared on behalf of the WiMAX Forum, therefore, some results may be too optimistic and beneficial towards Mobile WiMAX.

In [WoKa05], a comparison between Portable Internet, which is a subset of IEEE 802.16e, and CDMA, the basis of UMTS/HSDPA, is presented. This study focuses mainly on aspects like service area and technical issues, comparing characteristics such as TDD, FDD, CDMA and OFDMA. There is also a concern regarding network topology, and whether a technology should be implemented, or not, based on business models and service characteristics. Portable Internet offers several technical advantages, such as high bit rate and high spectral efficiency. On the other hand, CDMA has the advantage of providing better QoS and higher mobility functionalities. A considerable aspect is service deployment, as it is important for Portable Internet to be available soon, in order to compete with the technology already implemented.

Chapter 3

Model and Simulator Description

In this chapter, an overview of both the single user radius model and the UMTS/HSDPA/Mobile WiMAX simulator is presented. The former is intended to provide an overview of network planning, regarding cell radius for UMTS/HSDPA and Mobile WiMAX for a single user. These models can be used in the first phase of network planning. The latter, based on an existing simulator, has the objective of enabling the analysis of a more realistic case, with users performing multiple services, randomly spread over the cell coverage area. The outputs of this simulator are the average network radius, average instantaneous network throughput, among others. At the end of this chapter, the simulator assessment is presented.

3.1 Single User Radius Model

In this section, a functional description of the radius calculator for single service is presented. The user interface of this model is shown in Annex B. To calculate the cell radius, it is considered that a single user is requesting a certain throughput and then the physical distance between the user and the BS is calculated. For single user analysis, the inputs are the throughput and radio parameters, which differ from the chosen system.

For UMTS/HSDPA, the considered radio parameters are:

- Transmission power
- Frequency
- Number of HS-PDSCH codes
- BS and MT antenna gains
- Environment: pedestrian, vehicular, indoor with low and high losses.

Other parameters, such as the throughput according to the number of selected codes, additional losses, noise factor, and traffic power percentage, can also be modified. This model was developed in collaboration with [Lope08]. From (3.1), the maximum throughput at the physical layer is 0.96 Mbps per HS-PDSCH code, being 4.8, 9.6 and 14.4 Mbps for 5, 10 and 15 codes, respectively. In real networks, only 14 HS-PDSCH codes are used for data, since usually, 2 HS-SCCH codes must be reserved for signalling and control. So, the maximum throughput at the physical level is 13.44 Mbps.

$$SF = \frac{\text{Chip rate}}{\text{Symbol rate}} \Leftrightarrow 16 = \frac{3.84}{\frac{\rho_P}{4}} \Leftrightarrow \rho_P = 0.96 \text{ Mbps} \tag{3.1}$$

Considering a coding rate of 75%, the maximum throughput at the Radio Link Control (RLC) layer is 3.6, 7.2 and 10.08 for 5, 10 and 15 HS-PDSCH codes, correspondingly. The maximum allowed throughput at the application level considered is 3.36, 6.72 and 9.4 Mbps for 5, 10 and 15 HS-PDSCH codes, respectively, considering 93.3% of 3.6, 7.2 and 10.08, due to the overhead of the MAC and RLC layers. These are the available throughputs at the application level, with the more realistic values being around 3, 6 and 8.46 Mbps, considering a BLER and application overhead of 10%. For UMTS/HSDPA single user, the only limiting factor is the available number of HS-PDSCH codes that restrain the maximum application throughput.

For Mobile WiMAX, the radio parameters are the ones considered for UMTS/HSDPA with the exception of the number of HS-PDSCH codes. Instead, the channel bandwidth and the TDD split are parameters to be taken into account. Other parameters, such as diversity gain, additional losses, noise figure, and implementation margin, can also be changed. The implementation margin is a parameter that represents non-ideal receiver effects, such as channel estimation errors, tracking and quantisation errors.

The maximum allowed throughput for Mobile WiMAX is calculated taking as a basis the values in

Table 2.5. These values represent the throughput at the physical layer for 44 OFDM data symbols and TDD split 1:0. Then throughput values are calculated taking the 11 OFDM symbols due to frame overhead into account, from the total 48 OFDM symbols. Therefore, only 37 data OFDM symbols are considered for data transmission. Throughout this work, only 11 OFDM symbols of frame overhead are considered, not varying according to the number of users allocated to each frame. After this calculation, only 93.3% of those values are considered due to Medium Access Protocol (MAP) overhead and 90% due to BLER. Only DL data rates and TDD splits 1:1, 2:1 and 3:1 are the ones considered in the simulations. For TDD split 1:1, the number of data symbols considered is 37*(1/2), for TDD split 2:1 is 37*(2/3), and for TDD split 3:1 is 37*(3/4). Maximum application throughput for TDD splits 1:1, 2:1 and 3:1 considering a 5 or a 10 MHz channel are given by Table 3.1.

Table 3.1. Maximum application throughput for several TDD splits.

TDD split	Channel bandwidth [MHz]	Maximum application throughput [Mbps]
1:1	5	5.04
	10	10.07
2:1	5	6.70
	10	13.42
3:1	5	7.54
	10	15.09

The objective of this model is to demonstrate a way to maximise the cell radius for a certain throughput, introduced in the user interface. To do so, several considerations are taken into account, namely perfect channel conditions, absence of interference of both external factors and multiple users. This model is based on a snapshot of the cell under the best radio conditions, but both slow and fast fading margins of each environment are considered. The transmission power, antenna gains, frequency and other parameters used in the link budget are listed in, Table 4.2.

UMTS/HSDPA and Mobile WiMAX receivers' sensitivity are calculated in Annex A. The total path loss is determined by (A.12). From the COST-231 Walfisch-Ikegami propagation model, one has [DaCo99]:

$$L_{p[\text{dB}]} = L_{0[\text{dB}]} + L_{tt[\text{dB}]} + L_{tm[\text{dB}]} = EIRP_{[\text{dBm}]} - P_{r[\text{dBm}]} + G_{r[\text{dBi}]} - M_{[\text{dB}]} \quad (3.2)$$

where:

- L_0 :free space loss,
- L_{tt} : rooftop-to-street diffraction loss,
- L_{tm} : approximation for the multi-screen diffraction loss,
- $EIRP$: equivalent isotropic radiated power, given by (A.2) and (A.3),
- P_r : available receiving power at the antenna port,
- G_r : receiving antenna gain,
- M : total margin, given by (A.11) and (A.13), for UMTS/HSDPA and Mobile WiMAX, respectively.

Through the manipulation of (3.2) the L_{tt} and L_0 expressions from the COST-231 Walfisch-Ikegami model, the cell radius can be calculated by:

$$r_{[\mathrm{km}]} = 10^{\frac{EIRP_{[\mathrm{dBm}]} - P_{r[\mathrm{dBm}]} + G_{r[\mathrm{dBi}]} - M_{[\mathrm{dB}]} - L'_{tt[\mathrm{dB}]} - K_f \cdot \log(f_{[\mathrm{MHz}]}) - L'_{tm} - 10 \cdot \log(f_{[\mathrm{MHz}]})_{[\mathrm{dB}]} - 32.4 - 20 \cdot \log(f_{[\mathrm{MHz}]})}{20 + k_d}} \tag{3.3}$$

where:

- $L'_{tt} = L_{tt} - k_d \cdot \log(d_{[\mathrm{km}]}) - k_f \cdot \log(f_{[\mathrm{MHz}]})$,
- k_d : dependence of the multiscreen diffraction loss versus distance,
- k_f : dependence of the multiscreen diffraction loss versus frequency,
- $L'_{tm} = L_{tm} - 10 \cdot \log(f_{[\mathrm{MHz}]})$.

3.2 UMTS/HSDPA and Mobile WiMAX Simulator

3.2.1 Simulator Overview

The simulator is adapted from the one developed on [CoLa06], [Card06] and [SeCa04]. The simulator's main structure is presented in Figure 3.1. The new UMTS/HSDPA and Mobile WiMAX modules, highlighted in red in Figure 3.1, were added, but the simulator main structure was not modified. The UMTS/HSDPA module was elaborated in collaboration with [Lope08].

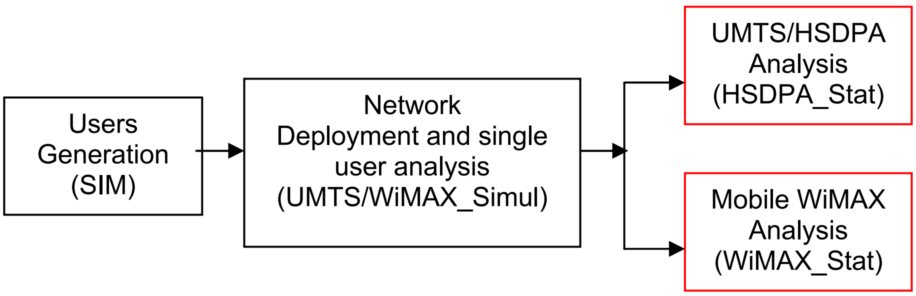


Figure 3.1. Simulator overview (adapted from [CoLa06]).

This simulator has the primary objective of enabling the analysis of the performance of a UMTS-FDD/Mobile WiMAX-TDD network. The simulator consists of four major modules:

- Users Generation,
- Network deployment and single user analysis,
- UMTS/HSDPA analysis,
- Mobile WiMAX analysis.

The user generation module is described in detail in [CoLa06]. The only modification was to create a new type of scenario, the indoor high loss one, in order to establish a difference between indoor scenarios with low and high penetration attenuation. This modification is due to the fact that most users access wireless networks mainly in indoor scenarios. The input files for the traffic distribution and the service penetration percentage are described in Annex C.

The network deployment module is described in detail in [CoLa06]. This module places the users from the output file of the SIM program in the city of Lisbon, distributed throughout the most populated areas. After the user placement, the network is deployed. Then, a first network analysis is performed, the cell radius being calculated for a single user for each service and for a reference throughput. The link budget used in this analysis is the one presented in Annex A. In Annex D, a user manual of the UMTS_MobileWiMAX_Simul is presented.

3.2.2 UMTS/HSDPA and Mobile WiMAX Implementation

A module is implemented to analyse the impact of UMTS/HSDPA and Mobile WiMAX in the network. It has as main objectives the analysis of network capacity and coverage through a snapshot, calculating instantaneous network results, and an estimation for the busy hour in terms of data volume and number of users. This module performs an analysis in the BS, and then network results are obtained through the average values of all BSs.

In order to do an accurate network analysis, some parameters are taken into account. For UMTS/HSDPA, one has:

- BS DL transmission power,
- Frequency,
- MT antenna gain,
- User and cable losses,
- Noise factor,
- Signalling and control power percentage,
- Number of HS-PDSCH codes,
- Strategy reduction,
- Reference service,
- Interference margin,
- Environment,
- Service percentage penetration,
- QoS priority,
- File size for each service.

Each of these parameters can be modified, and all have influence in the simulations' results. Radio parameters, such as BS DL transmission power, frequency, MT antenna gain, user and cable losses, and noise factor, are the same as the ones considered in Section 3.1. As UMTS/HSDPA is not a stand alone system, being deployed on top of UMTS/R99, even for a dedicated carrier, such as the one considered throughout this work, a percentage of the total BS DL transmission power is reserved for signalling and control for R99. Additionally, some power percentage must be assured for signalling and control of UMTS/HSDPA.

The number of HS-PDSCH codes is one a key parameter for network evaluation, as it is responsible for the throughput that the end user can benefit from. The maximum throughput associated to the number of HS-PDSCH codes also implies that the maximum instantaneous throughput capacity of the BS is 3 Mbps for 5 codes, 6 Mbps for 10 codes and 8.46 Mbps for 15 codes. These results are the ones calculated in Section 3.1, adapted to the scenario of multiple users, as the capacity in UMTS/HSDPA is shared among all users. In this simulator, one did not considered shared transmission power, as this would require a per-TTI analysis, which is out of the scope of this thesis. In the simulator, a mixture of MTs is not considered, i.e. for the 5 HS-PDSCH codes, only terminals that support 5 codes are considered, and the same procedure is used for 10 and 15 HS-PDSCH codes simulations.

For Mobile WiMAX, the considered parameters are essentially the same as the ones considered in Section 3.1. Additionally, strategy reduction, reference service, interference margin, environment, service percentage penetration, QoS priority, and file size for each service, are parameters to be thought-out. The channel bandwidth and the TDD split are relevant factors when dealing with the capacity for Mobile WiMAX, as they are directly responsible for the throughput that the end user is capable of receiving. The channel bandwidth determines how many data sub-carriers are available for throughput in one OFDM data symbol, and the TDD split is responsible for the number of OFDM data symbols used for DL transmission in one Mobile WiMAX frame. As in UMTS/HSDPA, in Mobile WiMAX, the capacity is also shared among all users.

The reduction strategies, described in detail in Annex E, considered for both systems are:

- “Throughput reduction”, where all users are reduced by a certain percentage defined in UMTS/HSDPA and Mobile WiMAX settings window.
- “QoS class reduction”, where all the users from the same service are reduced by 10%, services are reduced according to the services’ priorities list, Table 4.3.
- “QoS one by one reduction”, where for a certain service, each user is reduced one by one; services are reduced according to priority list, Table 4.3.

The reference service stands as an indicator of how many users are going to be considered during simulations. This is due to the fact that a higher throughput for the reference service has as consequence a smaller nominal BS radius, serving fewer users. This analysis is for a single user only, with the purpose of not considering the users that are beyond the BS radius.

The interference margin is a parameter that intends to emulate the load in the cell, as there is no specific interference margin in DL. This margin is only considered in the multiple users scenario, and its calculation is explained in Annex A. This parameter represents the main difference between the single user and the multiple users scenarios. By considering the interference margin, path loss decreases, leading to a lower cell radius and throughput, when one compares the single user with the multiple users scenario. Bearing the environment in mind, this has an influence on the radius calculation, as the different types of environment have different attenuation margins. These values are presented in Section 4.1. Afterwards, the radius for all the considered services is calculated, as well as the radius for the reference service, as shown in Figure D.9.

The next step is to define the maximum and minimum throughputs for each of the services considered. This is done by using the User Profile window. For UMTS/HSDPA, maximum throughput values are given by system limitations, i.e., the number of HS-PDSCH codes chosen and for Mobile WiMAX, they are given by the available number of data sub-carriers, Table 3.2. The user and BSs inclusion is defined in Subsection 3.2.1.

During simulation, the number of users that are physically inside the coverage area of the BSs is calculated. Two files are generated and used in HSDPA_Stat or WiMAX_Stat modules:

- “data.dat”, containing the BS that the user is connected to and its corresponding distance and the service requested, among others;
- “definitions.dat”, with the radio parameters considered, minimum and maximum throughput for each service, and other simulations’ settings regarding each of the systems.

Table 3.2. Maximum throughput for UMTS/HSDPA and Mobile WiMAX.

		Maximum throughput [Mbps]
UMTS/HSDPA Number of HS-PDSCH codes	5	3
	10	6
	15	8.46
Mobile WiMAX TDD spit / Channel bandwidth [MHz]	1:1 / 5	5.04
	1:1 / 10	10.07
	2:1 / 5	6.70
	2:1 / 10	13.42
	3:1 / 5	7.54
	3:1 / 10	15.09

In the next module, the first step is to associate every user to a certain BS, according to the distance, being connected to the closest BS, since each user is usually in the coverage area of several BSs. Next, the throughput associated to the user’s distance is calculated, i.e., the maximum throughput that is possible to serve considering the user’s path loss. This algorithm is explained in detail in Annex A. The user is considered in either of three conditions:

- served with the requested throughput, when the throughput given by distance is higher than the service’s throughput;
- served with the throughput given by distance, when it is higher than the minimum and lower than the maximum service throughput;
- otherwise, the user is delayed.

The services’ throughput are obtained from the file “definitions.dat” and compared with the throughput given by the user distance, after being multiplied by a random number between 0 and 1, which represents a more realistic approach, since, in some cases, the throughput limitation is not imposed by the network but by the server's congestion at a certain time. This procedure is shown in Figure 3.2.

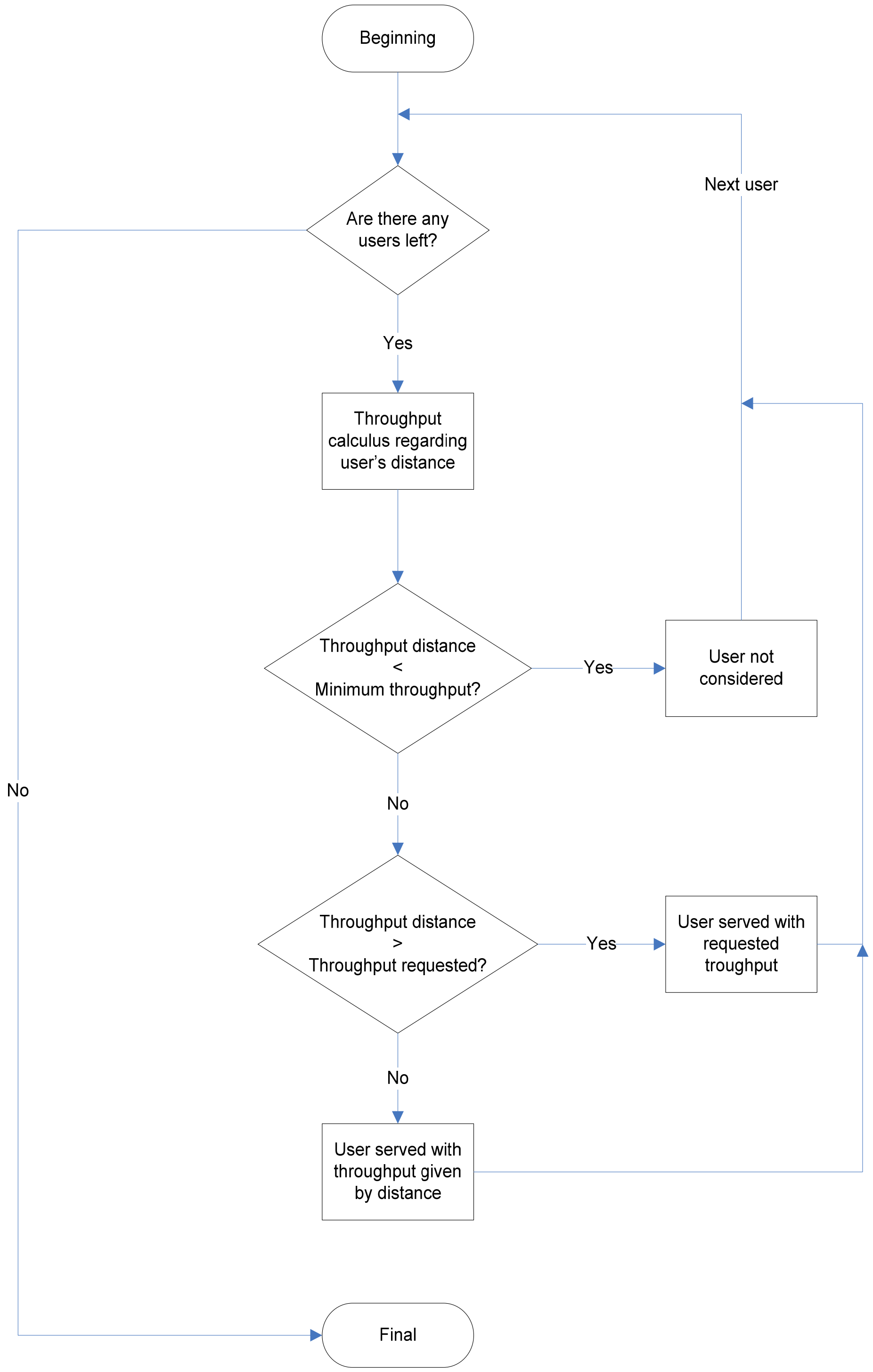


Figure 3.2. User's throughput calculation algorithm.

The following process is to analyse system's capacity, at the BS level. To do so, one calculates the sum of every instantaneous throughput that each user is performing. The two possible cases for this situation are:

- if the sum is lower than the maximum allowed throughput for the BS, all users are served without reduction;

- otherwise, the chosen reduction strategy is applied, Annex D.

The latter process is detailed in Figure 3.3.

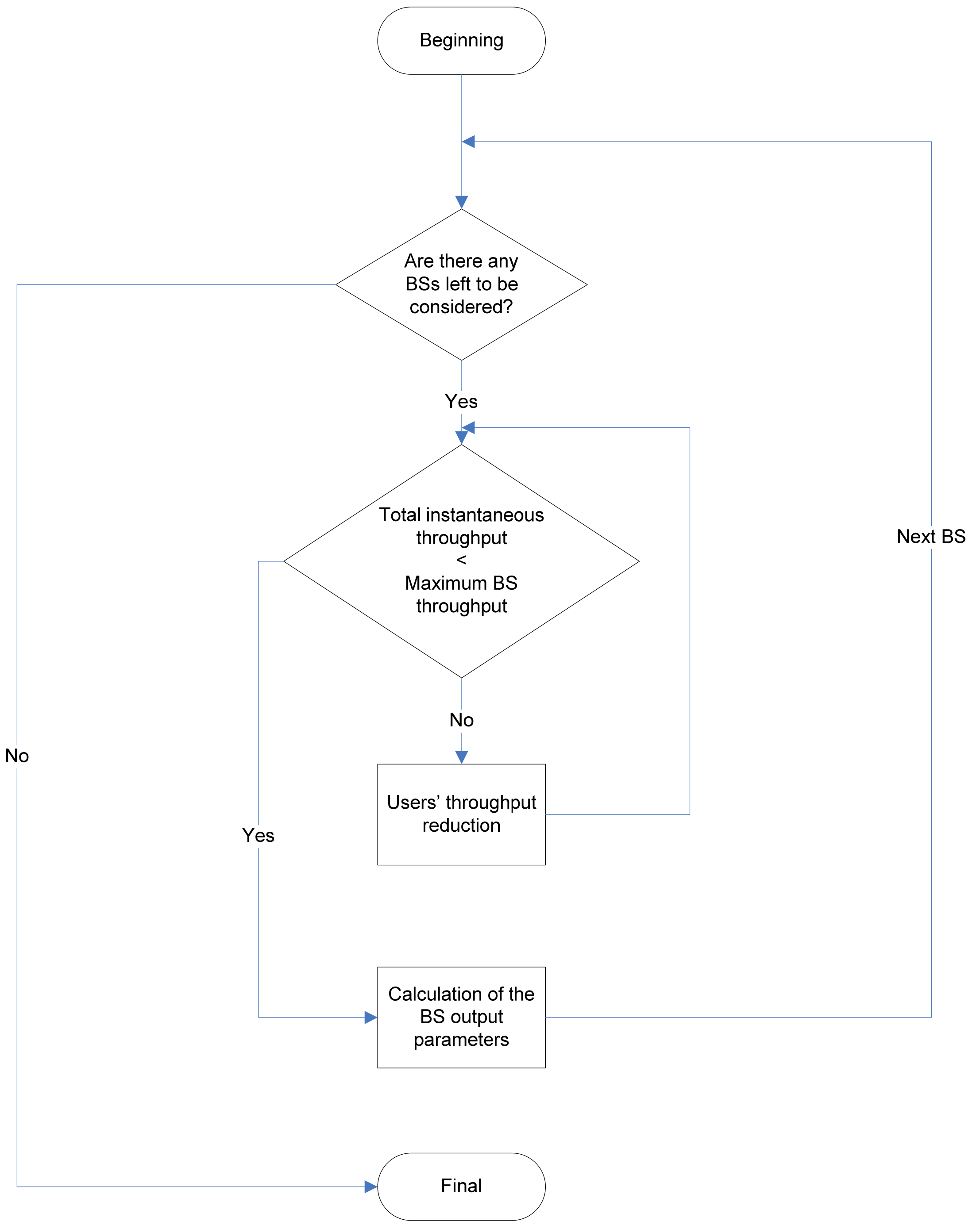


Figure 3.3. Capacity algorithm for each BS.

After the capacity analysis, several network parameters are calculated. The most important results per BS are:

- instantaneous throughput served, being the sum of all users' throughput;
- normalised throughput, parameter presenting the ratio between the instantaneous throughput served and the maximum allowed throughput;

- radius, given by the average of the three sectors;
- number of users served and delayed;
- percentage of satisfied and unsatisfied users, where a satisfied user is the one being served with the requested throughput;
- average instantaneous throughput per user, given by the ratio between the instantaneous throughput served by the BS and the number of served users;
- satisfaction grade, being the ratio between the served and requested throughputs;
- total BS volume of data transferred in one hour;

These parameters, except, for the radius one, are also presented when dealing with a services detail analysis, where all parameters are now considered only for the users performing each one of the services. This analysis is then performed for all the BSs in the network, and the average of each of the parameters is calculated for the network, taking now the total number of users performing each service into account. The outputs for these results are shown in Figure D.12 and Figure D.13.

For the network analysis, the most important parameters are:

- percentage of served users, being the ratio between the number of served users and the total number of users in the network,
- average network satisfaction grade,
- average network radius, being the average of all BS individual radius throughout the network,
- average network throughput, with the average of all BS individual instantaneous throughput for the whole network.

After the instantaneous analysis, results are extrapolated for the "busy hour" analysis, using the traffic models detailed in Subsection 4.1. The parameters studied in this analysis are:

- total network traffic per hour, being the sum, in GB, of all the sessions' volume in one hour,
- total number of users per hour.

3.2.3 Input and Output Files

To run the simulator, it is necessary to insert the following files in the UMTS/WiMAX_Simul:

- "Ant65deg.TAB", with the BS antenna gain for all directions,
- "DADOS_Lisboa.TAB", with information regarding the city of Lisbon and all its civil parishes,
- "ZONAS_Lisboa.TAB", with the area characterization like streets, gardens, along with others,
- "users.txt", containing the users in the network, being the output of SIM module,
- "BSs_Lisbon_map.TAB", with the information of the location of the BSs in the network.

The UMTS/WiMAX_simul module creates two files that are going to be used by the UMTS/HSDPA and Mobile WIMAX modules, such as:

- “data.dat”, containing the BS that the user is connected to and its corresponding distance, and the service requested, among others,
- “definitions.dat”, with the radio parameters considered, minimum and maximum throughputs for each service, and other simulations’ settings regarding each of the systems.

Based on these files, the UMTS/HSDPA and Mobile WiMAX modules perform the network analysis, producing two output files associated to UMTS/WiMAX_Simul to present the results:

- “stats.out”, which includes all the results for the instantaneous analysis, both for the network analysis as well as the statistics by service,
- “stats_per_hour.out”, where the results for the hour analysis are displayed.

3.3 Simulator Assessment

All the steps responsible for carrying out a simulation were validated using several tools. The propagation model and link budget used were confirmed by performing various calculations using Matlab and EXCEL, in order to make sure the results were correct and according to what is expected theoretically.

Regarding the users’ insertion in the network, some validations were performed. As SHO is not considered in UMTS/HSDPA and Mobile WiMAX, it must be assured that each user is only connected to one BS. To do so, an output file was created containing the user’s information considering the BS to which the user was connected. Even though the user may be in the coverage area of several BSs, the simulator only contemplates the nearest BS to the user.

All three strategies were analysed through a controlled scenario, i.e., using a simulation with approximately 500 users and 3 BSs. After performing this simulation, the total instantaneous throughput was the parameter to be taken into account. Forcing the situation where the total instantaneous throughput requested by all users was higher than the one allowed by the BS, the list of user’s throughput was then placed in an Excel sheet, to monitor every step of the strategy reduction chosen. After the simulation, the output results, such as summations, averages and standard deviations were confirmed, by using the respective well-know formulas. This procedure was carried out in the BS analysis, as well as when considering the whole network.

As the users’ geographical position is random, together with the requested throughput, which is affected by a random function, several simulations must be taken to assure the validation of the results. The default number of users considered was approximately 1600. Considering this value, 30 simulations were performed, using different users’ input files, with the objective of finding the ideal number of simulations, Table 3.3. This is achieved by considering the standard deviation and the duration of each simulation. These simulations were executed in a Pentium 4, CPU 3 GHz, 960 MB RAM, with a duration of 30 minutes each. The parameters considered in this analysis are: percentage of served users, satisfaction grade, average network throughput and average network radius.

Taking the results in Figure 3.4, Figure 3.5, Figure 3.6, Figure 3.7 and in Table 3.3 into account, one considered that 10 simulations are enough to validate the results of the simulator, for the given simulation duration evolution of the standard deviation. As seen in Table 3.3, the average is almost constant for each parameter, while the standard deviation presents a smooth variation.

These results were obtained for UMTS/HSDPA. As the simulator principle is essentially the same for UMTS/HSDPA and Mobile WiMAX, the number of simulations obtained for UMTS/HSDPA is equal for Mobile WiMAX.

Table 3.3. Average and standard deviation values of the parameters considering 30 simulations.

Number of simulations	Average ratio of served users		Average satisfaction grade		Average network throughput [Mbps]		Average network radius [km]	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
5	0.51	0.01	0.86	0.04	2.39	0.10	0.29	0.05
10	0.51	0.01	0.87	0.04	2.39	0.08	0.28	0.01
15	0.51	0.01	0.87	0.03	2.39	0.08	0.29	0.01
20	0.52	0.01	0.86	0.03	2.41	0.09	0.29	0.01
25	0.52	0.01	0.86	0.03	2.39	0.09	0.29	0.01
30	0.52	0.01	0.86	0.03	2.38	0.09	0.29	0.01

In Figure 3.4 it is possible to observe the ratio between the standard deviation and the average for each parameter. As there is no relevant decrease of this ratio along the number of simulations and considering the duration of each simulation, one considered that 10 simulations it the most appropriate number.

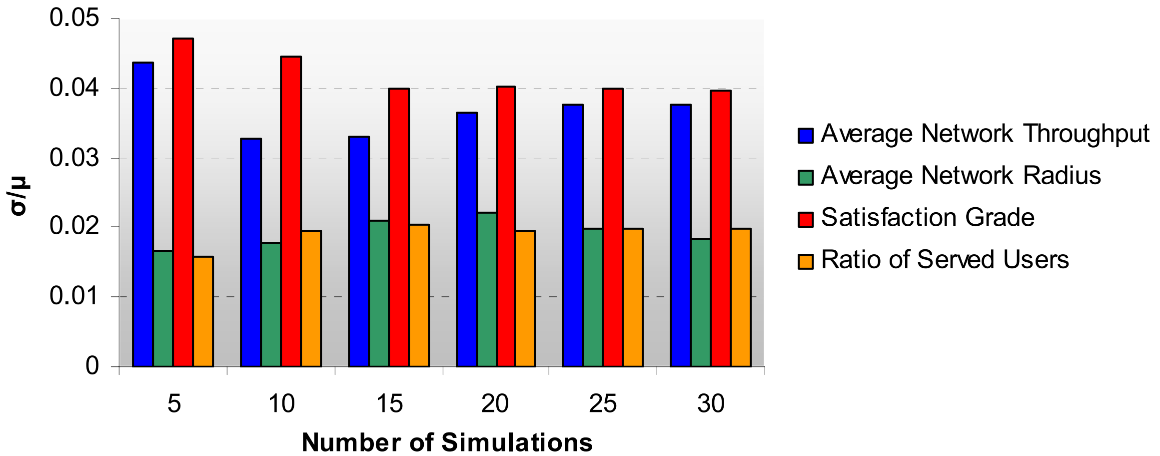


Figure 3.4. Analysis regarding the number of simulations considered.

Chapter 4

Results Analysis

In this chapter, the results for UMTS/HSDPA and Mobile WiMAX for the single user radius model as well as for the simulator representing the multiple users' scenario, are presented. First, the single user radius model results are analysed for both systems, separately, considering the variation of several parameters, and their influence in the cell radius. The results obtained from the simulator described in Chapter 3 are also presented. The variation of various parameters is considered, such as the number of HS-PDSCH codes for UMTS/HSDPA and the channel bandwidth for Mobile WiMAX. Also common parameters for both systems, like reduction strategies, are studied regarding their influence in the network analysis. At the end of this chapter, a comparison between UMTS/HSPDA and Mobile WiMAX is shown, concerning the single user model and the multiple users scenario results.

4.1 Scenarios Description

The two scenarios taken into account throughout this work are the single user and the multiple users ones. The single user scenario considers that there is only one user in the cell, therefore, all the available resources are reserved to him. This scenario is used to calculate the maximum cell radius for the chosen throughput. The multiple users scenario considers users uniformly distributed along the coverage area of the BS, performing different services.

For both scenarios, the environments considered are pedestrian, vehicular, indoor low loss and indoor high loss. The pedestrian environment represents a user at the street level with low attenuation margins; the vehicular one stands for users performing services moving at considerable speed, where a large value for the slow fading margin is considered; the indoor environment represents users performing services inside buildings, where the high loss one is used for users in deep indoor locations. The percentage of users inside each cell is distributed as follows:

- Pedestrian: 10%
- Vehicular: 10%
- Indoor low loss: 50%
- Indoor high loss: 30%

Indoor environments represent the largest part of the overall percentage, as it is, at present, the most common environment for users performing the types of services analysed. Table 4.1 shows the attenuation margins associated to each environment.

Table 4.1. Slow and fast fading and penetration margin values (based on [CoLao6]).

	Environment			
	Pedestrian	**Vehicular**	**Indoor Low Loss**	**Indoor High Loss**
M_{SF} [dB]	4.5	7.5	7.0	7.0
M_{FF} [dB]	0.3	1	0.3	0.3
L_{int} [dB]	0	11	11	21

The parameters used for link budget estimation for both scenarios, and the default values considered, are shown in Table 4.2. For the single user scenario, the interference margin and the reduction strategy are not considered. Regarding the maximum BS antenna gain, the considered value is 17 dBi and for other directions, the antenna gain is given by the 65º antenna radiation pattern detailed in [CoLa06].

The default throughput values for the services considered for the multiple users scenario, as well as the QoS priority list, are presented in Table 4.3 for the default scenario. For the QoS priority list, the first services to be reduced are the ones with higher QoS values.

Table 4.2. Parameters values used in UMTS/HSDPA and Mobile WiMAX for link budget assessment (based on [CoLa06], [EsPe06] and [WiMF06a]).

Parameter name	UMTS/HSDPA	Mobile WiMAX
BS DL Transmission Power [dBm]	44.7	43
TDD split	---	2:1
DL Frequency (single user) [MHz]	2112.5	3500
DL Frequency (multiple user) [MHz]	2142.5	
Channel bandwidth [MHz]	---	10
Number of HS-PDSCH codes	10	---
MT Antenna Gain [dBi]	0	-1
Maximum BS Antenna Gain [dBi]	17	17
Cable losses between emitter and antenna [dB]	3	0.7
Losses due to user [dB]	1	
DL Noise Figure [dB]	9	---
Noise Figure + Implementation margin [dB]	---	7
Interference margin [dB]	6	2
Percentage of signalling and control power [%]	R99: 25 UMTS/HSDPA: 10	---
Strategy reduction	"QoS class reduction"	

Table 4.3. Default throughput values and QoS priority list.

Types of services	Maximum DL throughput [Mbps]	Minimum DL throughput [Mbps]	QoS
Web	1.536	0.512	1
P2P	1.024	0.128	6
Streaming	1.024	0.512	2
Chat	0.384	0.064	5
Email	1.536	0.384	3
FTP	2.048	0.384	4

The UMTS/HSDPA and Mobile WiMAX traffic models used for each service are:

- Web:
    - average page size [OPTW06]: 300 kB
    - average reading time [Seba07]: 40 s

- average number of pages per session: 10

- FTP:
  - average file size [SBER03]: 10 MB
  - average number of files per session: 1

- P2P:
  - average file size: 12.5 MB
  - average session initiation time: 30 s

- Chat [CSEE06]:
  - average MSN message size: 50 Bytes
  - average number of received messages during one session: 25

- E-mail [Seba07]:
  - average file size: 100 kB
  - average number of e-mails per session: 1

- Streaming:
  - average video duration [VNUN07]: 150 s
  - average video size: 9.6 MB
  - average number of videos per session [COMS07]: 3

Considering the user throughput and the service that the user is performing, the duration of one session, in seconds is calculated. The total number of sessions per hour gives the total number of users in one hour, performing each service. Based on the number of users in the hour, the total traffic for each service is calculated, taking into account the volume in MB of each session, given by the traffic models. In this “busy hour” analysis, the total number of users, the total network traffic, the average volume and average number of users per BS, as well as the average volume per user, are calculated, Figure D.13. The services’ percentage penetration and QoS priority are shown in Annex C. The default number of users considered in the network is approximately 1600. Using the number of simulations calculated in Section 3.4, several numbers of users were examined, Table 4.4.

As expected, the average network throughput increases with the number of users, but parameters like satisfaction grade, percentage of served users, and the average instantaneous throughput, decrease, the average network radius variation not being significant. Considering the parameters’ evolution, the number of users that maximise the correlation among them is 1600.

Table 4.4. Evaluation of the number of users taking into account several parameters.

Parameters	Approximate number of users							
	800		1200		1600		2000	
	Average	Std deviation	Average	Std deviation	Average	Std deviation	Average	Std deviation
Average Network Throughput [Mbps]	1.56	0.08	1.99	0.08	2.39	0.08	2.71	0.07
Average Network Radius [km]	0.26	0.01	0.27	0.01	0.28	0.01	0.29	0.01
Average Satisfaction Grade	0.91	0.03	0.90	0.02	0.87	0.04	0.86	0.02
Average Ratio of Served Users	0.55	0.02	0.53	0.01	0.51	0.01	0.49	0.01
Average Instant. Throughput/user [Mbps]	0.57	0.02	0.58	0.02	0.56	0.01	0.56	0.01

4.2 Single User Radius Model Analysis

In this Section, the results for the single user radius model are presented, being assumed that the user is performing only one service i.e., requesting one throughput at a time. The minimum throughput considered in the simulations for the single user scenario is 0.384 Mbps. First, the UMTS/HSDPA results are presented, followed by the Mobile WiMAX ones. In Annex F, the results obtained are presented.

4.2.1 UMTS/HSDPA

Regarding UMTS/HSDPA, Figure 4.1 presents the cell radius for several environments for the default values show in Table 4.2. In Figure 4.1, the variation of the cell radius with the throughput for each of the environments is shown. For all the environments, it is possible to observe that the cell radius decreases with the increase of the throughput. This is due to the fact that higher throughputs require higher SINR values, Figure A.1. With the increase of the SINR value, the path loss decreases, along with the cell radius, taking (A.6), (A.1) and (3.3) into account.

Considering the different environments, it is seen that the pedestrian one presents a higher cell radius compared with the others. As in Table 4.1, it is observed that the pedestrian environment presents lower attenuation margins. This justifies the higher cell radius for the pedestrian environment, as the sum of the three margins is considered in the path loss, as seen in (A.11) and (A.12). This explains the results for vehicular and indoor low loss being so similar, since the sum of the three margins for each environment are approximately the same, even though the environments' characteristics are different. Considering the indoor low loss scenario, it is observed that when the throughput ranges from 2 to 6 Mbps, the cell radius goes from 0.4 to 0.2 km, a decrease of 50 %

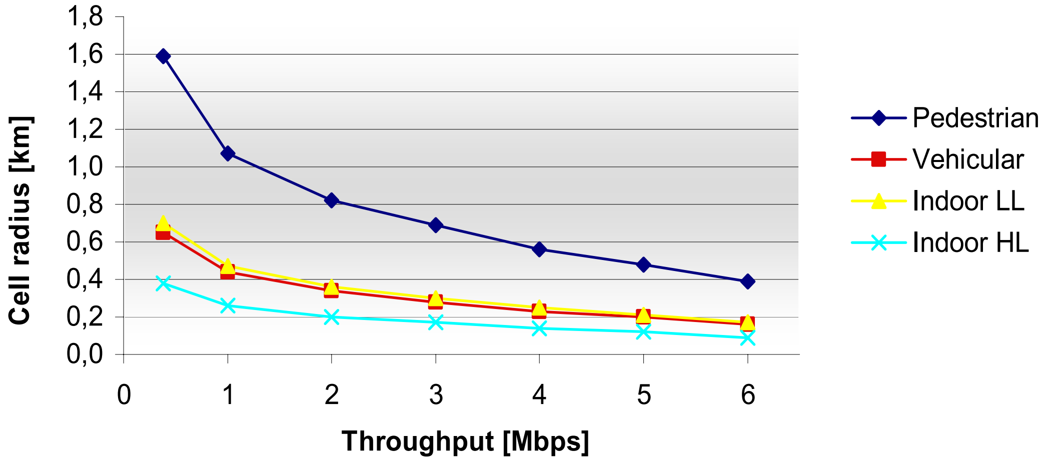


Figure 4.1. UMTS/HSDPA cell radius for 10 HS-PDSCH codes.

In Figure 4.2, the cell radius variation with the total BS DL transmission power is shown, considering a fixed throughput of 3 Mbps, and the pedestrian environment for 5, 10 and 15 HS-PDSCH codes. For all these calculations, the frequency is 2112.5 MHz. One considered 3 Mbps as it is the highest throughput among all analysed HS-PDSCH codes analysed. Figure 4.2 shows that by fixing a number of HS-PDSCH codes, it is possible to examine the influence of the total BS DL transmission power. With the increase of the transmission power, the cell radius increases, as there is a direct relationship between these two parameters, as seen in (A.2), (A.1) and (3.3).

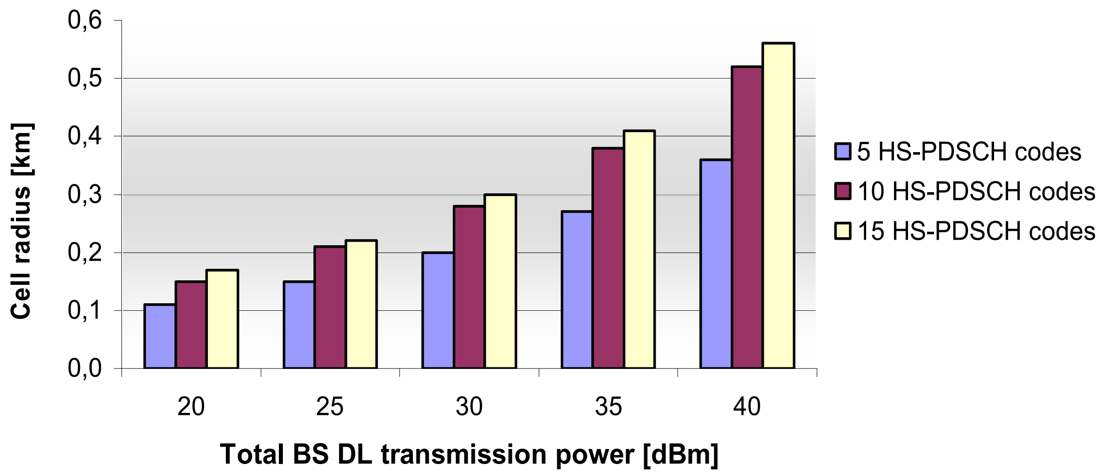


Figure 4.2. UMTS/HSDPA cell radius with total BS DL transmission power variation.

For each transmission power value, the same pattern repeats, i.e., a higher number of HS-PDSCH codes implies a higher cell radius. This is due to the curves presented in Figure A.1, where it is possible to see that, for the same throughput, SINR values decrease as the number of HS-PDSCH increases. Therefore, using (A.6), (A.1) and (3.3), one concludes that 15 HS-PDSCH codes allow to achieve a higher cell radius than 10 or 5 ones.

In Figure 4.3, a mix of Figure 4.1 and Figure 4.2 is presented, with the cell radius variation taking the number of HS-PDSCH codes and the type of environment into account. Figure 4.3 is obtained by considering a throughput of 3 Mbps.

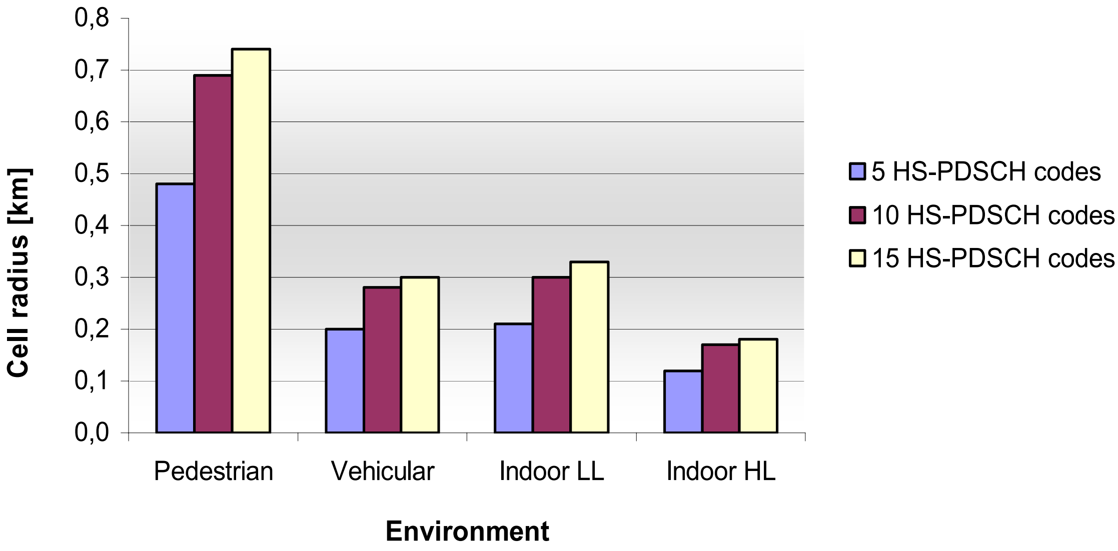


Figure 4.3. UMTS/HSDPA cell radius variation considering several environments.

As seen in Figure 4.3, for the same number of HS-PDSCH codes, the cell radius variation is due to the different margins associated to each environment, as the SINR is independent from the type of environment. The variation in the cell radius concerning the type of environment is not the same, as there is an exponential relationship between the margins and the cell radius, (A.12) and (3.3). The tables used to make the figures shown in this subsection, as well as other tables, are presented in Annex F.

4.2.2 Mobile WiMAX

Considering Mobile WiMAX, Figure 4.4 represents the cell radius for several environments taking the default values presented in Table 4.2 into account.

It is seen in Figure 4.4 that, as observed in UMTS/HSDPA, the cell radius for Mobile WiMAX also decreases when the throughput increases, for the several environments considered. This is due to the same fact explained in Subsection 4.2.1, as the attenuation margins' values for each environment are the same for both systems. Considering one environment, the cell radius decreases, because the SNR increases when the requested throughput also increases, considering a constant DL transmission power. Therefore, by using (A.9), (A.1) and (3.3), it is possible to calculate the cell radius for each throughput chosen.

In Figure 4.5, the cell radius variation with the requested throughput is shown, but now considering the three different frequencies used in Mobile WiMAX. The results are for a 10 MHz channel bandwidth, TDD split 2:1, and DL BS transmission power of 43 dBm.

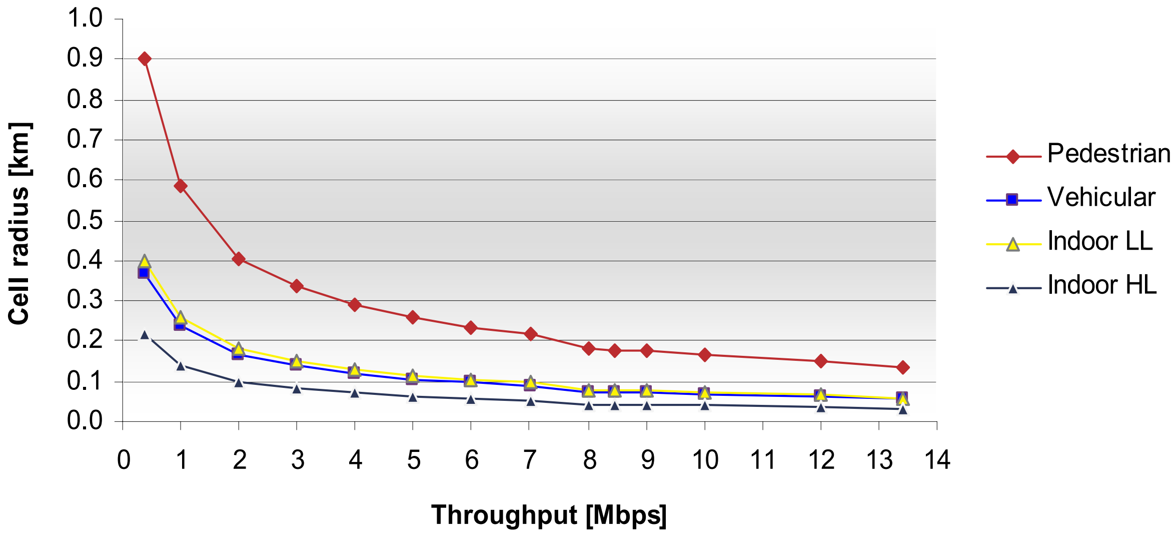


Figure 4.4. Mobile WiMAX cell radius variation regarding the environment.

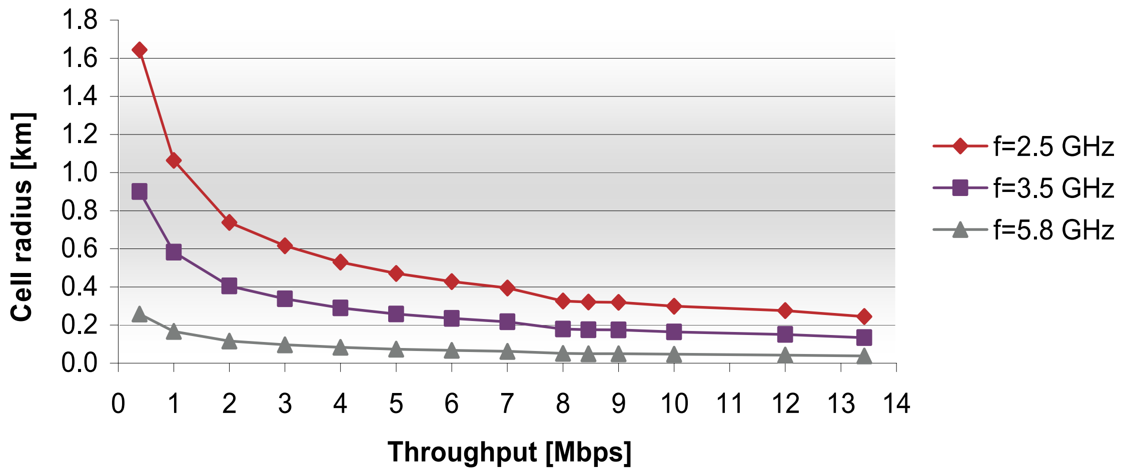


Figure 4.5. Mobile WiMAX cell radius variation considering several frequencies.

Figure 4.5 demonstrates the influence of the frequency regarding cell radius. It is possible to observe that for 2.5 GHz the cell radius for 2 Mbps increases 300 %, being almost 0.6 km higher than the one for 5.8 GHz and increases 100 % when comparing to the cell radius for 3.5 GHz, being approximately 0.4 km higher, considering the same throughput. This is due to fact that with the increase of the frequency, the cell radius decreases, as demonstrated in (3.3).

Considering the DL BS transmission power, Figure 4.6 shows the cell radius variation when considering 13.42 Mbps, which is the maximum allowed throughput for TDD split 2:1 and 10 MHz channel bandwidth. It is seen that with a maximum DL transmission power of 43 dBm, the cell radius almost duplicates when considering 30 dBm of BS DL transmission power. This is observed for the three frequencies. The influence of the transmission power is well demonstrated in (A.1), where it is possible to see the direct relationship between transmission power and path loss. With the decrease of the path loss, the cell radius also decreases, as seen in (3.3).

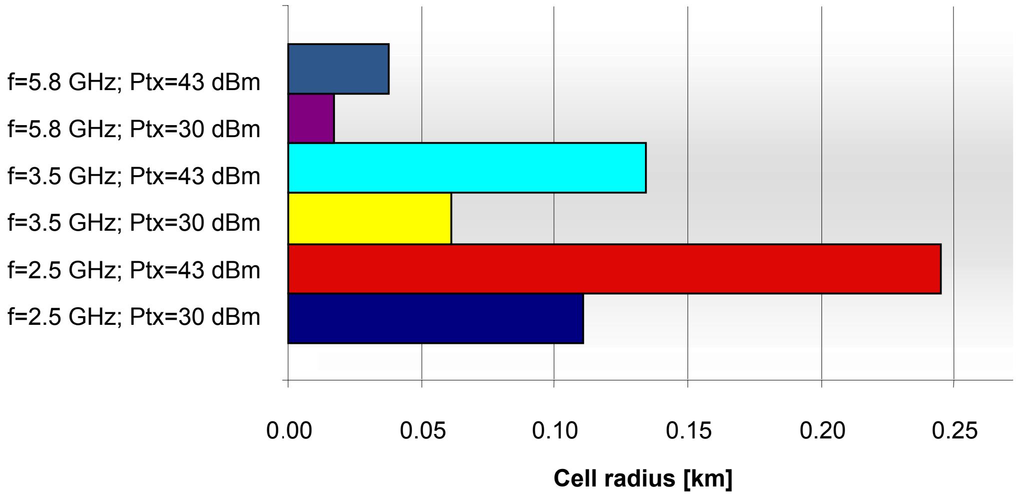


Figure 4.6. Mobile WiMAX cell radius variation with transmission power.

4.3 UMTS/HSDPA Analysis in Multiple Users Scenarios

In this section, the UMTS/HSDPA simulator results for the multiple users scenario are analysed. First, the results for the default scenario introduced in Section 4.1 are presented. Afterwards, the results considering system parameter variation as well as different user profiles, are studied. Some complementary results are presented in Annex G.

4.3.1 Default Scenario

For the served users in all performed simulations, Figure 4.7 can be computed, where the users' distance and throughput are presented. Considering the total number of users in Figure 4.7, one divided the distance in 10 m intervals, and then calculated the average and standard deviation user throughput for the users within each interval, Figure 4.8.

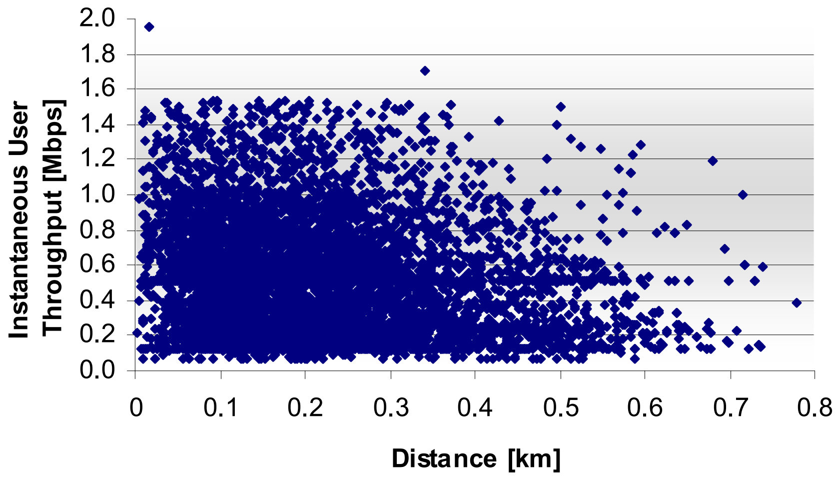


Figure 4.7. UMTS/HSDPA instantaneous user throughput for all users depending on the distance.

Observing Figure 4.8, it is possible to see that, for distances higher than around 0.5 km, the network concerning the user throughput is irregular. This fact is explained by the reduced number of users that can be served when the user's distance increases, as seen by the low standard deviation for distances above 0.6 km.

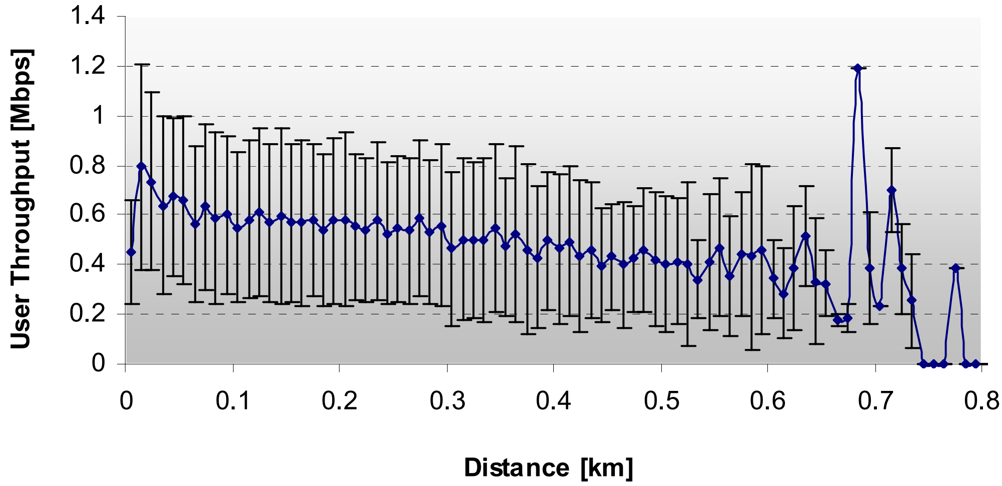


Figure 4.8. Average and standard deviation instantaneous throughput considering 10 m intervals for UMTS/HSDPA.

Limiting now the distance to 0.5 km, where the network behaviour is somehow regular, one computed (4.1), representing the network trend regarding distance and average user throughput in multiple users scenarios, Figure 4.9.

Other interpolation orders were studied, and, as expected, the correlation increases for higher values of the interpolation order. For the 6th order interpolation, the correlation is 0.95, however the increase in correlation does not compensate for the increase in the complexity of the expression, therefore, one chose a linear interpolation, (4.1), with a correlation of 0.9, with a mean relative error of 5.5 %.

$$\rho_{[Mbps]} = -0.521 \cdot d_{[km]} + 0.672 \tag{4.1}$$

where:

- d : distance to the BS

It is observed, in Figure 4.9, that the average instantaneous throughput per user decreases with distance, because the influence of the interference margin is not significant for shorter distances, as the SINR value is still above the threshold for the requested throughput, which is the limiting factor for this case. For higher distances, the SINR is the limiting factor, and with the introduction of the interference margin due to the multi-user scenario, the SINR value given by the distance for a user farther away from the BS becomes lower than the SINR given by the requested throughput, leading to a reduction of the throughput given to each user. For the range of throughput values considered, between 0 and 2 Mbps, the SINR curves present a high derivative, as seen in Figure A.1, implying that the throughput decreases with the increase of the user's distance to the BS.

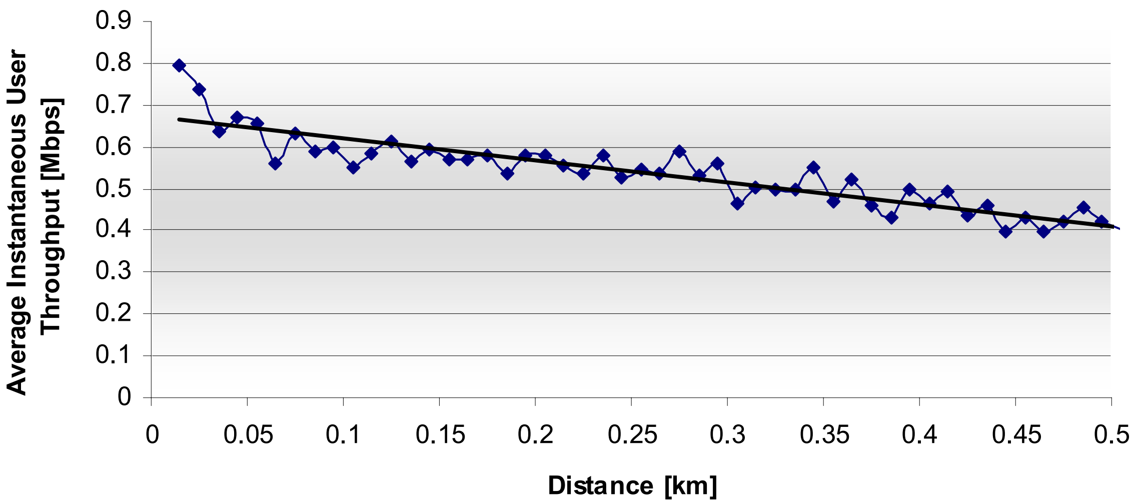
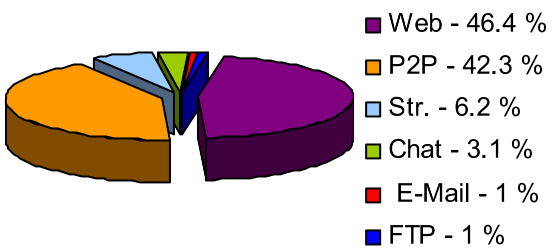
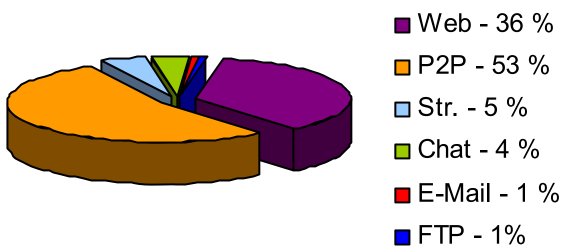


Figure 4.9. First order interpolation for average instantaneous UMTS/HSDPA user throughput

In Figure 4.10, the percentages of served and offered traffic are presented. It is possible to see that there is a difference in the served and offered percentages, due to the reductions that users performing certain services suffer. Figure 4.10(b) represents the services' percentages according to the final number of users that are effectively served. Web is one of the services that shows most significantly the reduction, because it has a high percentage of users and a high minimum throughput, therefore, more users are delayed when reductions are to be made. On the other hand, P2P percentage increases, as fewer users are delayed, due to the low minimum throughput associated to P2P.The explanation for Web and P2P is the same for Streaming and Chat, respectively.



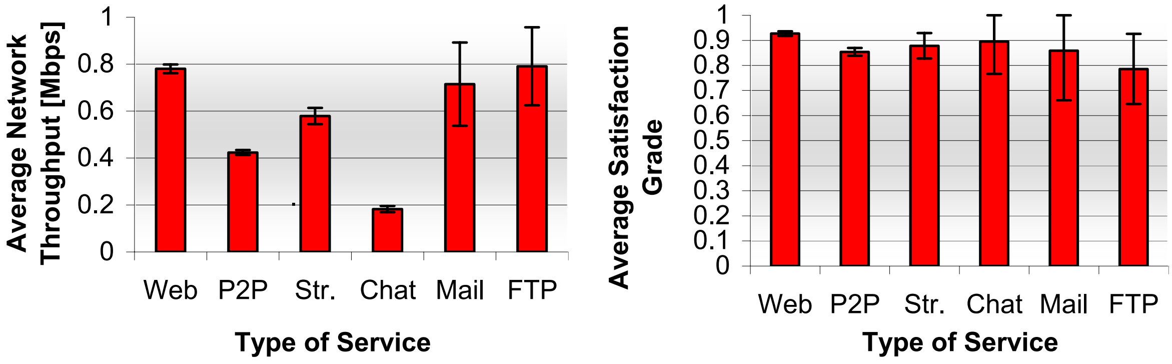
(a) Offered Traffic.



(b) Served Traffic.

Figure 4.10. UMTS/HSDPA traffic percentage.

Figure 4.11 shows the average network throughput and average satisfaction grade for each service. The average network throughput for P2P is somewhat low, as it is the first service to be reduced. On the other hand, its average satisfaction grade is high, due to the fact that even though all users are reduced, leading to the low average throughput, one can demonstrate that a single user is reduced approximately only two times. In Figure 4.11, it is also possible to observe the QoS priorities, as the services are considered differently. Chat presents low average throughput values, due to its low percentage of users and service throughput. Web, Streaming, E-Mail and FTP have the highest priority, therefore, present better results for the average network throughput. E-Mail and FTP have a high standard deviation, as they are the ones with the lowest percentages of users.

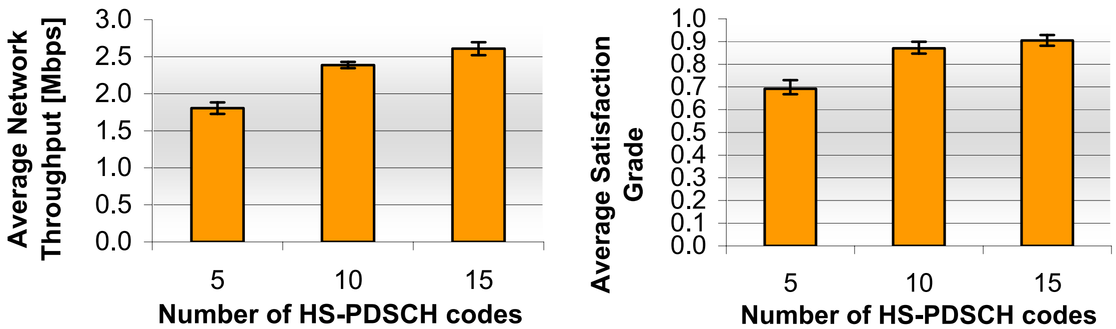


(a) Average Network Throughput. (b) Average Satisfaction Grade.

Figure 4.11. UMTS/HSDPA network parameters (Throughput and Satisfaction Grade).

4.3.2 Number of HS-PDSCH Codes

In this subsection, one analyses the influence of the number of HS-PDSCH codes in the network. When increasing this number, the average network throughput increases approximately 0.3 Mbps, improving around 9.2 %, when changing from 10 to 15 codes, as the maximum throughput allowed for a single BS is higher, due to the fact that more codes are available for data transmission. On the other hand, when changing from the default number of codes to 5, the average network throughput decreases 0.5 Mbps, suffering a reduction of 25 %, for the same reason, Figure 4.12(a). The variation of the average network radius is not significant, since, for every simulation, the users are the same and positioned in the same place, although the throughput each user is performing is different due to the used random function, Figure G.1(a).



(a) Average Network Throughput. (b) Average Satisfaction Grade.

Figure 4.12. UMTS/HSDPA network parameters, varying the number of codes (Throughput and Satisfaction Grade).

The impact of the variation of the number of codes is visible in the average satisfaction grade and the average ratio of served users. With more codes available, each user is served, on average, with a higher throughput, leading to an increase in the satisfaction grade, Figure 4.12(b) and more users can be served, as it can be seen in Figure G.1(b). For the same reason, each user performs its session more quickly, meaning that more users can be served within the hour. Therefore, the total network traffic increases with the number of codes. Regarding network traffic and total number of users per hour, there is an increase of 4.5 % and 5.5 % for 15 codes and there is a reduction of 16 % and 19 % fo 5 codes, Figure G.2.

Figure 4.13 demonstrates the variation of the average instantaneous throughput per user for 5, 10 and 15 HS-PDSCH codes.

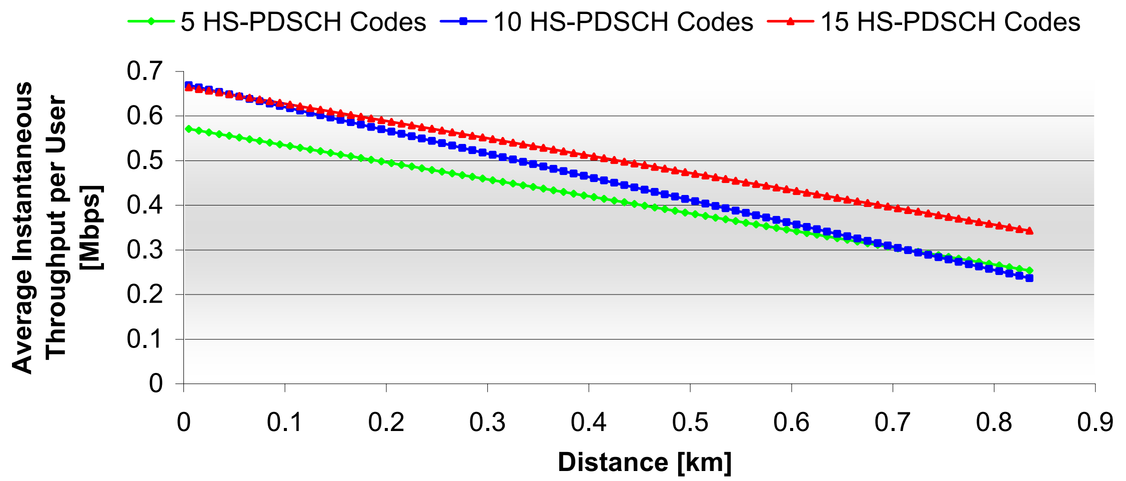


Figure 4.13. UMTS/HSDPA average instantaneous throughput per user variation for 5, 10 and 15 HS-PDSCH codes.

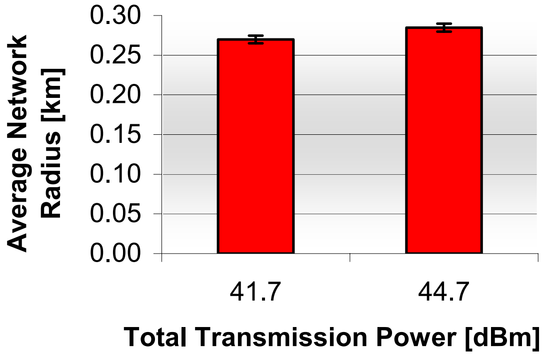
The introduction of 10 codes brings an improvement in the user throughput for distances up to 0.4 km, beyond this distance, the improvement becomes insignificant. With 15 codes, the behaviour is different, for shorter distances, there is not a considerable difference from 10 codes, but for distances higher than approximately 0.4 km, one can achieve an enhancement of 0.1 Mbps in comparison with 5 or 10 codes. Even though 5, 10 and 15 HS-PDSCH codes cover a similar network area, 15 codes allow an improvement in terms of capacity, as for the same distance, the served throughput is higher. For 5 and 15 HS-PDSCH codes, the average instantaneous throughput as function of the users' distance can be calculated by (4.2) and (4.3). To compute (4.2) and (4.3), the same method as the one described for the 10 HS-PDSCH codes was used, with a correlation for 5 and 15 codes of 0.883 and 0.861, respectively. The relative mean error is 5.1 % and 5.5 % for 5 and 15 codes, respectively.

$$\rho_{[\mathrm{Mbps}]} = -0.382 \cdot d_{[\mathrm{km}]} + 0.5729 \tag{4.2}$$

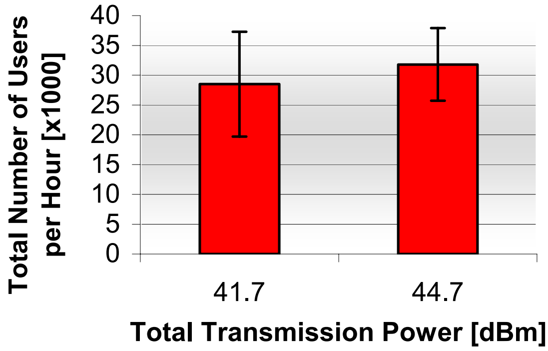
$$\rho_{[\mathrm{Mbps}]} = -0.387 \cdot d_{[\mathrm{km}]} + 0.6662 \tag{4.3}$$

4.3.3 Total Transmission Power

The total transmitted power has a direct influence in the path loss, as seen in Subsection 4.2.1, less transmitted power leads to a lower average network radius, a decrease of 5 %, around 20 m, Figure 4.14(a), therefore, fewer users are served, Figure G.4(a). This implies a lower average network throughput of approximately 0.2 Mbps, representing a reduction of 6 %, Figure G.3(a). Concerning the average satisfaction grade, when reducing the transmitted power, the average satisfaction grade should decrease, as the power assigned to each user is lower, but as there are fewer users to be served, the overall satisfaction grade is approximately the same, Figure G.3(b).



(a) Average Network Throughput.



(b) Average Network Radius.

Figure 4.14. UMTS/HSDPA network parameters, varying the transmitted power (Throughput and Radius).

Concerning the "busy hour" analysis, it is observed in Figure 4.14(b) that with more power transmitted, more users can be served in the hour period, implying an increase of 8 %, approximately 6 GB/h, of total network traffic, Figure G.4(b). The influence of the transmission power is only visible for distances higher than 0.2 km, Figure 4.15. For distances lower than that value the user's SINR has no significant influence, as the throughput given by distance is higher than the requested one. Beyond 0.2 km, the user's throughout starts to be limited by distance, and so the influence of the total transmission power becomes relevant. With a higher total transmission power, higher values of throughput can be achieved.

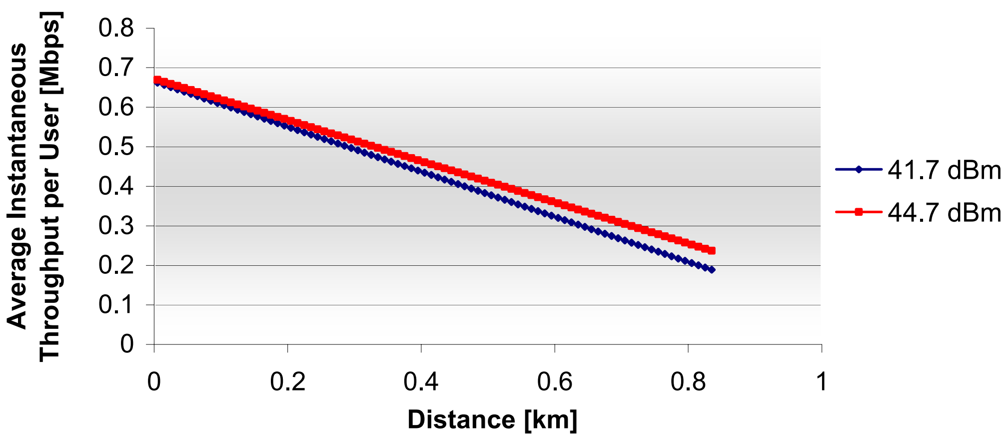
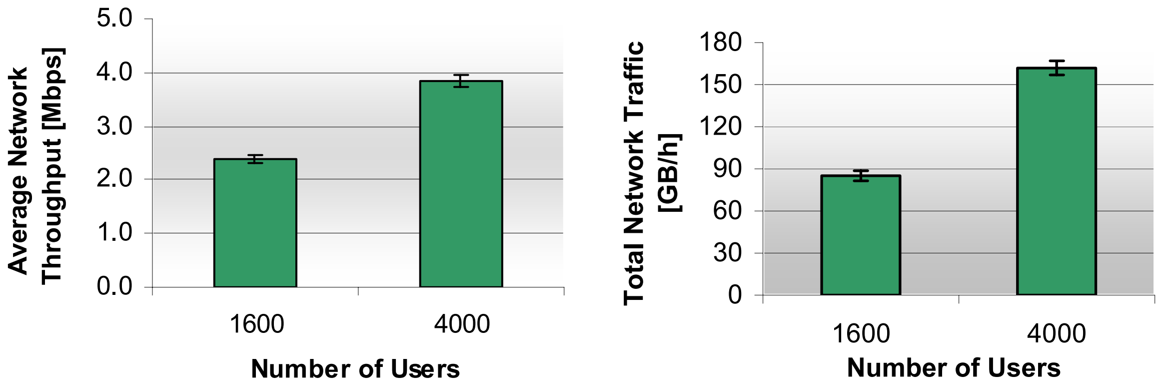


Figure 4.15. Influence of the transmitted power in the user's throughput for UMTS/HSDPA.

4.3.4 Number of Users

Considering the number of users, it is observed in Figure 4.16(a) that the average network throughput suffers an increase of about 1.5 Mbps, almost 60 %, as there are more users in the network to be served. This increase is mostly due to the higher number of users served in the BS located outside the areas with higher traffic, since the first BSs are already overloaded. The average network radius is higher, increasing around 10 %, because the probability of users being near the maximum nominal radius is higher, Figure G.5(a). This is only admitted when there are available resources to serve those users. As there are more users in the network, and the resources are the same, there is a reduction in the average satisfaction grade of almost 18 %, Figure G.5(b). Even though there is a reduction on the average ratio of served users, the total number of served users for the 4000 users scenario is higher than the effective served users in the 1600 scenario, Figure G.6(a). For the 4000 users scenario, there are approximately 1600 users served, being, on average, 7 users served per BS, while in the 1600 users scenario, there are 800 users served, with 4 users served per BS, on average.



a) Average Network Throughput. (b) Total Network Traffic.

Figure 4.16. UMTS/HSDPA network parameters, varying the number of users (Throughput and Network Traffic).

As expected, since there are more users served instantaneously, the total number of users supplied within the hour approximately duplicates when considering 4000 users, Figure G.6(b). The same happens for the total network traffic, Figure 4.16(b), changing from around 85 GB/h, with 350 MB per BS, to 160 GB/h, with 700 MB per BS. It s observed that there is an increase of approximately 90% of total network traffic.

4.3.5 Alternative Profiles

In this subsection, two other profiles of services' percentages are taken into account to evaluate network performance. In Table 4.5, the services' penetration percentage profiles and QoS priority list are presented. For the alternative profiles, the influence of P2P is reduced with the intention of representing a more day-time approach, as E-Mail and Chat services are usually more used throughout the day. On the contrary, the P2P service is somehow a night service, as operators offer the so-called "Happy-Hour". The two considered alternative profiles are: the Interactive Background Balanced (IBB) and the Interactive Oriented (IAO). For these alternative profiles, a different QoS priority list is used. Streaming is now considered to be with the highest QoS priority, followed by Web; on the opposite side of the list, there is now E-Mail, instead of P2P. The modification in the priority list is one additional factor that influences the results in this subsection.

As observed in Table 4.5, when comparing with the default profile, the alternative ones present a significant reduction on the percentage of users performing P2P, which is one of the most demanding services in terms of throughput and volume. On the other hand, there is an increase in the percentage of users performing Chat, Email and FTP. In an overall perspective, it can be said that both alternative profiles are more demanding, in terms of users' throughput, than the default one. IBB is even more demanding than IAO, as the difference for P2P from IBB to IAO is more significant than the difference in Chat.

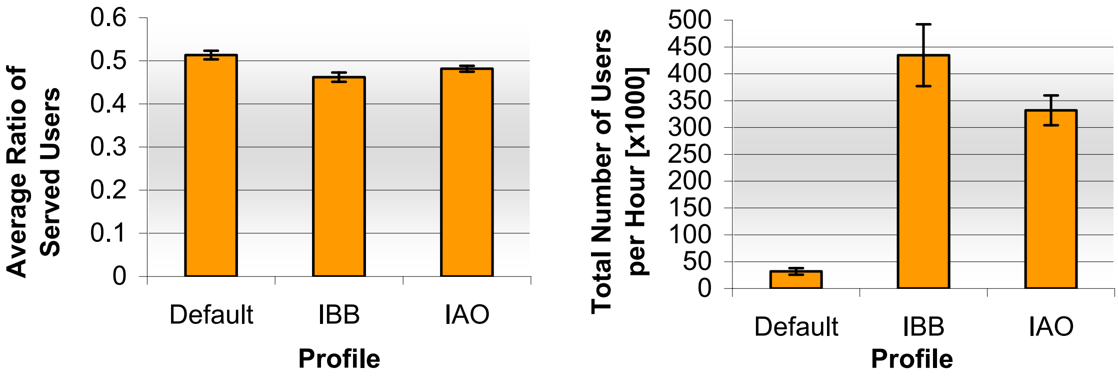
Table 4.5. Default and alternative percentage values for each of the services.

Services	Default Profile		Alternative Profiles		
	Penetration Percentage [%]	QoS priority	Penetration Percentage [%]		QoS priority
			IBB	IAO	
Web	46.4	1	40	40	2
P2P	42.3	6	10	5	5
Streaming	6.2	2	10	10	1
Chat	3.1	5	10	20	3
E-Mail	1.0	3	20	15	6
FTP	1.0	4	10	10	4

The average network throughput remains approximately the same, Figure G.7(a). For the default profile and considering the simulations' parameters, the average network throughput cannot exceed 2.4 Mbps, as seen in Subsection 4.3.2. Therefore, for the same parameters, but now considering a more demanding profile, the average network throughput is nearly the same, because the system reaches its full capacity. This applies for both alternative profiles. The average network radius is approximately constant, Figure G.7(b), since the distribution of users throughout the city area is similar.

Regarding the average ratio of served users, the main reasons for the reduction of this parameter are the minimum throughput considered for each service and the fact that for the same average network throughput, which is the maximum for the case, fewer users are served for the most demanding profiles. P2P has the second lowest minimum throughput, therefore, these users can be successively reduced, leading to a lower probability of being delayed. In a dominant P2P profile, like the default one, fewer users are delayed. Comparing the two alternative profiles, the same method can be applied, now regarding Chat and Email. IAO has more users performing Chat, which has the lowest minimum throughput, and so more users can be served, Figure 4.17(a).

For the average satisfaction grade, there is an increase when changing from the default to the alternative profiles. The default profile has a significant number of users performing P2P, which is the first service to be reduced, leading to a lower average satisfaction grade. The percentage of users performing P2P in the alternative profiles is reduced, being now the second service to be reduced, as seen in Table 4.5. The percentage of users performing Chat, whose maximum throughput considered is 0.384 Mbps, increases. These users can be more easily served by the network, therefore, less reductions are necessary. This implies an overall increase of the average satisfaction grade for the alternative profiles, Figure G.8(a). The alternative profiles present a significant increase in the total number of users per hour, as these profiles are characterised by services with a lower volume per session and services with higher throughput, which leads to a higher number of sessions per hour, Figure 4.17(b).



(a) Average Ratio of Served Users.

(b) Total Number of Users per Hour.

Figure 4.17. UMTS/HSDPA network parameters, varying the user profiles (Ratio of Served Users and Number of Users).

The difference between the number of users per hour in IBB and IAO derives from the fact that IBB has a higher average instantaneous throughput per user. From Figure G.7(a), the average network throughput is approximately the same but in Figure 4.17(a) the average ratio of served users for IBB is lower, meaning that the users actually served have a higher average instantaneous throughput. In terms of total network volume per hour, the default profile has a considerable number of P2P users, whose sessions are characterised by a high volume of data. Therefore, the total traffic is around 85 GB/h. As for the alternative profiles, although having a high number of users per hour, the difference of total network traffic for the default one is not that significant, because the first ones are mainly composed by users performing low volume services, like Chat and Email, Figure G.8(b). In the IAO profile there is an increase of 943 % regarding the number of served users per hour, while in the IBB the increase is 1265 %. Regarding the number of users per BS, there are, on average, approximately 3 users per BS for every profile.

4.3.6 Strategies

The analysis of the impact of the reduction strategies is the one to be considered in a microscopic level, i.e., taking into account the BSs behaviour instead of considering the macroscopic environment, represented by the whole network. When dealing with the network, the difference between the strategies considered is small. This is due to the fact that, as there are some BSs where the effect of the reduction strategies is more visible, there are others where that effect is less evident, leading to an overall result where it is difficult to study the consequence of the reduction strategies.

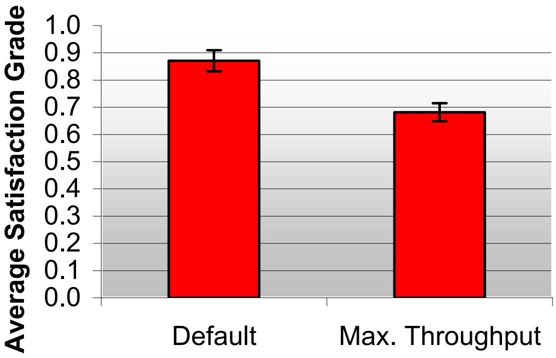
Therefore, one has chosen 10 BSs in the most populated area of the network to demonstrate the effect of the three reduction strategies studied. The considered BSs have users performing four services, Web P2P, Streaming and Chat, and results are taking the absence of the random function into account, so that the conditions to compare the three strategies could be as similar as possible. In these 10 BSs, E-Mail and FTP are not considered, as there are no users performing these services due to their low percentages. Even though just having four services, in these BSs, it is possible to observe the difference between the three strategies. In Figure G.9, it is possible to see that the "QoS One by One Reduction" strategy is the best, as it allows a higher total average BS throughput, since reductions are performed user by user, taking the service the user is performing into account, as explained in Section 3.2. The difference between the "QoS One by One Reduction" strategy and the "Throughput Reduction" one is approximately 0.25 Mbps, representing an improvement of 4.5 %, and when compared with "QoS Class Reduction" it is nearly 0.15 Mbps, an increase of 2.2 %. The standard deviation decreases from the "Throughput Reduction" to the "QoS One by One Reduction" as the latter, by reducing each user at a time, is always closer to the BS limit than the other ones.

The effect of the reduction strategy within each service is demonstrated in Figure G.10 and Figure G.11. Once more, the "QoS One by One Reduction" strategy is the one that presents better results, when analysing the average throughput offered to each user, and the overall satisfaction grade observed in the BSs considered. For Chat, the average instantaneous user throughput and the average satisfaction grade are lower in the "QoS One by One Reduction" strategy. In this strategy, Chat is considered in more BSs than in the other two strategies, and as Chat has a low average instantaneous throughput per user, the average value decreases, but more users are served.

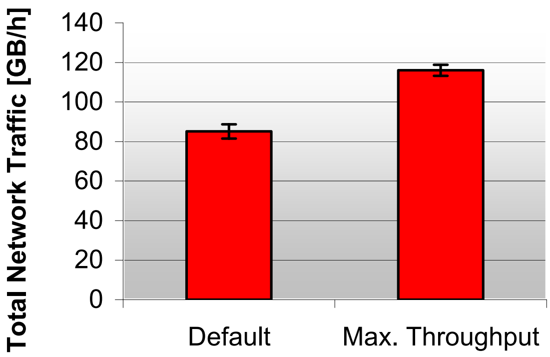
4.3.7 Maximum Throughput

A maximum throughput analysis is performed without considering the throughput random function. Is has the objective of observing the network behaviour, when users are performing the same services as the default scenario, but with the standard throughput values, Table 4.3. The average network throughput increases 41 %, around 1 Mbps, Figure G.12(a), as the system does not reach its full capacity, and so some resources are still available. The average network radius is approximately constant, as the users considered are the same in both simulations, default and maximum throughput, Figure G.12(b).

The average satisfaction grade decreases 22 %, approximately 0.2, Figure 4.18(a), as each user is now performing higher throughputs. Therefore, in comparison with the default scenario, and for the same BS limit, there are more reductions to be performed. In Figure G.13(a), one can observe that the average ratio of served users does not vary, due to the fact that for both simulations the users are the same. As the average throughput per user is higher in this analysis, the average duration of each session is lower, and so more users can be served during the hour period, Figure G.13(b); therefore, the total network traffic increases approximately 36.4 %, 30 GB/h, Figure 4.18(b).



(a) Average Satisfaction Grade.



(b) Average Ratio of Served Users.

Figure 4.18. UMTS/HSDPA network parameters, without the random function (Satisfaction Grade and Network Traffic).

4.4 Mobile WiMAX Analysis in Multiple User Scenario

In this section, the results for Mobile WiMAX in a multiple users scenario are presented. The first step is to analyse the network behaviour for the default scenario described in Section 4.1. Then, the results for the parameters' variation are studied. Additional results are shown in Annex H.

4.4.1 Default Scenario

Considering all the users served in the network, one can compute Figure 4.19, where the users' throughput and the distance that they are from the BS is shown.

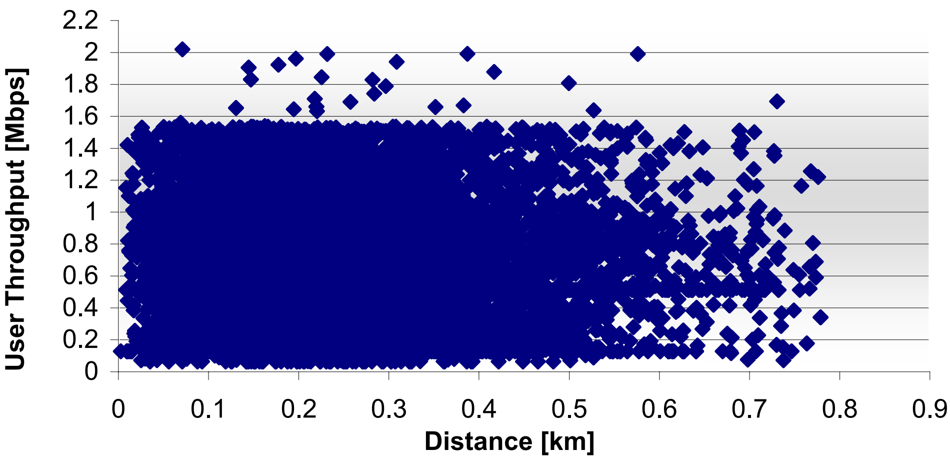


Figure 4.19. Mobile WiMAX instantaneous user throughput for all users depending on the distance.

The procedure used to analyse the UMTS/HSDPA default scenario is the same to study the Mobile

WiMAX one, i.e., the distance is divided in 10 m steps, and then the average throughput and its corresponding standard deviation for all the users within each step are calculated, Figure 4.20.

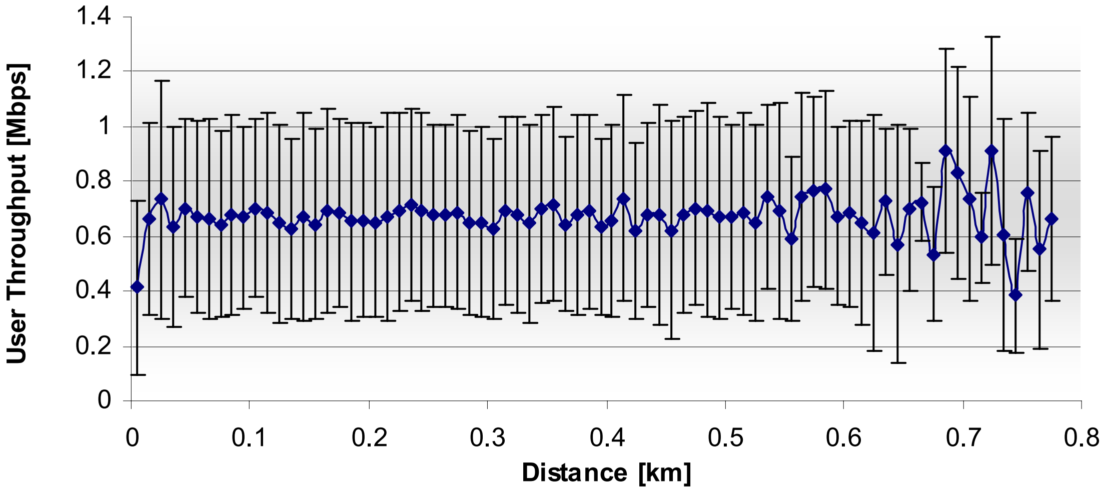


Figure 4.20. Average and standard deviation instantaneous throughput considering 10 m intervals for Mobile WiMAX.

It can be seen in Figure 4.20 that above approximately 0.5 km, the network behaviour tends to be irregular, which is due to the fact the few users are served with the requested throughput when they are placed beyond 0.5 km. Limiting now the distance to 0.5 km where network behaviour is somehow regular, (4.4) is calculated, which represents the network trend for the users' distance and average throughput, Figure 4.21. The average throughput is around 0.67 Mbps.

$$\rho_{[\text{Mbps}]} = 0.0401 \cdot d_{[\text{km}]} + 0.6571 \qquad (4.4)$$

The correlation for (4.4) is approximately zero, with an average relative error of 4.4 %. The low correlation value is due to the low derivative of the regression curve. For the constant curve considering 0.6571 Mbps, the mean relative error is 4.6 %. The procedure used for UMTS/HSPDA is the same used for Mobile WiMAX, i.e., with the increase of the polynomial order, correlation also increases, but this enhancement does not compensate for the complexity of the expression.

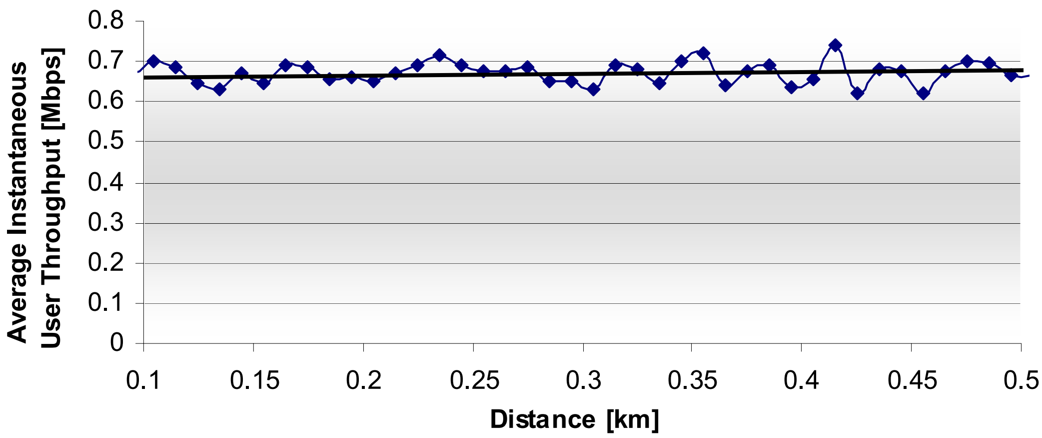
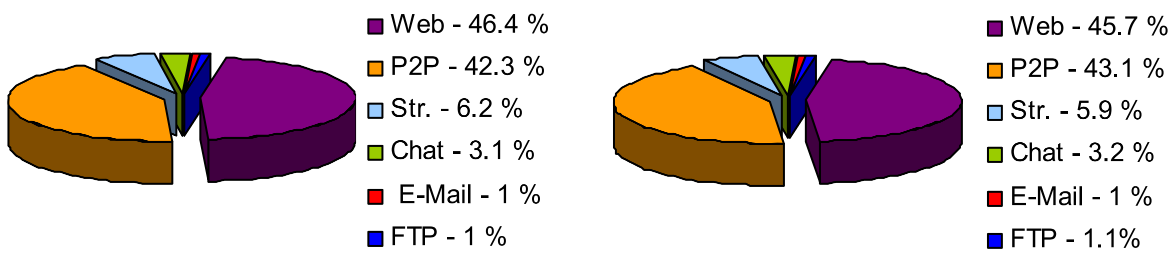


Figure 4.21. First order interpolation for average instantaneous Mobile WiMAX user throughput.

From Figure 4.21, one can observe that the user's throughput does not decrease with the distance, unlike UMTS/HSDPA. This is due to the fact that for the range of considered throughputs, between 0 and 2 Mbps, the SNR value is the same, and, in almost every case, above the SNR threshold. Therefore, even when introducing the interference margin, due to the multi-user scenario, the SNR value given by the user's distance does not cross the SNR value for the requested throughput. This justifies the approximately constant value for the average instantaneous user throughput up to 0.5 km.

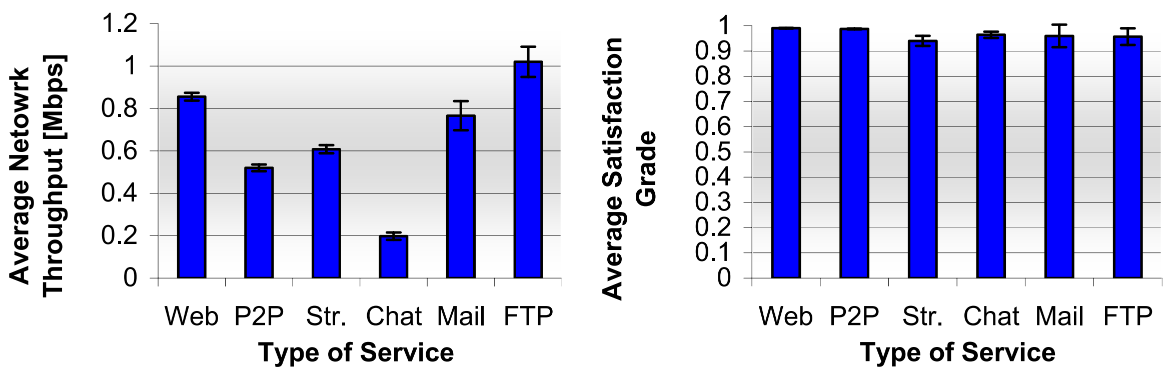
In Figure 4.22, the percentages of served and offered traffic are represented. It is possible to see that the difference between them is not significant. One can conclude that Mobile WiMAX is capable of serving practically all the traffic requested to the network. The only difference happens for Web and Streaming. These services are the ones that present the highest minimum throughput, therefore, more users are delayed when reductions have to be made. P2P, Chat and FTP are the first services to be reduced, but as they have the lowest minimum throughput, fewer users are reduced. This leads to that, when considering the overall number of effective users, these services present higher percentages of served traffic by the network, when comparing to the requested ones.



(a) Offered Traffic. (b) Served Traffic.

Figure 4.22. Mobile WiMAX traffic percentage.

Figure 4.23 shows the average network throughput and average satisfaction grade for each service.



(a) Average Network Throughput. (b) Average Satisfaction Grade.

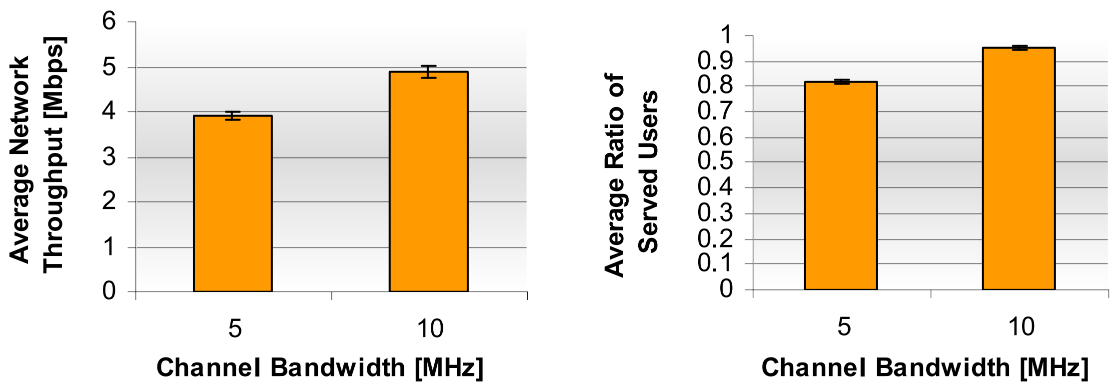
Figure 4.23. Mobile WiMAX network parameters (Throughput and Satisfaction Grade).

For P2P, it is possible to observe that the average network throughput is low, as it happens for UMTS/HDPA, because it is the first service to be reduced. The average satisfaction grade for P2P is high, due to the large number of users performing P2P. It is also possible to observe the QoS priorities. Web, Streaming, E-Mail and FTP have the highest QoS priority, so they present better results regarding the average network throughput, Figure 4.36(a). In Figure 4.36(b), it is possible to see the high value for the standard deviation of Chat, since it is one of the services with the lowest percentage of users.

4.4.2 Channel Bandwidth

In this subsection, the influence of the channel bandwidth in the behaviour of several parameters is discussed. As expected, with the increase of the channel bandwidth, more sub-carriers are available for data transmission, therefore, more users can be served, or considering the same number of users, they can be served with higher throughputs, Figure 4.24(a). The average cell radius is approximately constant, when varying the channel bandwidth, as the influence in the path loss is insignificant, Figure H.1(a).

The average ratio of served users decreases when changing to the 5 MHz channel, as there are less users to be served, Figure 4.24(b), and the ones that are really served, receive less throughput than the requested one, leading to a lower average satisfaction grade, Figure H.1(b). When considering the 10 MHz channel bandwidth, the average network throughput is approximately 25 % higher, 1 Mbps, than the one for 5 MHz. It also implies that the overall network traffic during one hour is higher, Figure H.2(a), as there are more users performing services, due to the fact that a higher average instantaneous throughput offered to the user means a quicker performed session from each user, therefore, more users can perform sessions within the hour, Figure H.2(b).



(a) Average Network Throughput, (b) Average Ratio of Served Users,

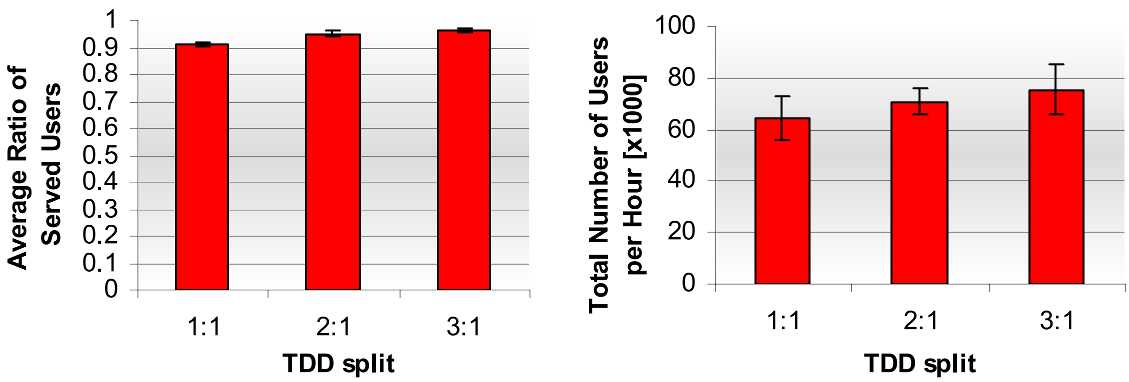
Figure 4.24. Mobile WiMAX network parameters, varying channel bandwidth (Throughput and Ratio of Served Users).

4.4.3 TDD Split

The variation in the TDD split implies a modification in the maximum allowed throughput by a single BS. Therefore, by changing the TDD split from 2:1 to 1:1, less throughput is obtainable to serve all users, as fewer OFDM data symbols are available for DL, leading to an overall decrease of 6 %, approximately 0.3 Mbps in the average network throughput. The opposite behaviour can be observed, when varying from TDD split 2:1 to 3:1, increasing 2 %, around 0.1 Mbps, as illustrated in Figure H.3(a). The average network radius is constant, as the variation in the TDD split does not influence the cell radius, Figure H.3(b).

When considering the TDD split 3:1, the average throughput increases, which means that, for the same number of users considered, they can be served with a higher throughput, therefore the satisfaction grade is higher, Figure H.4(a). Also, having more available resources enables the network to provide more users with the requested throughput, Figure 4.25(b). On the other hand, by varying the TDD split from 2:1 to 1:1, the behaviour is opposite, as there is a decrease in the available throughput.

As expected, there are more users within the hour in the TDD split 3:1 due to the fact that sessions are shorter in time, for the same service considered, because each user is performing at a higher throughput. There is a smooth difference in the total number of users per hour between TDD splits 2:1 and 3:1, Figure 4.25(b), which means that when considering the total network traffic, the difference is not that significant, presenting approximately 160 GB/h, being on average 700 MB per BS. For the TDD split 1:1, there is a decrease in the total number of users per hour of approximately 9 %, 5000 users, and the total network traffic is approximately 5.7 % lower, 10 GB/h, when comparing to the default scenario, Figure H.4(b).



(a) Average Ratio of Served Users. (b) Total Number of Users per Hour.

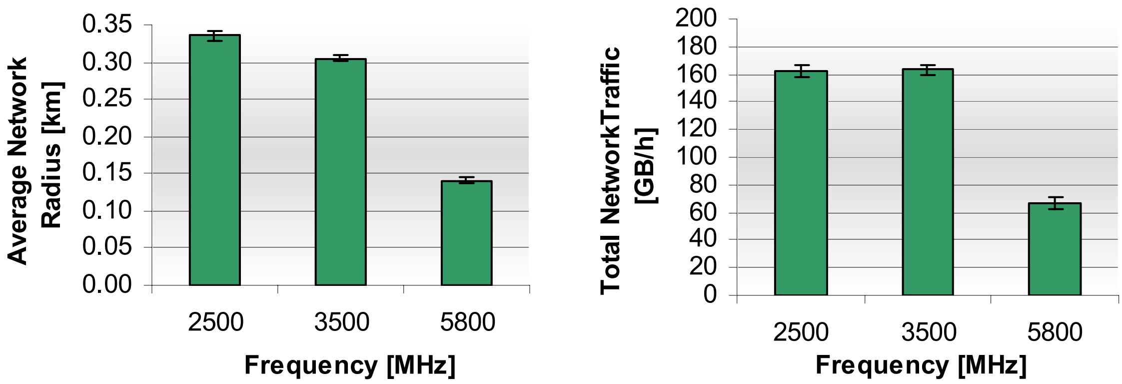
Figure 4.25. Mobile WiMAX network parameters, varying the TDD split (Satisfaction Grade and Ratio of Served Users).

4.4.4 Frequency

Based on the propagation model explained in Subsection 3.1, frequency has a direct influence on the path loss, affecting the cell radius. When varying the frequency from 3.5 to 2.5 GHz, the cell radius increases, implying that more users are inside the cell coverage area. For the 5.8 GHz, the trend is the opposite, leading to a decrease of approximately 50 %, Figure 4.26(a). This leads to fewer users being served, therefore the overall average network throughput is lower than for the default frequency around 2.4 Mbps, representing a decrease of almost 50 %. For 2.5 GHz frequency, the average network throughput is similar to the one for 3.5 GHz, in the order of 4.8 Mbps, as served users are approximately the same, around 1562 for the default scenario and 1588 for 2.5 GHz, Figure H.5(a), with approximately 7 users per BS for both scenarios

Regarding the average satisfaction grade, it is possible to observe in Figure H.5(b) that it is similar for the default scenario as for 2.5 GHz. This is due to the fact that the number of served users is approximately the same, therefore, the resources available are distributed in an equal way, and the number of throughput reductions that each user performs is similar. On the other hand, for the 5.8 GHz frequency the average satisfaction grade is almost the maximum value, because as there are a smaller number of users within the cell coverage area, fewer users are to be reduced. This is due to the fact that there are available resources, i.e., data sub-carriers, to serve all users with the requested throughput. The same procedure can be applied regarding the average ratio of served users, where for 5.8 GHz the maximum value is again almost achieved. The average ratio of served users for the default scenario and for 2.5 GHz is nearly the same, because the number of served users is almost identical, Figure H.6(a).

Taking the identical number of served users for 2.5 and 3.5 GHz frequencies in a certain instant into account, for the extrapolation to the hour, the number of users served within the hour period is also similar, around 70000. For 5.8 GHz, the total number of users per hour is 26000, Figure H.6(b), representing a decrease of 63 %. As expected, the total network traffic for the default scenario and for 2.5 GHz frequency is identical, being around 160 GB/h, with 700 MB per BS, and for 5.8 GHz being 65 GB/h, with 285 MB per BS, corresponding to a decrease of 60 %, Figure 4.26(b).

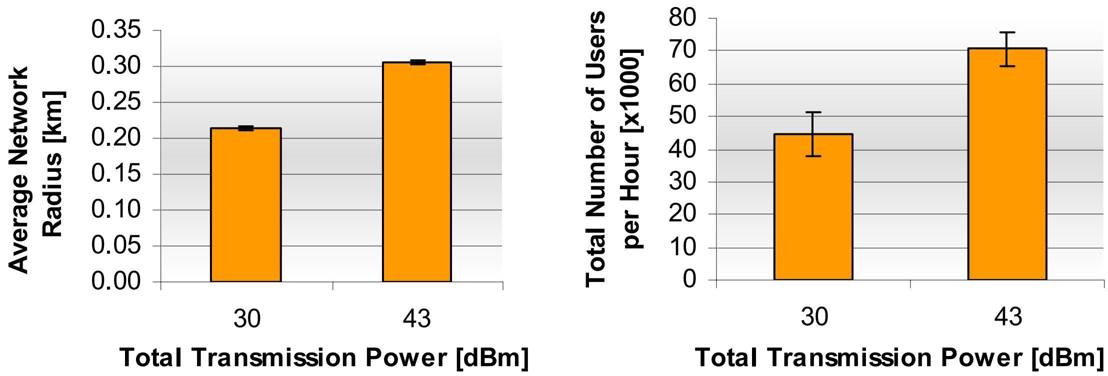


(a) Average Network Radius. (b) Total Network Traffic.

Figure 4.26. Mobile WiMAX network parameters, varying the frequency (Radius and Network Traffic).

4.4.5 Total Transmission Power

The total transmission power is a parameter that has a direct influence on the cell radius, as explained in Subsection 4.3.3, therefore, less transmitted power leads to a lower cell radius, Figure 4.27(a).



(a) Average Network Radius. (b) Total number of Users per Hour.

Figure 4.27. Mobile WiMAX network parameters, varying the transmitted power (Radius and Number of Users per Hour).

When changing from 43 dBm to 30 dBm of transmitted power, the reduction is approximately 30%, 100 m, implying that fewer users are to be served, Figure H.8(a). This has a direct influence on the average network throughput, which can be seen in Figure H.7(a). For the 43 dBm transmitted power, the average network throughput is around 4.9 Mbps, and for the 30 dBm is nearly 1 Mbps less, representing a reduction of approximately 23 %.

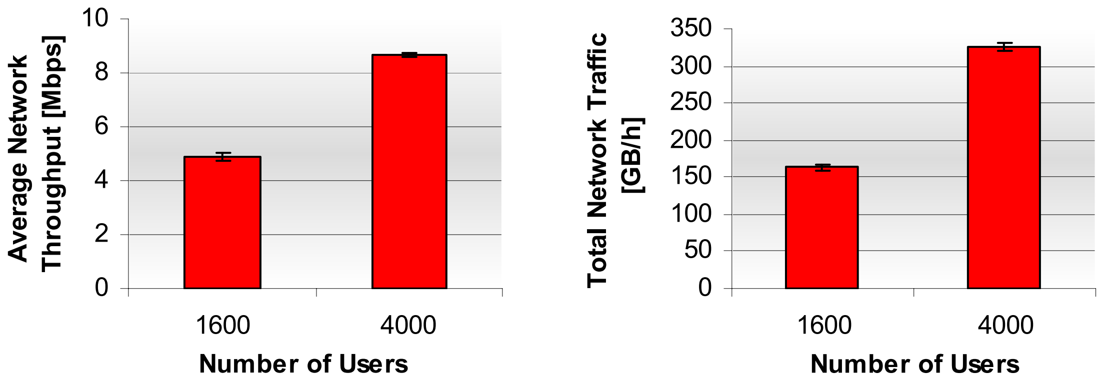
For the average satisfaction grade and average ratio of served users, the explanation is the same as the one used in Subsection 4.4.4, because the behaviour is somehow similar when changing the frequency from 3.5 to 5.8 GHz. The cell radius is lower for 30 dBm of transmitted power, therefore, fewer users are served but the ones that are effectively served can be so with the requested throughput, leading to a higher satisfaction grade, Figure H.7(b). For the average ratio of served users, it can be seen, in Figure H.8(a) that the 30 dBm of transmitted power presents better results than for 43 dBm. This is due to the fact that even though considering fewer users in the network radius, the ones that are considered are almost all served, because the available data sub-carriers are the same for 30 or 43 dBm transmitted power. For 43 dBm, more users are considered, but the number of delayed users is also higher, leading to a lower average ratio of served users.

For the number of served users within the hour, it can be seen, from Figure 4.27(b), that there is a difference of about 25000 users between 43 dBm and 30 dBm transmission power, corresponding to a reduction of 37 %. This is due to the fact that if more users are served in a certain instant for 43 dBm, it is expected that for the hour period it still has more users served, considering that for both scenarios the users are performing the same services. The total network traffic for the default scenario is approximately 160 GB/h, and for the 30 dBm one it is nearly 115 GB/h, being 500 MB per BS, on average, Figure H.8(b), representing a reduction of 30 %.

4.4.6 Number of Users

For the number of users' analysis, one performed several simulations to observe the network behaviour when more users are placed in the network. The average network throughput for 4000 users increases around 77 %, 4 Mbps, comparing with the 1600 users scenario, Figure 4.28(a). This is due the fact that more users are requesting throughput. The average network radius is higher for the 4000 users' scenario, increasing about 9 %, because the probability of users being near the network maximum nominal radius is higher. The difference between the two scenarios is approximately 30 m, Figure H.9(a).

In Figure H.10(a) one shows the average satisfaction grade for both scenarios. Considering 4000 users, the average satisfaction grade is approximately 15 % lower than the one for 1600 users, as there are now more users to be served, but the available resources are still the same. The average ratio of served users also decreases for 4000 users. Even though presenting a lower value of around 0.15, it still presents a higher number of users that are effectively served, around 3886, against the 1562 of the default scenario, Figure H.9(b). The number of served users per BS, on average, is 17 users for the 4000 users scenario and 7 users for the default one.



(a) Average Network Throughput. (b) Total Network Traffic.

Figure 4.28. Mobile WiMAX network parameters, varying the number of users (Throughput and Network Traffic).

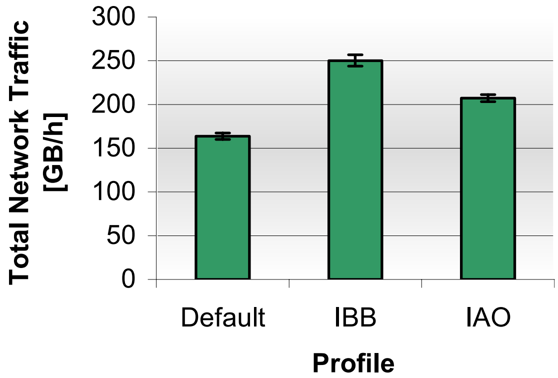
As expected, since there are more users served instantaneously, more users are served during the hour. For 1600 users' scenario, there are 70000 users served in the hour, increasing 121 % to approximately 160000, for the 4000 users' scenario, Figure H.10(b). The same behaviour happens in the total network traffic, increasing 90 %, changing from 160 GB/h to nearly 330 GB/h, Figure 4.28(b), where, per BS, the total network traffic is, on average, 700 MB for the default scenario and 1.4 GB for the 4000 users' scenario.

4.4.7 Alternative Profiles

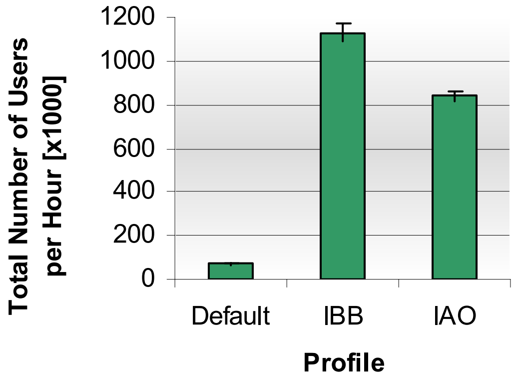
The profiles taken into account in this subsection are the same as the ones detailed in Table 4.6. As already mentioned in Subsection 4.3.5, the two alternative profiles are more demanding in terms of user's throughput than the default one. This aspect can be observed in Figure H.11(a). Comparing with the default profile, the average network throughput for IBB is approximately 0.5 Mbps higher, representing an increase of 10 %, and for IAO it is similar. One can also conclude that the network for the default profile is not at its full capacity, because when introducing a more demanding profile, the network is capable of serving the users as it still has available resources. As for the average network radius, for the three profiles, it is approximately the same, around 0.3 km, because the users' distribution in the network is similar, Figure H.11(b). Regarding the average satisfaction grade and the average ratio of served users, it can be seen, in Figure H.12 that the alternative profiles present results closer to the ones for the default profile.

When introducing more demanding profiles, such as IBB and IAO, the network is still capable of serving the same users as the ones for the default profile. This fact explains the approximate same value for the average ratio of served users, around 0.95, Figure H.12(b). As for the average satisfaction grade, there is a smooth increase when changing from the default to the alternative profiles. This is due to the fact that the default profile has a significant number of users performing P2P, which is the first service to be reduced, leading to a lower average satisfaction grade. The alternative profiles present a low percentage of P2P, which is now the second service to be reduced, as seen in Table 4.6. There is also an increase in terms of percentage of Chat, whose maximum throughput is 0.384 Mbps, which can be more easily served by the network, therefore, less reductions have to be performed. This implies an overall increase of the average satisfaction grade for the alternative profiles, Figure H.12(a).

Concerning the total number of users per hour, the same procedure used for UMTS/HSDPA can be applied to Mobile WiMAX. The alternative profiles are characterised by services with lower volume per session and higher throughputs, therefore, more sessions can be performed within the hour period. The default profile presents 70000 users per hour, and the IBB and IAO profiles present approximately 1130000 and 850000, respectively, Figure 4.29(b). This corresponds to an increase of 1500 % and 1092 % for IBB and IAO, respectively.



(a) Total Network Traffic.



(b) Total Number of Users per Hour.

Figure 4.29. Mobile WiMAX network parameters, varying the user profile (Network Traffic and Number of Users).

The difference in the total number of users per hour between IBB and IAO has its origin in the average network throughput associated to each profile. Regarding the total network traffic, the alternative profiles present higher values than the default one, due to the total number of users in the hour period associated to each alternative profiles. Even though presenting a low number of users per hour, the difference between the default profile and the alternative ones is not that significant, as the default profile is portrayed by presenting a high percentage of services with a high volume of data. For the default profile the total network traffic is nearly 160 GB/h, and for IBB and IAO profiles is approximately 250 and 200 GB/h, representing an increase of 53 % and 27 %, respectively, Figure 4.29(a).

4.4.8 Strategies

The analysis of the impact of the reduction strategies for Mobile WiMAX is similar to the one used for UMTS/HSDPA, explained in Subsection 4.3.6; a microscopic environment of 10 BSs chosen in the most populated area of the network is considered. The objective is to have a group of BSs that are nearly at its full capacity, demonstrating the effect of the three strategies, taking the same parameters for all three into account, only varying the reduction strategy. It is possible to see, in Figure H.13, the network behaviour for the three strategies.

As observed in UMTS/HSDPA, the network behaviour for Mobile WiMAX is the same, i.e., “QoS One by One Reduction” is the one presenting better results, as it allows a higher average network throughput, because users are reduced one by one, taking the service the user is performing into account. The difference between “QoS One by One Reduction” and the “Throughput Reduction” and “QoS Class Reduction” is approximately 0.1 Mbps. The difference between “Throughput Reduction” and “QoS Class Reduction” one is almost insignificant. This is due to the fact that “Throughput Reduction” performs a 10 % reduction in all classes at the same time, and “QoS Class Reduction” only performs a 10 % reduction for each class until the total throughput is below the maximum allowed by the BS.

In Figure H.14 it is possible to observe that, among the three strategies, the only service that has different average instantaneous throughput per user is Web, which is the last one to be reduced. This means that, for “QoS Class Reduction”, all services are reduced except Web, because it is not necessary, as the total BS throughput is below the allowed maximum before reducing Web. This explains the different value for Web when comparing “Throughput Reduction” with “QoS Class Reduction”.

Figure H.15 shows the average satisfaction grade for each service, where it is possible to observe that for Web the value is higher for “QoS One by One Reduction”. The results for the other strategies are the same, because the number of reductions made is the same for all services, except for Web, which is the last service to be reduced. When users performing Web are the next ones to be reduced, the network is capable of serving all users, therefore, no more services have to be reduced.

4.4.9 Enhanced Throughput

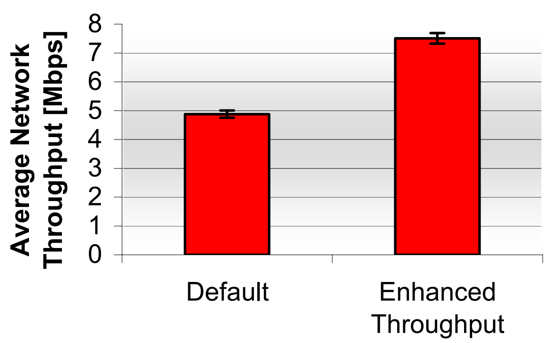
The present subsection analyses network behaviour when there is an enhancement in terms of throughput for certain services. Table 4.6 shows the services that have a throughput increase, and the new value considered. The four services that suffer an increase of throughput are the ones that are more suitable of having higher throughputs, as they are the most demanding services. Chat is an example of a service that does not need an increase, because it is based essentially in sending and receiving small amounts of data.

Table 4.6. Alternative percentage values for each of the services.

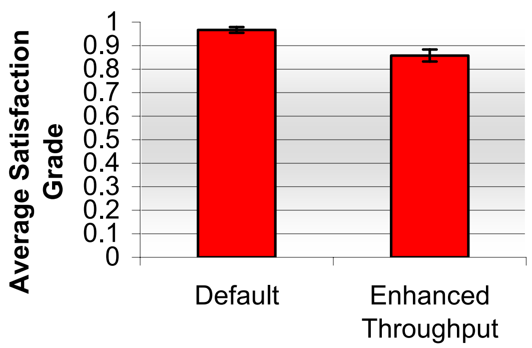
Service	Default Throughput [Mbps]	Enhanced Throughput [Mbps]
Web	1.536	3
P2P	1.024	2
Streaming	1.024	2
Chat	0.384	0.384
Email	1.536	1.536
FTP	2.048	3

As expected, the average network throughput, Figure 4.30(a), is approximately 54 % higher, corresponding to 2.5 Mbps, when considering the “Enhanced Throughput” scenario, due to the fact that services request higher throughputs than the ones for the default scenario. As for the average network radius, results are similar for both scenarios, because the users’ positions in the network are the same. Even though spending more resources in the “Enhanced Throughput” scenario, the users that are at high distances from the BS can be served, because the network still has available data sub-carriers that can be assigned for that specific users, Figure H.16(a).

Regarding the average satisfaction grade, the default scenario presents better results, since the throughput associated to each service is lower than the ones for the “Enhanced Throughput” scenario, therefore less reductions are performed, implying a higher average satisfaction grade, Figure 4.30(b).



(a) Average Network Throughput.



(b) Average Satisfaction Grade.

Figure 4.30. Mobile WiMAX network parameters, increasing services’ throughput (Throughput and Satisfaction Grade).

Concerning the average ratio of served users, the “Enhanced Throughput” scenario presents worse results than the default one, due the fact that, as said previously for the analysis of the average satisfaction grade, more throughput reductions have to be made. This implies that more users performing services that do not have a throughput increase have to be delayed, because they are the ones closer to the minimum throughput for each service, leading to a lower average ratio of served users, Figure H.16(b).

In Figure H.17(b), it is possible to see that the difference between the total number of users per hour is not significant, around 2000 users, when comparing the two scenarios. In Figure H.16(b), it is possible to see that instantaneously, fewer users are served in the “Enhanced Throughput” scenario, therefore, in the hour analysis, the total number of users per hour for the default scenario should be higher. Due to the higher throughputs for the four services presented in the “Enhanced Throughput” scenario, the sessions of these services are performed quicker, which leads to an increase of the overall users per hour, even overcoming the result for the default scenario. Figure H.17(a) presents the results for the total network traffic. The four services that have a throughput increase also present a high volume of data per session, being the ones that are more represented in the network in this scenario, comparing with the default one. This is due to the fact that the users performing the two services that do not have a throughput increase, Chat and E-Mail, are now the first ones to be delayed. The default scenario presents a total network traffic of approximately 160 GB/h, and the “Enhanced Throughput” one reaches nearly 225 GB/h, with 1GB per BS, on average, representing an increase of about 36 %.

4.5 Comparison between UMTS/HSDPA and Mobile WiMAX

In the present section, the comparison between UMTS/HSDPA and Mobile WiMAX is performed. First the comparison for the single user model, considering the variation of several parameters is performed. The next analysis is the comparison in a multiple users scenario, where users are spread all over the city area, performing several services. The systems’ behaviour is compared, when varying the number of users and the profiles. The parameters that are characteristic of each system are not taken into account, so that the comparison can be performed based on common parameters.

4.5.1 Single User Scenario

This subsection presents the comparison regarding several parameters, such as cell radius and throughput, considering the variation of various parameters for a single user in the network. Figure 4.31 shows the cell radius for the maximum throughput for 5, 10 and 15 HS-PDSCH codes for UMTS/HSDPA and for the several TDD splits and channel bandwidths that are studied for Mobile WiMAX. The frequency considered for the latter system is 3.5 GHz and for UMTS/HSDPA it is 2112.5 MHz.

In Figure 4.31 it is possible to see that, as expected, due to the frequency considered for each system, the cell radius for UMTS/HSDPA is higher than the one for Mobile WiMAX. The influence of frequency in the calculation of the cell radius is also demonstrated in Subsections 4.2.1 and 4.2.3. For 10 and 15 HS-PDSCH codes, it is observed that the cell radius is the same for different maximum throughputs; for 10 HS-PDSCH codes the maximum throughput is 6 Mbps and for 15 codes is 8.46 Mbps. The same cell radius presented for both values is due to the fact that the SINR value is the same, i.e., the curve for 10 codes and 6 Mbps corresponds to an SINR value equal to the one obtained by the same process for the 15 codes' curve and 8.46 Mbps, as seen in Figure A.1.

Regarding Mobile WiMAX TDD split, there is a variation in cell radius due to the fact that for higher throughputs supported by a higher TDD split. With the increase of the requested throughput, a higher modulation order is used, therefore, there is an increase in the SNR value, since for each modulation and codification, there is a SNR value associated, Tables A.5, A.6 and A.7. Therefore, using (A.9), (A.4) and (A.1), path loss decreases, leading to a lower cell radius. Within the same TDD split, changing the channel bandwidth from 5 to 10 MHz allows achieving a higher throughput, so concerning cell radius for the maximum throughput for each channel, 5 MHz presents a higher cell radius than the 10 MHz channel. The highest cell radius considering the maximum throughput for Mobile WiMAX with 3.5 GHz is obtained by a TDD split 1:1 with a 5 MHz channel bandwidth. It is approximately 0.3 km lower than the cell radius for the maximum throughput for UMTS/HSDPA, obtained with 5 codes, representing a reduction of approximately 66 %.

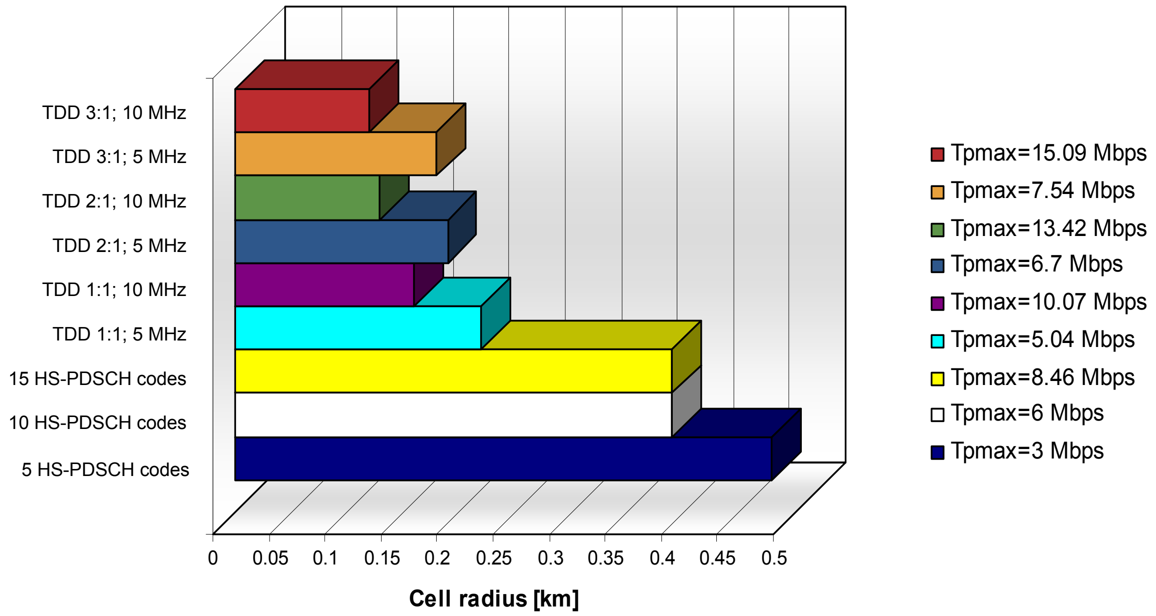


Figure 4.31. UMTS/HSDPA and Mobile WiMAX cell radius variation for the maximum throughput.

In Figure 4.32, one shows a direct comparison for the same cell radius, the maximum achievable throughput being calculated. The frequency taken into account for Mobile WiMAX is 3.5 GHz, and for UMTS/HSDPA, is 2112.5 MHz.

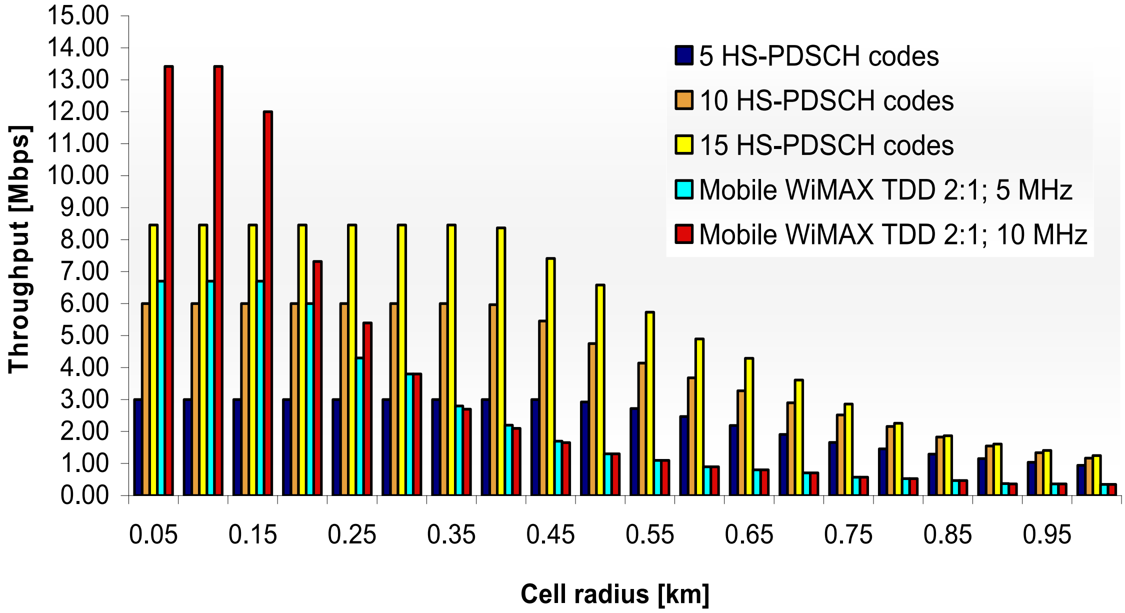


Figure 4.32. UMTS/HSDPA and Mobile WiMAX throughput comparison for the same cell radius.

It can be seen from Figure 4.32 that, up to approximately 0.15 km, Mobile WiMAX TDD 2:1 and 10 MHZ channel bandwidth provide a significantly higher throughput compared to UMTS/HSDPA. From 0.15 km upwards, there is an abrupt decay of the maximum Mobile WiMAX throughput, for 5 or 10 MHZ channel bandwidth. Up to 0.1 km, it is possible to ensure the maximum throughput for 10 MHz, and for 5 MHz the maximum throughput can be achieved up to 0.15 km. On the other hand, UMTS/HSDPA presents lower maximum throughput values, but the maximum throughput can be obtained up to 0.4 km for 10 and 15 HS-PDSCH codes, and up to 0.45 km for 5 HS-PDSCH codes. After reaching the maximum cell radius for the maximum throughput, the variation for UMTS/HDSDPA is somehow smoother than the one for Mobile WiMAX. This is due to the SNR and SINR values, respectively for Mobile WiMAX and UMTS/HSDPA, Table A.6 and Figure A.1.

Figure 4.33 presents the comparison regarding the frequencies that are studied for each system. For UMTS/HSDPA, the frequency is 2112.5 MHz, and for Mobile WiMAX, the frequencies taken into account are 2.5, 3.5 and 5.8 GHz. The TDD split for Mobile WiMAX is 2:1, and the channel bandwidth is 10 MHz. For UMTS/HSDPA, the results for 15 HS-PDSCH are the ones to be presented, as it is the one with closest maximum throughput compared with Mobile WiMAX.

As observed in Figure 4.33, with a frequency of 2.5 GHz for Mobile WiMAX, which is the one closer to the frequency of UMTS/HSDA, the cell radius is equal, when considering a throughput of 0.384 Mbps. With the increase of the requested throughput, the cell radius for Mobile WiMAX becomes lower than the one for UMTS/HSDPA, for the same throughput, because the influence of the frequency is more significant than the receiver sensitivity for high throughputs. For other Mobile WiMAX frequencies, the variation and lower cell radius results are explained in Subsection 4.2.2. When comparing the results for UMTS/HSDPA with the ones obtained for the default frequency of Mobile WiMAX considered throughout this work, i.e., 3.5 GHz, it is possible to observe that for a single user in the network, UMTS/HSDPA presents a higher cell radius for the same throughput.

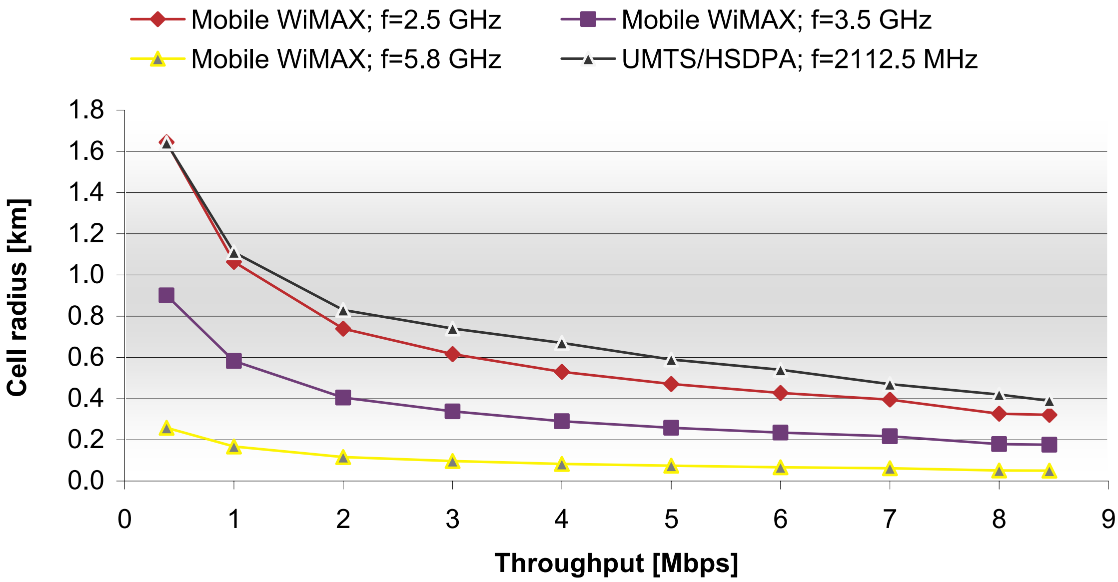


Figure 4.33. UMTS/HSDPA and Mobile WiMAX cell radius comparison for several frequencies.

For a throughput of 0.384 Mbps, the cell edge for UMTS/HSDPA considering 15 HS-PDSCH and codes is approximately 1.64 km and for Mobile WiMAX with frequency of 3.5 GHz is around 0.9 km, representing a reduction of 45 %. Table 4.8 summarises the cell radius for UMTS/HSDPA and Mobile WiMAX considering a throughput of 0.384 Mbps. The pedestrian environment is the one taken into account.

Table 4.7. Cell radius for UMTS/HSDPA and Mobile WiMAX for a single user requesting a throughput of 0.384 Mbps.

		Cell radius [km]
UMTS/HSDPA Number of HS-PDSCH codes	5	1.53
	10	1.59
	15	1.64
Mobile WiMAX Frequency [GHz] / Channel bandwidth [MHz]	2.5 / 5 and 10	1.64
	3.5 / 5 and 10	0.90
	5.8 / 5 and 10	0.26

4.5.2 Multiple Users Scenario

This subsection compares the performance in a multiple users scenario. The results taken into account for this analysis for both systems are the ones obtained for the default scenario for each system, and also when varying the number of users in the network and the user profiles concerning traffic percentages.

Considering the results for the default scenario for UMTS/HSDPA and Mobile WIMAX, Figure 4.34 represents both systems' trend for the average instantaneous user throughput as a function of the users' distance. These results are the same ones presented separately when UMTS/HSDPA and Mobile WiMAX defaults scenarios are analysed in Subsections 4.3.1 and 4.4.1, respectively, but now put together in the same figure. It is possible to observe that the average instantaneous throughput per user for Mobile WiMAX for distances up to 0.5 km is approximately constant and around 0.65 Mbps and for UMTS/HSDPA decreases with the distance. For distances equal to 0.5 km, the difference between Mobile WiMAX and UMTS/HSDPA is approximately 0.25 Mbps, representing a reduction of 40 % when changing from Mobile WIMAX to UMTS/HSDPA.

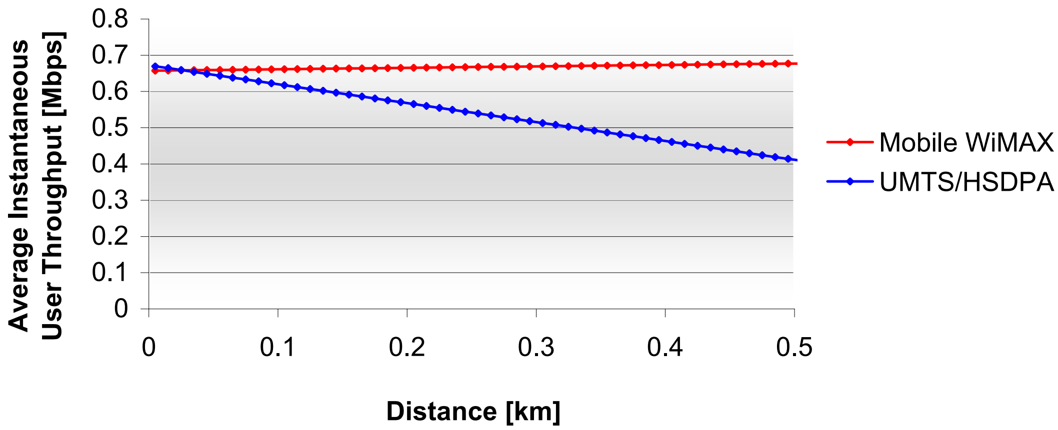
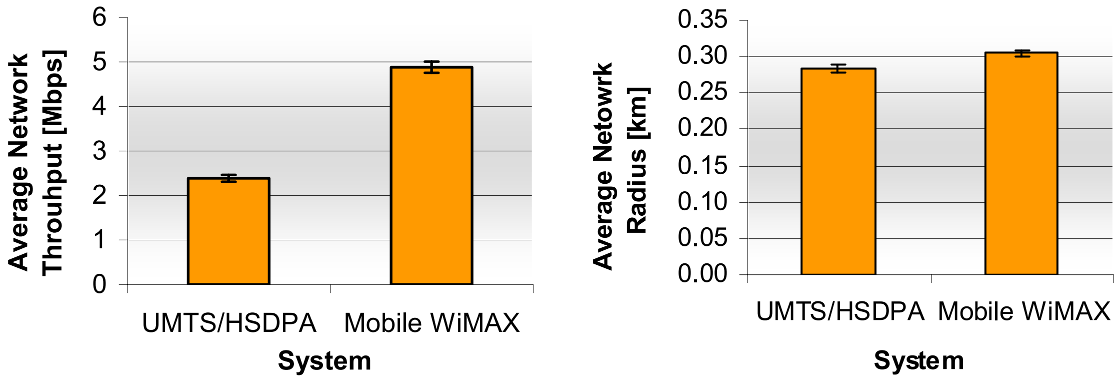


Figure 4.34. UMTS/HSDPA and Mobile WiMAX evolution of the average instantaneous throughput per user with the distance.

The average network throughput for Mobile WiMAX is nearly 2.5 Mbps higher than the one for UMTS/HSDPA. This is due to the fact that Mobile WiMAX can serve more users than UMTS/HSPDA, as it can be seen in Figure 4.36(b). The average ratio of served users for Mobile WiMAX practically duplicates when comparing to the average ratio of served users of UMTS/HSDPA. This difference resides mainly in the fact that Mobile WiMAX can provide a higher throughput than UMTS/HSDPA. When several users are considered, Mobile WiMAX can serve a larger number of users than UMTS/HSDPA. This is due to the fact that each user is considered independently and then the sum of the throughputs from all users is compared with the maximum allowed by each BS. Since Mobile WiMAX BSs can provide higher throughputs, more users can be served comparing to the ones served by UMTS/HSPDA, considering the same requested throughput by users. The average network radius for Mobile WIMAX is approximately 0.3 km and for UMTS/HSDPA is nearly 0.28 km, representing a reduction of 7 %, Figure 4.35(b). This difference in terms of average network radius is due to the receiver sensitivity for each system.

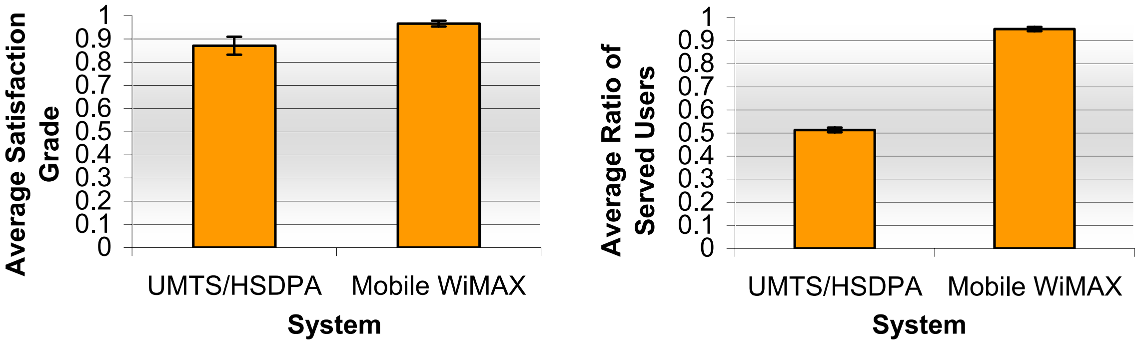
Considering the same distance, Mobile WiMAX can serve higher throughputs than UMTS/HSDPA. When considering users far away from the BS there is a higher probability of being reduced in a UMTS/HSDPA network, because of its lower capacity. This is due to the fact that when a user is far from the BS, the throughput that the user is capable of receiving is near the minimum throughput allowed for each service, therefore, when reductions have to be performed, the users far away from the BS are delayed. In Mobile WiMAX this effect is smoother, because its higher capacity allows that almost every user is served and fewer reductions are performed, so the probability of a user far away from the BS being delayed is lower. Regarding the average satisfaction grade, it is observed through Figure 4.36(a) that the result for Mobile WiMAX is approximately 0.96 and for UMTS/HSPDA is around 0.85, corresponding to a reduction of 11 %. This is explained by the fact that, for the effective number of users served, fewer reductions are needed for Mobile WiMAX, due to its higher throughput available, leading to an overall satisfaction grade higher than the one for UMTS/HSDPA.



(a) Average Network Throughput.

(b) Average Network Radius.

Figure 4.35. UMTS/HSDPA and Mobile WiMAX network parameters (Throughput and Radius).

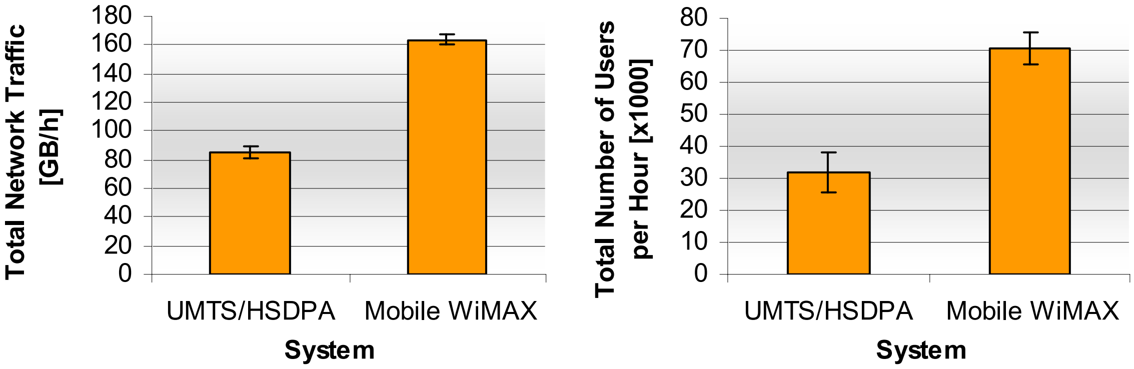


(a) Average Satisfaction Grade

(b) Average Ratio of Served Users

Figure 4.36. UMTS/HSDPA and Mobile WiMAX network parameters (Satisfaction Grade and Ratio of Served Users).

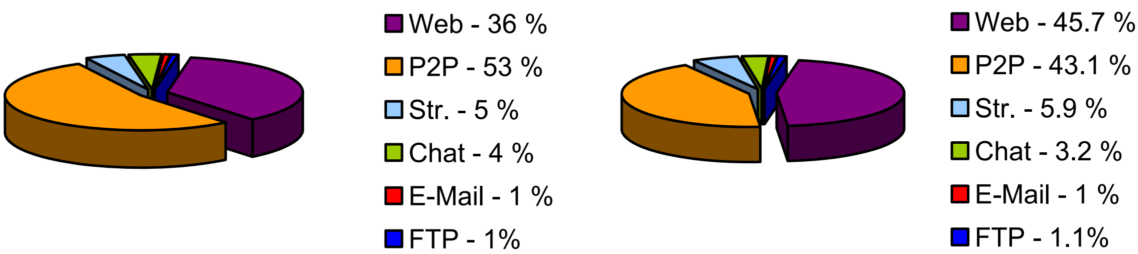
Considering the total number of users per hour, Mobile WiMAX presents a larger number of users served within the hour. This result is expected, since, instantaneously, Mobile WiMAX can serve more users, as seen in Figure 4.36(b). Mobile WiMAX can serve in the hour period approximately 70000 users, and UMTS/HSDPA around 30000 users, Figure 4.37(b). The total network traffic for UMTS/HSPDA is approximately 85 GB/h, and for Mobile WiMAX is around 160 GB/h, where, per BS, on average, UMTS/HSDPA presents 370 MB and Mobile WiMAX, 700 MB, Figure 4.37(a). This represents an increase of 88 % of when changing from UMTS/HSDPA to Mobile WiMAX.



(a) Total Network Volume per Hour (b) Total Number of Users per Hour

Figure 4.37. UMTS/HSDPA and Mobile WiMAX network parameters (Network Traffic and Number of Users).

In Figure 4.38, it is possible to analyse the difference in the served traffic percentage between UMTS/HSDPA and Mobile WiMAX, taking into account that the offered traffic to both networks is the same, detailed in the individual analysis for both UMTS/HSDPA and Mobile WiMAX default scenarios.



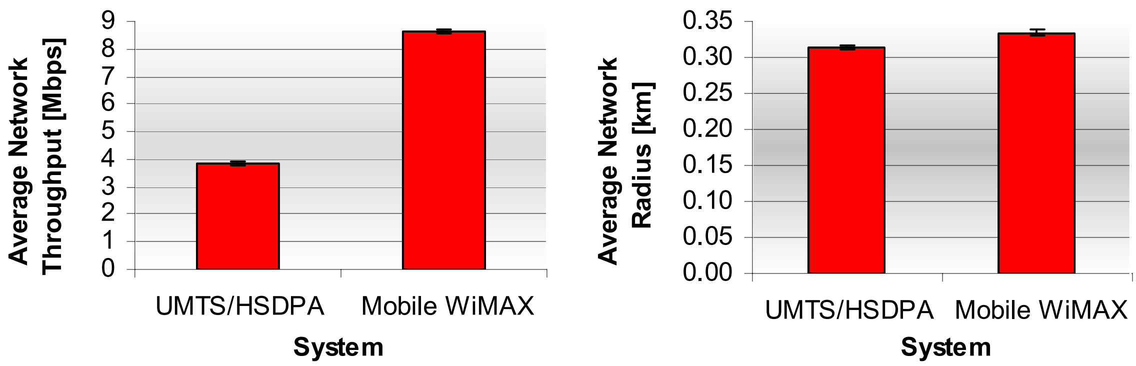
(a) UMTS/HSDPA (b) Mobile WiMAX

Figure 4.38. Served traffic percentage

The presented percentages are considering the effective number of users that are actually served, being approximately 800 users of UMTS/HSDPA and around 1500 users for Mobile WiMAX. The difference between the served and offered traffic, for UMTS/HSDPA and Mobile WIMAX, is already in Subsections 4.3.1 and 4.4.1, respectively. From the analysis of the results for both systems, it can be seen that Mobile WIMAX, for the considered offered traffic, is the one that presents better results, because the percentages of served traffic are similar to the ones offered to the network, unlike UMTS/HSDPA. This is due to the higher capacity and higher throughputs that Mobile WiMAX is capable of offering, comparing to UMTS/HSPDA, because, even though considering more users effectively served, the percentages of served traffic are approximately the same as the requested one.

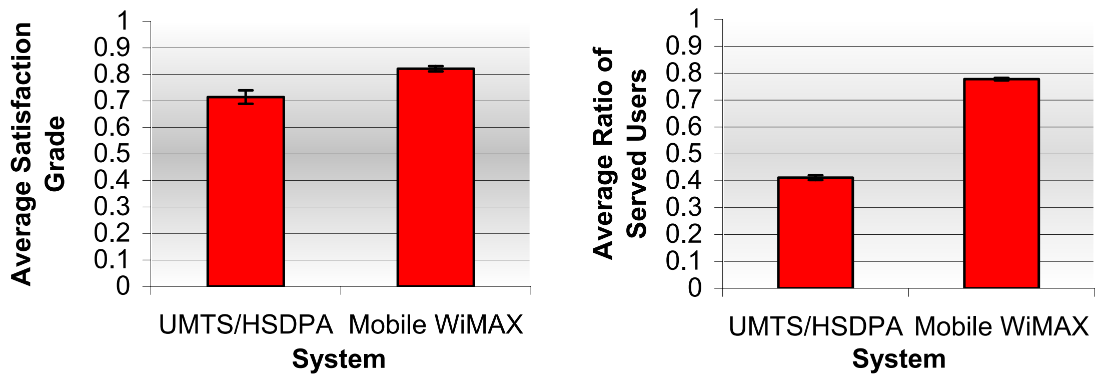
The number of users is a fundamental parameter when performing a comparison both systems. It is interesting to observe the network behaviour for both systems, when the number of users increases, and compare them. All the simulations to study the increase of the number of users are performed for 4000 users, considering the same percentages of services, for both sytems.

When considering the network with 4000 users, it is possible to see, in Figure 4.39(a), that the average network throughput for Mobile WiMAX is nearly 5 Mbps higher than the one for UMTS/HSDPA, representing an increase of 125 %. This is due to the fact that Mobile WiMAX can serve more users than UMTS/HSPDA, as it can be seen in Figure 4.40(b). The average ratio of served users for Mobile WiMAX is approximately 0.8, and for UMTS/HSDPA it is around 0.4, corresponding to a reduction of 100 %. Mobile WiMAX presents approximately 0.8 of average satisfaction grade, while the results for UMTS/HSDPA are around 0.7, Figure 4.40(a). The average network radius is approximately 6 %, 20 m, higher for Mobile WiMAX comparing to the one for UMTS/HSDPA, Figure 4.39(b). The explanation for the differences in the average network throughput, network radius, satisfaction grade and ratio of served users, is the same used in Subsection 4.5.1, when analysing the default scenarios, but now taking more users in the network into account.



(a) Average Network Throughput. (b) Average Network Radius.

Figure 4.39. UMTS/HSDPA and Mobile WiMAX network parameters, with 4000 users in the network (Throughput and Radius).

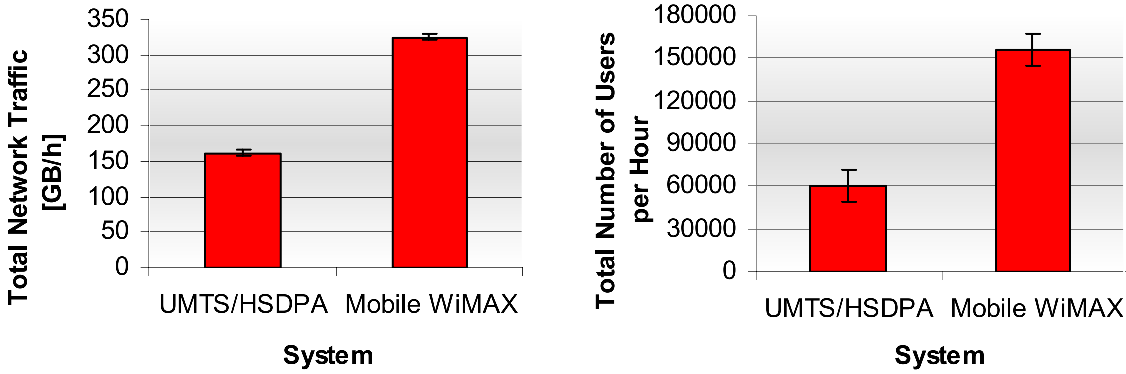


(a) Average Satisfaction Grade. (b) Average Ratio of Served Users.

Figure 4.40. UMTS/HSDPA and Mobile WiMAX network parameters, with 4000 users in the network (Satisfaction Grade and Ratio of Served Users).

For the total number of users per hour, Mobile WiMAX can serve in the hour period approximately 150000 users, and UMTS/HSDPA around 60000 users, Figure 4.41(b). The total network traffic for UMTS/HSPDA is approximately 150 GB/h, and for Mobile WiMAX is around 320 GB/h, Figure 4.41(a). The results for traffic per hour per BS are, on average, 650 MB for UMTS/HSDPA and 1.4 GB for

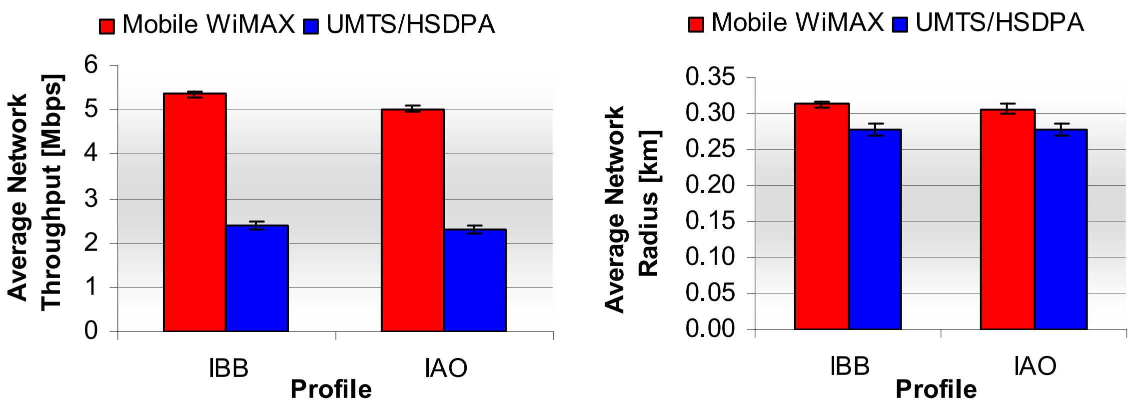
Mobile WIMAX, representing an increase of 115%.



(a) Total Network Traffic. (b) Total Number of Users per Hour.

Figure 4.41. UMTS/HSDPA and Mobile WiMAX network parameters, with 4000 users in the network (Network Traffic and Number of Users).

For the analysis of the two alternative profiles introduced in Subsection 4.3.5, all the parameters considered are the same as for the default scenarios, except for the percentages of penetration of each service, which are now different. For the average network throughput, it can be seen in Figure 4.42(a), that for both alternative profiles, Mobile WiMAX presents better results than UMTS/HSDPA. The results for the average network radius demonstrate that for both alternative profiles, Mobile WiMAX results are approximately 0.31 km, while for UMTS/HSPDA is around 0.28 km, corresponding to a reduction of 10 %, Figure 4.42(b). The difference for the network radius between both systems is the same as the one used for the default scenario.



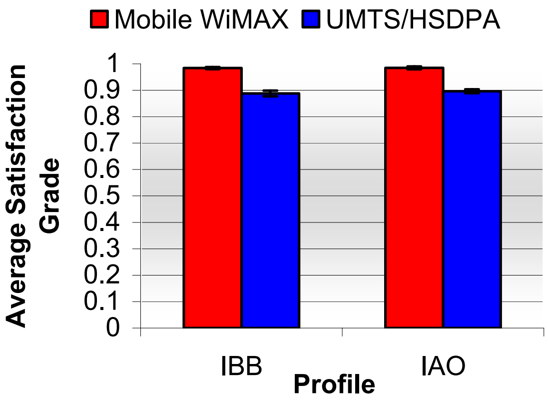
(a) Average Network Throughput (b) Average Network Radius

Figure 4.42. UMTS/HSDPA and Mobile WiMAX network parameters, for different user profiles (Throughput and Radius).

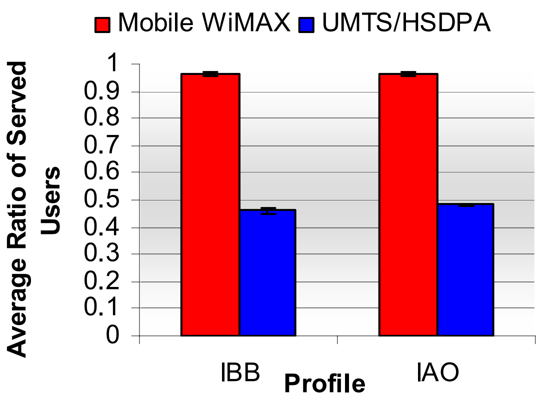
The average network throughput for Mobile WiMAX is almost the double than the one for UMTS/HSDPA. Since Mobile WiMAX's capacity is higher than UMTS/HSDPA, being capable of serving more users instantaneously, as seen in Figure 4.43(b), its average network throughput for both profiles is also higher. The average satisfaction grade for the Mobile WiMAX is approximately 0.1

higher than the one for UMTS/HSDPA, for both profiles. Since Mobile WiMAX is capable of serving a higher throughput than the ones offered by UMTS/HSDPA, considering the same number of users for both systems, the average satisfaction grade for Mobile WiMAX is higher, because less throughput reductions are needed, leading to an increase in the average satisfaction grade, Figure 4.43(a)

As for the total number of users per hour, as expected, Mobile WiMAX can serve more users than UMTS/HSDPA, because, instantaneously, Mobile WIMAX is able to serve more users, therefore, when extrapolated to the hour analysis, more users can be served, taking into account the same profile. Mobile WiMAX can serve approximately 1100000 users for the IBB profile and 840000 users for the IAO profile, while UMTS/HSDPA can only serve around 430000 and 330000 users for the IBB and IAO profiles, respectively, Figure 4.44(b). For the total network traffic, Mobile WiMAX presents 250 GB/h for the IBB profile and 200 GB/h for the IAO one, while UMTS/HSDPA results for the total network traffic go up to 100 GB/h and 85 GB/h for the IBB and IAO profiles, respectively, Figure 4.44(a). For the IBB profile and comparing Mobile WIMAX to UMTS/HSPDA, there is a reduction of approximately 60 % and for the IAO profile the reduction is around 57 %

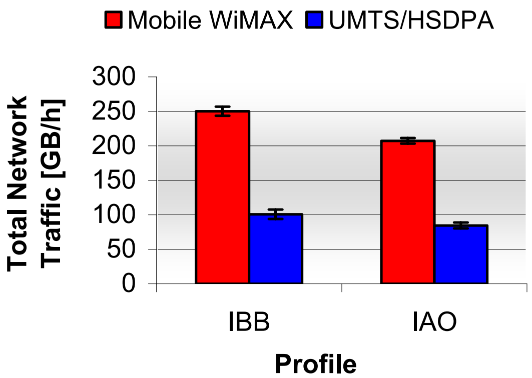


(a) Average Satisfaction Grade.

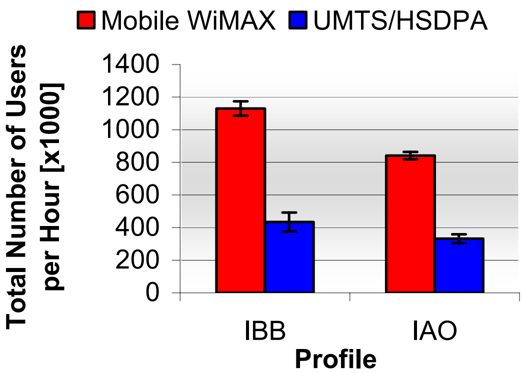


(b) Average Ratio of Served Users.

Figure 4.43. UMTS/HSDPA and Mobile WiMAX network parameters, for different user profiles (Satisfaction Grade and Ratio of Served Users).



(a) Total Network Traffic.



(b) Total Number of Users per Hour.

Figure 4.44. UMTS/HSDPA and Mobile WiMAX network parameters, for different user profiles (Network Traffic and Number of Users).

Regarding the single user scenario, it can be concluded that UMTS/HSDPA presents a higher cell radius than Mobile WiMAX for the same throughput, due to the influence that the frequency used by each system has in the path loss. UMTS/HSDPA uses the 2GHz frequency and the default frequency for Mobile WiMAX, the one thought to be used in Europe, is 3.5 GHZ.

For the multiple users scenario, in almost every parameter, Mobile WiMAX presents better results than UMTS/HSPDA because of its higher capacity, being capable of serving more users and even at higher throughputs. The average cell radius for Mobile WiMAX is slightly higher in the multiple users scenario because it is capable of serving users that are far away from the BS, as it has more resources available than UMTS/HSDPA.

Chapter 5

Conclusions

In this chapter, the conclusions of this work are presented, and some future work regarding some of the features studied in this thesis is suggested.

The main objective of this thesis was to make a comparison of the performances of UMTS/HSDPA and Mobile WiMAX. For this purpose, two scenarios were considered: the single user and the multiple users ones. The single user model is intended to provide an overview of network planning, regarding cell radius for UMTS/HSDPA and Mobile WiMAX for a single user. This model was implemented in a simple C++ program, where it is possible to calculate the cell radius for a certain throughput requested by a single user in the network, varying several parameters of each system.

The multiple users scenario had the objective of studying a realistic case, where users are performing multiple services and placed randomly over the network area. One of the major differences between the single user and the multiple users scenarios is the introduction of the interference margin, due to users' interference. Other difference is the calculation of the throughput that the user is capable of receiving, concerning its distance to the BS. If the throughput given by the distance is lower than the minimum throughput of the requested service, the user is delayed. After considering all users whose throughputs are within the minimum and maximum throughput of each requested service, a BS analysis is performed to evaluate if the BS is capable of serving all users placed in its area, in the same instant. If the BS is not capable to serve all users, a reduction strategy is applied, reducing the user's throughput according to QoS requirements. With all served users taken into account, a network analysis is performed to evaluate its performance, regarding several parameters, such as average network throughput and radius. The goal is to analyse both systems individually, and then compare its default scenarios, as well as when increasing the number of users in the network, and changing the user profile in terms of the services' percentages considered.

Regarding the single user scenario for UMTS/HSDPA, the radio parameters considered are transmission power, frequency, number of HS-PDSCH codes, BT and MT antenna gains, noise figure and traffic power percentage. The margins associated to each environment are also considered. For all the environments, it is observed that the cell radius decreases with the increase of the throughput, because higher throughputs require higher SINR values. With the increase of the SINR value, the path loss decreases, as well as the cell radius. Considering the different environments, one can conclude that the pedestrian one presents higher cell radius compared to the others, since it presents lower attenuation margins. For the indoor low loss scenario, when the throughput ranges from 2 to 6 Mbps, the cell radius decreases 50%, changing from 0.4 to 0.2 km.

For the cell radius variation with the total BS DL transmission power, a fixed throughput of 3 Mbps is considered, as well as a pedestrian environment, to calculate the cell radius for 5, 10 and 15 HS-PDSCH codes. With the increase of the transmission power, the cell radius also increases, as there is a direct relationship between these two parameters. The cell radius for 20 dBm of transmission power and 15 HS-PDSCH codes is nearly 0.18 km, and for 40 dBm it is approximately 0.6 km, representing an increase of 233 %.

Regarding the single user scenario for Mobile WiMAX, some of the radio parameters taken into account are the same as the ones for UMTS/HSDPA, such as transmission power, frequency and BS and MT antenna gains. Additionally, parameters characteristic of Mobile WiMAX, like channel bandwidth, TDD mode, noise figure, and implementation margin were also considered. As it happens in UMTS/HSDPA, the cell radius for Mobile WiMAX also decreases when the throughput increases, for the several environments considered, due to the attenuations margins' values for each environment. Considering one environment, the cell radius decreases because the SNR value increases when the throughput requested also increases.

Regarding frequency, one can conclude that for 2.5 GHz the cell radius for 2 Mbps is almost 0.6 km higher than the one for 5.8 GHz, increasing 300 %, and approximately 0.4 km higher than the cell radius for 3.5 GHz, corresponding to an increase of 100%, considering the same throughput and the pedestrian environment. This is due to fact that with the increase of the frequency, the cell radius decreases, because of its influence in the path loss.

Concerning the multiple users scenario for UMTS/HSDPA, and considering the default values, the average instantaneous throughput per user decreases with distance. For shorter distances the SINR value is still above the threshold SINR for the requested throughput. On the other hand, for higher distances, the SINR is the limiting factor, due to the introduction of the interference margin in the multi-user scenario. Therefore, the SINR value for a user further away from the BS becomes lower, leading to a reduction of the throughput given to each user. For the various percentages of traffic, it is observed that there is a difference between the served and offered traffics, due to the reductions that users performing certain services suffer. Web is the service that presents more delayed users, because of its high percentage of users and high minimum throughput, which is a factor that implies more users delayed when reductions have to be made.

Regarding the number of HS-PDSCH codes, it is observed that when varying from 10 to 15 codes, the average network throughput increases approximately 0.3 Mbps, improving around 9.2 %, since more codes are available for data transmission. When changing the number of codes from 10 to 5, the average network throughput decreases 25 %, representing a reduction of about 0.5 Mbps. More codes available lead to an increase of the average satisfaction grade and average ratio of served users. The total network traffic and total number of users per hour increase with the increase of the number of codes, because each user session is performed quicker, since the throughput that each user receives is higher.

Regarding the number of users in the network, it can be seen that when introducing more users, the average network throughput presents an increase of 60 %, approximately 1.5 Mbps. With more users in the network, the average satisfaction grade and average ratio of served users decrease, because the resources are the same to serve more users. The average ratio of served users is lower but the number of effective served user when considering 4000 users is higher. The total network traffic in the busy hour increases 100 %, being around 160 GB/h for 4000 users and around 85 GB/h for 1600 users.

Considering the three strategies analysed, it can be concluded that the "QoS One by One Reduction" strategy is the one presenting better results for the average network throughput. The difference to the

“QoS Class Reduction” strategy is approximately 0.15 Mbps, representing an increase of 2.2 %, and to the “Throughput Reduction” one is nearly 0.25 Mbps, corresponding to an increase of 4.5 %.

For the multiple users analysis for Mobile WiMAX, one can say that the average throughput per user it approximately 0.65 Mbps, and it does not decrease with distance, due to the fact that for the range of throughputs considered, the SNR value given by the user’s distance and even considering the interference margin is, in the majority of the cases, above the SNR given by the throughput requested.

In Mobile WiMAX, the difference in the percentages of served and offered traffics for the default scenario is not significant, because Mobile WiMAX is able to serve practically all the traffic requested. The only major differences occur in Web and Streaming, because these services present the highest minimum throughput, which means that more users are delayed, due to the necessary throughput reductions that have to be made.

Regarding the channel bandwidth in Mobile WiMAX, it can be seen that when changing the channel bandwidth from 5 to 10 MHz, more users can be served, or, considering the same number of users, they can be served with higher throughputs. This is due to the fact that the 10 MHz channel has more data sub-carriers available. The average network throughput for 10 MHz channel is around 1 Mbps, higher than the one for 5 MHz, representing an increase of 25 %. Average satisfaction grade, average ratio of served users, total traffic per hour and total number of users served within an hour also presents better results for 10 MHz channel.

Concerning the frequency in Mobile WiMAX, one can conclude that when changing the frequency from 3.5 GHz to 2.5 GHz, the cell radius increases, leading to more users being in the coverage area. This is due to the direct influence that frequency has in the path loss, so when the frequency increases the cell radius decreases. The average network throughput was approximately the same, approximately 4.8 Mbps, since the number of effective users served is similar. For the 5800 MHz simulations the average network radius decreases approximately 50 %, compared to the 3500 MHz frequency, and the average satisfaction grade and average ratio of served users almost reaches the maximum value. This has to do with the fact that with lower cell radius, fewer users are in the coverage area, so the resources available are distributed among fewer users, leading to a higher throughput offered to a single user.

When 4000 users are introduced in the network, the average network throughput increases 77 %, approximately 4 Mbps, compared with the default number of users of 1600. Considering 4000 users, the average satisfaction grade and average ratio of served users decreases, because the resources are the same, but now distributed to more users, leading to more reductions and delayed users.

Comparing UMTS/HSDPA with Mobile WiMAX for the single user model, it is observed that for the frequencies considered for both systems, i.e. 2112.5 MHz for UMTS/HSPDA and 3.5 GHz for Mobile WIMAX, the cell radius for UMTS/HSDPA is higher than the one for Mobile WiMAX. When comparing UMTS/HSDPA with Mobile WiMAX TDD mode 2:1, one can conclude that up to 0.15 km, Mobile

WiMAX TDD 2:1 and 10 MHz channel bandwidth can provide 5 Mbps higher than UMTS/HSDPA. From 0.15 km, there is an abrupt decay of the maximum Mobile WiMAX throughput, whether is a 5 or a 10 MHz channel bandwidth. Up to 0.1 km, it is possible to assure the maximum throughput for 10 MHz, and for 5 MHz the maximum throughput can be achieved up to 0.15 km. UMTS/HSDPA presents lower maximum throughput values, but the maximum throughput can be obtained up to 0.4 km for 10 and 15 HS-PDSCH codes, and up to 0.45 km for 5 HS-PDSCH codes. After reaching the maximum cell radius for the maximum throughput, the variation for UMTS/HSDPA and Mobile WiMAX is due to the SINR and SNR values, respectively.

The cell edge for UMTS/HSDPA for 15 HS-PDSCH codes is approximately 1.64 km and for Mobile WiMAX with frequency of 3.5 GHz is around 0.9 km, representing a reduction of 45 %, when a single user is requesting a throughput of 0.384 Mbps. These results were obtained for the pedestrian environment.

Comparing UMTS/HSDPA with Mobile WiMAX in the multiple users scenario, and considering the default values, it is observed that the average instantaneous throughput per user for Mobile WiMAX for distances up to 0.5 km is approximately constant and around 0.65 Mbps and for UMTS/HSDPA decreases with the distance, even tough having values of approximately 0.67 Mbps near the BS. Comparing the average instantaneous throughput per user offered by each system for distances equal to 0.5 km, the difference is approximately 0.25 Mbps, representing a reduction of 40 % when changing from Mobile WIMAX to UMTS/HSDPA. As for the average network throughput, Mobile WiMAX presents nearly 2.5 Mbps higher than the one for UMTS/HSDPA, due to the higher number of served users, which is almost the double when comparing to UMTS/HSDPA. Considering the average network radius, it is observed that, for Mobile WIMAX, it is approximately 0.3 km and for UMTS/HSDPA nearly 0.28 km, representing a reduction of 7 %. The average satisfaction grade is higher for Mobile WiMAX due to its higher capacity, because even tough serving more users, fewer reductions are needed for Mobile WiMAX.

For the total number of users per hour, it is possible to verify the difference between Mobile WiMAX and UMTS/HSDPA. Since, in a certain instant, Mobile WiMAX is capable of serving more users than UMTS/HSDPA, it serves, as expected, more users within the hour. The frame overhead used for Mobile WiMAX is always 11 OFDM symbols, not changing as a function of the number of users served within each frame. The fact that the average throughput per user is higher in Mobile WiMAX also allows users' sessions to be performed quicker, so within the busy hour more users can be served. For Mobile WiMAX, it is around 70000 and for UMTS/HSPDA approximately 30000 users, representing an increase of 133 % when changing from UMTS/HSDPA to Mobile WiMAX. As a result of this fact, the total network traffic for Mobile WiMAX is higher than the one for UMTS/HSPDA, with values of approximately 160 GB/h and 85 GB/h, respectively. Regarding the percentages of services, one can conclude that for the considered offered traffic, Mobile WiMAX presents better results, as the percentages of served traffic are similar to the ones offered to the network, as opposed to UMTS/HPSDA. This is due to the higher capacity and higher throughputs offered by Mobile WiMAX.

The served percentages for both systems are obtained taking into account the effective number of users served by each system, being approximately 800 users for UMTS/HSDPA and around 1500 users for Mobile WiMAX, corresponding to an increase of almost 88 %.

For the network simulations with 4000 users, Mobile WiMAX presents an average network throughput of almost 5 Mbps higher than the one for UMTS/HSDPA, corresponding to an increase of 125 %. This is due to the fact that Mobile WiMAX is capable of serving more users, therefore the overall throughput in the network is higher. Considering 4000 users, the average satisfaction grade is 0.8 for Mobile WiMAX and 0.7 for UMTS/HSDPA. Even though serving more users, approximately the twice the number of users of UMTS/HSDPA, Mobile WiMAX is capable of providing higher throughputs than UMTS/HSDPA, due to its higher capacity.

Considering the alternative profiles, the systems' behaviors is the same as the ones observed for the default profile, i.e., Mobile WiMAX's average network throughput is almost twice than the one for UMTS/HSDPA, for both profiles. The average satisfaction grade and the average ratio of served users are also higher for Mobile WiMAX. Regarding the total network traffic per hour, Mobile WiMAX presents 250 GB/h for the IBB profile and 200 GB/h for the IAO one and the results for UMTS are approximately 100 GB/h and 85 GB/h for the IBB and IAO profiles, respectively. There is an increase of 150 % for IBB and 135 % for IAO, regarding network traffic, when changing from UMTS/HSDPA to Mobile WiMAX

One can conclude that for a single user in the network, UMTS/HSDPA presents a higher cell radius than Mobile WiMAX, for the same throughput. This is due to the effect that the frequencies considered, 2112.5 MHz for UMTS/HSDPA and 3.5 GHz for Mobile WiMAX in Europe have in the path loss. For the multiple users scenario, Mobile WiMAX presents better results in almost every parameter analysed, even in the average network radius. This fact happens because as Mobile WiMAX is capable of serving more users, it can provide throughputs to users that are farther away from the BS; UMTS/HSDPA presents lower throughput capacity, therefore, users distant from the BS are delayed, due to more reductions that have to be performed in UMTS/HSPDA.

For future work, it would be interesting to study Mobile WiMAX in the 2.3 GHz frequency to observe the effect in the cell radius, as it is an important factor when it comes to coverage, and also the TDD split 5:1, to improve DL data rates. As for UMTS/HSPDA, a mixture of terminals of 5, 10 and 15 HS-PDSCH codes in the same network would give a more realistic approach. Another suggestion would be an analysis where the user, if placed in the coverage area of two BSs, to be connected to the BS presenting more resources available, and not to the one that is actually closer. It would also be interesting to simulate the use of MIMO in both systems. Given the advances in Mobile Communications Systems, a comparison between Mobile WiMAX and the OFDM feature of UMTS, High Speed OFDM Packet Access (HSOPA), would also be appealing.

Annex A – Link Budget

The link budget used throughout this work is based on the Release 99 one, described in detail in [CoLa06] and [Sant04], adapted to UMTS/HSDPA and Mobile WiMAX.

The path loss can be calculated by [Corr06]:

$$L_{P[\text{dB}]} = P_{t[\text{dBm}]} + G_{t[\text{dBi}]} - P_{r[\text{dBm}]} + G_{r[\text{dBi}]} = EIRP_{[\text{dBm}]} - P_{r[\text{dBm}]} + G_{r[\text{dBi}]} \tag{A.1}$$

where:

- L_p : path loss
- P_t : transmitting power at antenna port;
- G_t : transmitting antenna gain
- P_r : available receiving power at antenna port
- G_r : receiving antenna gain

The Equivalent Isotropic Radiated Power (EIRP) can be calculated for DL by (A.2) and UL by (A.3):

$$EIRP_{[\text{dBm}]} = P_{Tx[\text{dBm}]} - L_{c[\text{dB}]} + G_{t[\text{dBi}]} \tag{A.2}$$

$$EIRP_{[\text{dBm}]} = P_{Tx[\text{dBm}]} - L_{u[\text{dB}]} + G_{t[\text{dBi}]} \tag{A.3}$$

where:

- P_{Tx} : transmitted power
- L_c : cable losses between emitter and antenna
- L_u : body loss

The received power can be calculated by (A.4) for DL and (A.5) for UL:

$$P_{Rx[\text{dBm}]} = P_{r[\text{dBm}]} - L_{u[\text{dB}]} \tag{A.4}$$

$$P_{Rx[\text{dBm}]} = P_{r[\text{dBm}]} - L_{c[\text{dB}]} \tag{A.5}$$

where:

- P_{Rx} : received power at receiver input

The UMTS/HSDPA receiver sensitivity can be approximated by:

$$P_{Rx\min[\text{dBm}]} = N_{[\text{dBm}]} - G_{P[\text{dB}]} + SINR_{[\text{dB}]} \tag{A.6}$$

where:

- N : total noise power given by (A.7)
- G_P : processing gain, fixed and equal to 16
- $SINR$: signal to noise ratio

The total noise power is:

$$N_{[\text{dBm}]} = -174 + 10 \cdot \log(\Delta f_{[\text{Hz}]}) + F_{[\text{dB}]} + M_{I[\text{dB}]} \tag{A.7}$$

where:

- Δf : signal bandwidth, in UMTS/HSDPA it is equal to R_c
- F : receiver's noise figure
- M_I : interference margin

The interference margin is calculated by taking the number of users associated to a certain BS into account. To the users of the most populated BS is assigned a maximum interference margin value of 6 dB for UMTS/HSDPA and 2 dB for Mobile WiMAX [WiMF06a], and for the users associated to the other BSs, the interference margin for both UMTS/HSDPA and Mobile WiMAX is estimated by:

$$M_{I_j\,[\text{dB}]} = \frac{N_{u_j}}{N_{uBS_{\max}}} \cdot \chi_{[\text{dB}]} \tag{A.8}$$

where:

- χ : maximum interference margin considered
- M_{I_j} : interference margin to the users associated with BS j
- N_{u_j} : number of users of BS j
- $N_{uBS_{\max}}$: number of users of the most populated BS

For Mobile WiMAX, the MT receiver sensitivity, when sub-channelisation is considered, is given by [IEEE06]:

$$P_{Rx\min[\text{dBm}]} = -114 + SNR_{[\text{dB}]} + 10 \cdot \log\left(F_{S[\text{MHz}]} \cdot \frac{N_{DSC}}{N_{TSC}} \cdot \frac{N_{SCH}}{16}\right) + I_M N_{F[\text{dB}]} \tag{A.9}$$

where:

- $P_{Rx\min}$: receiver sensitivity
- F_s : sampling frequency
- N_{DSC} : number of data sub-carriers used
- N_{TSC} : total number of sub-carriers
- N_{SCH} : number of sub-channels used
- SNR : receiver signal-to-noise ratio

- I_M : implementation margin
- N_F : noise figure.

The sampling frequency is given by:

$$F_{s[\text{MHz}]} = n \cdot \Delta f_{[\text{MHz}]} \tag{A.10}$$

where:

- n : sampling factor (n =144/125 for a 5 MHz channel, and n =57/50 for a 10 MHz one)
- Δf : channel bandwidth

Some margins must be taken into account to adjust additional losses caused by radio propagation:

$$M_{[\text{dB}]} = M_{SF[\text{dB}]} + M_{FF[\text{dB}]} + L_{int[\text{dB}]} \tag{A.11}$$

where:

- M_{SF} : slow fading margin
- M_{FF} : fast fading margin
- L_{int} : indoor penetration losses

The total cell path loss is used as an input in the COST 231 Walfisch-Ikegami propagation model, described in detail in [DaCo99], to calculate the cell radius.

The total path loss can be calculated by:

$$L_{p\,total[\text{dB}]} = L_{p[\text{dB}]} - M_{[\text{dB}]} \tag{A.12}$$

where for UMTS/HSDPA M is given by (A.11) and for Mobile WiMAX it is given by :

$$M_{[\text{dB}]} = M_{SF[\text{dB}]} + M_{FF[\text{dB}]} + L_{\text{int}[\text{dB}]} + M_{I[\text{dB}]} \tag{A.13}$$

The DL frequency values used ([2110, 2170] MHz for UMTS/HSDPA and 2.5 and 3.5 GHz for Mobile WiMAX) exceed the frequency validation values, and some of the calculated cell radius are below the distance validation values, namely for high data rates. Nevertheless, the model was used, since it is adjusted to urban NLOS propagation. The COST 231 Walfisch-Ikegami propagation model is valid for [DaCo99]:

- frequency $\in [800, 2000]$ MHz ;
- distance $\in [0.02, 5]$ km
- building height $\in [4, 50]$ m
- MT height $\in [1, 3]$ m

In Table A.1, the values for the propagation model parameters are listed. For the parameter that represents the frequency losses dependence due to diffraction by a set of knife-edges, only the urban centre case was considered.

Table A.1. Default values used in the COST 231 Walfisch-Ikegami propagation model (based on [CoLa06]).

Parameter name	Value
Street Width [m]	24
Building Separation [m]	48
BS height [m]	26
Building height [m]	24
MT height [m]	1.8
Orientation angle [º]	90

Regarding UMTS/HSDPA, Figure A.1 represents the correspondence between SINR and throughput for 5, 10 and 15 HS-PDSCH codes.

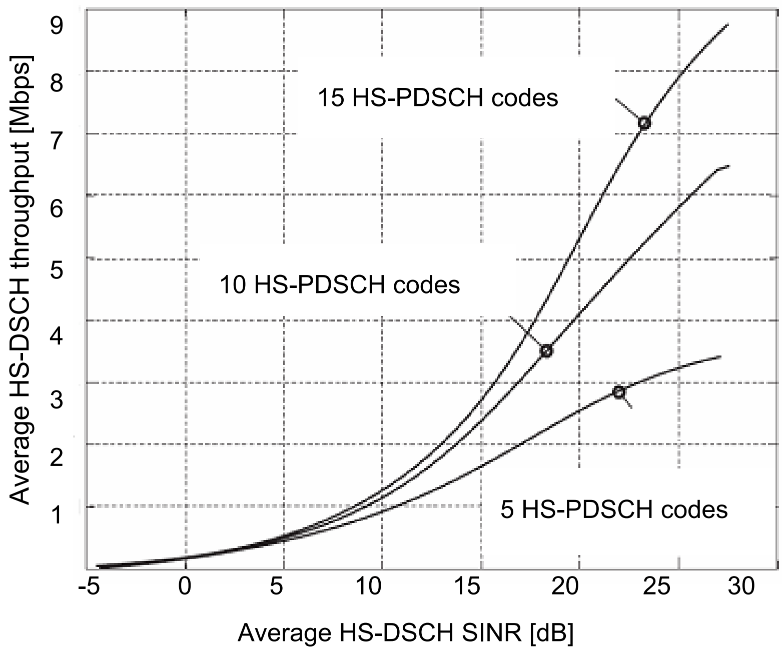


Figure A.1. Data rate as function of the average HS-DSCH SINR for 5, 10 and 15 HS-PDSCH codes (extracted from [PeDe05]).

The first step is to obtain values from Figure A.1, and create the real curves in Figure A.2. For UMTS/HSDPA, the values of SINR, as function of the throughput, were calculated by polynomial interpolation of the curves in Figure A.2, using Matlab and EXCELL. To confirm the validity of the interpolated curves, it is necessary to assure that the approximation relative error is below 5%, Table A.3. For 5 HS-PDSCH codes, one has:

$$\psi_{[dB]} = 0.1856 \cdot \rho_{[Mbps]}^{5} - 1.6176 \cdot \rho_{[Mbps]}^{4} + 6.7608 \cdot \rho_{[Mbps]}^{3} - 16.7997 \cdot \rho_{[Mbps]}^{2} + 27.3903 \cdot \rho_{[Mbps]} - 4.9847 \quad (A.14)$$

where:

- ρ : application throughput
- ψ : SINR

for 10 HS-PDSCH codes, the SINR is given by:

$$\psi_{[dB]} = 0.0382 \cdot \rho_{[Mbps]}^{5} - 0.6722 \cdot \rho_{[Mbps]}^{4} + 4.4891 \cdot \rho_{[Mbps]}^{3} - 14.2023 \cdot \rho_{[Mbps]}^{2} + 24.3795 \cdot \rho_{[Mbps]} - 4.6875 \quad (A.15)$$

and for 15 HS-PDSCH codes, the SINR can be calculated by:

$$\psi_{[dB]} = \begin{cases} 0.0061 \cdot \rho_{[Mbps]}^{5} - 0.1663 \cdot \rho_{[Mbps]}^{4} + 1.6581 \cdot \rho_{[Mbps]}^{3} - 7.8530 \cdot \rho_{[Mbps]}^{2} + 18.9881 \cdot \rho_{[Mbps]} - 3.9237, & \rho_{[Mbps]} \leq 5.4 \\ 0.0952 \cdot \rho_{[Mbps]}^{4} - 2.7432 \cdot \rho_{[Mbps]}^{3} + 29.4923 \cdot \rho_{[Mbps]}^{2} - 138.1340 \cdot \rho_{[Mbps]} + 257.0166, & 5.4 < \rho_{[Mbps]} \leq 8.46 \end{cases} \quad (A.16)$$

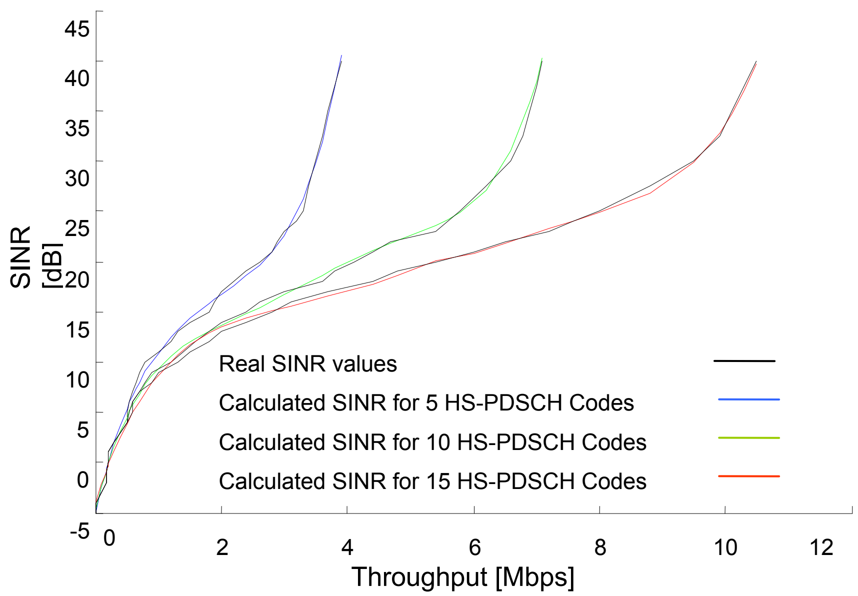


Figure A.2. Interpolation curves for 5, 10 and 15 HS-PDSCH codes.

As referred to in Section 3.1, although the results in (A.16) were obtained for 15 HS-PDSCH codes, one approximated those results for 14 HS-PDSCH codes, since there are no available simulations regarding the latter number of codes.

Table A.2. Relative error and variance for the interpolated curves in Figure A.2.

Number of codes	Relative error [%]	Standard deviation [Mbps]
5	2.9	0.24
10	2.1	0.20
15	3.4	0.23

For Mobile WiMAX, the considered values of SNR are different regarding the channel bandwidth [WiMF06a], [IEEE06]. The relationship between the requested throughput and the number of data sub-carriers necessary to provide it is given by:

$$\rho_{p[\text{bps}]} = \frac{N_{DSC} \cdot M_r \cdot \beta \cdot N_{DS}}{T_{F[\text{s}]}} \Leftrightarrow N_{DSC} = \frac{\rho_p \cdot T_{F[\text{s}]}}{M_r \cdot \beta \cdot N_{DS}} \quad \text{(A.17)}$$

where:

- ρ_p : physical layer throughput
- N_{DSC} : number of data sub-carriers
- M_r : modulation rate
- β : effective code rate
- N_{DS} : number of data symbols
- T_F : frame duration (for Mobile WiMAX it is considered 5 ms).

Each channel has a specific number of data sub-carriers, responsible for carrying data. The number of sub-carriers forming a sub-channel is also different when considering UL or DL transmission. Table A.2 gives the values for the different parameters when considering a 5 and a 10 MHz channel for DL and UL [WiMF06a].The number of OFDM data symbols is 44, when considering the physical layer. Due to MAC layer overhead, the number of OFDM symbols considered is 37.

The considered values for the application throughput are the ones presented in Table A.3. These values are the ones for TDD split of 1:0, i.e., where all 37 data symbols are used for DL and considering 93.3% and 90% of the physical throughput for application layer overhead and BLER, respectively. It is also shown the SNR values for the 5 and 10 MHz channel, whether for DL and UL.

Tables A.3, A.4, A.5 and A.6 show the values for the application throughput for TDD splits of 1:1, 2:1 and 3:1, repeating the same procedure as the one for 1:0, but now only considering 1/2, 2/3 and 3/4 of the 37 data symbols for DL when considering 1:1, 2:1 and 3:1, respectively.

Table A.3. Mobile WiMAX parameters for 5 and 10 MHz channels for UL and DL transmission (adapted from [WIMF06a]).

Mobile WiMAX Parameters	**5 MHz**		**10 MHz**	
	DL	**UL**	**DL**	**UL**
Number of data sub-carriers	360	272	720	560
Total number of sub-carriers	512	512	1024	1024
Total number of sub-channels	15	17	30	35
Number of data sub-carriers inside a sub-channel	24	16	24	16

Table A.4. Mobile WiMAX maximum application throughput for 5 and 10 MHz channels for DL and UL considering TDD split 1:0 (adapted from [WIMF06a]).

SNR [dB]	Modulation	Code Rate	5 MHz channel		10 MHz channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
5	QPSK	1/2	[0, 2.24]	[0, 1.61]	[0, 4.48]	[0, 3.32]
8	QPSK	3/4	]2.24, 3.36]	]1.61, 2.42]	]4.48, 6.71]	]3.32, 4.99]
10.5	16QAM	1/2	]3.36, 4.48]	]2.42, 3.23]	]6.71, 8.53]	]4.99, 6.65]
14	16QAM	3/4	]4.48, 5.59]	]3.23, 4.03]	]8.53, 10.98]	]6.65, 8.31]
16	64QAM	1/2	]5.59, 6.71]	]4.03, 4.84]	]10.98, 13.43]	]8.31, 9.97]
18	64QAM	2/3	]6.71, 8.95]	]4.84, 6.46]	]13.43, 18.60]	]9.97, 13.29]
20	64QAM	3/4	]8.95, 10.07]	]6.46, 7.26]	]18.60, 20.14]	]13.29, 14.95

Table A.5. Mobile WiMAX maximum application throughput for 5 and 10 MHz channels for DL and UL considering TDD split 1:1 (adapted from [WIMF06a]).

SNR [dB]	Modulation	Code Rate	5 MHz channel		10 MHz channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
5	QPSK	1/2	[0, 1.12]	[0, 0.81]	[0, 2.24]	[0, 1.66]
8	QPSK	3/4	]1.12, 1.68]	]0.81, 1.21]	]2.24, 3.36]	]1.66, 2.49]
10.5	16QAM	1/2	]1.68, 2.24]	]1.21, 1.61]	]3.36, 4.26]	]2.49, 3.32]
14	16QAM	3/4	]2.24, 2.80]	]1.61, 2.02]	]4.26, 5.49]	]3.32, 4.15]
16	64QAM	1/2	]2.80, 3.36]	]2.02, 2.42]	]5.49, 6.71]	]4.15, 4.98]
18	64QAM	2/3	]3.36, 4.47]	]2.42, 3.23]	]6.71, 9.30]	]4.98, 6.65]
20	64QAM	3/4	]4.47, 5.04]	]3.23, 3.63]	]9.30, 10.07]	]6.65, 7.48]

Table A.6. Mobile WiMAX maximum application throughput for 5 and 10 MHz channels for DL and UL considering TDD split 2:1 (adapted from [WIMF06a]).

SNR [dB]	Modulation	Code Rate	5 MHz channel		10 MHz channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
5	QPSK	1/2	]0, 1.49]	[0, 1.07]	[0, 2.99]	[0, 2.21]
8	QPSK	3/4	]1.49, 2.24]	]1.07, 1.62]	]2.99, 4.47]	]2.21, 3.32]
10.5	16QAM	1/2	]2.24, 2.99]	]1.62, 2.15]	]4.47, 5.68]	]3.32, 4.43]
14	16QAM	3/4	]2.99, 3.73]	]2.15, 2.69]	]5.68, 7.32]	]4.43, 5.54]
16	64QAM	1/2	]3.73, 4.47]	]2.69, 3.23]	]7.32, 8.95]	]5.54, 6.64]
18	64QAM	2/3	]4.47, 5.97]	]3.23, 4.30]	]8.95, 12.40]	]6.64, 8.86]
20	64QAM	3/4	]5.97, 6.70]	]4.30, 4.84]	]12.40, 13.42]	]8.86, 9.97]

Table A.7. Mobile WiMAX maximum application throughput for 5 and 10 MHz channels for DL and UL considering TDD split 3:1 (adapted from [WIMF06a]).

SNR [dB]	Modulation	Code Rate	5 MHz channel		10 MHz channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
5	QPSK	1/2	[0, 1.68]	[0, 1.21]	[0, 3.36]	[0, 2.49]
8	QPSK	3/4	]1.68, 2.52]	]1.21, 1.82]	]3.36, 5.03]	]2.49, 3.74]
10.5	16QAM	1/2	]2.52, 3.36]	]1.82, 2.42]	]5.03, 6.39]	]3.74, 4.98]
14	16QAM	3/4	]3.36, 4.20]	]2.42, 3.02]	]6.39, 8.23]	]4.98, 6.23]
16	64QAM	1/2	]4.20, 5.03]	]3.02, 3.63]	]8.23, 10.07]	]6.23, 7.47]
18	64QAM	2/3	]5.03, 6.71]	]3.63, 4.84]	]10.07, 13.95]	]7.47, 9.97]
20	64QAM	3/4	]6.71, 7.54]	]4.84, 5.45]	]13.95, 15.09]	]9.97, 11.21]

Regarding the situation where it is necessary to calculate the throughput that is due to the distance that the user is from the BS, the first step is to determine the path loss associated with the user distance, described in [CoLa06] and [Sant04]. Then, with the path loss calculated, the receiver sensitivity is determined taking (A.3) and (A.5) into account, resulting:

$$P_{Rx[\mathrm{dBm}]} = EIRP_{[\mathrm{dBm}]} - L_{P[\mathrm{dB}]} + G_{r[\mathrm{dB}]} - L_{u[\mathrm{dB}]} \quad \text{(A.18)}$$

For UMTS/HSDPA, the SINR associated to a certain user distance is calculated by:

$$SINR_{[\mathrm{dB}]} = P_{Rx[\mathrm{dBm}]} - N_{[\mathrm{dBm}]} + G_{p[\mathrm{dB}]} \quad \text{(A.19)}$$

Using Figure A.3, it is possible to estimate the throughput considering the user distance.

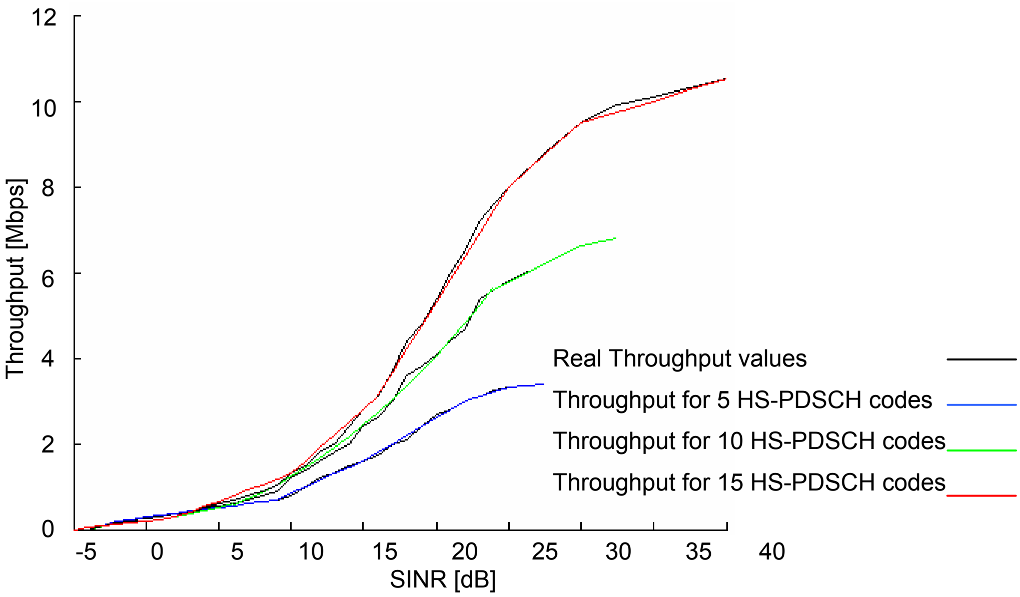


Figure A.3. Interpolation curves for 5, 10 and 15 HS-PDSCH codes.

The expressions of the interpolation curves in Figure A.3 are given by (A.20), (A.21) and (A.22) for 5, 10 and 15 HS-PDSCH codes respectively. These expressions are step-wise, due to the fact that all polynomial expressions given by Matlab and EXCEL present relative errors higher than 5%.

$$\rho_{[\mathrm{Mbps}]} = \begin{cases} 0, & \psi_{[\mathrm{dB}]} < -4 \\ 0.095 \cdot \psi_{[\mathrm{dB}]} + 0.38, & -4 < \psi_{[\mathrm{dB}]} \le -2 \\ 0.0464 \cdot \psi_{[\mathrm{dB}]} + 0.2828, & -2 < \psi_{[\mathrm{dB}]} \le 9 \\ 0.15 \cdot \psi_{[\mathrm{dB}]} - 0.65, & 9 < \psi_{[\mathrm{dB}]} \le 15 \\ 0.2 \cdot \psi_{[\mathrm{dB}]} - 1.4, & 15 < \psi_{[\mathrm{dB}]} \le 22 \\ 3, & \psi_{[\mathrm{dB}]} > 22 \end{cases} \tag{A.20}$$

$$\rho_{[\mathrm{Mbps}]} = \begin{cases} 0, & \psi_{[\mathrm{dB}]} < -4 \\ 0.085 \cdot \psi_{[\mathrm{dB}]} + 0.34, & -4 < \psi_{[\mathrm{dB}]} \le -2 \\ 0.0167 \cdot \psi_{[\mathrm{dB}]} + 0.2034, & -2 < \psi_{[\mathrm{dB}]} \le 1 \\ 0.076 \cdot \psi_{[\mathrm{dB}]} + 0.65, & 1 < \psi_{[\mathrm{dB}]} \le 6 \\ 0.085 \cdot \psi^2_{[\mathrm{dB}]} + 0.0271 \cdot \psi_{[\mathrm{dB}]} + 0.1141, & 6 < \psi < 24 \\ 0.1667 \cdot \psi_{[\mathrm{dB}]} + 1.599, & 24 \le \psi_{[\mathrm{dB}]} \le 26.4 \\ 6, & \psi_{[\mathrm{dB}]} > 26.4 \end{cases} \tag{A.21}$$

$$\rho_{[\mathrm{Mbps}]} = \begin{cases} 0, & \psi_{[\mathrm{dB}]} < -5 \\ 0.0367 \cdot \psi_{[\mathrm{dB}]} + 0.183, & -5 < \psi_{[\mathrm{dB}]} \le 1 \\ 0.09 \cdot \psi_{[\mathrm{dB}]} + 0.13, & 1 < \psi_{[\mathrm{dB}]} \le 3 \\ 0.1296 \cdot \psi_{[\mathrm{dB}]} + 0.014, & 3 < \psi_{[\mathrm{dB}]} \le 10 \\ 0.3 \cdot \psi_{[\mathrm{dB}]} - 1.7, & 10 < \psi_{[\mathrm{dB}]} \le 16 \\ 0.54 \cdot \psi_{[\mathrm{dB}]} - 5.5, & 16 \le \psi_{[\mathrm{dB}]} \le 25 \\ 0.3 \cdot \psi_{[\mathrm{dB}]} + 0.5, & 25 < \psi_{[\mathrm{dB}]} \le 26.5 \\ 8.46, & \psi_{[\mathrm{dB}]} > 26.5 \end{cases} \tag{A.22}$$

In Table A.8, the relative error and variance for each of the curves are presented.

Table A.8. Relative error and variance for the interpolated curves in Figure A.3.

Number of codes	Relative error [%]	Standard deviation [Mbps]
5	2.2	0.03
10	3.0	0.04
15	4.9	0.03

For Mobile WiMAX, the procedure to determine the throughput associated to a certain distance has several steps to be taken into account. First, the user receiver sensitivity is calculated by using (A.17). Then, the maximum sensitivity for each *SNR* are calculated, considering a 5 or a 10 MHz channel, using (A.9), Table A.9.

Table A.9. Receiver sensitivity for each value of SNR for 5 and 10 MHz channels

SNR **[dB]**	**Receiver Sensitivity [dBm]**	
	5 MHz	**10 MHz**
5	-96.21	-91.05
8	-93.21	-88.05
10.5	-90.21	-85.55
14	-87.21	-82.05
16	-85.21	-80.05
18	-83.21	-78.05
20	-81.21	-76.05

Using (A.18), the value for the user receiver sensitivity is compared with the values in Table A.6. If the user receiver sensitivity is higher than the first position in Table A.6, then it is compared with the next one, repeating this process until it is lower. Then, the correspondent value of SNR is used to calculate the number of data sub-carriers, by:

$$N_{DSC} = \sqrt{\frac{N_{TSC} \cdot 24 \cdot 16 \cdot 10^{\frac{(P_{r\,xmin[dBm]} + 114 - SNR_{[dB]} - I_M N_{F[dB]})}{10}}}{F_{S[MHz]}}} \quad \text{(A.23)}$$

The user throughput that is due to the distance to the BS is given by:

$$\rho_{[bps]} = \frac{N_{DSC} \cdot M_r \cdot \beta \cdot N_{DS}}{T_{F[s]}} \quad \text{(A.24)}$$

where:

- N_{DS} : number of OFDM data symbols considering the TDD split adapted
- M_r , β : modulation rate and effective code rate associated with the SNR chosen.

Annex B – Single User Model Interface

In this annex, the user interface for both UMTS/HSDPA and Mobile WiMAX single user models is presented.

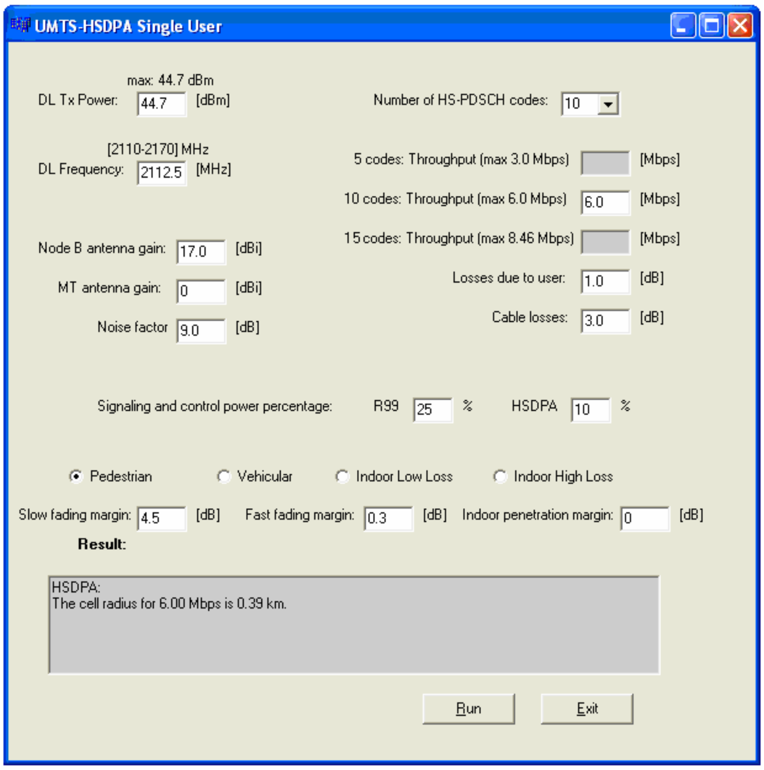


Figure B.1. UMTS/HSDPA single service user model user interface.

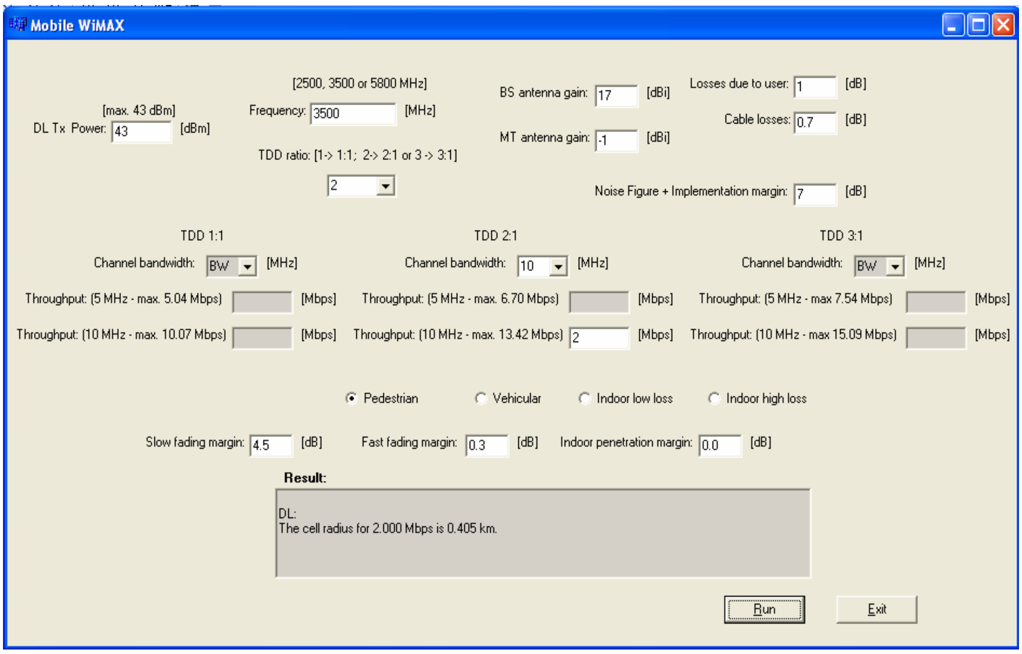


Figure B.2. Mobile WiMAX single service user model user interface.

Annex C – Services' Characterisation

The user generator program is based on parameters provided by the MOMENTUM project [MOME04]. The previously existing profiles were adapted to the new services, Table C.1. The correspondence between the services is due to the fact that they have similar service percentages. All the other input parameters are the ones used in [CoLa06]. In Table C.2, one presents the services' penetration percentage and QoS priority list for the default and alternative scenarios.

Table C.1. Traffic distribution file correspondence.

MOMENTUM traffic distribution file	New traffic distribution file	Service
Speech3.rst	Web.rst	Web
	P2P.rst	P2P
E-mail3.rst	Streaming.rst	Streaming
File_down3.rst	Chat.rst	Chat
MMS3.rst	Email.rst	Email
	FTP.rst	FTP

Table C.2. Default and alternative percentage values for each of the services and corresponding QoS priority.

Services	Penetration Percentage [%]	QoS priority	Penetration Percentage [%]		QoS priority
	Default		IBB	IAO	
Web	46.4	1	40	40	2
P2P	42.3	6	10	5	5
Streaming	6.2	2	10	10	1
Chat	3.1	5	10	20	3
E-Mail	1.0	3	20	15	6
FTP	1.0	4	10	10	4

Annex D – User's Manual

To start the application, it is necessary to introduce three input files:

- "Ant65deg.TAB", with the BS antenna gain for all directions,
- "DADOS_Lisboa.TAB", with information regarding the city of Lisbon and all its civil parishes,
- "ZONAS_Lisboa.TAB", with the area characterisation like streets, gardens along with others, Figure D.1.

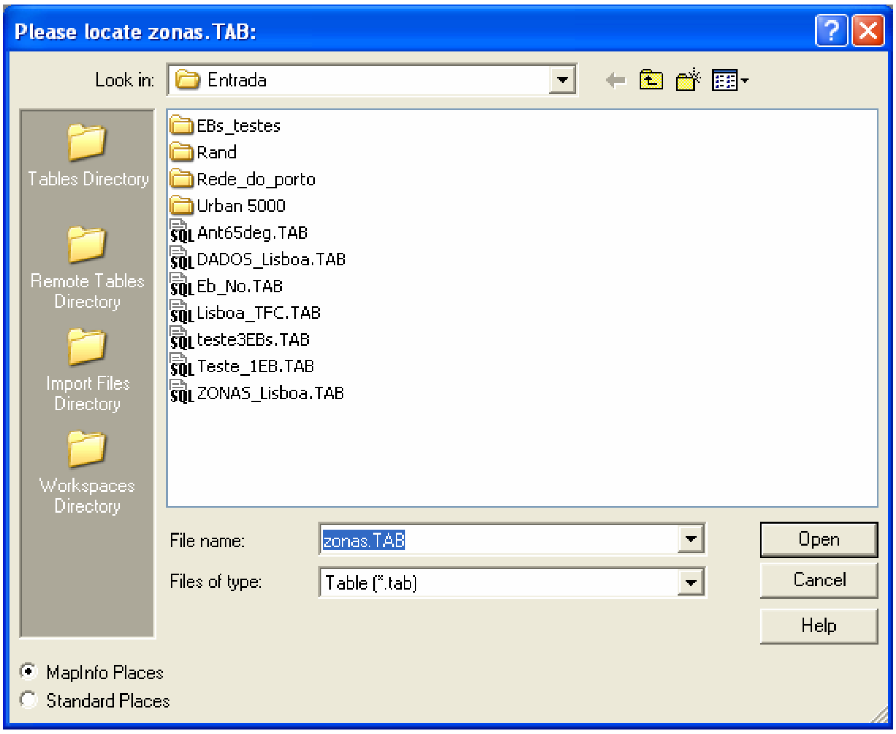


Figure D.1. Window for the introduction of ZONAS_Lisboa.TAB file.

After the introduction of the geographical information, it is displayed and a new options bar appears in MapInfo, where it is possible to choose between UMTS/HSDPA and Mobile WiMAX, Figure D.2, and define some characteristics of the simulations.

Among the several options that are available for UMTS/HSDPA and Mobile WiMAX, the windows for the propagation model, services and traffic properties are the same, Figure D.3, Figure D.4 and Figure D.5 respectively, because the propagation model parameters used in the simulations for both systems are equal.

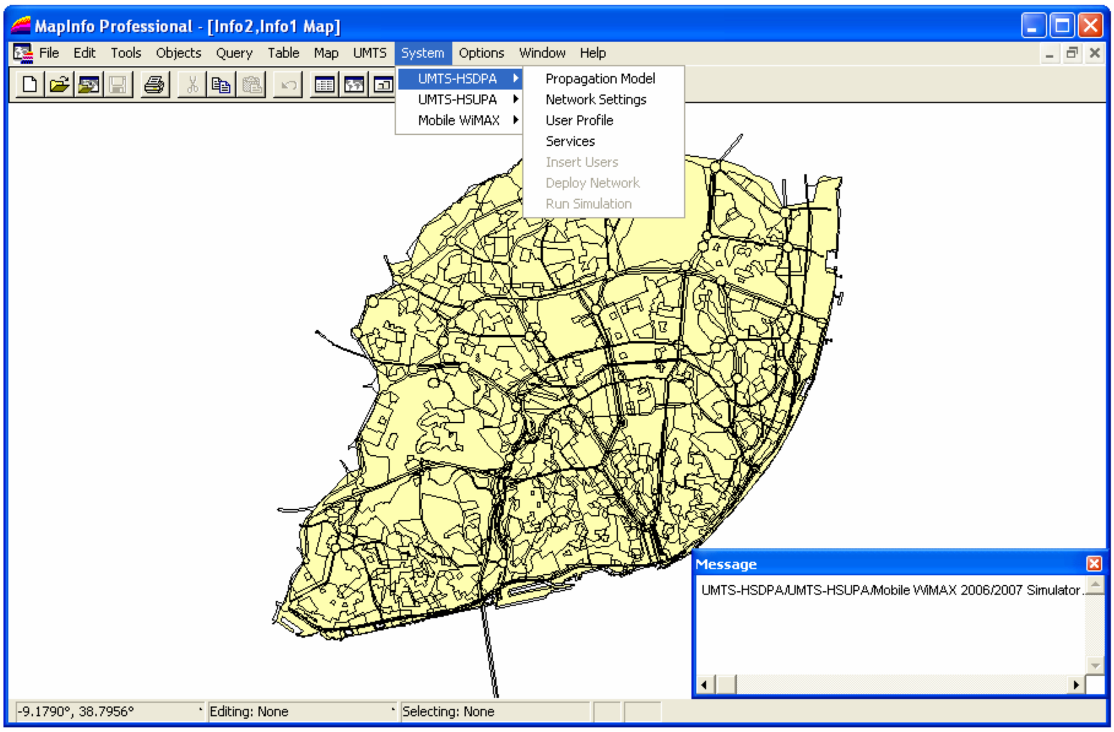


Figure D.2. View of the simulator and menu bar with the several options for each one of the systems.

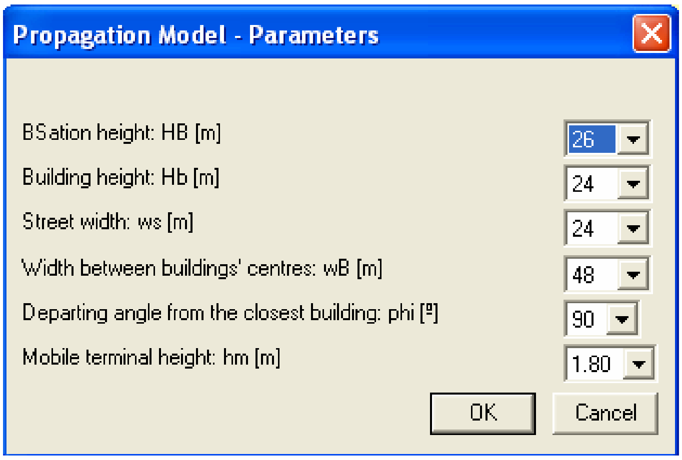


Figure D.3. Propagation model parameters.

Figure D.4. List of services considered.

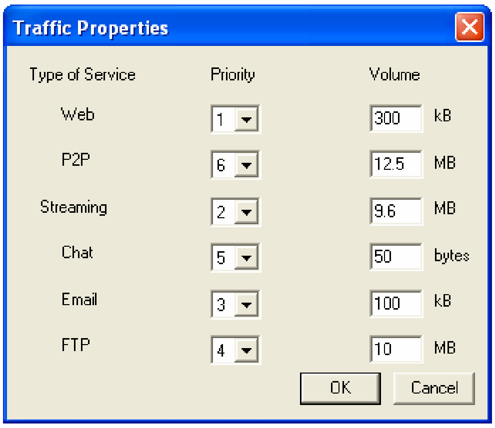


Figure D.5. Traffic properties window.

For both UMTS/HSDPA and Mobile WiMAX User Profile windows, Figure D.6 and Figure D.7 respectively, it is possible to change the maximum and minimum desired throughput for each service. The default values for the minimum throughput are the ones presented, not being possible to define a minimum service throughput lower than that.

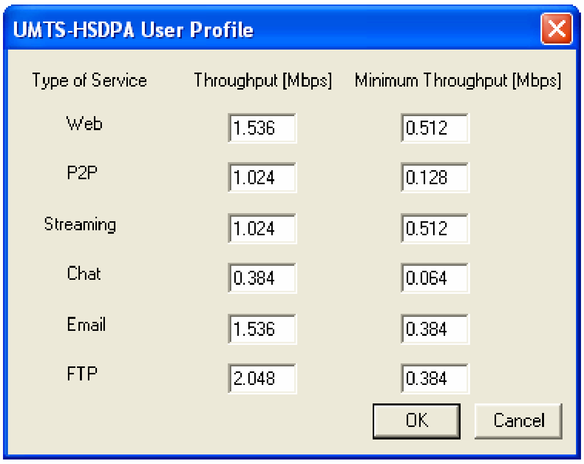


Figure D.6. UMTS/HSDPA maximum and minimum service throughput.

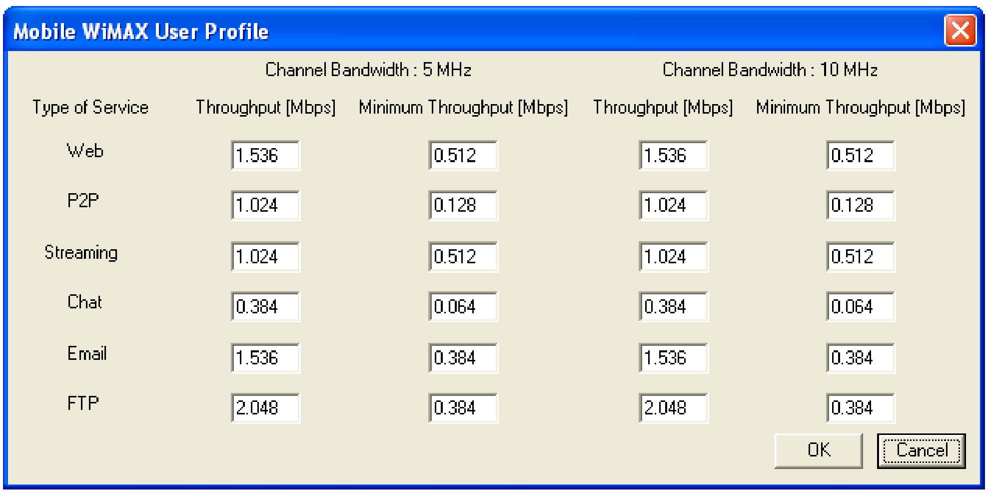


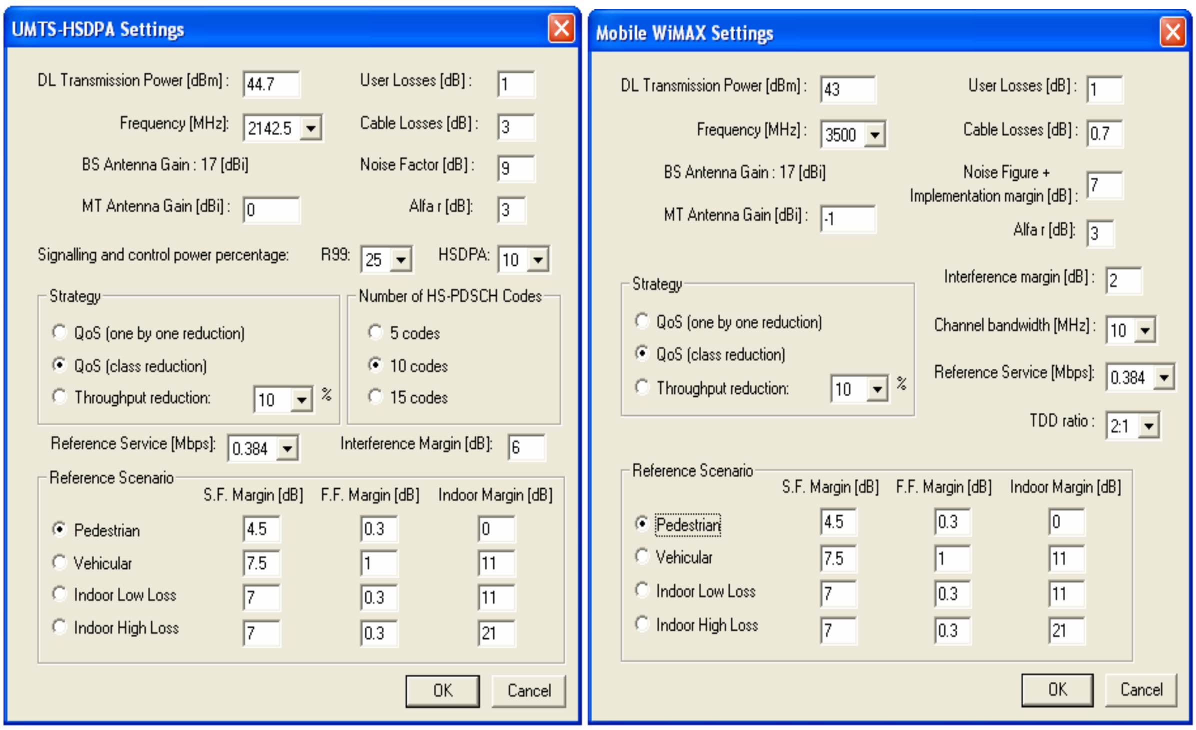
Figure D.7. Mobile WiMAX maximum and minimum service throughput.

Regarding UMTS/HSDPA and Mobile WiMAX Settings windows, Figure D.8, it is possible to modify the different radio parameters of the systems, among reference scenario, reference service and reduction strategy. The default values are presented in Section 4.1.

Table D.1 represents the relationship between the number of users effectively considered and the ones taken into account as input parameter in the SIM program, as there are some users that are placed outside of the network area.

Table D.1. Evaluation of the number of users considered taking into account several parameters.

SIM input number of users	Effective number of users
1000	800
1500	1200
2000	1600
2500	2000



(a) UMTS/HSDPA (b) Mobile WiMAX

Figure D.8. UMTS/HSDPA and Mobile WiMAX parameters' used in simulations.

After pressing the "OK" button, the results regarding the cell radius for the reference service and the different services considered in Figure D.6 and Figure D.7 are displayed in the "Message" window. The window in Figure D.9 represents the results for UMTS/HSDPA, but for Mobile WiMAX, it is the same procedure; so, from now on, only the windows for UMTS/HSDPA are presented.

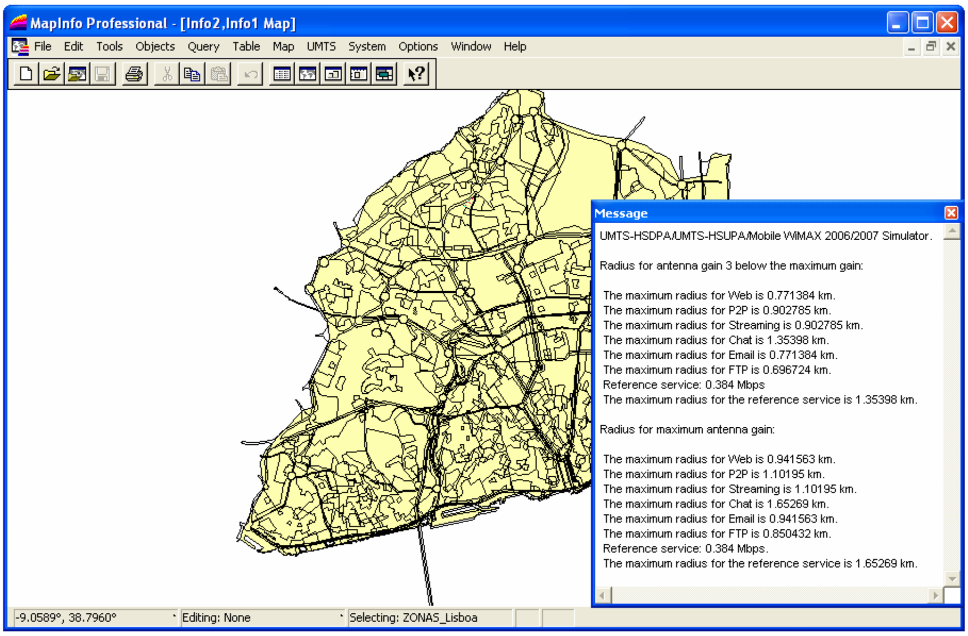


Figure D.9. Aspect of the application after running UMTS/HSDPA settings window

Following the network setting window, the functionality "Insert Users" is activated, to introduce users in Lisbon, by choosing one of the user files from the SIM application. Then, the menu "Deploy Network" becomes active, requesting a file containing the BSs' locations to be placed along the city, Figure D.10.

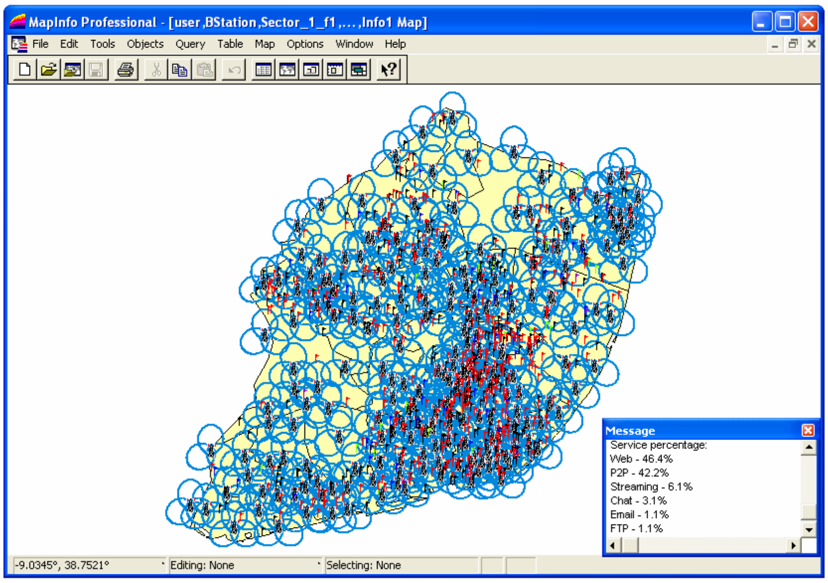


Figure D.10. Result of the "Deploy Network" menu with 228 tri-sectored BSs' coverage area.

After the Figure D.10 is displayed, the menu "Run Simulation" is switched on and the various simulations' results are displayed by pressing the "OK" button. In Figure D.11, Figure D.12 and Figure D.13, the results for 228 BSs and 2500 users are presented.

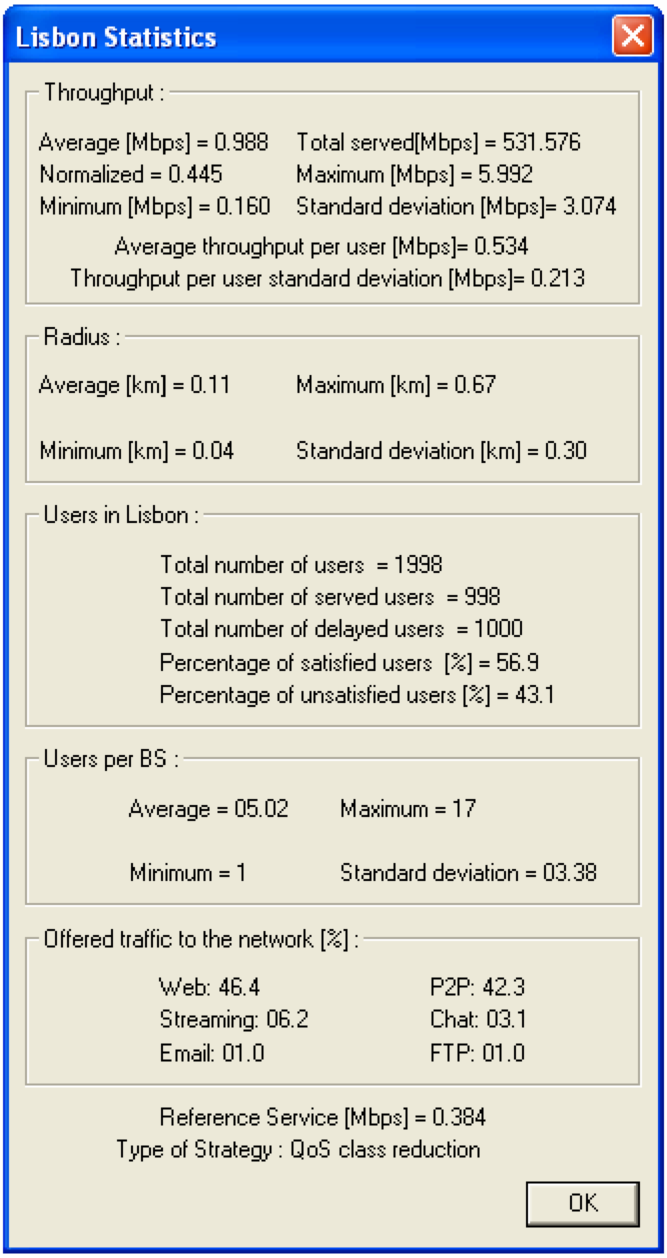


Figure D.11. UMTS/HSDPA instantaneous results for the city of Lisbon

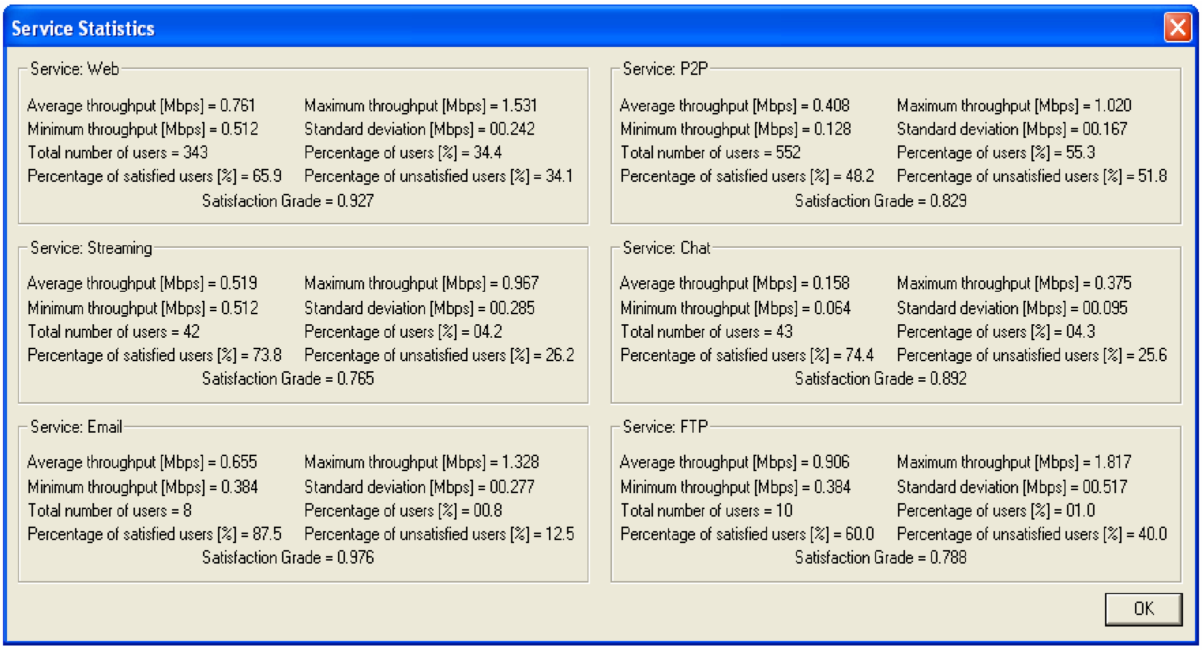


Figure D.12. UMTS/HSDPA instantaneous results detailed by service

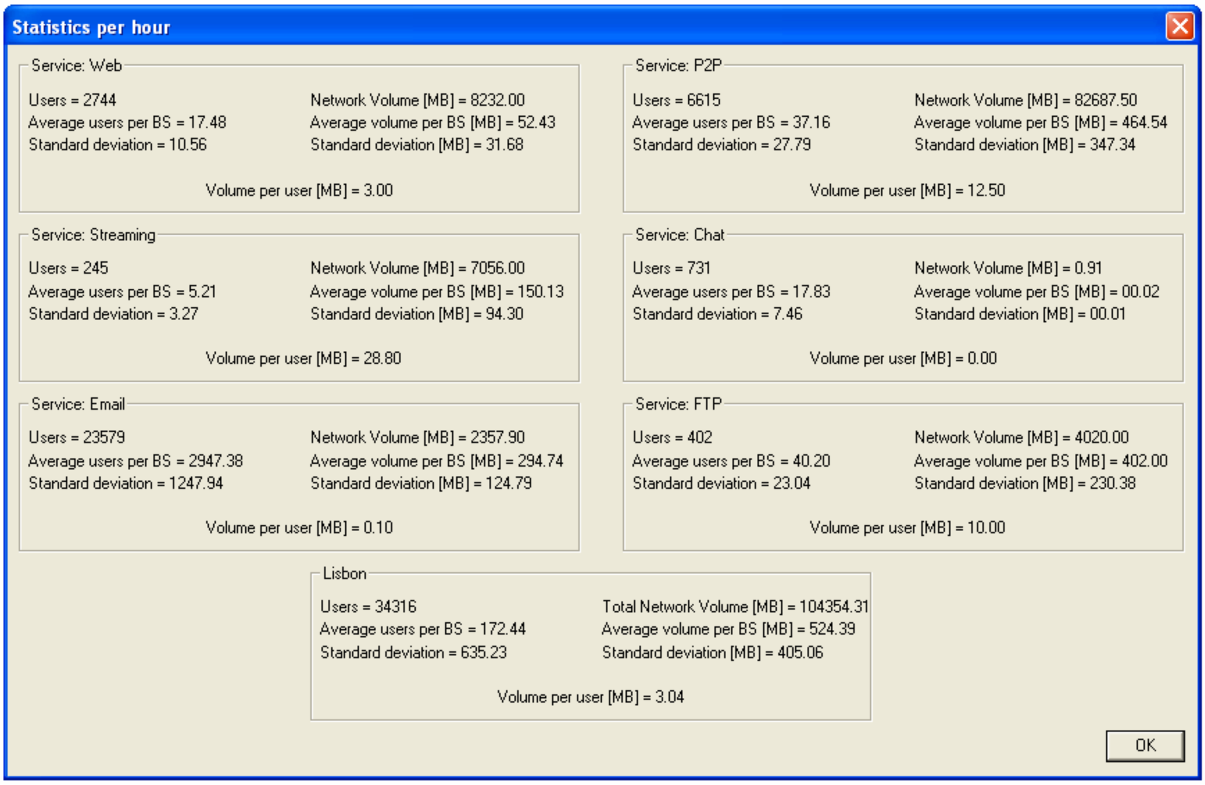


Figure D.13. UMTS/HSDPA extrapolation results for one hour

Annex E – Reduction Strategies

In this annex, the algorithms considering the reduction strategies are presented. The three reduction algorithms are: “Throughput reduction”, Figure E.1, “QoS Class Reduction”, Figure E.2 and “QoS One by One Reduction”, Figure E.3.

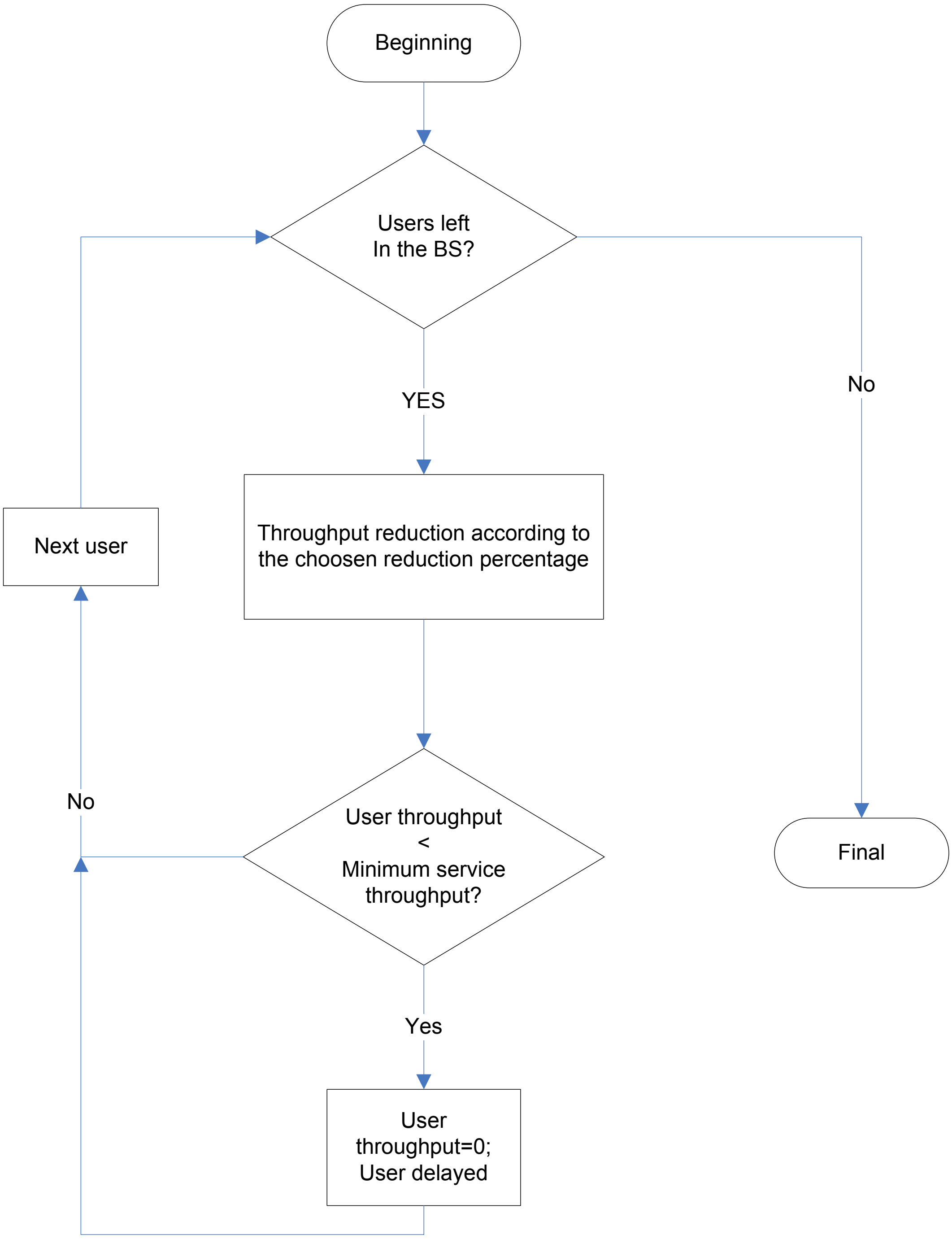


Figure E.1. Representation of the “Throughput Reduction” algorithm.

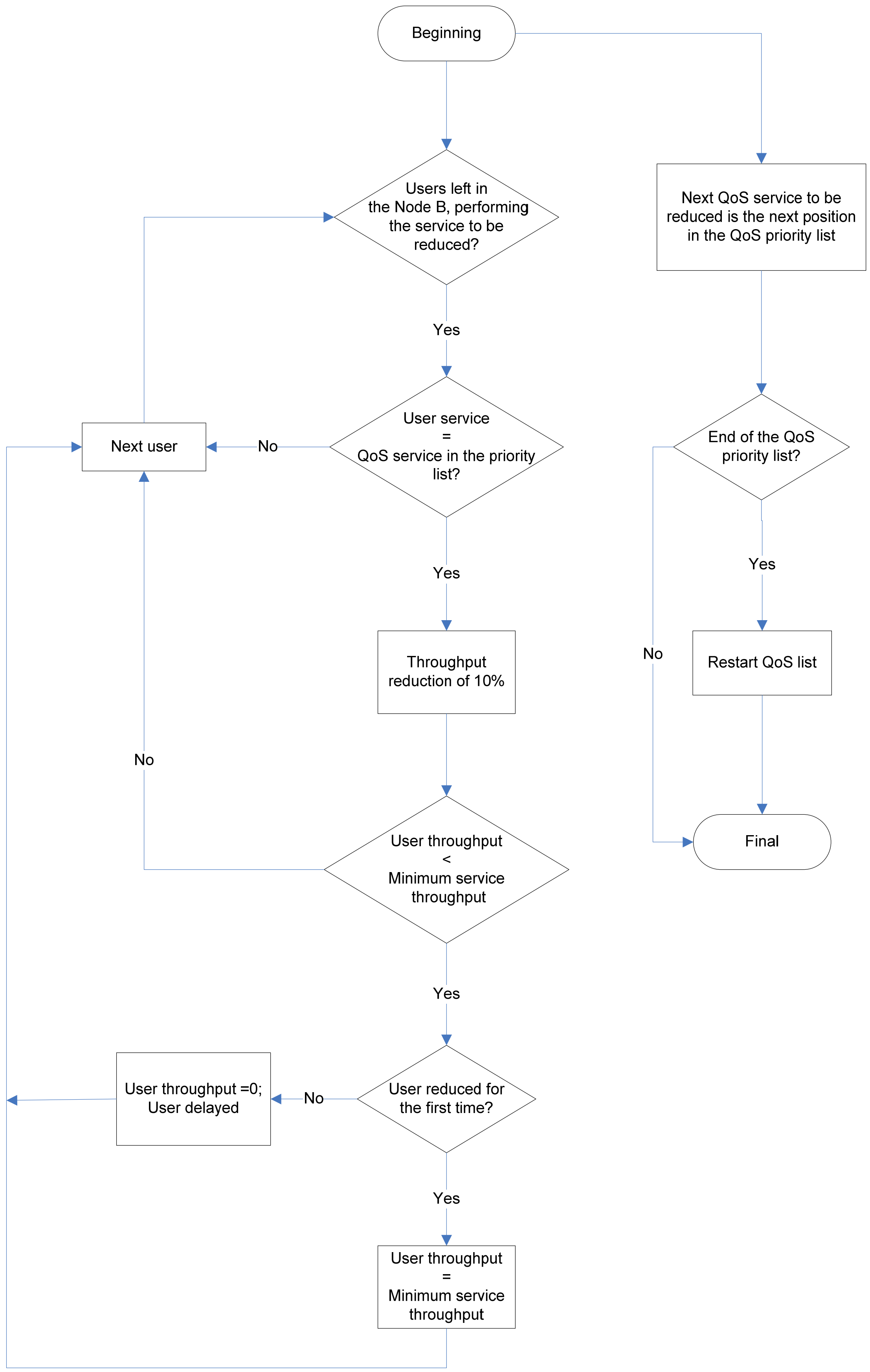


Figure E.2. “QoS Class Reduction” algorithm.

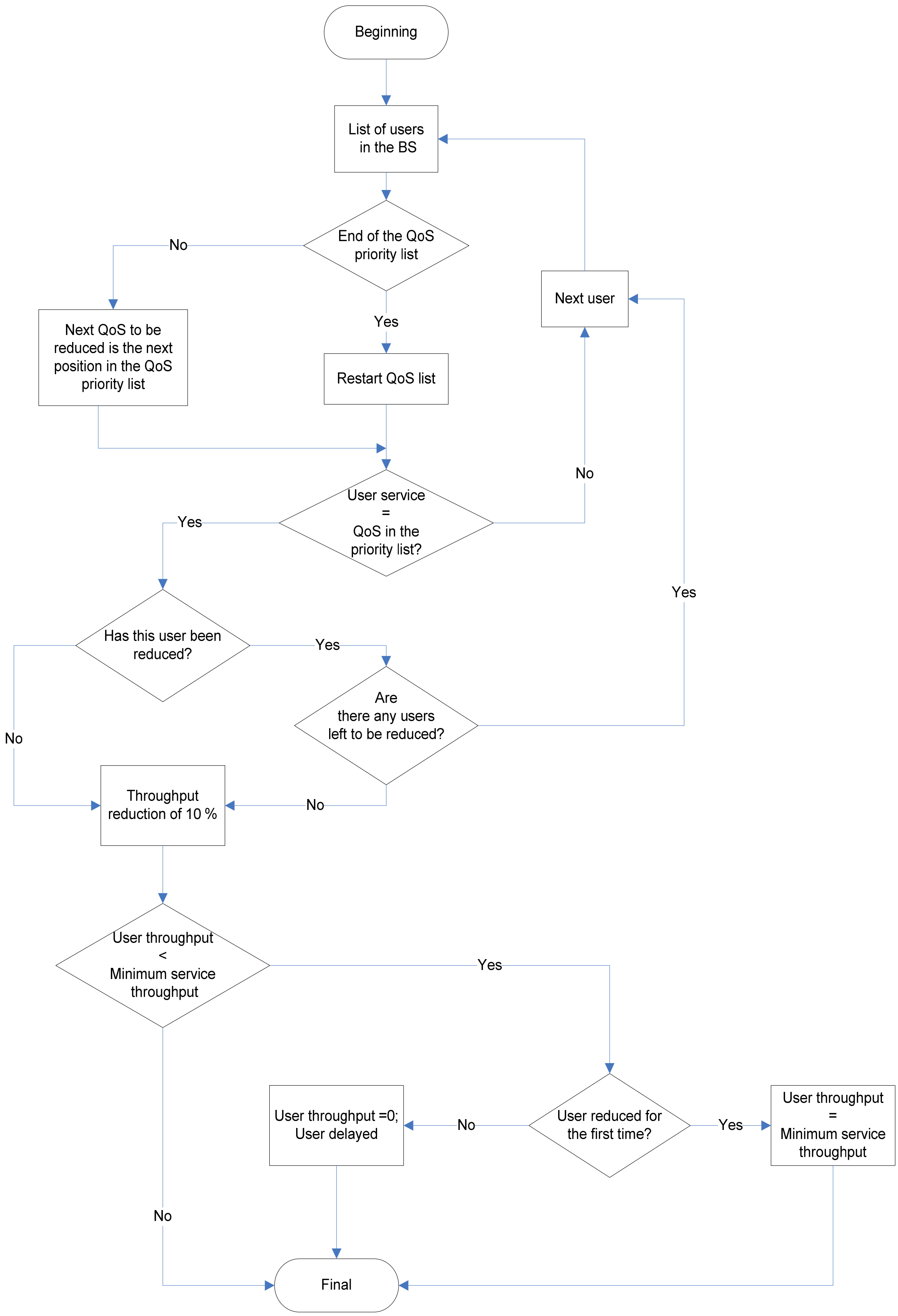


Figure E.3. “QoS One by One Strategy” reduction algorithm.

Annex F – Single User Radius Model Results

In this annex, the tables with several results obtained for the single user radius model for UMTS/HSDPA and Mobile WiMAX are presented.

Table F.1. UMTS/HSDPA cell radius in km considering different throughputs, environments and frequencies for DL transmission power of 44.7 dBm.

Freq. [MHz]	**Number of codes**	**Environment**	**Cell radius [km]**									
			Throughput [Mbps]									
			0.384	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**8.46**
2112.5	5	Pedestrian	1.53	0.97	0.68	0.48	-	-	-	-	-	-
		Vehicular	0.63	0.4	0.28	0.2	-	-	-	-	-	-
		Indoor LL	0.68	0.43	0.3	0.21	-	-	-	-	-	-
		Indoor HL	0.37	0.23	0.16	0.12	-	-	-	-	-	-
	10	Pedestrian	1.59	1.07	0.82	0.69	0.56	0.48	0.39	-	-	-
		Vehicular	0.65	0.44	0.34	0.28	0.23	0.2	0.16	-	-	-
		Indoor LL	0.7	0.47	0.36	0.3	0.25	0.21	0.17	-	-	-
		Indoor HL	0.38	0.26	0.2	0.17	0.14	0.12	0.09	-	-	-
	15	Pedestrian	1.64	1.11	0.83	0.74	0.67	0.59	0.54	0.47	0.42	0.39
		Vehicular	0.67	0.46	0.34	0.3	0.28	0.24	0.22	0.19	0.17	0.16
		Indoor LL	0.72	0.49	0.37	0.33	0.3	0.26	0.24	0.21	0.18	0.17
		Indoor HL	0.39	0.27	0.2	0.18	0.16	0.14	0.13	0.11	0.1	0.09
2167.5	5	Pedestrian	1.48	0.94	0.66	0.46	-	-	-	-	-	-
		Vehicular	0.61	0.38	0.27	0.19	-	-	-	-	-	
		Indoor LL	0.65	0.41	0.29	0.2	-	-	-	-	-	-
		Indoor HL	0.36	0.23	0.16	0.11	-	-	-	-	-	
	10	Pedestrian	1.53	1.03	0.79	0.66	0.54	0.46	0.38	-	-	-
		Vehicular	0.63	0.42	0.33	0.27	0.22	0.19	0.16	-	-	-
		Indoor LL	0.68	0.46	0.35	0.29	0.24	0.2	0.17	-	-	-
		Indoor HL	0.37	0.25	0.19	0.16	0.13	0.11	0.09	-	-	-
	15	Pedestrian	1.58	1.07	0.8	0.71	0.65	0.57	0.52	0.45	0.4	0.38
		Vehicular	0.65	0.44	0.33	0.29	0.27	0.23	0.21	0.19	0.17	0.16
		Indoor LL	0.7	0.47	0.35	0.32	0.29	0.25	0.23	0.2	0.18	0.17
		Indoor HL	0.38	0.26	0.19	0.17	0.16	0.14	0.12	0.11	0.1	0.09

Table F.2. Mobile WiMAX cell radius in km considering 43 dBm of BS DL transmission power, frequency of 2.5 GHz, TDD split 2:1 and 5 MHz channel bandwidth.

Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	6.70
Pedestrian	1.64	1.06	0.76	0.62	0.47	0.42	0.37	0.35
Vehicular	0.67	0.44	0.31	0.25	0.19	0.17	0.15	0.14
Indoor LL	0.72	0.47	0.34	0.27	0.21	0.19	0.16	0.15
Indoor HL	0.40	0.26	0.18	0.15	0.11	0.10	0.09	0.08

Table F.3. Mobile WiMAX cell radius in km considering 43 dBm of BS DL transmission power, frequency of 2.5 GHz, TDD split 2:1 and 10 MHz channel bandwidth.

Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	7
Pedestrian	1.64	1.06	0.74	0.62	0.53	0.47	0.43	0.40
Vehicular	0.68	0.44	0.30	0.25	0.22	0.19	0.18	0.16
Indoor LL	0.73	0.47	0.33	0.27	0.23	0.21	0.19	0.17
Indoor HL	0.40	0.26	0.18	0.15	0.13	0.11	0.10	0.10
Environment	Throughput [Mbps]							
	8	8.46	9	10	12	13.42	-	-
Pedestrian	0.33	0.32	0.32	0.30	0.28	0.25	-	-
Vehicular	0.13	0.13	0.13	0.12	0.11	0.10	-	-
Indoor LL	0.14	0.14	0.14	0.13	0.12	0.11	-	-
Indoor HL	0.08	0.08	0.08	0.07	0.07	0.06	-	-

Table F.4. Mobile WiMAX cell radius in km considering 43 dBm of BS DL transmission power, frequency of 3.5 GHz, TDD split 2:1 and 5 MHz channel bandwidth.

Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	6.70
Pedestrian	0.90	0.58	0.42	0.34	0.26	0.23	0.20	0.19
Vehicular	0.37	0.24	0.17	0.14	0.11	0.10	0.08	0.08
Indoor LL	0.40	0.26	0.18	0.14	0.11	0.10	0.09	0.08
Indoor HL	0.22	0.14	0.10	0.08	0.06	0.06	0.05	0.05

Table F.5. Mobile WiMAX cell radius in km considering 43 dBm of BS DL transmission power, frequency of 3.5 GHz, TDD split 2:1 and 10 MHz channel bandwidth.

Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	7
Pedestrian	0.90	0.58	0.41	0.34	0.29	0.26	0.24	0.22
Vehicular	0.37	0.24	0.17	0.14	0.12	0.11	0.10	0.09
Indoor LL	0.40	0.26	0.18	0.15	0.13	0.11	0.10	0.10
Indoor HL	0.22	0.14	0.10	0.08	0.07	0.06	0.06	0.05
Environment	Throughput [Mbps]							
	8	8.46	9	10	12	13.42	-	-
Pedestrian	0.18	0.18	0.18	0.16	0.15	0.13	-	-
Vehicular	0.07	0.07	0.07	0.07	0.06	0.06	-	-
Indoor LL	0.08	0.08	0.08	0.07	0.07	0.06	-	-
Indoor HL	0.04	0.04	0.04	0.04	0.04	0.03	-	-

Table F.6. Mobile WiMAX cell radius in km considering 43 dBm of BS DL transmission power, frequency of 5.8 GHz, TDD split 2:1 and 5 MHz channel bandwidth.

Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	6.70
Pedestrian	0.26	0.17	0.12	0.10	0.07	0.07	0.06	0.05
Vehicular	0.11	0.07	0.05	0.04	0.03	0.03	0.02	0.02
Indoor LL	0.11	0.07	0.05	0.04	0.03	0.03	0.03	0.02
Indoor HL	0.06	0.04	0.03	0.02	0.02	0.02	0.01	0.01

Table F.7. Mobile WiMAX cell radius in km considering 43 dBm of BS DL transmission power, frequency of 5.8 GHz, TDD split 2:1 and 10 MHz channel bandwidth.

Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	7
Pedestrian	0.26	0.17	0.12	0.10	0.08	0.07	0.07	0.06
Vehicular	0.11	0.07	0.05	0.04	0.03	0.03	0.03	0.03
Indoor LL	0.11	0.07	0.05	0.04	0.04	0.03	0.03	0.03
Indoor HL	0.06	0.04	0.03	0.02	0.02	0.02	0.02	0.02
Environment	Throughput [Mbps]							
	8	8.46	9	10	12	13.42	-	-
Pedestrian	0.05	0.05	0.05	0.05	0.04	0.04	-	-
Vehicular	0.02	0.02	0.02	0.02	0.02	0.02	-	-
Indoor LL	0.02	0.02	0.02	0.02	0.02	0.02	-	-
Indoor HL	0.01	0.01	0.01	0.01	0.01	0.01	-	-

Table F.8. Mobile WiMAX cell radius in km considering 30 dBm of BS DL transmission power, frequency of 3.5 GHz, TDD split 2:1 and 5 MHz channel bandwidth.

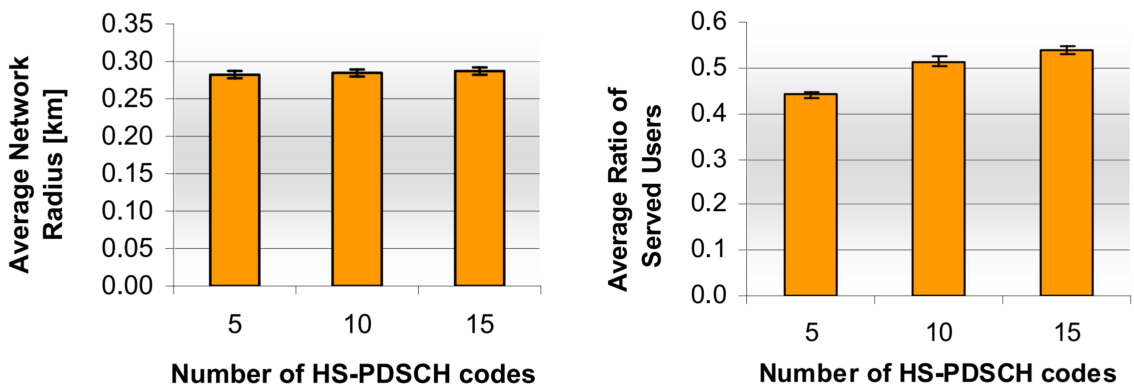
Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	6.70
Pedestrian	0.41	0.27	0.19	0.15	0.12	0.11	0.09	0.09
Vehicular	0.17	0.11	0.08	0.06	0.05	0.04	0.04	0.04
Indoor LL	0.18	0.12	0.08	0.07	0.05	0.05	0.04	0.04
Indoor HL	0.10	0.06	0.05	0.04	0.03	0.03	0.02	0.02

Table F.9. Mobile WiMAX cell radius in km considering 30 dBm of BS DL transmission power, frequency of 3.5 GHz, TDD split 2:1 and 10 MHz channel bandwidth.

Environment	Cell radius [km]							
	Throughput [Mbps]							
	0.384	1	2	3	4	5	6	7
Pedestrian	0.41	0.27	0.18	0.15	0.13	0.12	0.11	0.10
Vehicular	0.17	0.11	0.08	0.06	0.05	0.05	0.04	0.04
Indoor LL	0.18	0.12	0.08	0.07	0.06	0.05	0.05	0.04
Indoor HL	0.10	0.06	0.04	0.04	0.03	0.03	0.03	0.02
Environment	Throughput [Mbps]							
	8	8.46	9	10	12	13.42	-	-
Pedestrian	0.08	0.08	0.08	0.08	0.07	0.06	-	-
Vehicular	0.03	0.03	0.03	0.03	0.03	0.03	-	-
Indoor LL	0.04	0.04	0.04	0.03	0.03	0.03	-	-
Indoor HL	0.02	0.02	0.02	0.02	0.02	0.02	-	-

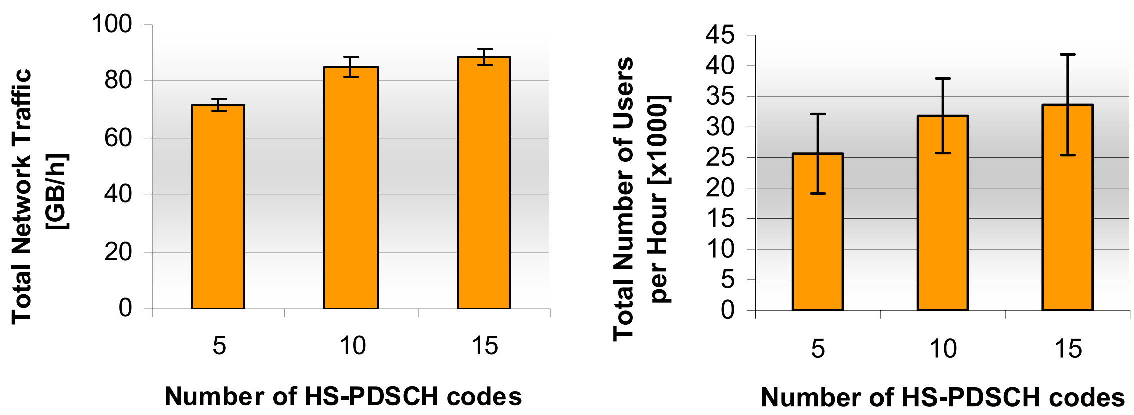
Annex G – UMTS/HSDPA Additional Results

In this annex some complementary results for UMTS/HSPA for the multiple users scenario are shown. Regarding the number of codes, the average network throughput and average ratio of served users are presented in Figure G.1, and the total network traffic and the total number of users per hour in Figure G.2



(a) Average Network Radius. (b) Average Ratio of Served Users.

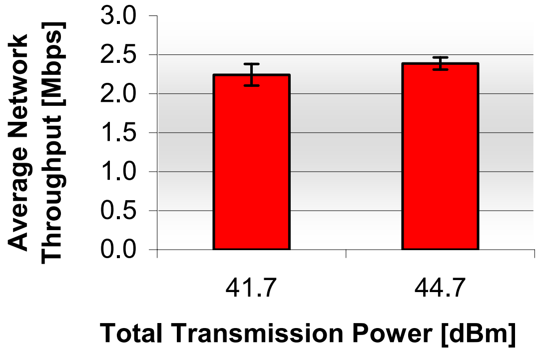
Figure G.1. UMTS/HSDPA network parameters, varying the number of codes (Radius and Ratio of Served Users).



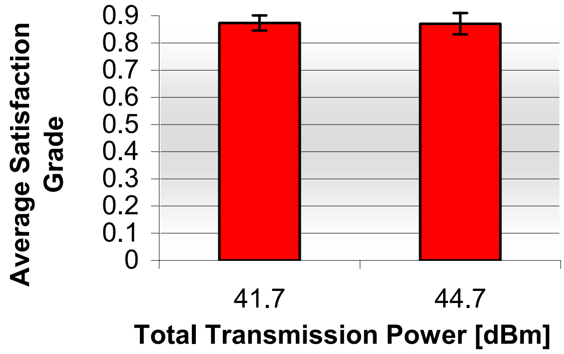
(a) Total Network Traffic. (b) Total Number of Users per Hour.

Figure G.2. UMTS/HSDPA network parameters, varying the number of codes (Network Traffic and Number of Users).

For the transmission power analysis, the average network throughput and average satisfaction grade are presented in Figure G.3, and the average ratio of served users and network traffic in Figure G.4.

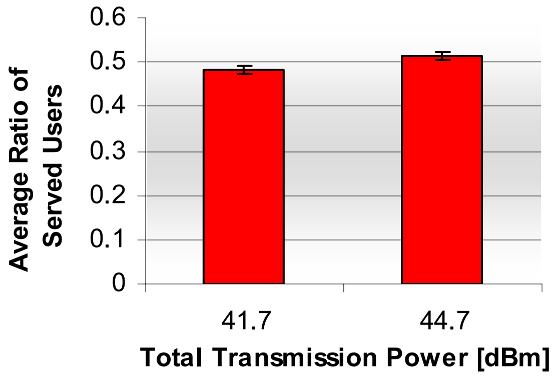


(a) Average Network Throughput.

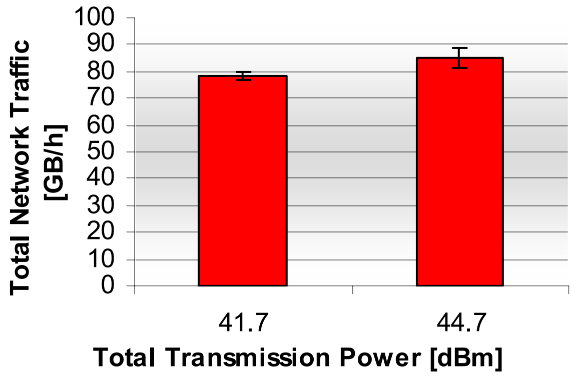


(b) Average Satisfaction Grade.

Figure G.3. UMTS/HSDPA network parameters, varying the transmitted power (Throughput and Satisfaction Grade)



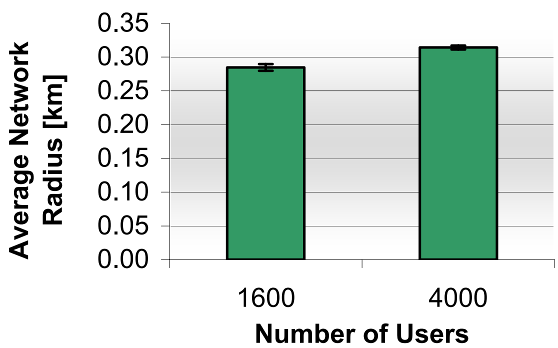
(a) Average Ratio of Served Users.



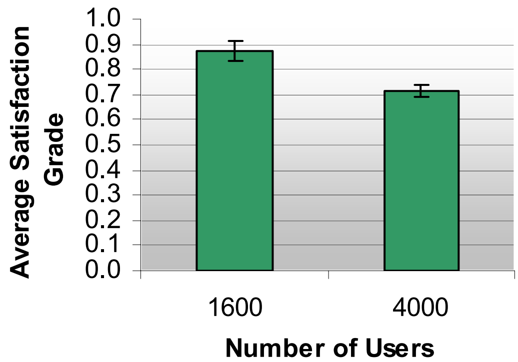
(b) Total Network Traffic.

Figure G.4. UMTS/HSDPA network parameters, varying the transmitted power (Ratio of Served Users and Network Traffic)

In Figure G.5, one presents the average network throughput and the average satisfaction grade for the analysis of the variation of the number of users, and in Figure G.6 the average ratio of served users and the total number of users per hour.

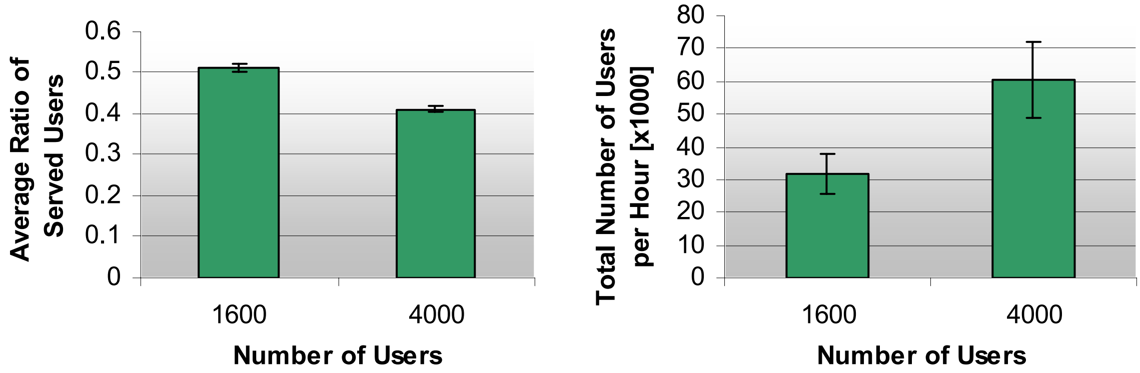


(a) Average Network Radius.



(b) Average Satisfaction Grade.

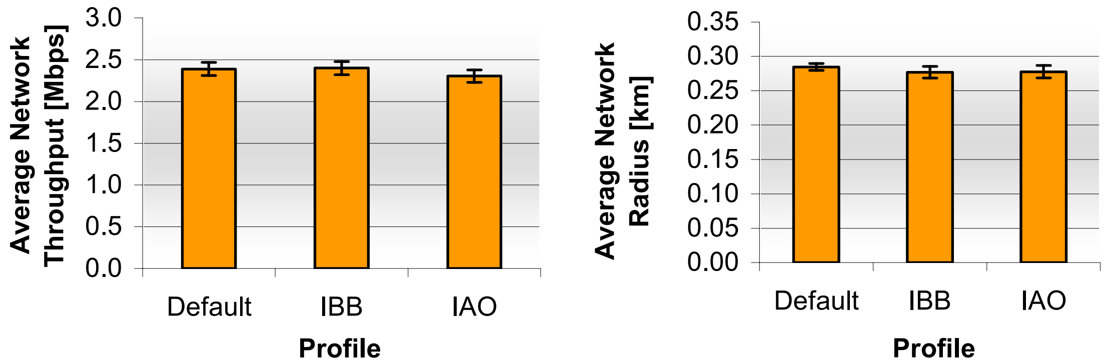
Figure G.5. UMTS/HSDPA network parameters, varying the number of users (Radius and Satisfaction Grade).



(a) Average Ratio of Served Users. (b) Total Number of Users per Hour.

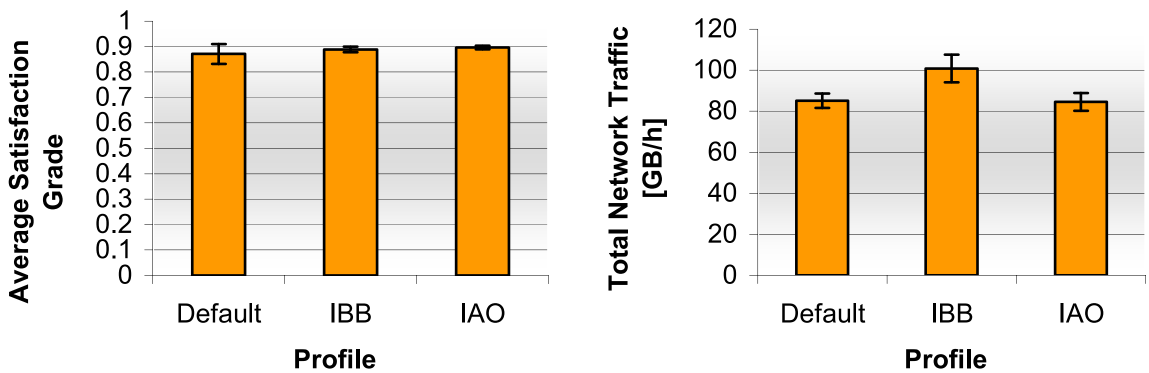
Figure G.6. UMTS/HSDPA network parameters, varying the number of users (Ratio of Served Users and Number of Users).

Considering the alternative profiles studied, Figure G.7 presents the average network throughput and the average network radius. Figure G.8 shows the average satisfaction grade and the total network traffic.



(a) Average Network Throughput (b) Average Network Radius

Figure G.7. UMTS/HSDPA network parameters, for different user profiles (Throughput and Radius).



(a) Average Satisfaction Grade (b) Total Network Traffic

Figure G.8. UMTS/HSDPA network parameters, for different user profiles (Satisfaction Grade and Network Traffic)

Regarding the three reduction strategies considered, one presents in Figure G.9 the total average throughput for the 10 BSs taken into account for the analysis, in Figure G.10 the average instantaneous user throughput per BS, and in Figure G.11 the average satisfaction grade for the users in the 10 BSs used for sample.

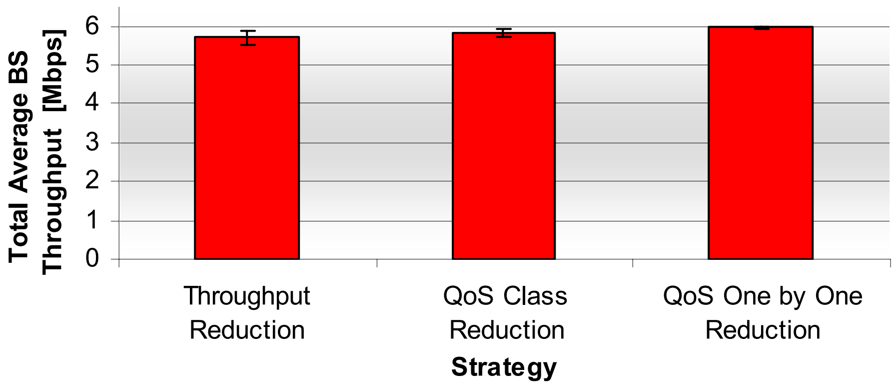


Figure G.9. Total average BS throughput for the three strategies for UMTS/HSDPA.

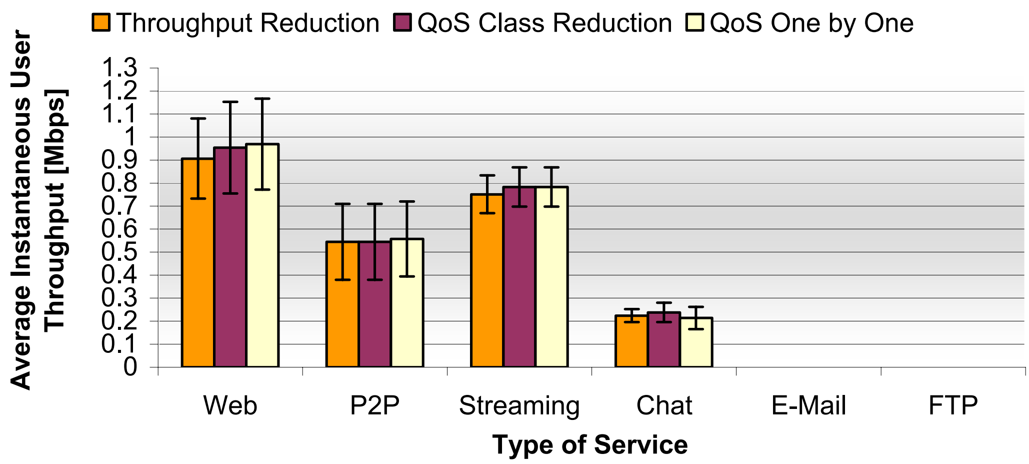


Figure G.10. Average instantaneous throughput per BS when considering different services for each strategy in a 10 BSs sample.

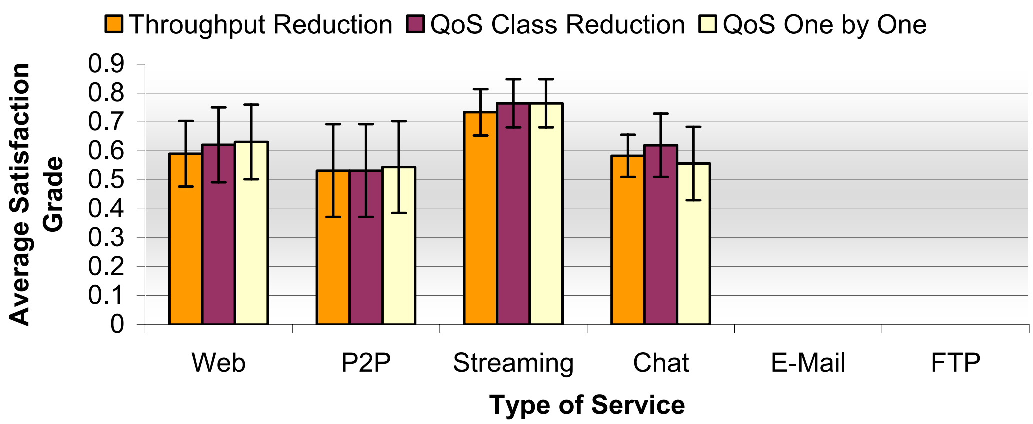
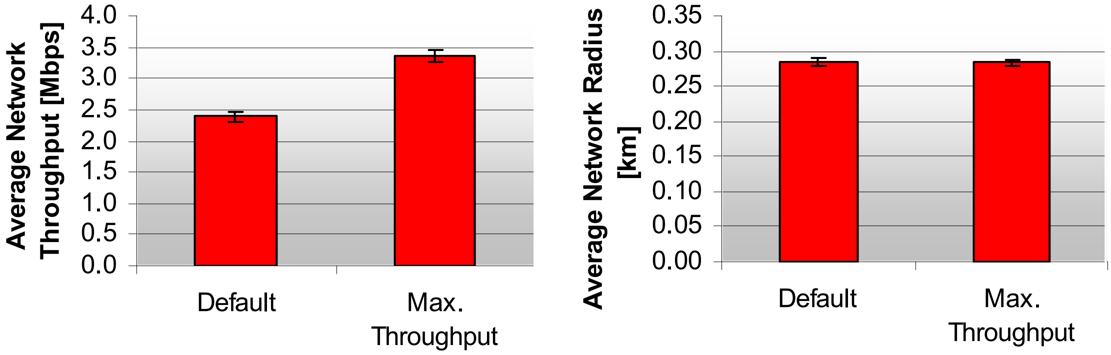


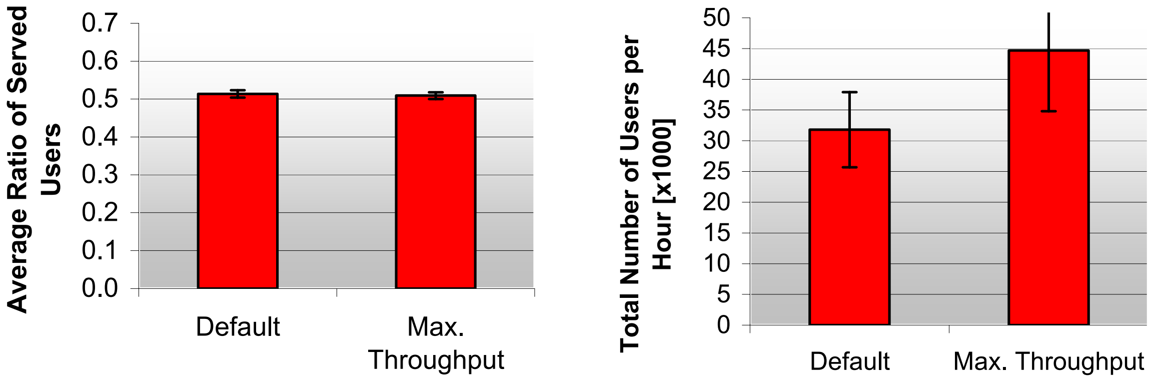
Figure G.11. Average satisfaction grade per BS for the different services for each strategy in a 10 BSs sample.

For the maximum throughput analysis, the results regarding the average network throughput and the average network radius are presented in Figure G.12, and the average ratio of served users and the total number of users per hour are presented in Figure G.13.



(a) Average Network Throughput. (b) Average Network Radius.

Figure G.12. UMTS/HSDPA network parameters, without the random function (Throughput and Radius).

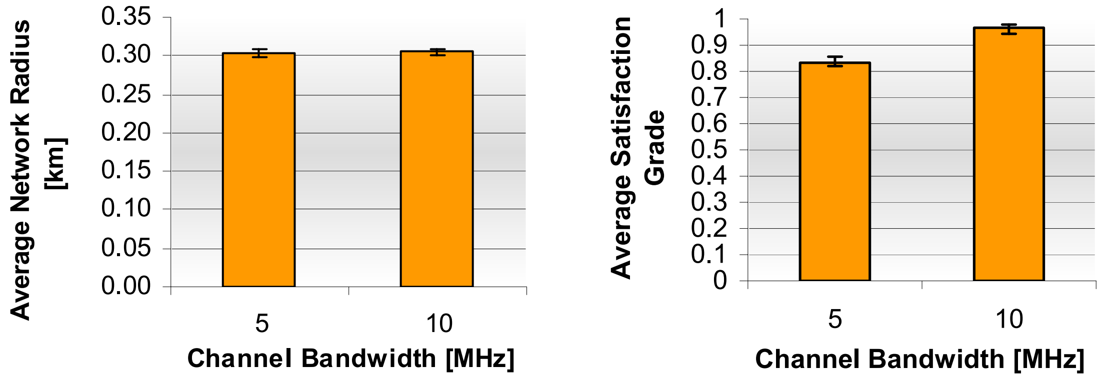


(a) Average Ratio of Served Users. (b) Total Number of Users per Hour.

Figure G.13. UMTS/HSDPA network parameters, without the random function (Ratio of Served Users and Number of Users).

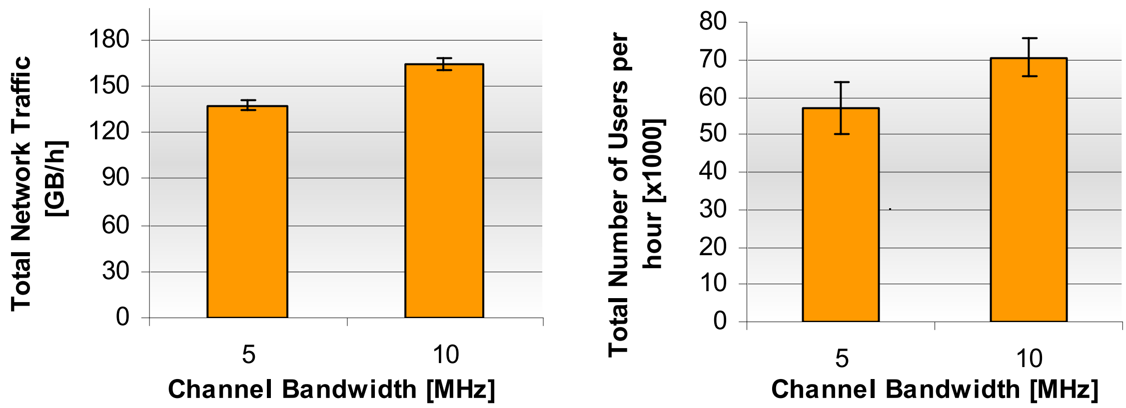
Annex H – Mobile WiMAX Additional Results

This Annex presents some complementary results for Mobile WiMAX for the multiple users scenario. Regarding the channel bandwidth, the average network radius and average satisfaction grade are presented in Figure H.1, and the total network traffic and the total number of users per hour are presented in Figure H.2



(a) Average Network Radius. (b) Average Satisfaction Grade.

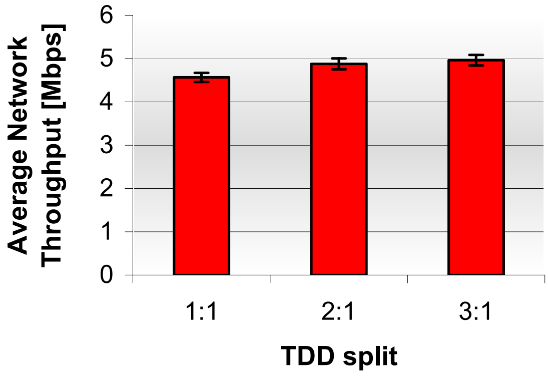
Figure H.1. Mobile WiMAX network parameters, varying the channel bandwidth (Radius and Satisfaction Grade)



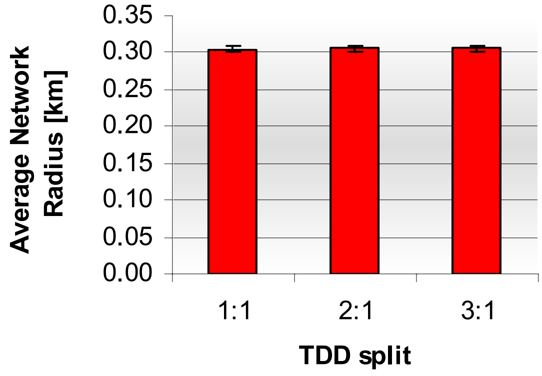
(a) Total Network Traffic. (b) Total Number of User per Hour.

Figure H.2. Mobile WiMAX network parameters, varying the channel bandwidth (Network Traffic and Number of Users).

Considering the TDD split used throughout the work, Figure H.3 presents the average network throughput and average network radius, and in Figure H.4 one shows the average satisfaction grade and the total network traffic per hour.

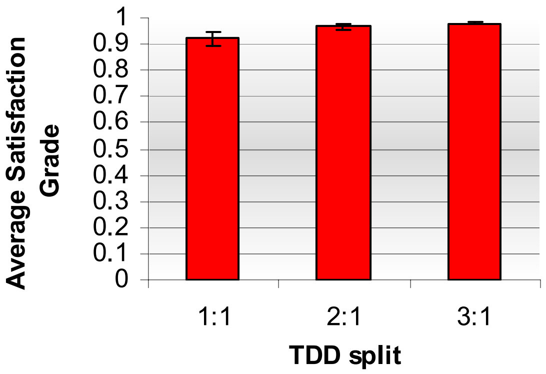


(a) Average Network Throughput.

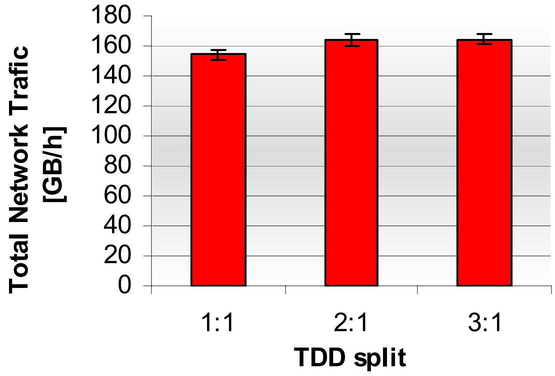


(b) Average Network Radius.

Figure H.3. Mobile WiMAX network parameters, varying the TDD split (Throughput and Radius).



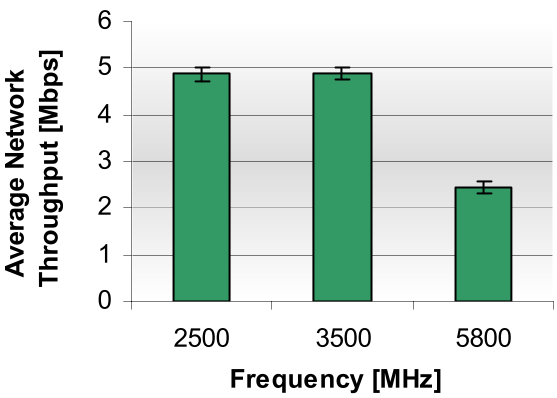
(a) Average Satisfaction Grade.



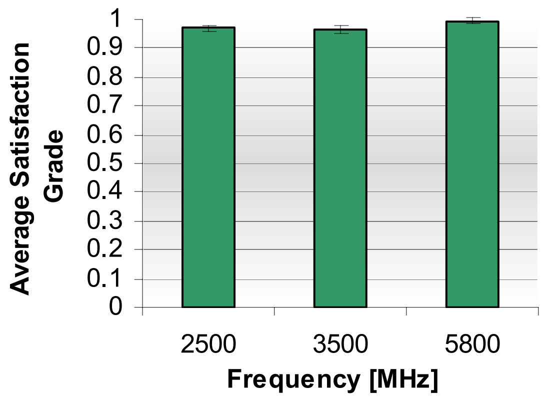
(b) Total Network Traffic.

Figure H.4. Mobile WiMAX network parameters, varying the TDD split (Satisfaction Grade and Network Traffic).

Regarding the different frequencies studied, one presents in Figure H.5 the average network throughput and average satisfaction grade, and in Figure H.6 the average ratio of served users and the total number of users per hour.

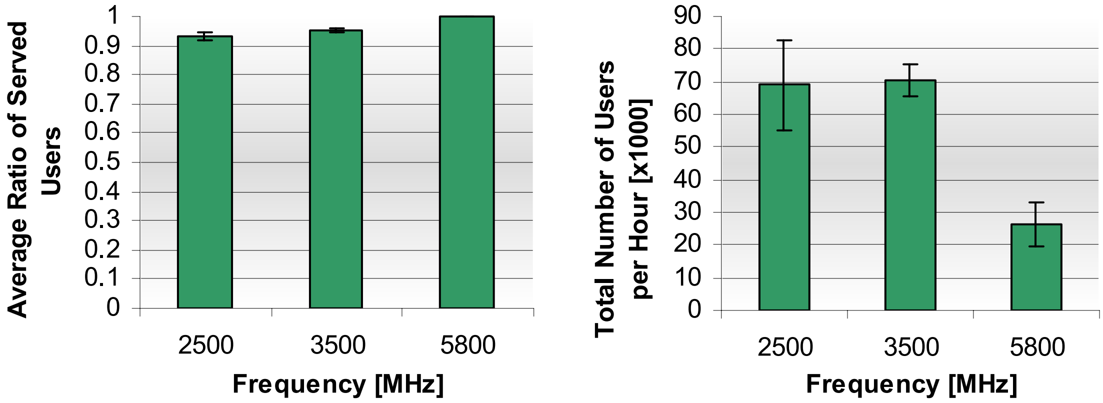


(a) Average Network Throughput.



(b) Average Satisfaction Grade.

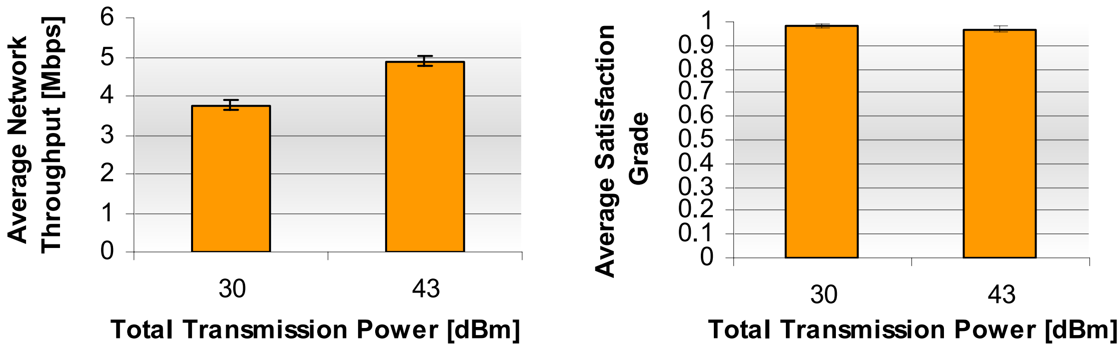
Figure H.5. Mobile WiMAX network parameters, varying the frequency (Throughput and Satisfaction Grade).



(a) Average Ratio of Served Users. (b) Total Number of Users per Hour.

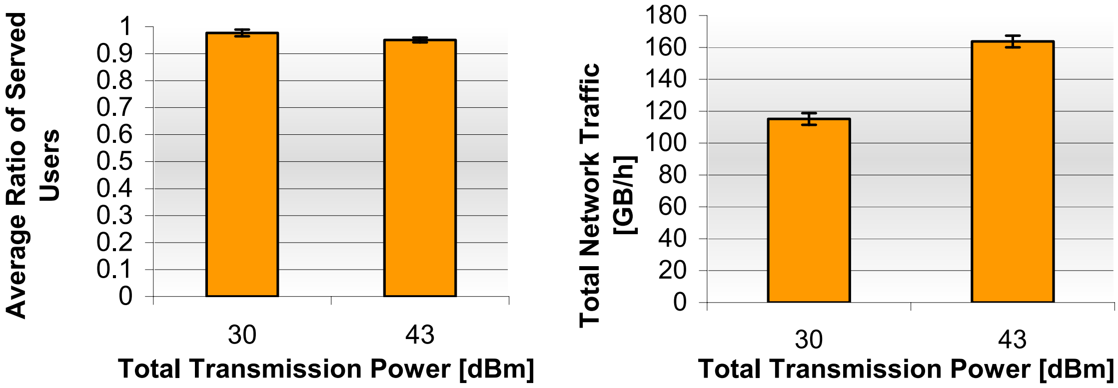
Figure H.6. Mobile WiMAX network parameters, varying the frequency (Ratio of Served Users and Number of Users).

For the transmission power analysis, the average network throughput and average satisfaction grade are presented in Figure H.7, and the average ratio of served users and network traffic in Figure H.8.



(a) Average Network Throughput. (b) Average Satisfaction Grade.

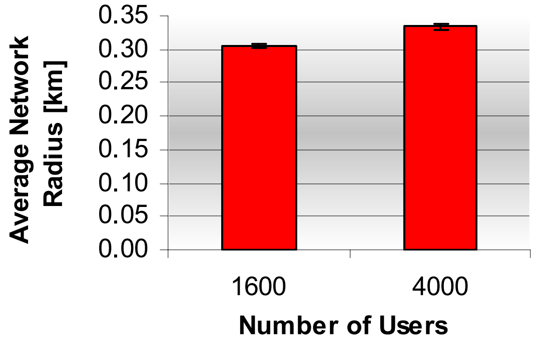
Figure H.7. Mobile WiMAX network parameters, varying the transmitted power (Throughput and Satisfaction Grade).



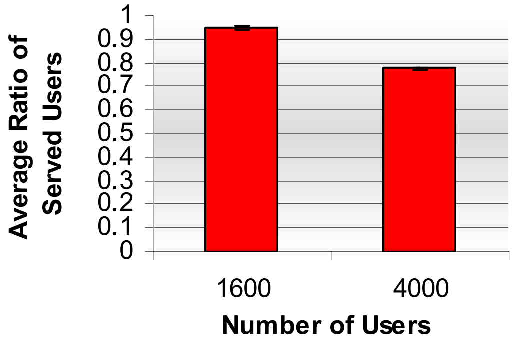
(a) Average Ratio of Served Users. (b) Total Network Traffic.

Figure H.8. Mobile WiMAX network parameters, varying the transmitted power (Ratio of Served Users and Network Traffic).

For the variation on the number of users introduced in the network, Figure H.9 represents the average network radius and the average ratio of served users, while Figure H.10 shows the average satisfaction grade and the total number of users per hour.

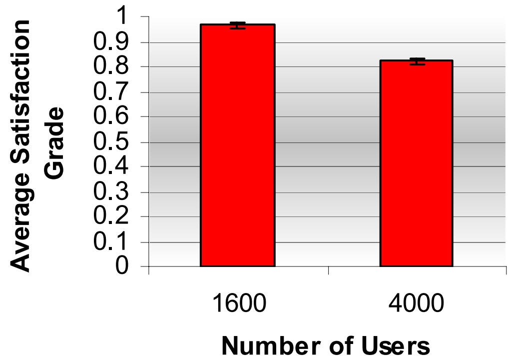


(a) Average Network Radius.

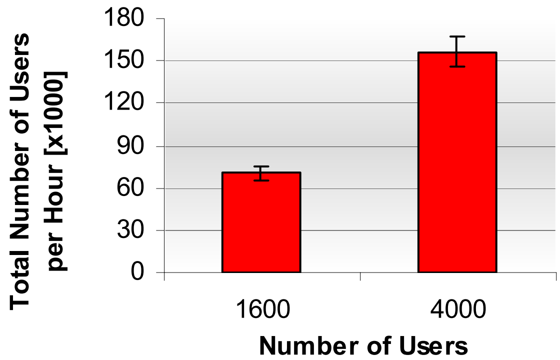


(b) Average Ratio of Served Users.

Figure H.9. Mobile WiMAX network parameters, varying the number of users in the network (Radius and Ratio of Served Users)



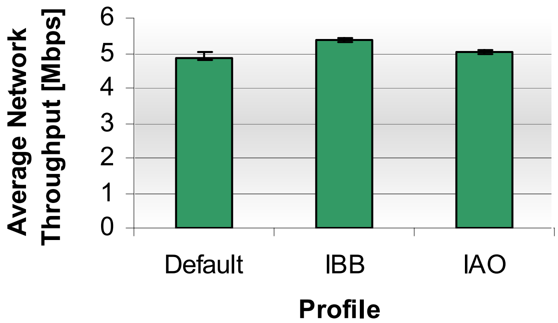
(a) Average Satisfaction Grade.



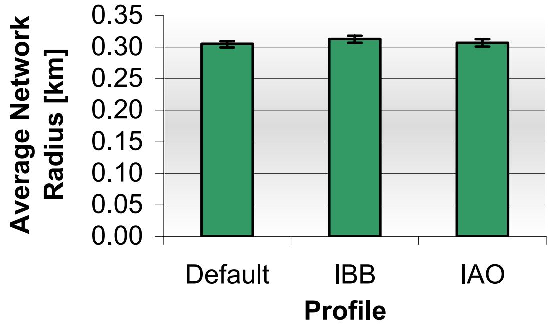
(b) Total Number of Users per Hour

Figure H.10. Mobile WiMAX network parameters, varying the number of users in the network (Radius and Ratio of Served Users).

Regarding the alternative profiles studied, it is presented in Figure H.11 the average network throughput and the average network radius



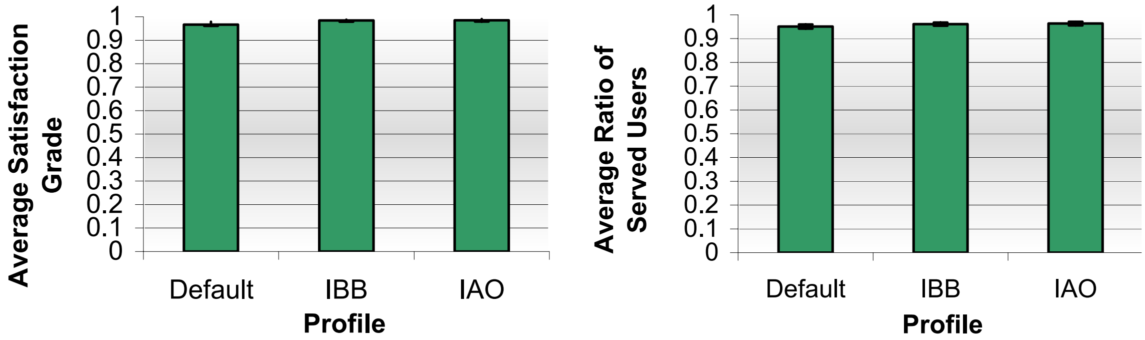
(a) Average Network Throughput



(b) Average Network Radius

Figure H.11. Mobile WiMAX network parameters, for different user profiles (Throughput and Radius)

Figure H.12 presents the average satisfaction grade and the average ratio of served users, for the different profiles.



(a) Average Satisfaction Grade (b) Average Ratio of Served Users

Figure H.12. Mobile WiMAX network parameters, for different user profiles (Satisfaction Grade and Ratio of Served Users)

Figure H.13, H.14 and H.15 present the average network throughput, the average instantaneous user throughput and the average satisfaction grade, respectively, for the three reduction strategies studied

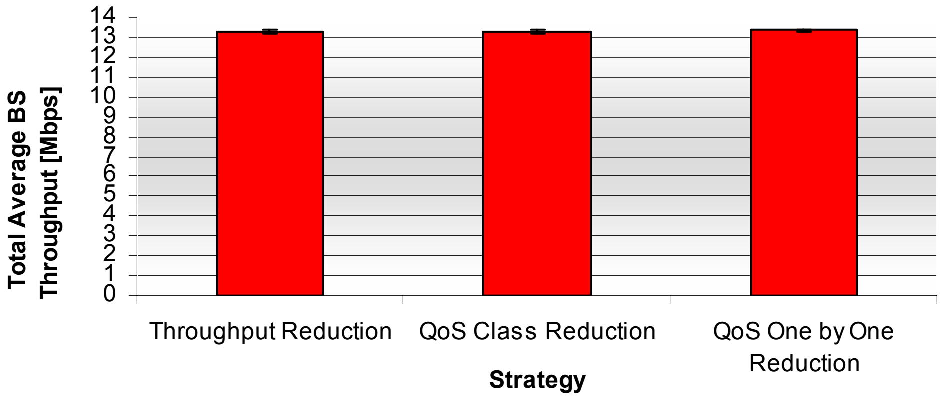


Figure H.13. Total average BS throughput for the three strategies for UMTS/HSDPA

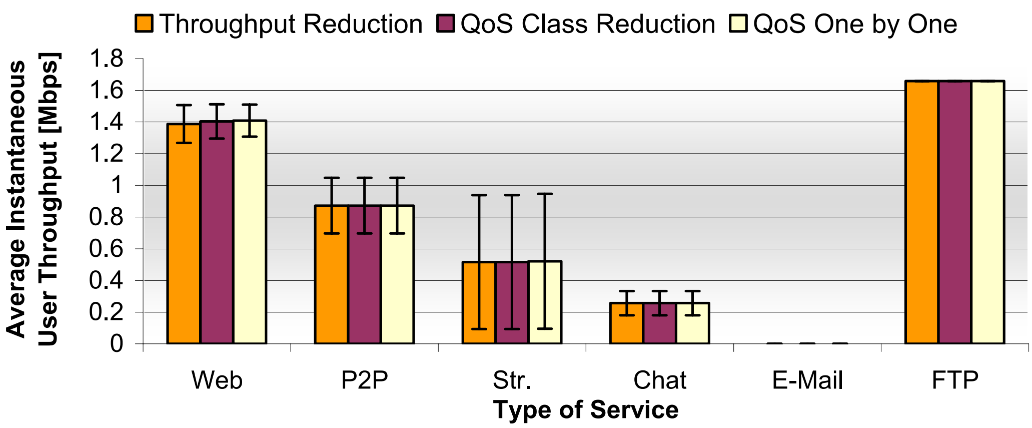


Figure H.14. Average instantaneous throughput per user when considering different services for each strategy in 10 BSs

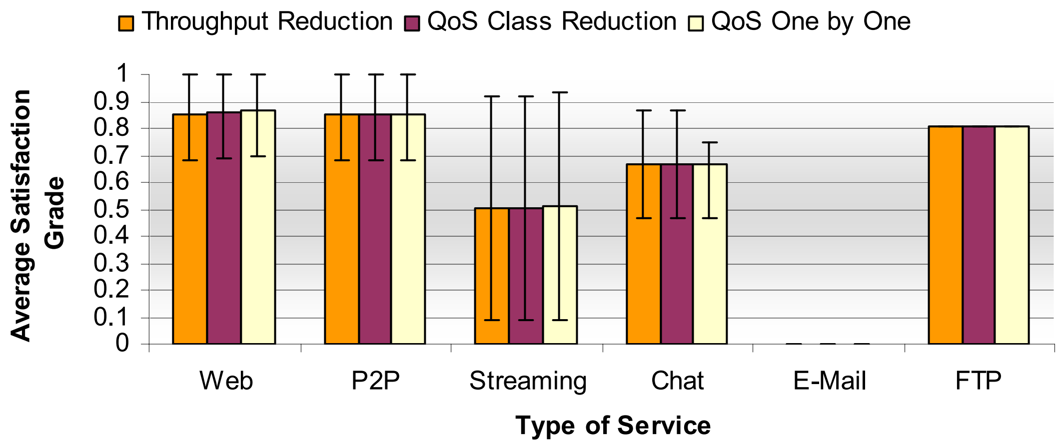
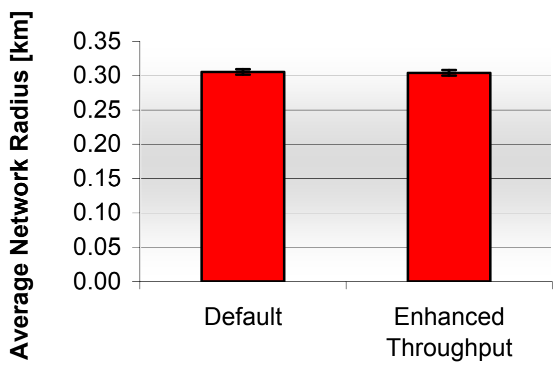
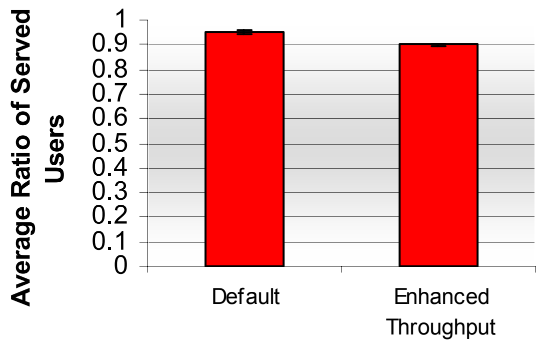


Figure H.15. Satisfaction grade for the different services for each strategy in 10 BSs

Regarding the enhanced throughput simulations, one presents in Figure H.16 the average network radius and average ratio of served users, and in Figure H.17 the total network traffic and the total number of users per hour.

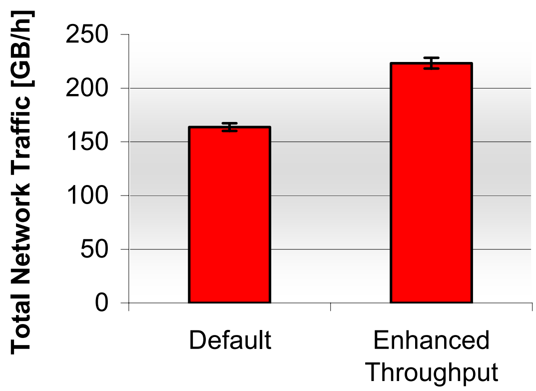


(a) Average Network Radius

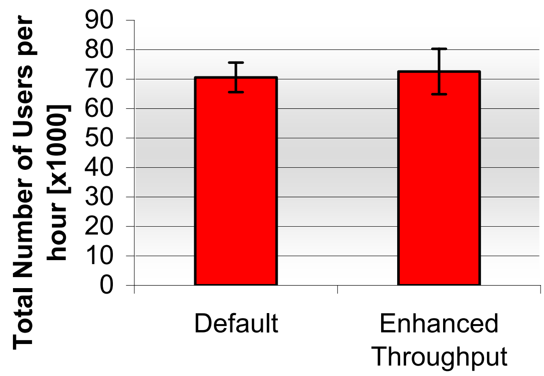


(b) Average Ratio of Served Users

Figure H.16. Mobile WiMAX network parameters, increasing services' throughput (Radius and Ratio of Served Users)



(a) Total Network Traffic.



(b) Total Number of Users per Hour.

Figure H.17. Mobile WiMAX network parameters, increasing services' throughput (Network Traffic and Number of Users).

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