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

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To my parents and sister

"Leaders have to act more quickly today. The pressure comes much faster."

(Andy Grove)

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Abstract

The main purpose of this thesis was to compare the performance of HSPA+ and Mobile WiMAX. Two scenarios were considered: single and multiple users. In the single user scenario, only one user is placed in the cell requesting a certain throughput, and then the maximum distance to the base station for the requested application throughput is calculated. Afterwards, the model was adapted to a multiple user and multiple services scenario, a more realistic approach. A simulator was developed to obtain the analysis of the network for several parameters in an urban scenario with variable slow and fast fading margins. The results for single user model show that, in an indoor scenario, HSPA+ can serve 14.4 Mbps up to 0.17 km, in downlink, and 7.2 Mbps up to 0.05 km, in uplink. Still considering an indoor scenario, Mobile WiMAX can serve 14.4 Mbps up to 0.04 km, in downlink, and 7.2 Mbps up to 0.02 km in uplink. Considering the multiple users scenario, HSPA+ presents better results than Mobile WiMAX, both for downlink and uplink, regarding average network throughput and number of served users, because of its higher coverage. As for the network radius, the results are similar.

Keywords

UMTS, HSPA+, Mobile WiMAX, Capacity, Coverage, Multi-Service

Resumo

O objectivo principal desta tese foi a comparação dos sistemas HSPA+ e Mobile WiMAX em termos de desempenho. Foram criados dois cenários distintos: o de monoutilizador e o de múltiplos utilizadores. No cenário de monoutilizador, apenas um utilizador é colocado na rede e a distância para o qual o utilizador consiga receber o ritmo de transmissão desejado é calculada. Posteriormente, o modelo foi adaptado a um caso mais realista num cenário de múltiplos utilizadores e de multi-serviço. Um simulador foi desenvolvido para obter a análise dos sistemas para diversos parâmetros num cenário urbano com margens de desvanecimento lento e rápido variáveis. Os resultados para um único utilizador mostram que, num cenário interior, o HSPA+ consegue servir 14.4 Mpbs até 0.17km, no sentido descendente e 72 Mbps até 0.05 km, no sentido ascendente. O Mobile WiMAX, no mesmo cenário, consegue servir 14.4 Mbps até 0.04 km, no sentido descendente e 7.2 Mbps até 0.02 km, no sentido ascendente. Quanto ao cenário de vários utilizadores na rede, o HSPA+ apresentou melhores resultados que o Mobile WiMAX, em ambos os sentidos, relativamente aos ritmos de transmissão médios na rede e ao número de utilizadores servidos, devido à sua maior cobertura. Os resultados para o raio da célula são semelhantes.

Palavras-chave

UMTS, HSPA+, Mobile WiMAX, Capacidade, Cobertura, Multi-Serviço.

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List of Acronyms

16QAM	16 Quadrature Amplitude Modulation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
AAA	Authentication Authorisation and Accounting
AAS	Adaptive Antenna System
ACK	Acknowledgment
AMC	Adaptive Modulation and Coding
AoA	Angle of Arrival
AoD	Angle of Departure
ARQ	Automatic Repeat Request
ASN	Access Service Network
ASN-GW	ASN Gateway
BE	Best Effort
BER	Bit Error Ratio
BLER	Block Error Rate
BS	Base Station
BTS	Base Transceiver Station
BWA	Broadband Wireless Access
CC	Chase Combining
CDMA	Code Division Multiple Access
CN	Core Network
CPC	Continuous Packet Connectivity
CPCH	Uplink Common Packet Channel
CPE	Consumer Premises Equipment
CQI	Channel Quality Indicator
CQICH	Channel Quality Indicator Channel
CRC	Cyclic Redundancy Check
CS	Circuit Switched
CSN	Connectivity Service Network
CTC	Convolutional Turbo Code
DCH	Dedicated Chanel
DL	Downlink

DL FUSC	DL Fully Used Sub-Carrier
DL PUSC	DL Partially Used Sub-Carrier
DSCH	Downlink Shared Channel
DTX	Discontinuous Transmission
E-DCH	Enhanced Uplink Dedicated Channel
EIRP	Equivalent Isotropic Radiated Power
ertPS	Extended Real-time Polling Service
FBSS	Fast Base Station Switching
FCH	Frame Control Header
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FRCs	Fixed Reference Channels
FTP	File Transfer Protocol
GGSN	Gateway GPRS Support Node
GIS	Geographic Information Systems
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HHO	Hard Handover
HLR	Home Location Register
HOM	Higher Order Modulation
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed DSCH
HSPA	High Speed Packet Access
HSPA+	HSPA Evolution
HS-PDSCH	High Speed Physical Downlink Shared Channel
HS-SCCH	High Speed Shared Control Channel
HSUPA	High Speed Uplink Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IMT-2000	International Mobile Telecommunications-2000
IP	Internet Protocol
IR	Incremental Redundancy
IRC	Interference Rejection Combining
ITU-R	International Telecommunications Union
LoS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MAP	Medium Access Protocol
MBS	Multicast and Broadcast Service

MCS	Modulation and Coding Scheme
MDHO	Macro Diversity Handover
ME	Mobile Equipment
MIMO	Multiple Input Multiple Output
MMS	Multimedia Message Service
MPEG	Moving Pictures Experts Group
MS	Mobile Station
MSC	Mobile Services Switching Centre
MT	Mobile Terminal
MWMAN	Mobile WMAN
NAP	Network Access Provider
NLoS	None Line of Sight
NRM	Network Reference Model
nrtPS	Non-real-time Polling Service
NSP	Network Service Provider
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
OVSF	Orthogonal Variable Spreading Factor
P2P	Peer-to-Peer
PCH	Paging Channel
PDU	Protocol Data Unit
PLMN	Public Land Mobile Network
PS	Packet Services
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quaternary Phase Shift Keying
RAN	Radio Access Network
RFM	Network Reference Model
RLC	Radio Link Control
RMG	Relative MIMO Gain
RNC	Radio Network Controller
RNS	Radio Network Sub-System
RP	Reference Point
RRC	Radio Resource Control
RRM	Radio Resource Management
rtPS	Real-time Polling Service
Rx	Receiver
SF	Spreading Factor
SGSN	Serving GPRS Support Node

SIMO	Single Input Multiple Output
SINR	Signal-to-Interference-plus-Noise-Ratio
SIR	Signal-to-Interference Ratio
SISO	Single Input Single Output
SLA	Service Level Agreement
SM	Spatial Multiplexing
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SOFDMA	Scalable OFDMA
SPWG	Service Provider Working Group
SS	Subscriber Station
TDD	Time Division Duplex
ToA	Time of Arrival
TTA	Telecommunications Technology Association
TTI	Transmission Time Interval
Tx	Transmitter
UE	User Equipment
UGS	Unsolicited Grant Service
UL	Uplink
UL PUSC	UL Partially Used Sub-Carrier
UMTS	Universal Mobile Telecommunications System
USIM	UMTS Subscriber Identity Module
UTRAN	UMTS Terrestrial RAN
VLR	Visitor Location Register
VoD	Video on Demand
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WiBro	Wireless Broadband
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access Forum
WMAN	Mobile Wireless Metropolitan Network

List of Symbols

α	DL Orthogonality factor
β	Coding rate
δ	Sigmoid function
Δf	Signal bandwidth
Δf_c	Nominal channel bandwidth
η_{DL}	Downlink load factor
η_{UL}	Uplink load factor
μ_{dist}	Mean value of the distribution
μ_{RMG}	Average RMG
v_j	Activity factor
ξ	Maximum interference margin considered
ρ	SNR
σ	Standard deviation
σ^2	Variance
σ^2_{RMG}	RMG distribution variance depending on the cell-type, N_T and N_R
Ω	Correlation between links in a MIMO system
a_{pd}	Average power decay
C_{MIMO}	Capacity gain of a MIMO system
C_{SISO}	Capacity gain of a SISO system
d_{BS}	Distance between the user placed further away in the cell radius and the BS
d	Distance between BS and MT
E_b	Energy per bit
E_c	Energy per chip
F_s	Sampling frequency
G_{div}	Diversity gain
$G_{M/S}$	Relative MIMO Gain
G_p	Processing gain
G_r	Receiving antenna gain
G_t	Transmitting antenna gain
i_{DL}	Inter- to intra-cell interferences ratio for DL
I_M	Implementation margin
i_{UL}	Inter- to intra-cell interferences ratio for UL

k_d	Dependence of the multiscreen diffraction loss versus distance
k_f	Dependence of the multiscreen diffraction loss versus frequency
L_0	Free space loss
L_c	Cable losses between transmitter and antenna
L_{int}	Indoor penetration losses
L_p	Path loss
L_{ptotal}	Total path loss
L_{ref}	Propagation model losses
L_{tm}	Approximation for the multi-screen diffraction loss
L_{tt}	Rooftop-to-street diffraction loss
L_u	User losses
M	Total margin
M_{FF}	Fast fading margin
M_I	Interference margin
M_{SF}	Slow fading margin
n	Sampling factor
N	Total noise power
N_0	Noise power spectral density
N_{DS}	Number of OFDM data symbols
N_{DSC}	Number of data sub-carriers used
N_F	Noise figure
N_R	Number of Rx antennas
N_{rf}	Noise Spectral density of the receiver
N_s	Number of samples.
N_{SB}	Number of symbol bits
N_{SCH}	Number of sub-channels used
N_{sect}	Number of sectors in the BS
N_{serv}	Number of data services considered
N_T	Number of Tx antennas
N_{TSC}	Total number of sub-carriers
N_u	Number of users
N_{uBS}	Number of users served in the BS
N_{uhBS}	Number of users per hour in the BS
N_{uhnet}	Total number of served users per hour in the network
N_{uhserv}	Number of users per hour performing a certain service
N_{umax}	Number of users of the most populated BS
$P_{\text{HS-DSCH}}$	Received power of the HS-DSCH summing over all active HS-PDSCH codes
P_{inter}	Received inter-cell interference
P_{intra}	Received intra-cell interference

P_{noise}	Received noise power
P_r	Available receiving power at antenna port
P_{RX}	Received power at receiver input
P_{RXmin}	Receiver sensitivity
P_{Sig}	Signalling power
P_t	Transmitting power at antenna port
P_{Tx}	Total BS transmission power
r	Cell radius
R_b	Bit rate
$\overline{r_{net}}$	Average network radius
R_{bBS}	Instantaneous served throughput in the BS
R_{bmax}	Maximum BS allowed throughput
R_{bNORM}	Normalised throughput
R_{breq}	Requested throughput
R_{bserv}	Served throughput
R_c	WCDMA chip rate
$\overline{r_{net}}$	Average network radius
s	Slope of the Sigmoid function
SF_{16}	HS-PDSCH spreading factor of 16
S_G	Satisfaction grade
$\overline{S_{Gnet}}$	Average network satisfaction grade
$\overline{S_U}$	Average ratio of served users
T_{BS}	Total BS traffic transferred in an hour
T_D	Useful symbol duration
T_F	Frame duration
T_G	Guard time
T_{net}	Total network traffic in an hour
T_{OFDM}	Duration of an OFDM symbol
u	Random value with a Uniform distribution
V_u	Data volume per user
z_i	Sample *i*
z_r	Reference value

List of Software

Borland C++ Builder	ANSI C++ Integrated Development Environment
MapBasic	Programming software and language to create adittional tool and funcionalities for the MapInfo
MapInfo	Geographic Information Systems (GIS) software
Matlab	Computational math tool
Microsoft Excel	Calculation tool
Microsoft Visio	Design tool (e.g. flowcharts, diagrams, etc)
Microsoft Word	Text editor tool

Chapter 1

Introduction

This chapter gives a brief overview of the work. Before establishing targets and original contributions, the scope and motivations are brought up. A brief state of the art concerning the scope of the work is also presented. At the end of the chapter, the work structure is provided.

1.1 Overview

In just a few years, the Internet has transformed the way to access information, communication and entertainment services at home and at work. Broadband connections have made the Internet experience richer for millions of people, and in the coming years, millions more will turn to wireless technology to deliver their broadband experience. As a consequence, Internet broadband connectivity has become one of the most widespread communications developments ever, and the growth in demand for high-speed Internet connections is set to continue [Eric07].

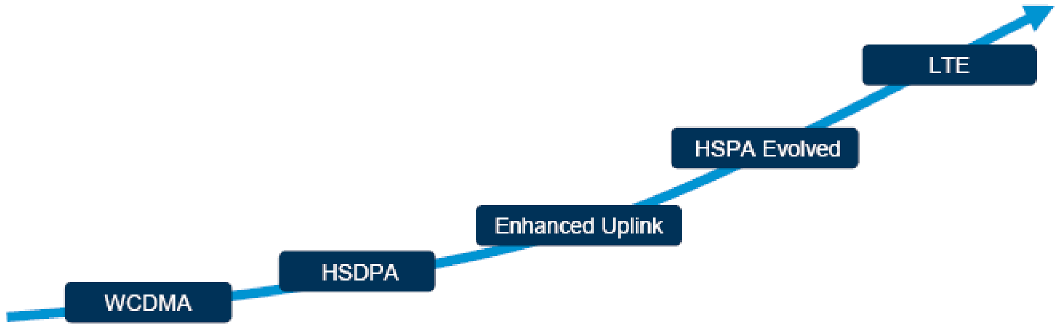
Currently, third generation (3G) systems, e.g., the Universal Mobile Telecommunications System (UMTS), are designed for multimedia communication: with these, person-to-person communication can be enhanced with high-quality images and video, and access to information and services on public and private networks will be improved by the higher data rates and new flexible communication capabilities of 3G systems [HoTo07] . Many new services are based on multimedia applications, such as Voice over Internet Protocol (VoIP), video conferencing, Video on Demand (VoD), massive online games, and Peer-to-Peer (P2P) [CiLM06].

In standardisation for a Wideband Code Division Multiple Access (WCDMA) has emerged as the most widely adopted 3G air interface. Its specification has been created in the 3rd Generation Partnership Project (3GPP), which is also responsible for important evolution steps on top of WCDMA: High Speed Packet Access (HSPA) for downlink (DL) in Release 5 and uplink (UL) in Release 6. The DL solution, High Speed Downlink Packet Access (HSDPA) was commercially deployed in 2005 and the UL counterpart, High Speed Uplink Packet Access (HSUPA), during 2007. The initial peak data rate of HSDPA was 1.4 Mbps but, by the end of 2007, 7.2 Mbps were available, with the peak data rate of 14.4 Mbps foreseen for a near future, starting the mobile Internet Protocol (IP) revolution [HoTo06]. HSUPA started to be deployed at the end of 2007, with peak data rates of 1.4 Mbps, being expectable that the maximum peak data rate is around 6 Mbps. Furthermore, Release 7, also known as HSPA Evolution or HSPA+, has its commercial deployment foreseen for 2009 [HoTo06]. The HSPA+ is currently also being standardised by 3GPP in Release 8.

HSPA+ offers a number of enhancements, providing major improvements to end-user performance and network efficiency. The aim of Release 7 is to further improve the performance of WCDMA through higher peak data rates, lower latency, greater capacity and increased battery time. Multiple Input Multiple Output (MIMO) and Higher Order Modulation (HOM) extend the peak data rate to 43.2 Mbps in the DL and 11.5 Mbps in UL, [BEGG08] and [PWST07]. The roadmap for 3GPP technologies is presented in Figure 1.1. The next emergent technology is Long Term Evolution (LTE) which is being specified as part of Release 8, and further pushes the radio capabilities higher, with larger bandwidth and lower latency .

Worldwide Interoperability or Microwave Access (WiMAX) is an emerging wireless communication system that can provide broadband access with large-scale coverage, supporting fixed and mobile accesses. The former is based on Institute of Electrical and Electronics Engineers (IEEE) 802.16-2004, published in April 2002, and is optimised for fixed and nomadic access. The latter is designed to support portability and mobility, being based on the IEEE 802.16e amendment to the standard that provides Wireless Metropolitan Area Network (WMAN). IEEE 802.16.e, released in February 2006, offers improved support for MIMO and Adaptive Antenna Systems (AAS), as well as hard and soft handovers. Mobile WiMAX certifications profiles are for the Time Division Duplex (TDD) mode, which enables to adjust the DL/UL ratio to efficiently support asymmetric traffic [WiMF06a] and [Nuay07].

The WiMAX Forum was founded with more than 300 members companies. According to the WiMAX Forum, technology is attractive in a wide variety of environments, including high-speed Internet Access, Wireless Fidelity (WiFi) hot-spot backhaul, cellular backhaul, public safety services and private networks [CiLM06].



3GPP	R99/1999	R5/2002	R6/2005	R7/2007*	R8/2008**
Peak	0.384 Mbps DL	14 Mbps DL	14 Mbps DL	28/42 Mbps DL*	160 Mbps DL
Data Rate	0.064 Mbps UL	0.384 Mbps UL	6 Mbps UL	12 Mbps UL	50 Mbps UL
Commercial Availability	2001	2005	2006	2008	2009

*Expected: 28Mbps with MIMO, 42 Mbps with MIMO + 64QAM
**Expected: LTE specification ready end 2007

Figure 1.1. Evolution of the 3GPP family of standards (extracted from [Eric07]).

Mobile WiMAX is a Broadband Wireless Access (BWA) solution that enables convergence of mobile and fixed networks, through a common wide area broadband radio access technology and flexible network architecture. The Mobile WiMAX Air Interface adopts Orthogonal Frequency Division Multiple Access (OFDMA) for improved multi-path performance in None Line of Sight (NLoS). Scalable OFDMA (SOFDMA) is introduced in IEEE 802.16e, to support scalable channel bandwidths from 1.25 to 20 MHz. The use of Adaptive Modulation and Coding (AMC) allows WiMAX to support different modulations and adaptively to exploit highest available data rate based on link quality. The system offers scalability in both radio access technology and network architecture, thus, providing a great deal of flexibility in network deployment options and service offerings. The features supported by Mobile WiMAX enable the technology to support peak DL data rates up to 63 Mbps per sector, and UL ones to 28 Mbps per sector, in a 10 MHz channel. Regarding Quality of Service (QoS), sub-channelisation and Media Access Protocol (MAP) bases signalling schemes provide a flexible mechanism for optimal scheduling of space, frequency and time [WiMF06a].

In October 2007, the Radiocommunication Sector of the International Telecommunications Union (ITU-R) approved the inclusion of WiMAX in the International Mobile Telecommunications (IMT-2000) set of standards. This decision escalates opportunities for global deployment, especially within the [2.5, 2.69] GHz band, to deliver Mobile Internet to satisfy both rural and urban markets demand [WiMA08].

The WiMAX Forum regularly considers additional Mobile WiMAX performance profiles based on market opportunities. These would address alternative frequency bands, channel bandwidths, and may include Full or Half-Duplex Frequency Division Duplex (FDD) variations to comply with local regulatory requirements in selected markets [WiMF06a]. The roadmap for Mobile WiMAX technology is presented in Figure 1.2.

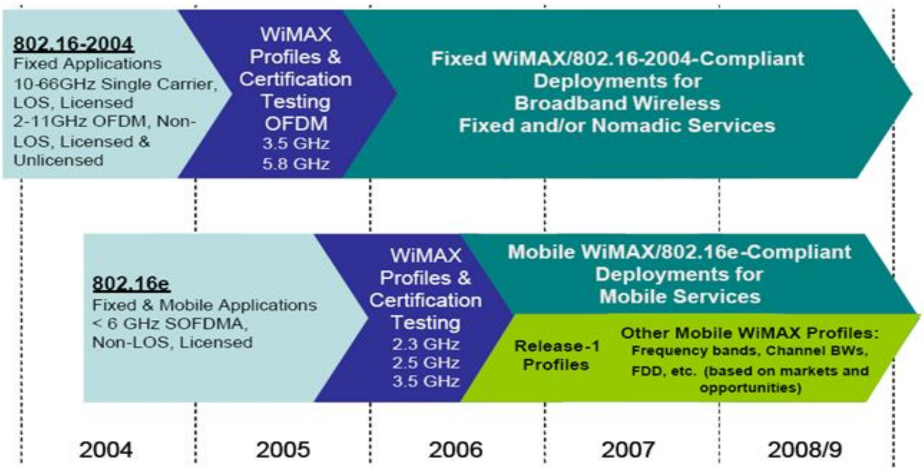


Figure 1.2. Roadmap for WiMAX technology (extracted from [WiMF06a])

The development roadmaps, for both 3G and Mobile WiMAX are presented in Figure 1.3. The technologies are being developed simultaneously, which makes possible to believe that Mobile WiMAX services will also complement existent and future broadband technologies, both wired and wireless, to best ensure the coverage and capacity requirements of consumers [WiMF06c].

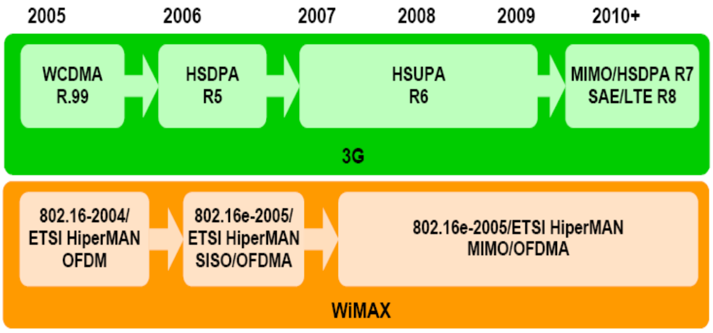


Figure 1.3. Development roadmaps for 3G and WiMAX (extracted from [WiMF06c]).

The 802.16m standard is the next generation standard beyond 802.16e-2005, and will become adopted by the WiMAX Forum once the standard is completed in the 2009 time frame. The IEEE 802.16m standard is considered to be a leading candidate as a Fourth Generation (4G) technology, [WiMA08].

1.2 Motivation and Contents

The main scope of this thesis is to compare two emergent systems: HSPA+ and Mobile WiMAX. The former is being developed in Releases 7 and 8 and the latter is currently in the phase of entering the market of Mobile Communications. Therefore, the objective of the analysis is to study, for both DL and UL, the capacity and coverage aspects, taking the cell radius and average data rate that each system provides into account, among other parameters.

The main contribution of this thesis is the development of two simulators: one to evaluate the maximum cell radius for a requested throughput for a single user, where a differentiation of the overheads is done, and the other to analyse HSPA+ and Mobile WiMAX in a real network with multiple users, according to several parameters, with the obtaining of useful results. Furthermore, by using these simulators, one can have a very good comparison of the two technologies at stake.

The present work was performed in partnership with Vodafone, a multinational mobile operator that is one of the players in the national market of telecommunications. This collaboration had an important role regarding several technical details, and some technical advices and insight view of technologies were also important to provide the most relevant results.

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

In Chapter 2, UMTS/HSPA+ and Mobile WiMAX basic concepts related to architecture, radio interface and performance are explained and analysed. Regarding UMTS, a special emphasis is given to the evolution from Release 99 to HSPA+. Then, a comparison between the two systems is performed concerning the previous aspects. Finally, services and applications of each system are discussed.

Chapter 3 starts with the description of the single user radius model, explaining its fundamentals and procedures. Later on, the simulator developed for multiple users and services, based on a previous simulator, is presented, the main introductions being pointed out, and HSPA+ and Mobile WiMAX modules being described in detail. Input and output files are highlighted and, finally, the simulator assessment is presented.

Chapter 4 begins with the description of the default scenario and the listed of the parameters values considered in the simulations, for both single and multiple users perspectives. Afterwards, the main simulation results for single user model are presented, first to each system individually, and next in a perspective of a comparison. Later on, a comparison between the two systems concerning coverage and capacity, based on the multiple users simulator´s results, is performed for DL. Finally, the same comparison is done for UL.

This thesis concludes with Chapter 5, where the main conclusions are drawn and suggestions for future work are pointed out.

A set of annexes with auxiliary information and results are also included, being referenced in the thesis when they are necessary to a better comprehension of several aspects. They include the link budget, expressions for the models, additional results and simulator’s interfaces, among others.

Chapter 2

Basic Concepts

This chapter provides an overview of UMTS/HSPA and Mobile WiMAX, mainly focusing on the architecture, capacity and coverage aspects. The evolution from UMTS to HSPA+ is presented in Section 2.1. In Section 2.2, an overview of Mobile WiMAX is provided. Later in the chapter, in Section 2.3, a brief comparison between the two systems is presented giving the current state of the art. Finally, Section 2.4 addresses the services and applications of both systems also in a comparison perspective.

2.1 UMTS and HSPA

In this section, Universal UMTS Release 99 basic concepts are presented, based on [HoTo04], namely network architecture, capacity and coverage aspects. It is briefly explained and its elements are presented. Concepts that influence capacity and coverage aspects of the system follow the network architecture. Afterwards, a description of HSDPA and HSUPA principles, such as new technologies and channels, are presented. Finally, HSPA Evolution is analysed giving emphasis to new enhancements that contribute to the improvement of capacity and coverage.

2.1.1 UMTS Network Architecture and Radio Interference

UMTS network architecture consists of a number of logical elements with a specific function, which are grouped according to their functionality, Figure 2.1, or based on which sub-network they belong to.

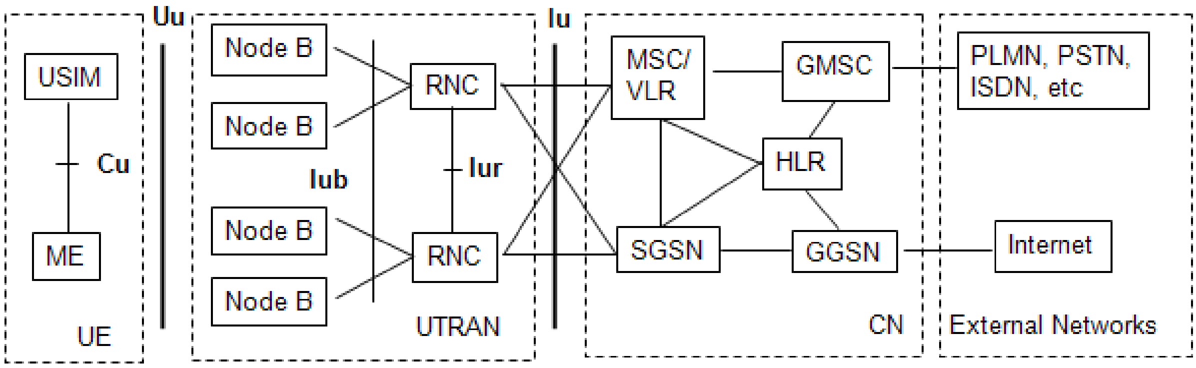


Figure 2.1. UMTS network architecture (extracted from [HoTo04]).

Functionally, networks elements are grouped into the Radio Access Network (RAN), UMTS Terrestrial RAN (UTRAN) that deals with all radio related functionality, Core Network (CN) that handles switching and routing calls and data connections to external networks, and, finally, User Equipment (UE) that is, basically, the interface with the user.

The UE consists of two parts:

- The Mobile Equipment (ME) is the radio terminal used for radio communication over the Uu interface.
- The UMTS Subscriber Identity Module (USIM) is a smartcard that holds subscriber identity, executes authentications algorithms and stores information.

UTRAN consists of one or more Radio Network Sub-Systems (RNS) and is also composed of two different elements:

- The Node B converts the data flow between the Iub and Uu interfaces, and takes also part of the radio resource management.

- The Radio Network Controller (RNC) owns and controls the radio resources in Node Bs connected to it.

CN is adapted from Global System for Mobile Communications (GSM) CN and the mains elements are:

- Home Location Register (HLR) is a database located in the user's home system.
- Mobile Services Switching Centre (MSC)/Visitor Location Register(VLR) is the switch and database that serves the UE in its current location for Circuit Switched (CS) services.
- Gateway MSC (GMSC) is the switch at the point where occur the connection between external CS networks and UMTS Public Land Mobile Network (PLMN).
- Serving GPRS (General Packet Radio Service) Support Node (SGSN) functionality is similar to that of MSC/VLR but is in relation Packet Switch (PS) services.
- Gateway GPRS Support Node (GGSN) functionality is close of that of GMSC but relative to PS services.

In WCDMA, user information bits are spread over a wide bandwidth by multiplying the user data with quasi-random bits (chips) derived from Code Division Multiple Access (CDMA) spreading codes. In order to reach higher bit rates, channelisation/spreading codes of UTRA are based on the Orthogonal Variable Spreading Factor (OVSF) technique. In addition to spreading, scrambling is used to separate mobile terminals (MTs) or base stations (BSs) from each other not changing the signal bandwidth. The chip rate of 3.84 Mcps leads to a carrier bandwidth of approximately 4.4 MHz. WCDMA supports two modes of operation: FDD and TDD but, in this thesis, only the former is considered. In FDD, both in UL and DL, carriers are separated by 5 MHz. The frequency bands used for FDD are [1920, 1980] MHz for UL and [2110, 2170] MHz for DL.

In UTRA, data is generated at higher rates and carried out over the air with transport channels, which are mapped onto different physical channels. The mapping takes place in the physical layer. There are two types of transport channels: dedicated and common ones. In a common channel, a resource is divided among all or a group of users in a cell, whereas a dedicated channel resource is identified by a code on a certain frequency being reserved for only a single user only.

The Dedicated Chanel (DCH) is the only dedicated transport channel carrying all the information to a certain user from layers above the physical one. DCH supports soft handover.

In Release 99, there are six common transport channels [HoTo04]. The DL shared channel (DSCH) is a transport channel intended to carry dedicated user data and/or control information.

The data transfer services of the Medium Access Control (MAC) layer are provided on logical channels, which can be classified into two groups: Control and Traffic Channels. They define the transfer of a specific type of information between the MT and the network. To avoid that a single overpowered MT blocks a whole cell, WCDMA uses fast closed loop power control. In UL, the parameter that is estimated is the received Signal-to-Interference Ratio (SIR) in the BS.

The trade-off between capacity and interference is of key importance in cellular networks. In UMTS, capacity depends, essentially, on the number of users, and on their type of services, via the interference margin and the sharing of transmitting power. This margin is given by [Corr06]:

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

where η represents the load factor. A raise of the load factor leads to a reduction in coverage, via the increase of the interference margin.

The UL and DL load factors, η_{UL} and η_{DL}, for a given user j are given by [Corr06]:

$$\eta_{UL} = 1 + i_{UL}\sum_{j=1}^{N_u}\frac{1}{1+\dfrac{G_{Pj}}{\left(E_b/N_0\right)_j \nu_j}} \quad (2.2)$$

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

where:

- ν_j: activity factor of user j (typically 0.67 for speech and 1.0 for data),
- E_b: energy per bit,
- G_{Pj}: processing gain of user j, defined as R_c / R_{bj},
- i_{DL}: inter- to intra-cell interferences ratio for DL,
- i_{UL}: inter- to intra-cell interferences ratio for UL,
- N_0: Noise power spectral density,
- N_u,: number of users per cell,
- R_{bj}: bit rate associated to service of user j,
- R_c: WCDMA chip rate,
- α_j: DL code orthogonality factor of user j (typically between 0.4 and 0.9 in multipath channels).

WCDMA employs orthogonal codes in DL to separate users. The number of available codes in a cell depends on the number of users and on the necessary bit rate to offer the service that users have required. The Spreading Factor (SF) defines the number of available channelisation codes. The bit rate and spreading factor, and therefore the number of codes, are inversely proportional.

In UMTS, a BS is shared among a number of users. However, capacity and coverage are limited because there is a maximum value for the transmitting power. The BS transmitting power, P_{TX}, is expressed by [Corr06]:

$$P_{TX[\mathrm{W}]} = \frac{N_{rf}R_c}{1-\bar{\eta}_{DL}}\sum_{j=1}^{N_u}L_j\nu_j\frac{\left(E_b/N_0\right)_j}{G_{Pj}} \quad (2.4)$$

where:

- $\bar{\eta}_{DL}$: average DL load factor value across the cell,
- L_{Pj}: path loss between Node B and user j,
- N_{rf}: noise spectral density of MT receiver (between -169 and -165 dBm).

The radius of a given cell can be calculated using the defintion of the path loss and the model of the average power decay with distance.

The radius of a cell is given by [Corr06]:

$$r_{[\mathrm{km}]} = 10^{\frac{P_{t\,[\mathrm{dBm}]} + G_{t\,[\mathrm{dBi}]} - P_{r\,[\mathrm{dBm}]} + G_{r\,[\mathrm{dBi}]} - L_{ref\,[\mathrm{dB}]}}{10 a_{pd}}} \tag{2.5}$$

where:

- a_{pd},: average power decay,
- G_r: receiver antenna gain,
- G_t: transmitting antenna gain,
- L_{ref}: propagation model losses,
- P_r : available receiving power at antenna port,
- P_t: transmitting power at antenna port,
- r: cell radius.

2.1.2 Release 99 Evolution

HSPA is deployed on top of the Release 99 network, and the physical layer needs to be adapted, as illustrated in Figure 2.2, since new services and higher data rates require higher cell capacity and spectral efficiency.

For the network elements and the terminal the use of HSPA causes a lot of changes on the physical layer, as mentioned before, and on the MAC and Radio Link Control (RLC) layers. Mobility events allow sharing Iub resources dynamically among all users.

In Release 99, radio transmissions are organised in frames with a 10 ms of duration and transport data blocks are transmitted over an integer number of frames. The transmission duration is called Transmission Time Interval (TTI), and is, usually, between 10 and 80 ms. HSDPA and HSUPA support a frame length of 2ms, which has as consequence the reduction of latency and a fast scheduling among different users as consequence.

In HSPA, the Node B is responsible for the local scheduling instead of RNC, where occurs Release 99 all scheduling. As a consequence, the response of the system is faster and signalling is reduced, especially in the link between Node B and RNC. The moving of scheduling from RNC to Node B implies a change in the overall Radio Resource Management (RRM) architecture [Mulv07].

HSPA has the capacity to be used for retransmission at the physical layer under the control of Node B. Hence, a significant number of errors can be corrected quickly without the influence of RNC.

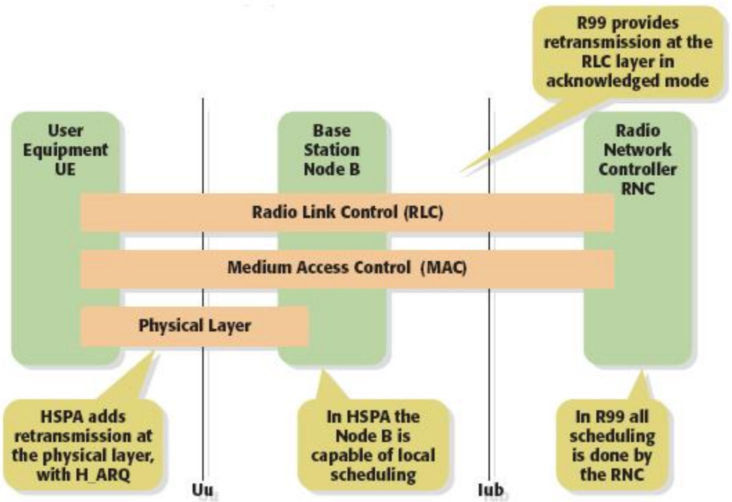


Figure 2.2. HSPA Physical Layer in the 3G Context (extracted from [Mulv07]). (Note: The author uses H_ARQ instead of HARQ)

Hybrid Automatic Repeat Request (HARQ) is an error control method that, instead of Automatic Repeat Request, uses all received transmissions to recover the original message. It can be configured either to repeat the previous transmission, as Automatic Repeat Request (ARQ) does, or to send new data containing only the coding bits, now reducing the total number of bits transmitted omitting some of the coding bits according to a pattern known by the receiver. HSPA also uses turbo coding to realise error correction [Mulv07]. Turbo coding consists in transmitting the original data bits and two sets of redundant coding bits together.

2.1.3 HSDPA Key Upgrades, Capacity and Coverage

HSDPA is deployed with the purpose of increasing DL packet data throughput and to reduce round-trip times and latency times. The standard provides new physical channels for data transmission and signalling. Dynamic AMC on a frame by frame basis allows for an optimum use of radio conditions.

Four new physical channels are introduced in HSDPA [Mulv07]. The High Speed Shared Control Channel (HS-SCCH) channel supports three basic principles: fast link adaptation, fast HARQ and fast scheduling as result of placing this functionality in the Node B instead of the RNC. Each UE to which data can be transmitted on the High Speed DSCH (HS-DSCH) has an associated Dedicated Channel (DCH) that is used to carry power control commands and the control information necessary to realise the UL like ARQ acknowledgement and Channel Quality Indicator (CQI). The main characteristics of HS-DSCH and the DSCH are compared in Table 2.1. Compared with DCH, the most important difference in mobility is the absence of soft handover for HS-DSCH.

For user data transmission, HSDPA uses a fixed spreading factor of 16, which means that user data can be transmitted using up to 15 orthogonal codes.

With Release 5, there are some changes on HS-DSCH, namely the deactivation of variable spreading factor and fast power control. These features are replaced by AMC, short packet size, extended multicode operation and fast L1 HARQ, which that occurs in the lowest layer of the Open Systems Interconnection (OSI) Reference Model. In order to modulate the carrier, Release 99 uses Quaternary Phase Shift Keying (QPSK). On the other hand, HSDPA can also use 16 Quadrature Amplitude Modulation (16QAM), which in theory doubles the data rate.

Table 2.1. Comparison of basic properties between DSCH and HS-DSCH (extracted from [3GPP07b]).

Feature	Release 99 DSCH	Release 5 HS-DSCH
Variable spreading factor	Yes (4 – 256)	No (16)
Fast power control	Yes (1500 Hz)	No
Fast L1 HARQ	No (~100 ms)	Yes (~10 ms)
TTI [ms]	10 or 20	2
Location of MAC	RNC	Node B
Peak data rate [Mbps]	~2 Mbps	~10 Mbps

In HSDPA, the possibility to support the features is optional from the point of view of the MTs. When supporting HSDPA operation, the MT indicates which of the 12 different categories specified, Table C.1. The achievable maximum data rate varies between 0.9 and 14.4 Mbps in agreement with the category of the MT.

The new link adaptation functionality has new metrics to evaluate the performance of HSDPA. Release 99 uses E_b/N_0. This metric is not appropriate for HSDPA, since the bit rate on HS-DSCH is varied every TTI using different modulation schemes, effective code rates, and a number of High Speed Physical Downlink Shared Channel (HS-PDSCH) codes. Therefore, the metric used for HSDPA is the average HS-DSCH Signal-to-Interference-plus-Noise-Ratio (SINR) that represents the narrowband SINR ratio after the process of de-spreading of HS-PDSCH. Link adaptation selects the modulation and coding schemes with the purpose of optimising throughput and delay for the instantaneous SINR, [HoTo06].

The HS-DSCH SINR for a single antenna Rake receiver can be defined as:

$$SINR = SF_{16} \frac{P_{HS-DSCH}}{(1-\alpha)P_{intra} + P_{inter} + P_{noise}} \tag{2.6}$$

where:

- SF_{16}: HS-PDSCH SF of 16,
- $P_{\text{HS-DSCH}}$: received power of the HS-DSCH summing over all active HS-PDSCH codes,
- P_{intra}: received intra-cell interference,
- P_{inter}: received inter-cell interference,
- P_{noise}: received noise power.

Figure 2.3 illustrates the single-user average throughput, including link adaptation and HARQ, as a function of the average HS-DSCH SINR. Results are shown for 5, 10 and 15 codes. For a certain inter-to-intra-cell-interferences ratio, SINR is not constant, but depends on a number of factors, such as orthogonality and MT receiver capabilities. The mapping from SINR onto throughput is fairly constant for different environments and MT receiver capabilities.

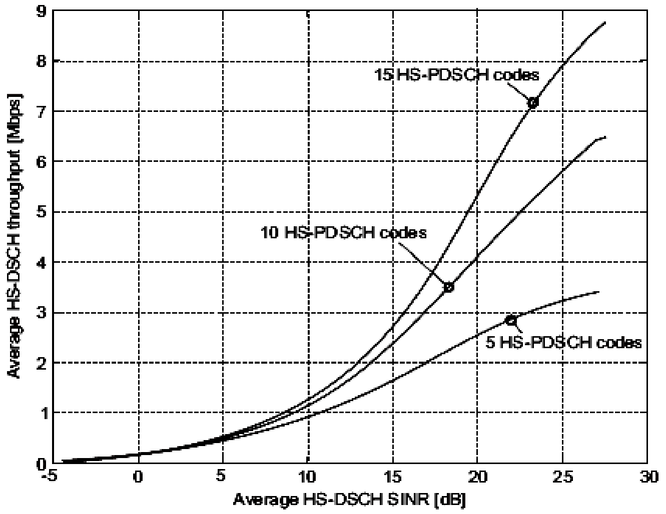


Figure 2.3. HSDPA data rate as function of average HS-DSCH SINR (extracted from [Pede05]).

The average cell throughput increases with the number of HS-PDSCH codes, having a growth of 50% when the number of codes is modified from 5 to 10. Fast link adaptation and HARQ contribute to having a capacity gain of almost 70 % compared to Release 99 [HoTo06].

2.1.4 HSUPA Key Upgrades, Capacity and Coverage

HSUPA uses most of the basic features of WCDMA Release 99 in order to work. The main changes take place in the way of deliverer user data from the user equipment to the Node B. It is based on a dedicated user data channel rather than a shared channel. HSUPA also operates in soft handover because with HSUPA all the Node Bs in the active set are involved.

In UL, the critical issue is the power control of scheduling. UL capacity is limited by the level of interference to each user signal from the other users, which is proportional to their transmission power. The BS can specify the power level used by the MT to transmit HSUPA messages, relative to the power level of the normal data channel for Release 99 [Mulv07].

HSUPA introduces five new physical channels [Mulv07]. A new UL transport channel, Enhanced UL Dedicated Channel (E-DCH), supports new features such as fast BS based scheduling, fast physical layer HARQ with incremental redundancy and, optionally, a shorter 2-ms transmission TTI. Each MT has its own dedicated E-DCH data path to the BS. A comparison between the DCH in Release 99, the HS-DSCH in HSDPA and the E-DCH in HSUPA is done in Table 2.2 [HoTo06].

The performance of HSUPA depends on the scenario and on deployment and service parameters. To evaluate the link performance of E-DCH some metrics are used. 3GPP defined a set of E-DCH channel configurations called Fixed Reference Channels (FRCs), which together with associated MT categories, are presented in Table C.2 [HoTo06].

Table 2.2. DCH, HSDPA and HSUPA comparison table (extracted from [HoTo06]).

Feature	DCH	HSDPA (HS-DSCH)	HSUPA (E-DCH)
Variable spreading factor	Yes	No	Yes
Fast power control	Yes	No	Yes
Adaptive modulation	No	Yes	No
Base Transceiver Station (BTS)	No	Yes	Yes
Fast L1 HARQ	No	Yes	Yes
Soft handover	Yes	No	Yes
TTI length [ms]	80,40,20,10	2	10,2

The required energy chip bit over noise in order to receive a certain bit rate with a certain block error probability, E_c/N_0, is one of the metrics mentioned before. The dependence of the bit rate on it is shown in Figure 2.4. Note that power control is not performed and the analysis is done per BS antenna. It is clearly that the curves corresponding to FRC2 with 2 ms TTI and FRC6 with 10 ms TTI are similar. Nevertheless, FRC2 can reach higher peak data rates in circumstances of high enough values of E_c/N_0. Values of received E_c/N_0 higher than approximately 0 dB allow, in both cases, to obtain data rates beyond 2 Mbps [HoTo06].

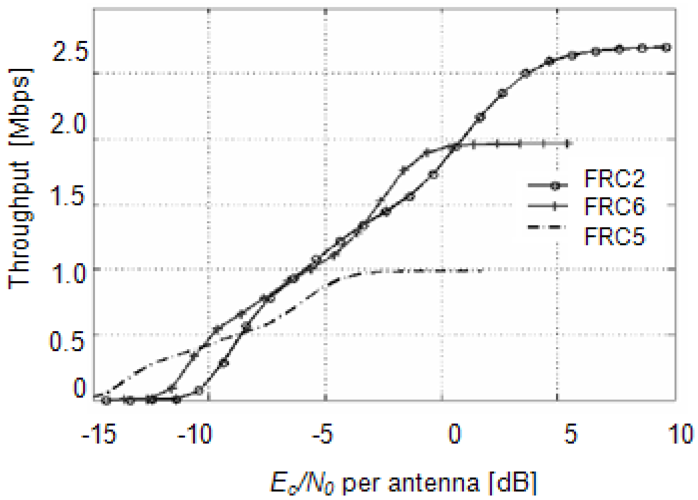


Figure 2.4. HSUPA throughput in Vehicular A at 30 km/h (extracted from [HoTo06]).

BS based scheduling has a control signalling that operates faster than RNC-based scheduling with L3 control signalling. The performance of the system is improved by the faster adaptation to interference variation and faster reallocation of radio resources among users. The gain introduced by the use of BS scheduling instead of RNC-based scheduling is between 6% and 9%, not depending on the average number of users per cell. The capacity gain from HSUPA is mainly achieved by the use of L1 HARQ and BS scheduling [HoTo06].

HSUPA, by using HARQ and soft combination of HARQ retransmissions, allows a decrease of the necessary E_b/N_0 at the BS comparing with Release 99 for a certain data rate. Therefore, UL spectral efficiency also increases. The capacity improvement due to the use of HARQ is expected to be between 15% and 20% [HoTo06].

There are 2 available TTIs: the 2 ms is appointed to high data rates with good radio channel conditions, and the 10 ms is the default value for cell edge coverage suffering from a high number of retransmissions due to the increase of associated path loss [HoTo06].

UL spectral efficiency and data rates can be improved with antenna and baseband solutions and Interference Rejection Combining (IRC) has an important role because in high peak data rates can be associated with interference scenarios characterised by dominant interferers providing significant capacity and coverage gains [HoTo06].

2.1.5 HSPA Evolution

In this subsection, HSPA+ main concepts are presented, based on [BEGG08], [HTRP07] and [PWST07]. HSPA + consists of introducing of MIMO and HOM, protocols optimisation and optimisations for VoIP. The deployment of existing HSPA is, from the point of view of operators, easily updated. In Annex D, the basic concepts of MIMO, one of the most important enhancements brought up by HSPA+, are presented.

HSPA evolution uses MIMO in order to transmit two separately encoded streams to a MT. Therefore, the process of successive interference cancellation receiver becomes more attractive, which allows a better system performance compared with linear receivers. As a consequence, streams are modulated and spread separately, and the spreading codes can be reused over both streams. The link adaptation has two types of components: a spatial one and a temporal one [PWST07].

Release 6 HSPA systems support the use of QPSK and 16QAM in DL and the BPSK and QPSK modulation schemes in the UL. 16QAM and QPSK provide high enough data rates for macro-cell environments. However, for indoor or small-cell deployments, higher Signal to Noise Ratio (SNR) and HOM can be supported. The best combination of modulation and coding rate for a given SNR is determined by Modulation and Coding Schemes (MCS) tables. In this manner, peak rate is limited by the output of the MCS table, in other words, a higher order modulation with the least amount of coding. The potential gain reachable with MIMO combined for HOM is illustrated in Figure 2.5 for the 90^{th} percentile throughput, for DL. Simulation conditions can be found at [PWST06]. The improvements verified for UL, can be observed in Figure 2.6.

Release 7 introduces 64QAM in DL, increasing the peak data rate by 50%, from about 14 to 21.6 Mbps. Note that the enhancements inherent to HSPA+ are reflected in the 16QAM modulation for DL, with the need for a smaller SNR value, to achieve the peak data rate, compared to HSDPA Release 5 depicted in Figure 2.3. In UL, the introduction of 16QAM allows for the peak data rate to reach about 11.5 Mbps (per 5MHz carrier), featuring an increase of 100% compared to the 5.74 Mbps of the enhanced UL in Release 6, with QPSK. In Release 7, MIMO is defined for transmitting up to two streams (2×2 MIMO scheme), which for DL, using 16QAM for each stream, leads to peak data rates of approximately 28 Mbps. The combination of MIMO and 64QAM, being considered for Release 8 extends the peak data rate to 43.2 Mbps (per 5MHz carrier).

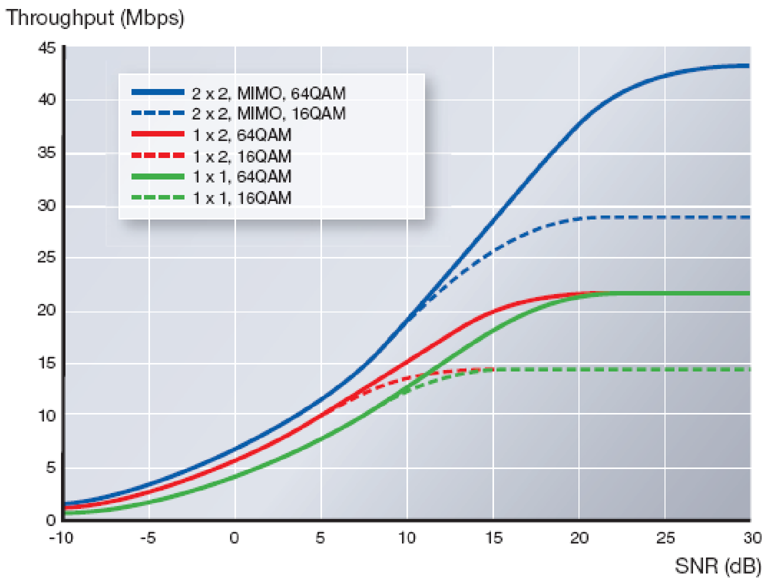


Figure 2.5. The 90th percentile throughput for HOM and MIMO (extracted from [BEGG08]).

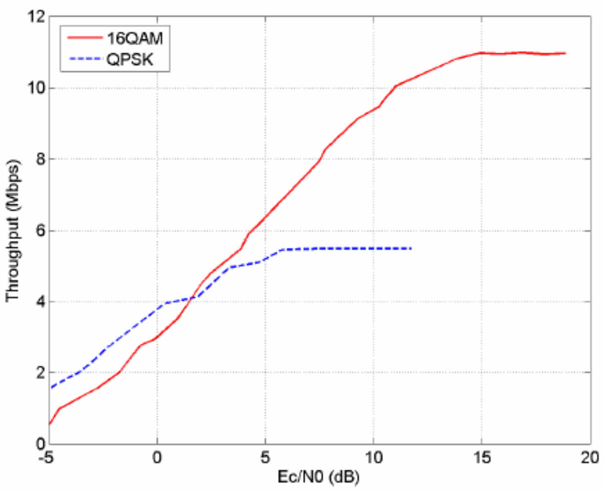


Figure 2.6. Throughput as a function of E_c/N_0 for UL HOM (extracted from [PWST07]).

The SNR and E_c/N_0 are important metrics used in the link budget, Annex A. The expressions for the DL and UL curves obtained in the scope of the thesis are presented in Annex B.

Continuous Packet Connectivity (CPC) improves the physical layer signalling. Therefore, the latency is lower and the capacity is improved. Layer-2 enhancements consist of an optimisation of layer 2 in order to support higher peak data rates and greater coverage reducing, at the same time, the processing and level-2 overhead.

In order to support MIMO and 64QAM modulation, a larger RLC Protocol Data Unit (PDU) is needed, therefore, in Release 7, flexible RLC PDU sizes are adopted, as well as MAC segmentation.

2.2 WiMAX Basic Concepts

This section contains a description of Mobile WiMAX principles, such as its architecture, radio interface, and capacity and coverage aspects, based on [AnGM07] and [Nuay07] and [WiMF06a].

2.2.1 Network Architecture

The WIMAX reference architecture takes some requirements into account, such as:

- High performance packed-based network,
- Full scalability of services and applications,
- Roaming and interworking with both fixed and mobile networks,
- A large variety of services and applications.

The WiMAX Network Reference Model (NRM), pictured in Figure 2.7, is a logical representation of the network architecture being composed of three components that are inter-connected, in a logical domain, by standardised interfaces or reference points (RPs) R1 to R5. Different elements of the network are: Mobile Station (MS) or Subscriber Station (SS), Access Service Network (ASN) and Connectivity Service Network (CSN). RPs are logical interfaces between several entities belonged to the WiMAX network.

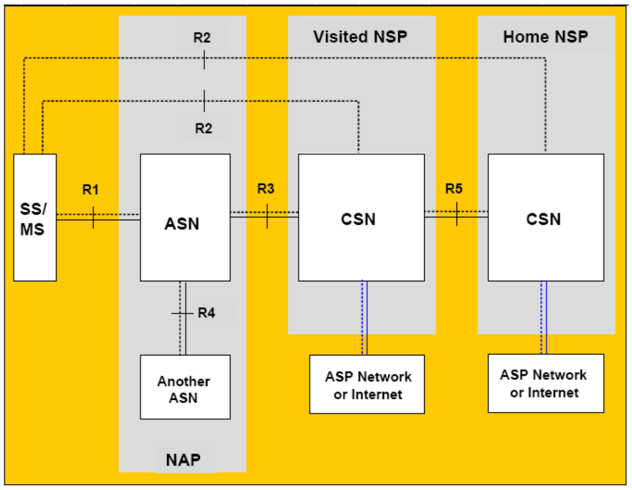


Figure 2.7. WiMAX network reference model (extracted from [WiMF06a]).

The ASN includes all functionalities related to radio connectivity to WiMAX subscribers defining a logical boundary. ASN is responsible for not only RRM aspects, like handover control and consequent execution, but also for establishing connectivity between WiMAX subscribers and Layer 2 and Layer 3, using the air interface and the CSN respectively.

One or several ANSs are interconnected through reference point R4, and may be deployed by a Network Access Provider (NAP), which provides radio access infrastructure to one or several Network Service Providers (NSP). According to the existing Service Level Agreements (SLA), NSP enables IP connectivity and WiMAX services to subscribers. The ASN usually consists of several BSs connected to respective ASN Gateways (ASN-GWs). BS is the element that is responsible for physical layer and

MAC mechanisms, and also contributes to the scheduling of user and to exchange of signalling messages with the ASN-GW through the R6 interface.

The CSN is defined as a set of network functions that provide IP connectivity to WiMAX subscribers. CSN functions comprise:

- User connection authorisation and Layer 3 access;
- QoS management;
- Mobility support based on Mobile IP;
- Tunnelling with other equipments and networks based on IP protocols;
- WiMAX services.

CSN is deployed by the NSP and includes, among others, network elements, such as routers, Authentication Authorisation and Accounting (AAA) server or proxy, firewalls, data bases and interworking gateways. With these components, interworking, interoperability, protection and security aspects are achieved.

In order to implement ASN, there are three different ASN profiles: A, B and C. They differ in the fact that several functionalities are implemented by the BS and others by the ASN-GW or another entity.

2.2.2 Radio Interface

In terms of frequency, the frequency used by WiMAX depends on the region or country where the system is implemented. The licensed bands comprise 2.3, 2.5, 3.3 and 3.5 GHz. A license-exempt band can be used for unlicensed WiMAX. In United States of America, the reported WiMAX frequency bands are 2.3, 2.5 and 5.8 GHz, and in Europe the frequency bands are 2.3, 3.5 and 5.8 GHz. The frequency band of 2.5 GHz, reserved for UMTS, became an alternative to take in account, being analysed to be globally available for Mobile WiMAX in order to provide interoperability.

IEEE 802.16-2004 WiMAX is also known as IEEE 802.16d WiMAX. It uses Orthogonal Frequency Division Multiplexing (OFDM) and supports fixed and nomadic access in Line of Sight (LOS) and NLOS environments, having better performance in scenarios with fixed applications. OFDM provides a higher spectral efficiency, resistance to multipath effects, frequency selective fading and narrow band interference.

Mobile WiMAX, IEEE 802.16e is designed and deployed to support terminal mobility, being optimised for dynamic mobile channels. It is based on the 802.16e additional features and provides support for handovers and roaming. The main differences introduced by IEEE 802.16e comparatively to IEEE 802.16-2004 are the following:

- Introduction of MSs to be used both in stationary and mobility scenarios;
- MAC layer handover procedures. It can supports hard handover and soft handover;
- Power save modes associated to the mobility of devices;
- SOFDMA
- Multicast and broadcast services (MBS);

- AAS techniques.

In [Pigg06], antenna techniques related to WiMAX are discussed, giving special emphasis to their applicability and the advantages of Spatial Multiplexing (SM) techniques.

OFDMA provides more flexibility to deal with a higher variety of antennas and devices. Sub-channelisation allows the operator to manage the available bandwidth and transmit power, which increases the efficiency of the use of resources. OFDMA is an access technique that divides the carrier space. Afterwards, OFDMA sub-carriers are divided into subsets of sub-carriers, each subset representing a sub-channel, which is the minimum time-frequency resource that can be allocated. In UL, the performance is also improved due to sub-channelisation. Since the system uses OFDMA, the devices transmit only through sub-channels allocated to them, instead of OFDM where devices transmit using the whole carrier space at once.

Figure 2.8 represents an OFDMA frame when operating in TDD mode. The frame is divided into two sub frames: DL and UL, separated by a guard time interval.

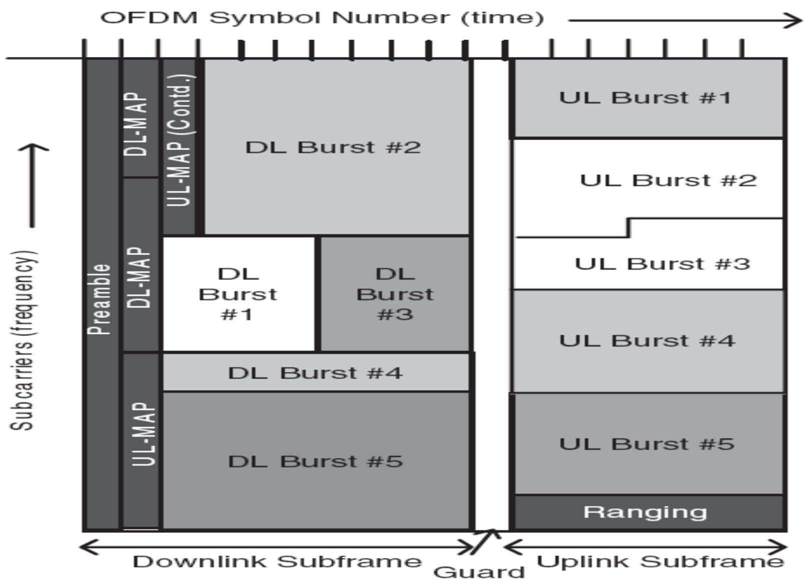


Figure 2.8. OFDMA frame structure for WiMAX operating in TDD mode (extracted from [AnGM07]).

The frame begins with a DL preamble used, for example, for time and frequency synchronisation and channel estimation. The DL preamble is followed by a frame control header (FCH), which provides frame configuration information, such as MAP message length, the modulation and coding scheme, and the number of used sub-carriers. A single DL frame may contain multiple bursts of varying size and type carrying data for several users.

The UL sub frame is made up of several UL bursts from different users. It has, also, a channel- quality indicator channel (CQICH) for the SS to give a feedback about the channel quality. This information is evaluated by the BS scheduler and an Acknowledgment (ACK) channel for the SS to feedback DL acknowledgements.

There are two types of sub-carriers permutations for sub-channelisation: diversity and contiguous. The former draws sub-carrier to form a sub-channel in a pseudo-random way, and the latter groups a block of contiguous sub-channel to form a sub-channel.

Diversity permutation provides frequency diversity and inter-cell interference averaging. It includes DL Fully Used Sub-Carrier (DL FUSC), DL Partially Used Sub-Carrier (DL PUSC) and UL PUSC, among other additional optional permutations.

The contiguous permutation includes DL AMC and UL AMC that have the some structure. A slot in AMC is a group of bins that consists of 9 contiguous sub-carries in a symbol, with 8 for data and one to pilot functions. AMC allows choosing the best sub-channel in respect of frequency response.

SOFDMA introduces the concept of scalability. It means that this technique has the capability to scale the size of the Fast Fourier Transform (FTT) to the channel bandwidth with the purpose of keeping the carrier spacing constant across different channel bandwidth [WiMF06a]. The supported FFT sizes are 2048, 1024, 512 and 128, but only 1024 and 512 are mandatory for Mobile WiMAX profiles, [Nuay07]. SOFDMA parameters are presented in Table 2.3. The sub-carrier spacing of 10.904 kHz was chosen with the purpose of satisfying the delay spread and Doppler spread requirements for operating and fixed and mobile environments.

Table 2.3. SOFDMA parameters (extracted from [WiMF06a]).

Parameter	**DL**	**UL**	**DL**	**UL**
System Bandwidth [MHz]	5		10	
Null sub-carriers	92	104	184	184
Pilot sub-carriers	60	136	120	280
Data sub-carriers	360	272	720	560
Number of sub-carriers	512		1024	
Sub-channels	15	17	30	35
OFDMA symbol duration [μs]	102.9			
Guard Time T_G [μs]	11.4			
Number of OFDM symbols in 5ms frame	48			
Data OFDM Symbols	44			

The 802.16e PHY supports TDD and Full and Half-Duplex FDD operation. However, TDD is the most suitable mode of operation, featuring the possibility to adjust the DL/UL ratio in order to adapt to an asymmetric type of traffic .

In Mobile WiMAX, support of QPSK, 16QAM and 64QAM in a requisite in DL while in the UL 64QAM is optional. Table 2.4 represents the data rate obtained for different combinations of modulation and code rates when all resources are allocated to DL or UL. An optional feature considered is Convolutional Turbo Code (CTC), which performance is explained in detail in [CKLC04]. Mobile WiMAX also supports HARQ, Chase Combining (CC) and Incremental Redundancy (IR), but the last one is an optional technique. All these features contribute to improve the retransmission performance.

Each burst allocation has an appropriate data rate. Buffer size and channel propagations at the receiver are analysed in scheduling process by BS. CQI is utilised to provide channel-state information from the MT to the BS scheduler.

Table 2.4. WiMAX IEEE 802.16e throughputs with PUSC, TDD Split 1:0 and TDD Split 0:1 (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	3/4	4.75	3.43	9.50	7.06
16QAM	1/2	6.34	4.57	12.67	9.41
	3/4	9.50	6.85	19.01	14.11
64QAM	1/2	9.50	6.85	19.01	14.11
	2/3	12.67	9.14	25.34	18.82
	3/4	14.26	10.28	28.51	21.17
	5/6	15.84	11.42	31.68	23.52

MIMO antenna techniques with flexible sub-channelisation schemes and AMC allows WiMAX to reach peak DL sector data rates up to 46 Mbps, assuming a DL/UL ratio of 3:1, and UL ones up to 14 Mbps, assuming a DL/UL ratio of 1:1 in a 10 MHz channel [WiMF06b]. The basic concepts of MIMO are presented in Annex D.

The standard defines signalling mechanisms for tracking SS as they move from the coverage range of one BS to another when active. Three handover methods are supported in IEEE 802.16e-2500 with two optional and one mandatory features. The mandatory handover method is called hard handover (HHO) and implies a transfer of connection from one BS to another in an abrupt way. The two optional methods for handover are fast BS switching (FBSS) and macro diversity handover (MDHO). Both in FBSS and MDHO, the SS maintains a valid connection simultaneously with more than one BS. In FBSS, the SS maintains a valid connection with more than one BS, while in MDHO the communication, both in DL and UL, occurs with all BSs in an active set [AnGM07].

2.2.3 WiMAX Capacity and Coverage Aspects

BS coverage from a BS depends on some radio parameters. Propagation environments influence the coverage of a certain service. For fixed WiMAX, solutions deploying outdoor Consumer Premises Equipments (CPEs), the coverage may be of several kilometres. Sub-channelisation is a new feature introduced in WiMAX, originating the existence of a trade-off between coverage and the maximum data rate achieved at cell edge. The duration of an OFDM symbol is calculated as follows [Nuay07]:

$$T_{OFDM[\mu s]} = \left[\frac{1}{\left(n \times \Delta f_{c[\mathrm{MHz}]} \big/ N_{TSC} \right)} \right] \left(1 + \frac{T_G}{T_D} \right) \tag{2.7}$$

where:

- *n:* the sampling factor;
- Δf_c: the nominal channel bandwidth;
- N_{TSC}: number of sub-carriers;
- T_G: guard time;
- T_D: useful symbol duration.

The numerical value for *n* is standardised and can assume to be different values: 8/7, 86/75, 144/125, 316/275 and 57/50. Possible values for the ratio $T_{G/}\,T_D$ are: 1/4, 1/8, 1/16, 1/32.

The resulting throughput is obtained by [Nuay07]:

$$R_{b\ [bps]}^{PHY} = \frac{N_{DSC} \times N_{SB} \times \beta}{T_{OFDM[s]}} \tag{2.8}$$

where:

- N_{DSC}: number of sub-carriers for useful data transmission,
- N_{SB}: number of symbol bits,
- β: coding rate.

The numerator of (2.8) corresponds to the number of uncoded bits per OFDM symbol.

2.3 Comparison between HSPA and Mobile WiMAX

It is worthwhile to compare the performance of the two systems analysed: HSPA over UMTS, and Mobile WiMAX. The first release of WiMAX is not considered, because represents a market completely different from the others.

HSPA is created with the purpose of providing data services over a network originally conceived for mobile voice services. On the other hand, WiMAX was initially developed for fixed broadband wireless access and is optimised for broadband data services.

UMTS/HSPA provides some advantages because its equipment was tested correctly and is already in the market and HSDPA networks are used, since 2005, in some countries [Nuay07].

Mobile WiMAX, on the other hand, is based on OFDM/OFDMA technology offering scalability in radio access technology and network architecture. Mobile WiMAX provides high data rates with MIMO antenna techniques in flexible sub-channelisation schemes [WiMF06b]. The physical layer is based on OFDM which provides higher spectrum-use efficiency [Nuay07].

The Table 2.5 summarizes the principal attributes of the two systems. DL and UL peak data rate are referred over the air. The higher value for DL is obtained considering the MIMO (2x2) mode. The higher peak data rates for DL and UL considers 4 OFDM symbols for overhead.

Besides the differences in some parameters, HSPA and Mobile WiMAX also share several features such as: AMC, HARQ, Fast Scheduling and Bandwidth Efficient Handover. Mobile WiMAX, however, due to the use of OFDM/OFDMA is more suitable for broadband wireless data communication and has also the capability to adapt the DL/UL ratio with TDD, which gives more flexibility to the system and a higher spectral efficiency.

Table 2.5. Summary of Comparative Features of UMTS/HSPA+ and Mobile WiMAX.

Attribute	UMTS/HSPA+	Mobile WiMAX
Base Standard	WCDMA	IEE 802.16e-2005
Duplex Mode	FDD	TDD
Multiple Access	CDMA	SOFDMA
Channel Bandwidth [MHz]	5.0	Scalable: 5,7,8.75,10,20
Frequency [GHz]	2	2.5, 3.5, 5.8
Frame Size – DL [ms]	2	5
Frame Size – UL [ms]	2, 10	5
Modulation – DL	16QAM, 64QAM	QPSK, 16 QAM, 64QAM
Modulation – UL	QPSK, 16QAM	QPSK, 16 QAM, 64QAM
Coding	CTC	
DL Peak Data Rate [Mbps]	43.2 (MIMO 2×2, 64QAM)	63.36, (DL/UL= 1:0, Channel Bandwidth = 10 MHz, MIMO 2×2)
UL Peak Data Rate [Mbps]	11.5 (16QAM)	28.22, (DL/UL= 0:1, Channel Bandwidth = 10 MHz, MIMO 2×2)
Scheduling	Fast Scheduling	

The network architecture is quite similar for the two systems. The architecture can be divided in three general areas, where each one performs a specific function in the connection.

UTRAN in UMTS/HSPA and ASN in Mobile WiMAX are the entities responsible for all functionalities concerned with radio connectivity. The handover control is located in RNC in HSPA. In Mobile WiMAX it can be inside the ASN-GW, in case of profile A, or inside the BS if the profile chosen is the profile C. Scheduling is an important feature of Radio Resource Control (RRC) and is handled in BS in HSPA and in ASN-GW or BS, depending on the profile, in Mobile WiMAX. CN is the functional area that connects external PS or CS and UMTS PLMN. In Mobile WiMAX, the functions and equipment that enable IP connectivity to subscribers are part of CSN. Finally, the end-user is known as SS in Mobile WiMAX and is denominated MT in UMTS/HSPA. In Table 2.6, the parallelism between the different areas of the systems and the consequent functions is presented.

In [WiMF06d], a brief comparison between WiMAX and HSPA, which is a capacity enhancement specified by 3GPP, is presented. This study focuses mainly on aspects like performance, throughput and spectral efficiency comparison. Performance simulations show that mobile WiMAX provides higher data rates and spectral efficiency compared to HSPA. HSPA is supported in FDD mode on a carrier frequency of 2.0 GHz, whereas mobile WiMAX uses the TDD mode of operation at 2.5 GHz. HSPA is implemented with a single Transmitter (Tx) antenna and dual Receiver (Rx) antennas with Rake receivers in both DL and UL. On the other hand, Mobile WiMAX is simulated with two different topologies: 1x2 Single Input Single Output (SIMO) and 2x2 MIMO.

Table 2.6. Correspondence between the different architecture of UMTS/HSPA+ and WiMAX.

Function	HSPA	Mobile WiMAX
Radio Connectivity	UTRAN	ASN
External Connectivity	CN	CSN
End-User	MT	SS

In [SKKO05], a performance comparison is done for Wireless Broadband (WiBro), which is fundamentally similar to WiMAX, and HSDPA, the most competitive systems for high data rate mobile services, according to the authors. WiBro is the new Korean standard for wireless and broadband portable Internet. It is standardised by Telecommunications Technology Association (TTA), being compatible with IEEE 802.16e, and it was assigned the 2.3 GHz band and 10 MHz bandwidth in Korea. The deployment was done at cell-planning tool, link and system level simulations. The difference verified into performance parameters is caused by the distinct physical layer and network structure. Therefore, HSDPA presents a lower performance in multipath fading channel, although, being more robust in Doppler Shift fading due to its shorter TTI. On the other hand, WiBro provides higher data rate transmission in multipath fading channel and, in general, presents a better overall performance in the air-link.

In [OdOK07], the strengths and weaknesses of different broadband wireless networks technologies are analysed and their relationship is presented. Mobile WiMAX is used for Mobile Wireless Metropolitan Networks (MWMANs) and can, easily, support and interface to other wireless technologies, providing a better QoS through smart antenna technology, and therefore a higher spectral efficiency. The connectivity established with Mobile WiMAX also explores multipath signals. The main barrier found by WiMAX is the delay in outdoors scenarios, in NLoS environments that can cause intersymbol interference. SOFDMA can attenuate this problem but, on the other hand, generates phase noise which increases the complexity of the system.

Concerning a technical comparison, in [Eric07], one can notice that HSPA and Mobile WiMAX are technologies designed for high speed packet data services. They feature similar technology enablers, including dynamic scheduling, link adaptation, HARQ with soft combining, multiple level QoS, and advanced antenna systems. Their performance differs in the physical layer signal format, handover mechanism and operating frequency bands. HSPA has a finer granularity of modulation and coding formats than Mobile WiMAX. Mobile WiMAX is based on OFDM, whereas HSPA is a direct sequence spread spectrum system. In terms of coverage, although Mobile WiMAX and HSPA are based on similar techniques, the link budget of Mobile WiMAX can be up to 6 dB worse than that of HSPA.

2.4 Services and Applications

UMTS networks are designed with the purpose of delivering any type of service, where each new service does not require a particular network optimisation. The WCDMA radio capabilities allow a fast introduction of new services that are built on Internet applications and protocols [HoTo04]. In wireless networks, QoS is, usually, managed at the MAC layer [CiLM06].

When the system load gets higher, it is important to establish levels of priority to the different services according to their requirements. This prioritisation is called QoS differentiation.

There are four different QoS classes that differ, essentially, in delay-sensitive of the traffic, as expressed in Table 2.7. QoS differentiation is useful in order to improve the network efficiency when the load is high and with different delay requirement services [3GPP07b].

Table 2.7. QoS classes main parameters and characteristics (adapted from [3GPP07b] and [Nuay07]).

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
Examples	Speech Voice Over IP Video Conference	Streaming Video	Web Browsing Server Access	E-Mail SMS Download

The Conversational class preserves time relation, or variation, between information entities of the stream following a stringent and low delay pattern. Conversational real-time services, based on both CS and PS traffic, are the most delay sensitive applications. Therefore, the limit for acceptable transfer delay is very strict to discard any demonstrations of lack of quality being the maximum transfer delay on end-to-end real-time conversations fixed based on human perception, below 400 ms.

Typically, in a voice conversation traffic is symmetric with each interlocutor occupying 50% of the available resources during a time interval. As a consequence, discontinuous transmission (DTX) is employed in order to reduce the bit rate, leading to lower interference, therefore, increasing the capacity of the network. Additionally, the autonomy of the MTs can be increased.

Multimedia streaming is a technique of transferring data that turns possible a steady and continuous stream. The client browser or plug-in can starts displaying data before the entire file has been transmitted. Streaming class services preserve time relation between information entities of the stream. Nevertheless, the acceptable delay variation is much greater that the delay variation given by the limits of human perception. Audio and video streaming, broadcast of multimedia contents and video on demand are examples of applications of the Streaming class.

Interactive class includes applications when the end-user, that can be a machine or a human, is online requesting data from remote equipment. Examples of applications are: web browsing, data base retrieval, tele-machines.

Background class scheme applies when the end-user, such as a computer, sends and receives data-files in the background. The destination is not expecting the data within a certain time and the payload content has to be preserved as in Interactive class. Resource transmissions are used only when none of the other classes are active. Applications of background class are: Multimedia Message Service (MMS), Short Message Service (SMS), exchange of email.

IEEE 802.16 defines five scheduling service types, also called QoS classes: Unsolicited Grant Service (UGS), Real-time Polling Service (rtPS), Non-real-time Polling Services (nrtPS), Best Effort (BE) and Extended Real-time Polling Service (ertPS) with the last one added in the 802.16e standard [Nuay07].

Data services and applications with varied QoS requirements supported by Mobile WiMAX are summarised in Table 2.8.

Table 2.8. Mobile WiMAX Applications and Quality of Service (extracted from [WiMF06a]).

QoS Category	Applications	QoS Specifications
UGS	VoIP	Maximum Latency Tolerance
rtPS	Streaming Audio or Video	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency Tolerance Traffic Priority
ertPS	VoIP	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency Tolerance Traffic Priority
nrtPS	File Transfer Protocol (FTP)	Minimum Reserved Rate Maximum Sustained Rate Traffic Priority
BE	Data Transfer Web Browsing	Maximum Sustained Rate Traffic Priority

The standards use specific request and grant mechanisms in which each SS informs the BS about the amount of the UL bandwidth it needs. So, The BS scheduler can make a prediction about the throughput and latency needs of UL traffic, using the scheduling service specified and its associated QoS parameters.

The UGS scheduling service type is conceived to support real-time data streams, consisting of fixed-size data packets on a real-time periodic basis, which ensure that grants are available to meet the streams real-time needs. This mechanism eliminates the overhead and latency of SS request.

The rtPS scheduling service type is designed to support real-time data streams consisting of variable-sised data packets that are issued at periodic intervals, such as Moving Pictures Experts Group (MPEG). The key QoS parameters for rtPS connections are the minimum reserved traffic rate and the maximum latency, which upper bounds the waiting time of a packet at the MAC layer. rtPS connections are required to notify the BS of their current bandwidth needs when the size of arriving packets is variable [CiLM06].

The ertPS class was added by the 802.16e amendment, being a scheduling mechanism based on the efficiency of both UGS and rtPS. The BS realises not asked unicast grants in order to save the latency of a bandwidth request. However, instead of UGS, ertPS allocations are dynamic being suitable for variable rate real-time applications with data rate and delay requirements.

The nrtPS supports data streams consisting of variable-size data packets with a minimum data rate requirement. In the scheduling service, a unicast UL request polls are provided by the BS with the purpose of guarantee that the service flow receives request opportunities even during situations of network congestion. A minimum bandwidth is reserved to improve the performance of applications like FTP.

Finally, the BE service is designed to support data streams with no QoS guarantee. The BS is not obliged to send unicast UL request polls for its SSs. Because of that, it is possible that long periods of time exist, with the network congested, without BE packets being transmitted.

Both UMTS/HSPA and Mobile WiMAX have the capability of providing a whole new class of services that exploit the increasing number of available network resources. QoS has an important role because, in wireless communications, the link characteristics are variable and unpredictable, depending on the location of users and the time of the access to a certain service. Therefore, the services are grouped into classes defined by a set of parameters, which are very important to the network that has the capability of accept or decline a service that is requested in a certain time. Both standards give more priority to the classes that represent real-time services instead of those that are responsible for delay-tolerant applications. The classes defined for the two systems are quite similar assuming a clear parallelism. Table 2.9 presents the classes association that exists between the two.

Table 2.9. QoS classes correspondence of UMTS/HSPA+ and Mobile WiMAX.

UMTS/HSPA+ QoS Class	Mobile WiMAX QoS Class
Streaming	rTPS
Interactive	nrtPS
Background	BE
Conversational	UGS
	ertPS

Chapter 3

Model and Simulator Description

In this chapter, an overview of the single user radius model and the HSPA+/Mobile WiMAX simulator is presented. The former is intended to provide an overview of network planning, regarding cell radius for HSPA and Mobile WiMAX, when a single user is at the cell edge requiring a certain service. This model can be used in the first phase of network planning to estimate cell radius. The multiple users simulator, based on an existing one, has the objective of analysing a more realistic scenario, with users performing multiple services and randomly spread over the coverage area. The main outputs of the simulator are the average network radius, average instantaneous network throughput and the extrapolation for the busy hour. This chapter concludes with the assessment of the simulator and the definitions of the number of users.

3.1 Single User Radius Model

In this section, a first evaluation of the performance of the two systems is done namely through the calculation of the radius for a single user (SU) being served with a certain service with the consequent throughput. The radius corresponds to the distance between the MT and the BS. In this analysis, the inputs are the throughput requested and radio parameters, which differ according to the system.

Another important issue of this model is to compare the influence of overheads in the performance of both systems. As known from the OSI model, the throughput available at application level is lower than the one at the physical level, due to the necessary overheads at the layers that are between the application and physical levels.

For HSPA+ DL, the considered radio parameters are:

- Transmission power,
- Frequency,
- Modulation scheme,
- System configuration,
- BS and MT antenna gains,
- Environment: pedestrian, vehicular and indoor.

Other parameters, such as additional losses, noise factor, traffic power percentages, coding rate and overheads can also be modified.

It is assumed that 15 spreading codes are available at spreading factor 16 with all codes being used by the MT. In spite of 15 HS-PDSCH codes, only 14 are used for data, with 2 HS-SCCH codes devoted to signalling and control functions.

The application throughput, R_b^{APP} , is calculated, in DL, considering only 81.0 % of the throughput at physical level, R_b^{PHY} , due to the necessary overheads - application (5%), MAC (3.125%) and RLC (2.5%) layers - and the Block Error Rate (BLER) (10%). The values chosen for MAC and RLC overheads were obtained from [3GPP07a].

Additionally, a codification rate of 100 % is considered, assuming total knowledge of the channel, which is according to the main purpose of this single user simulator: to obtain the maximum range of the cell for a certain service throughput.

The maximum application throughput is limited by both modulation and configuration chosen. The maximum throughputs at the physical layer and at the application level for different modulation schemes and antenna configurations - Single Input Single Output (SISO), and MIMO (2×2) are represented in Table E.1.

For HSPA+ UL, the radio parameters introduced are similar to DL with the exception of the different available modulations. The maximum peak throughput at physical layer is 11.5 Mbps. The application of the reductions necessary to include the effect of overheads, with exception of RLC overhead that is, for UL, 0.625%, leads to a maximum application throughput of 9.47 Mbps.

For Mobile WiMAX, the general radio parameters are, once more, the ones used for HSPA+. Two important parameters take an important role in the performance assessment of Mobile WiMAX: the channel bandwidth and the TDD split. Diversity gain, additional losses, noise figure and implementation margin can be changed in the simulator developed. The frequency used for the analysis of Mobile WiMAX in this thesis is 2.5 GHz, but simulator includes 3.5 and 5.8 GHz. This value allows a more realistic comparison between the two systems, since HSPA+ works, approximately, in the 2.1 GHz frequency for DL and 1.9 GHz for UL. In terms of coverage, one knows that higher frequency bands of Mobile WiMAX have a lower performance in terms of coverage.

The throughput values presented in Table 2.4 are relative to the physical layer for a TDD split 1:0 or TDD Split 0:1 with 44 OFDM data symbols which means that all symbols are used for DL or UL. The throughput available at the application level is obtained considering that only 37 OFDM symbols transmit data. This number of symbols is kept constant not depending on the number of users allocated to each frame, which has a duration of 5 ms. Moreover, the number of data symbols is distributed for DL and UL concerning the TDD Split chosen. The application overhead considered is 5% and a reduction of 10% is performed due to BLER. The channel bandwidths considered are: 5, 10 and 20 MHz, with the last one being calculated using an extrapolation from the other two bandwidths values. The application throughputs are listed for different TDD Split in Table A.3 to Table A.6.

Mobile WiMAX can support different antenna configurations in order to take advantage of higher peak data increasing both UL and DL throughputs. Using 2×2 MIMO, the peak data rate considered is the maximum theoretical capacity gain, i.e., the capacity is duplicated compared with SISO. In UL, the MT has only one transmit antenna, which allows that two users transmit data in the same slot as if two streams are spatially multiplexed from two antennas of the same user – collaborative SM.

In [WiMF06a], theoretical peak data rates for both SIMO and MIMO configurations and different DL/UL ratios are presented for a 10 MHz channel bandwidth, 5ms frame, PUSC sub-channel and 44 data OFDM symbols. The maximum application throughputs, applying the overheads, for different antenna configurations and channel bandwidths are represented in Table E.2.

The purpose of this model is to estimate the cell radius for the throughput selected in the user interface. As a consequence, the requested throughput is mapped onto SNR and E_c/N_0 in HSPA+, DL and UL respectively. In this manner, it is possible to calculate the receiver´s sensitivity, interpreted as the minimum received power that allows the user to be served with the requested service, which is characterised by a certain throughput. It is important to emphasise that power control is taken into account in this calculation. The interference margin is not considered, because there is only one user in the cell. Seeing that the main objective is to calculate the maximum cell radius, the maximum BS antenna gain and the lowest frequency in the available band are used. Several assumptions are taken, such as perfect channel conditions and the absence of interference of both external factors and multiple users.

This model is based on a snapshot analysis of the cell not taking variations occurred during the time frame into account. On the one hand, the model involves best radio conditions, but on the other, both constant slow and fast fading margins are included in the environment margins.

HSPA+ and Mobile WiMAX receiver´s sensitivity are calculated in Annex A. The path loss is determined from the COST-231 Walfisch-Ikegami propagation model [DaCo99]. The cell radius can be calculated as follows:

$$r_{[\mathrm{km}]} = 10^{\frac{EIRP_{[\mathrm{dBm}]} - P_{r[\mathrm{dBm}]} + G_{r[\mathrm{dBi}]} - M_{[\mathrm{dB}]} - L'_{tt[\mathrm{dB}]} - K_f \cdot \log(f_{[\mathrm{MHz}]}) - L'_{tm} - 10\cdot\log(f_{[\mathrm{MHz}]})_{[\mathrm{dB}]} - 32.4 - 20\cdot\log(f_{[\mathrm{MHz}]})}{20 + k_d}} \tag{3.1}$$

where:

- *EIRP*: equivalent isotropic radiated power, given by (A.3) and (A.4),
- k_d: dependence of the multiscreen diffraction loss versus distance,
- k_f: dependence of the multiscreen diffraction loss versus frequency,
- L_0:free space loss,
- L_{tt}: rooftop-to-street diffraction loss,
- L_{tm}: approximation for the multi-screen diffraction loss,
- $L'_{tm} = L_{tm} - 10 \cdot \log(f_{[\mathrm{MHz}]})$.
- $L'_{tt} = L_{tt} - k_d \cdot \log(r_{[\mathrm{km}]}) - k_f \cdot \log(f_{[\mathrm{MHz}]})$,
- *M*: total margin, given by (A.15).

3.2 HSPA+ and Mobile WiMAX Simulator

3.2.1 Simulator Overview

The simulator used in this thesis is an evolution of the one developed on [CoLa06], [Card06] and [SeCa04]. The global simulator´s main structure is presented in Figure 3.1.

The simulator allows a complete analysis and comparison between a FDD system, UMTS/HSPA, and a TDD system, Mobile WiMAX. The simulator can be represented by four main modules:

- Users Generation,
- Network deployment and single user analysis,
- UMTS/HSPA+ analysis sub-divided in DL and UL,
- Mobile WiMAX analysis sub-divided in DL and UL.

The yellow and green modules were implemented in the scope of this thesis, while the blue and red modules are inherited. The new modules were developed in C++ language and using MapBasic and Mapinfo software. The former is necessary to compute all the information about the network and the users, while the latter are used in order to give an intuitive interface to user, deploy the network and, finally, present the results.

The users generation module is described in [CoLa06]. Users are distributed in the city of Lisbon, according to the population density areas. This placement is the responsibility of the network deployment module, also described in [CoLa06]. Afterwards, the module deploys the network using the location of BSs. The WiMAX and HSPA+ BSs are co-located, i.e., the location of the BSs is common for both systems. Next, the cell radius is calculated for each service and a reference service.

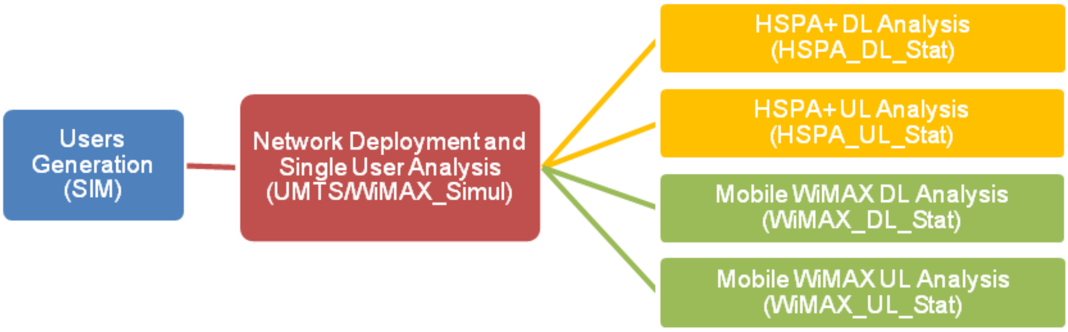


Figure 3.1. Mobile WiMAX and HSPA+ Simulator overview.

3.2.2 UMTS/HSPA+ and Mobile WiMAX Implementation

The four modules developed in the thesis context have the main responsibility to do the overall calculations that lead to the final output, i.e., the analysis of network capacity and coverage for both systems. With all necessary data collected for a snapshot model, an estimation for the busy hour is done, i.e., the data volume of the network and the number of users are obtained. The network results are obtained through the average value of all BSs.

The parameters taken into account for HSPA+ and Mobile WiMAX, both for DL and UL, are:

- BS DL Transmission Power,
- MT UL Transmission Power,
- Frequency,
- MT antenna gain,
- User and cable losses,
- Modulation,
- Antenna configuration,
- Noise Factor,
- Signalling and control power percentage,
- Strategy reduction,
- Reference service,
- Interference margin,
- Environment,
- Service Percentage penetration,
- QoS priority,
- File size for each of services.

The TDD split and the channel bandwidth are parameters exclusive of Mobile WiMAX parameters. All parameters can be modified in the interface and their change influences in the final results.

The transmission power is not shared in both systems, because its effect will only be perceptible if a per-TTI analysis is realised, which is out of the scope of the thesis, where a snapshot analysis is performed. It is important to note that each user performs only one service in the instant where the analysis is done.

The modulation is a parameter that limits the maximum achieved throughput for each user and, as a consequence, the capacity of a BS. In HSPA+, the maximum achieved throughput of a user is obtained through the respective modulation. In Mobile WiMAX, due to the AMC, the modulation chosen means that the user can be served by that modulation and other with lower SNR values, e.g., if a modulation of 16QAM is selected, the user can only be served by QPSK and 16QAM and the corresponding SNR and throughput.

The antenna configuration influences the capacity and coverage of the system. Diversity is essentially used to minimise the effects of fast fading consisting of the use of redundancy in signal reception. The use of diversity is associated to the use of signal combining: several replicas of the signal which exhibit some uncorrelation, are combined at the receiver, in order to get an improved signal, compared to the one obtained in the absence of combining [Corr06]. The use of SIMO in this thesis consists in the use of spatial diversity, i.e., the use of two antennas used for signal reception with some spacing in between. The use of SIMO, which have a diversity gain associated, increases the BS cell radius, compared to SISO.

The consideration of MIMO in the scope of this thesis consists in the use of two antennas in transmission and reception sending different information in parallel. The objective is to exploit the space and time diversity of the channels on different radio paths to improve the sensibility and capacity of the system [Nuay07]. In the multiple users (MU) analysis, the Relative MIMO Gain (RMG) model, Annex D, is applied with the aim of giving a more realistic approach when there are no expressions for MIMO configurations, as it happens with HSPA+ UL and Mobile WiMAX.

For DL, two different approaches can be foreseen for the power issue in MIMO configuration. The first one assumes the same feeding power for the two antennas as for SISO, i.e., assuming that both antennas would be fed with the maximum transmission power. In this approach, a new power amplifier for the other antenna must be added, which leads to significant additional upgrade costs. Contrary, the second approach considers that the overall power available for SISO system is split among the antennas, which means that the additional antenna for the use of MIMO is fed with half of the power used for SISO. Therefore, there is no need for additional power amplifiers, which means that the upgrade costs are reduced. Nevertheless, in the second approach, the expected coverage and throughputs obtained are lower being extremely important to measure the advantages and the disadvantages of each antenna power fed mode.

It is important to point that UMTS/HSPA+ is deployed on top of Release 99. So, it is necessary to reserve a percentage of the total BS or MT Transmission Powers not only for UMTS/HSPA+ but also for Release 99, even though there are dedicated channels.

The reductions strategies, explained in detail in [Lope08] and [Salv08], for both systems are:

- “Throughput reduction”, where all users are reduced for a certain percentage, HSPA+, or for a certain number of sub-channels, Mobile WiMAX.
- “QoS class reduction “, where all the users from the same services are reduced according to the services priority list.
- “QoS one by one reduction”, where for a certain service, each user is reduced one by one; services are also reduces according to a priority list.

In “QoS class reduction”, the throughput reduction can assume any value if the system is HSPA+ and there are some restrictions if the system is Mobile WiMAX, because the reductions have to take the sub-channels attribution into account. This happens due to the fact that the reduction of throughput in OFDMA is not a continuous process, because there is an allocation of sub-channels to users. The bursts of OFDMA frame structure, Figure 2.9, are considered with the same size. Since soft handover is not considered in HSPA+ UL, the strategies considered are similar to the DL ones.

The reference service is used to define the cell radius edge of the sectors of tri-sectorial BSs in analysis. If a user is not inside a sector cell radius, it is not covered and, therefore, it is not be considered in the analysis. The single user model defines, for the reference service, the SNR necessary. Later on, the maximum distance for that SNR is calculated corresponding to the cell radius adapted for the network. It is important to point that for this calculation, HSPA+ and Mobile WiMAX use different strategies taking the relevant parameters for each system, as seen in Annex A.

Contrary to the single user model, there are several BSs and users in the target region. So, the phenomenon of interference cannot be neglected. The calculation of the interference margin is explained in Annex A. This change influences the system performance, since path loss decreases and, consequently, the cell radius is lower compared to the one obtained without interference. The covered users, due to the interference margin, have a lower SNR, which lead to a throughput decrease. Another important aspect that influences the cell radius considered for the analysis is the environment, because indoor penetrations are different.

In order to simulate a typical urban scenario, the Log-Normal and Rayleigh distributions are implemented to simulate the slow and intense fast fading respectively.

With all necessary parameters collected, the next step is to define the maximum and minimum throughputs for each of the services using the values introduced in the User Profile Window. The procedure of introduction of BSs and users is described in Section 3.2.1. The maximum physical throughput supported by a HSPA+ BS corresponds to the maximum peak data rate obtained, considering the modulation and configuration chosen, for the cases of Figure 2.5 and Figure 2.6. For Mobile WiMAX, the capacity of a BS corresponds to the maximum throughput than can be reached for a combination of modulation, antenna configuration, TDD split and channel bandwidth. These values are calculated through Table 2.4, observing that for different TDD Splits, the throughput has to be multiplied by the respective constant, as explained in Annex A. The maximum peak data rate for the MIMO configuration is obtained multiplying the SISO ones by the RMG mean value given, Annex D.

During the process of simulation, the number of users that are inside the coverage area of the BSs is calculated followed by the generation of files used in the HSPA_DL_Stat, HSPA_UL_Stat, Mobile_WiMAX_DL_Stat or Mobile_WiMAX_UL_Stat modules:

- “data.dat”, which has, among other information, the BS that the user is connected with, the distance between them and the service that is requested.
- “definitions.dat”, containing the data parameters used, the minimum and maximum throughput for each service, the QoS priority list, the indoor penetration margins considered and another relevant information to the analysis.

With all settings stored, the modules developed start the process by associating every covered users to the closest BS. Usually, in urban scenarios, a user is inside the coverage of several BSs. In terms of capacity, one does not perform any optimisation of the resources of the BS, because the total network is only created later on. Using the link budget explained in Annex A, the user is associated with the maximum possible throughput for the path loss considered. As consequence, three situations can be possible:

- The user is served with the requested throughput, when the throughput given by the distance is higher than the service´s throughput;
- The user is served with the throughput given by the distance if the latter is higher than the minimum and lower than the maximum service throughput;
- Otherwise, the user is delayed.

In order to have a more realistic approach, the services´ throughput, obtained from the file “definitions.dat”, are multiplied for a random number between 0 and 1. Afterwards, the comparison is performed between the number achieved and the throughput associated to the distance. This consideration comprehends the situations when the major fact that limits the throughput is a punctual congestion of the network. This procedure was adapted from the one developed in [Lope08] and [Salv08], and the flowchart is presented in Annex F.

After the throughput calculation algorithm, the following process consists of analysing the system capacity, at the BS level. This process and the flowchart associated are also explained in detail in [Lope08] and [Salv08]. In the capacity context, there are two possible cases:

- all users are served without reduction, if the sum is lower than the maximum allowed for the BS considered;
- otherwise, the users suffered a throughout reduction chosen by the total user in the simulator interface.

Still regarding capacity aspects, it is important to note that the services analysis is not equal in the two systems. In UMTS, the operators have two carriers, one dedicated for Release 99 and the other to HSPA+. Services like voice and video-telephony are served by the Release 99 carrier and data services are transported by the HSPA+ carrier in such a way that, only data services contribute to the capacity of HSPA+. Mobile WiMAX, instead of UMTS, has an available bandwidth for all services, which makes that voice and video-telephony, in spite of not being analysed together with data services, have to be performed and, occupying the bandwidth, are reducing the capacity for data services, Figure 3.2.

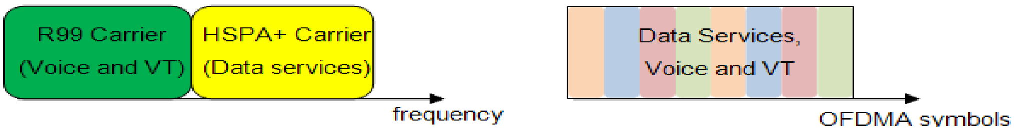


Figure 3.2. Distribution of services in UMTS/HSPA+ and Mobile WiMAX (Note: VT means Video-Telephony).

The next step of the process comprises a calculation of several network parameters for each BS.

- The instantaneous served throughput, R_{bBS}:

$$R_{bBS\,[\mathrm{Mbps}]} = \sum_{j=1}^{N_{uBS}} R_{bj\,[\mathrm{Mbps}]} \tag{3.2}$$

  where:

  - N_{uBS}: number of users served in a BS,
  - $R_{b,j}$: instantaneous throughput of the user j.

- The normalised throughput, R_{bNORM}:

$$R_{bNORM} = \frac{\sum_{j=1}^{N_{uBS}} R_{bj\,[\mathrm{Mbps}]}}{R_{b\max\,[\mathrm{Mbps}]}} \tag{3.3}$$

  where:

  - R_{bmax}: maximum BS allowed throughput.

- The cell radius of the BS, r:

$$r_{[\mathrm{km}]} = \frac{\sum_{j=1}^{N_{sect}} d_{BSj\,[\mathrm{km}]}}{N_{sect}} \tag{3.4}$$

  where:

  - N_{sect}: number of sectors of a BS,
  - d_{BSj}: distance between the user placed further away and the BS.

- The average instantaneous throughput per user, $\overline{R_{bj}}$:

$$\overline{R_{b,j\,[\mathrm{Mbps}]}} = \frac{R_{bBS\,[\mathrm{Mbps}]}}{N_{uBS}} \tag{3.5}$$

- The satisfaction grade, S_G :

$$S_G = \frac{\sum_{j=1}^{N_{u,BS}} R_{bserj\,[\mathrm{Mbps}]}}{\sum_{j=1}^{N_{u,BS}} R_{breqj\,[\mathrm{Mbps}]}} \tag{3.6}$$

  where:

  - R_{bserj} : served throughput of user j,
  - R_{breqj} : requested throughput of user j.

- The total BS traffic transferred in an hour, T_{BS}:

$$T_{BS[\text{GB/h}]} = \sum_{j=1}^{N_{services}} N_{uhservj} \times V_{uj[\text{GB/h}]} \quad (3.7)$$

where:

- $N_{uhservj}$: number of users per hour performing the service *j* in the BS,
- $N_{services}$: number of data services considered,
- V_{uj}: volume per user associated to service *j* in the BS.

- The average data volume per user, $\overline{V_{uj}}$:

$$\overline{V_{u[\text{MB}]}} = \frac{T_{BS[\text{MB}]}}{N_{uhBS}} \quad (3.8)$$

where:

- N_{uhBS}: number of users served in an hour in the BS.

- The number of users served in an hour in the BS, N_{uhBS}:

$$N_{uhBS} = \sum_{j=1}^{Nservices} N_{uhj} \quad (3.9)$$

Additionally, the following parameters are also calculated:

- number of delayed users, taking the sum of served and delayed users into account that corresponds to the total number of users covered,
- percentage of satisfied and unsatisfied users, considering a satisfied user like one being served with the request throughput.

The parameters analysed per service allow a perspective of the influence of each service in the global results. Next, the analysis is done for the entire network with the calculation of the average network using the number of users performing each service.

From the view point of network analysis, the most important parameters to be analysed are calculated:

- The average ratio of served users, $\overline{S_u}$:

$$\overline{S_u} = \frac{\sum_{j=1}^{N_{BS}} N_{uBSj}}{N_{uTOT}} \quad (3.10)$$

where:

- N_{BS}: number of active BS in the network,
- N_{uTOT}: total number of covered users.

- The average network satisfaction grade, $\overline{S_{Gnet}}$:

$$\overline{S_{Gnet}} = \frac{\sum_{j=1}^{N_{BS}} S_{Gj}}{N_{BS}} \quad (3.11)$$

- The average network radius, $\overline{r_{net}}$:

$$\overline{r_{net}} = \frac{\sum_{j=1}^{N_{BS}} r_j}{N_{BS}} \tag{3.12}$$

- The average network throughput, $\overline{R_{bnet}}$:

$$\overline{R_{bnet[\text{Mbps}]}} = \frac{\sum_{j=1}^{N_{BS}} R_{bBS[\text{Mbps}]}}{N_{BS}} \tag{3.13}$$

The network dimensioning takes into the account the capacity and coverage aspects for the busy hour of the day, i.e., the most demanding period of the day, when the probabilities of congestion are higher. In this analysis, the parameters studied are the total network throughput and the total number of served users per hour.

- The total network traffic per hour, T_{net} :

$$T_{net[\text{GB/h}]} = \sum_{j=1}^{N_{BS}} T_{BS[\text{GB/h}]} \tag{3.14}$$

- The total number of served users per hour in the network, N_{uhnet} can be expresses as:

$$N_{uhnet} = \sum_{j=1}^{N_{BS}} N_{uhBS} \tag{3.15}$$

The last analysis requires the successive determination of: users´ sessions duration, number of sessions per hour, number of users in the busy hour, and finally, the total traffic for each service.

3.2.3 Input and Output files

The simulations require the insertion of the following files in UMTS_Simul application:

- “Ant65deg.TAB”, containing the BS´s antenna gain for all direction,
- “DADOS_Lisboa.TAB”, with information of Lisbon and all its districts,
- “ZONAS_Lisboa.TAB”, with the area characterisation, such as streets, gardens, and others,
- “users.txt”, with the distribution of the users in the network, being an output from the SIM module;
- “BSs_Lisbon_map.TAB”, with the information of the location of the co-located BSs.

The UMTS_Simul module creates 2 files used by HSPA+ and Mobile WiMAX modules in order to realise the simulations:

- “stats.out”, which includes all results for the instantaneous analysis in a network context or in a service overview,
- “stats_per_hour.out”, containing the busy hour results.

The interfaces of the single user and a user manual for the multiple users simulator are presented in Annex G and H, respectively.

3.3 Simulator Assessment

Before performing simulations and its results analysis, the simulator must be assessed, namely the validity of the output and the necessary number of simulations that ensure statistical relevance. For this task, several tools and approaches, such as averages, relative mean errors and standard deviations were inspected. The propagation model and link budget were confirmed through inspections done in Matlab and Excel, which allows ensuring the correction and agreement with the theoretical model.

After the simulation, all the output results, namely summations, averages and standard deviations were tested and confirmed for each BS and, in a global perspective, by analysing the whole network.

The assessment of functions used for the calculation of slow and fast fading was done in [Bati08] and [Marq08] and the reduction strategies were assessed in [Lope08] and [Salv08].

Since users´s geographical positions and their requested throughput have a strong randomness associated, several simulations must be taken to ensure result validation. The number of users considered, rightly justified later on in this section, is approximately 1600. With this value, 30 simulations were performed, with an average duration of 30 minutes. The parameters considered in this examination are: average ratio of served users, average satisfaction grade, average network throughput and average network radius.

The average, μ, and the standard deviation, σ, were inspected using (3.16) and (3.17).

$$\mu = \frac{\sum_{i=1}^{n} z_i}{N_s} \tag{3.16}$$

where:

- z_i: sample i;
- N_s: number of samples.

$$\sigma = \sqrt{\frac{1}{N_s}\sum_{i=1}^{N_s}(z_i - \mu)^2} \tag{3.17}$$

The number of simulations is estimated based on the results presented in Table 3.1, where several parameters are considered for a variable number of simulations. The evolution of the average ratio of served users and the average satisfaction grade are illustrated in Figure 3.3. The evolution of the average network radius and the average network throughput are presented in Figure 3.4. Both average values and standard deviations have no significance variations with the increase on the number of simulations. Average network throughput is the parameter that presents higher values of standard deviation, due to the differences occurred between the first collection of simulations and the remaining ones.

Considering not only the precision of the results obtained, but also the duration of each simulation, one can conclude that 10 simulations are enough; if more simulations were considered, it could be impracticable for all demanding variations of the default scenario. The system considered in the assessment was the HSPA+, working in DL because, in DL, for the reference service adapted of 7.2 Mbps, all users are covered.

Table 3.1. Evaluation of several parameters for different number of simulations.

Number of simulations	Ratio of served Users		Satisfaction grade		Network throughput [Mbps]		Network radius [km]	
	µ	σ	µ	σ	µ	σ	µ	Σ
5	0.65	0.03	0.95	<0.01	8.66	0.46	0.29	0.01
10	0.64	0.03	0.95	<0.01	8.59	0.39	0.29	0.01
15	0.64	0.02	0.95	<0.01	8.58	0.36	0.29	0.01
20	0.64	0.02	0.95	<0.01	8.56	0.42	0.29	0.01
25	0.64	0.02	0.95	<0.01	8.57	0.43	0.29	0.01
30	0.64	0.02	0.95	<0.01	8.58	0.40	0.29	0.01

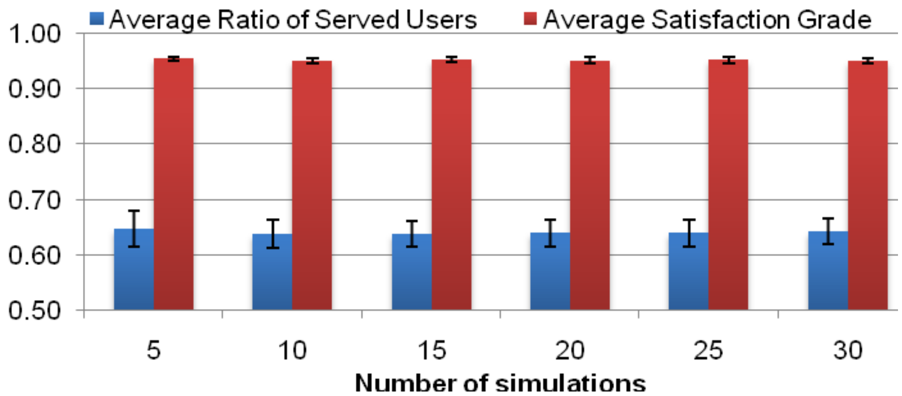
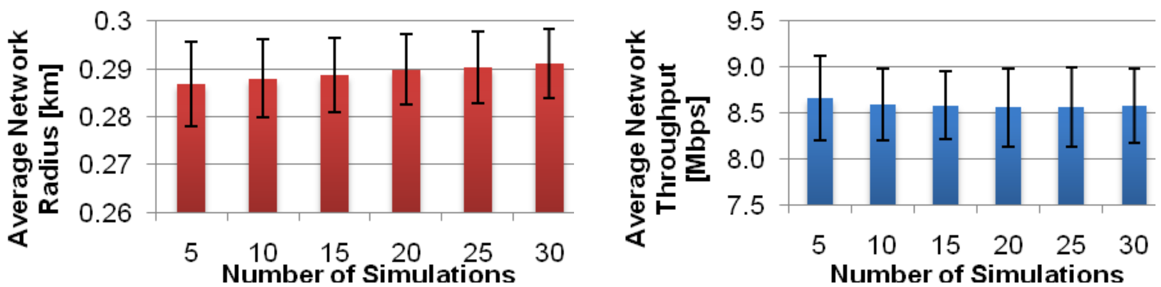


Figure 3.3. Evolution of the average ratio of served user and average satisfaction grade for 30 simulations.



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

Figure 3.4. Evolution of the average network radius and average network throughput for different number of simulations.

In Figure 3.5, it is possible to see the ratio of the standard deviation, σ, over the average value of each one, µ, in the analysed parameters. One can verify that there is no relevant decrease of this ratio with the increase of the number of simulations. This fact intensifies the trend to decide for 10 simulations as a reasonable number. The average ratio of served users and the average instantaneous throughput per user are the higher values achieved, but they are below 0.05, hence, a hypothetical increase in the number of simulations would not cause any impact on the results.

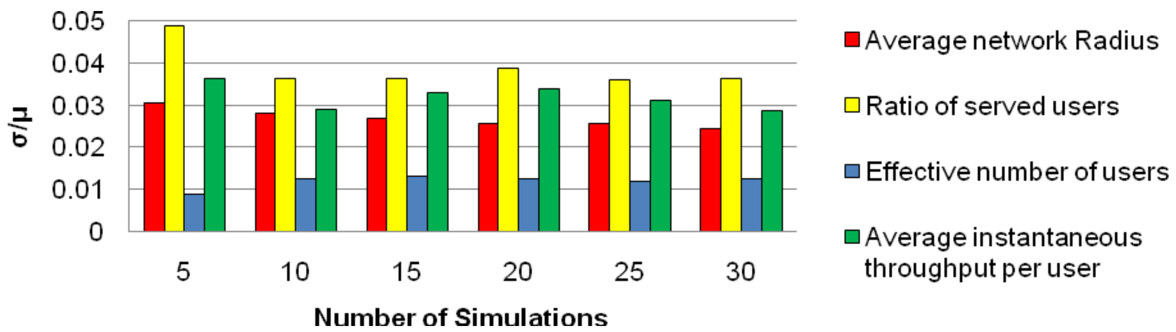


Figure 3.5. Analysis regarding the number of simulations considered.

Another important issue concerning the assessment of the simulator, as mentioned before, is the definition of the number of users that are introduced in the simulator. Not all the users introduced are observed in the map of Lisbon, because the module UMTS/WiMAX_Simul places some users out of the region under analysis. So, 10 simulations with 1000, 1500, 2000 and 2500 users were performed corresponding, approximately, to 800, 1200, 1600 and 2000 users examined. Several numbers of users are examined taking the most relevant parameters into account, Table 3.2.

Table 3.2 Evaluation of number of users taking several parameters into account.

Parameters	Approximate number of users							
	800		1200		1600		2000	
	μ	σ	μ	σ	μ	σ	μ	σ
Average Network Throughput [Mbps]	5.52	0.37	7.19	0.47	8.55	0.41	10.37	0.31
Average Network Radius [km]	0.28	0.01	0.28	0.01	0.29	0.01	0.30	0.01
Average Satisfaction Grade	0.96	0.01	0.95	0.01	0.95	0.00	0.95	0.01
Average Ratio of Served Users	0.65	0.03	0.66	0.02	0.65	0.02	0.65	0.01
Average Instantaneous Throughput/user [Mbps]	2.82	0.16	2.84	0.10	2.80	0.09	2.83	0.08
Effective Number of Users	793	13	1189	10	1586	12	1988	19

As expected, the average network throughput increases with the number of users. The remaining parameters have smooth variations, which can be explained by the use of MIMO in HSPA+ DL and by the use of the R99 carrier to support users performing voice and video-telephony. The maximum capacity is never reached; hence, the average ratio of served users, average satisfaction grade and average instantaneous throughput per user do not vary significantly. The reduction strategy does not have influence on the results. Regarding the effective number of users placed in Lisbon, one can observe that 800, 1200, 1600 and 2000 users are good approximations.

Chapter 4

Results Analysis

In this chapter, the results for both single user radius model and for the multiple users simulator are presented. First, the single user radius model is analysed, separately for HSPA+ and Mobile WiMAX, followed by a brief comparison between both systems. The results from the simulator introduced in Chapter 3 are then presented, considering always a comparison for both systems, considering capacity and coverage aspects. Several parameters variations are done in order to evaluate the impact relative to the default scenario, such as antenna configuration, modulation scheme, more users, enhanced throughputs, and alternative profiles. The results are presented separately for DL and UL. For DL, a district analysis is done in order to have a more specific overview of some BSs regarding the type of environment associated.

4.1 Scenarios

In this thesis, two different scenarios are considered with different purposes. The single user scenario is developed considering that the cell is composed by only one user, which has all available resources. For a certain service characterised by a throughput, the maximum cell radius is calculated. When using the single user scenario, all existent multipaths are considered completely uncorrelated with the objective of apply the MIMO gains. The multiple users scenario contemplates the existence of several users uniformly distributed along the coverage area of the BS, performing different services with different associated throughputs. The two scenarios mentioned are simulated with the same environments: pedestrian, vehicular and indoor.

The pedestrian environment consists of a user at the street level suffering low attenuation margins. The vehicular environment stands for users moving at a high speed, being affected by both slow fading, M_{SF}, and fast fading, M_{FF}. In the indoor environment, users are inside, buildings being also constrained, in some situations, by higher penetration attenuation, L_{int}.

The distribution of the different types of environments is as follows:

- Pedestrian – 10%;
- Vehicular – 10%;
- Indoor - 80%;

Indoor environments predominate on the others, representing the largest part of overall percentage. This assumption is taken because the considered services, especially the data ones, are performed, usually, inside buildings through Personal Digital Assistants (PDAs) or laptops.

In this thesis, two different profiles are considered: Voice Centric and Data Centric with the former giving special emphasis to voice and the latter to data, especially, to FTP and Web. In Table 4.1, the percentage of users for each service profile is presented based on[Voda08]. These values determine the number of users that perform each service.

Table 4.1. Voice centric and data centric service profiles.

Service	**Users [%]**	
	Voice Centric	**Data Centric**
Voice	48.6	22.3
Video Telephony	0.2	0.3
Streaming	7.1	7.1
FTP	16.9	30.0
Web	11.8	24.9
E-Mail	10.5	10.5
MMS	4.9	4.9

Attenuation margins associated to each environment for single user scenario as well as the standard deviations for slow and fast fading used in multiple users scenario are listed in Table 4.2. and

Table 4.3, respectively.

Table 4.2. Fading margins and indoor penetration used in SU scenario (extracted from [EsPe06]).

Fading margins and indoor penetration [dB]	**Environment**		
	Pedestrian	Vehicular	Indoor
M_{SF} [dB]	7.6	5.0	7.6
M_{FF} [dB]	2.0	0.0	2.0
L_{int} [dB]	0.0	8.0	20.0

Table 4.3. Distributions and standard deviations used for slow and fast fading margins in MU scenario.

	Environment		
	Pedestrian	Vehicular	Indoor
M_{FF} σ[dB]	Rayleigh Distribution		
	4	2	4
M_{SF} σ[dB]	Log-Normal Distribution		
	4	7	4

The default parameters used for link budget estimation for both scenarios are shown in Table 4.4 for HSPA+ and Table 4.5 for Mobile WiMAX. The bold parameters represent the default values for multiple users simulations, since in single user there are different combinations to emphasise certain aspects and to create similar intervals of throughput to compare the resulting cell radius.

Table 4.4. Default Values used in HSPA link budget (based on [CoLa06] and [EsPe06]).

Parameter	**HSPA+ DL**	**HSPA+ UL**
BS DL Transmission Power [dBm]	44.7	---
MT Transmission Power [dBm]	---	24
Frequency – Single User [MHz]	2112.5	1922.5
Frequency – Multiple Users [MHz]	2142.5	1952.5
Modulations	16QAM, **64QAM**	QPSK, **16QAM**
Configurations	SISO, SIMO, **MIMO**	SISO, **SIMO**, MIMO
MT Antenna Gain [dBi]	0	
Maximum BS Antenna Gain [dBi]	17	
User Losses [dB]	1	
Cable losses between emitter and antenna [dB]	3	
Noise Figure [dB]	9	5
Diversity Gain [dB]	---	2
Interference Margin [dB]	6	
Total Percentage of power for signalling and control (Release 99 + HSPA) [%]	SU: 35 MU: 25	SU: 30 MU: 15
Antenna Power Fed	Split, **Dedicated**	---
Reduction Strategy	"QoS Class Reduction"	
Service throughput reference [Mbps]	7.2	3.6
Services profile	**Voice Centric** and Data Centric	

Table 4.5. Default Values used in Mobile WiMAX link budget (based on [WiMF06a]).

Parameter	Mobile WiMAX - DL	Mobile WiMAX – UL
BS DL Transmission Power [dBm]	43	---
MT UL Maximum Power [dBm]	---	23
TDD split	1:1, 2:1, **3:1**	**1:1**, 2:1, 3:1
DL and UL Frequency – Single User and	**2.5**, 3.5, 5.8	
Channel Bandwidth [MHz]	5, **10**, 20	
Modulations	QPSK, 16QAM, **64QAM**	QPSK, **16QAM,** 64QAM
Configurations	SISO, SIMO, **MIMO**	SISO, **SIMO**, MIMO
MT Antenna Gain [dBi]	-1	
Maximum BS Antenna Gain [dBi]	17	
Cable losses between emitter and antenna	0.7	
User Losses [dB]	1	
Noise Figure + Implementation margin [dB]	8	5
Diversity Gain [dB]	3	
Interference margin [dB]	2	3
Percentage of signalling and control power [%]	0	0
Antenna Power Fed	Split, **Dedicated**	---
Reduction Strategy	“QoS Class Reduction”	
Service throughput reference [Mbps]	7.2	3.6
Services profile	**Voice Centric** and Data Centric	

For HSPA+ and Mobile WiMAX, the maximum BS antenna gain considered is 17 dBi. For the other directions, the antenna gain is given by the horizontal 65º antenna radiation pattern detailed in [CoLa06].

The default throughput values for the different associated services the QoS priority list are presented in Table 4.6.

Table 4.6. Maximum and minimum throughput for the default scenario (based on [Voda08]).

Service	Maximum Throughput [Mbps]		Minimum Throughput [Mbps]		QoS
	DL	UL	DL	UL	
Voice	0.0122		0.0122		1
Video-Telephony	0.064		0.064		2
Streaming	3.6	0.512	0.512		4
FTP	10.0	3.6	1.024		7
HTTP/Web	7.2	3.6	1.024		3
E-mail	3.6		1.024		5
MMS	0.512		0.128		6

The services with a higher value of QoS are the first ones to be reduced if the reduction strategies are applied. The higher throughputs reflect the strong trend of requesting, by users, of more demanding applications in terms of networks capacity. Voice and video-telephony throughputs are not modified, compared with the present technology, because an eventual improvement does not cause perceptible advantages to the users.

The traffic models characteristics for services taken into account are presented in Table 4.7. The values are common to both systems.

Table 4.7. HSPA+ and Mobile WiMAX traffic models.

Service	Parameter	DL	UL
Voice	Average conversation duration [s]	120	120
	Average number of calls per user in an hour	0.825	0.825
Video Telephony	Average conversation duration [s]	120	120
	Average number of calls per user in an hour	0.825	0.825
Streaming	Average video duration [s]	180	180
	Average video size [MB]	10.5	0.02
	Average number of videos per session	3	3
FTP	Average file size [MB]	20	2
	Average number of files per session	2	1
HTTP	Average page size [kB]	300	20
	Average reading time [s]	45	45
	Average number of pages per session	12	12
E-mail	Average file size [kB]	200	200
	Average number of e-mails per session	2	2
MMS	Average file size [kB]	200	200
	Average number of messages per session	2	2

The reduction strategy considered for the simulations is the “QoS Class Reduction” in order to study the eventual impact of the different QoS priority of the services. The antenna power fed to default scenario is the dedicated one in order to achieve higher throughputs.

4.2 Single User Radius Model Analysis

In this section, HSPA+ and Mobile WiMAX results, considering the single user analysis, are presented. Since the study of overheads and their influence on throughput is relevant in the performance of both systems, all throughputs observed are referred to the application level.

4.2.1 HSPA+

Concerning HSPA+, Figure 4.1 presents the cell radius for the different types of environments, for both DL and UL. The modulations adopted are 64 QAM for DL and 16 QAM for UL. The configuration chosen is SISO for both DL and UL. As expected, one can observe that the cell radius decreases with the increase of throughput for all environments. This fact occurs because higher throughputs are associated to higher values of SNR, for DL, and E_c/N_0 for UL, Figure 2.5 and Figure 2.6. Thus, according to (A.1), (A.10) and (A.11), path loss decreases together with the cell radius.

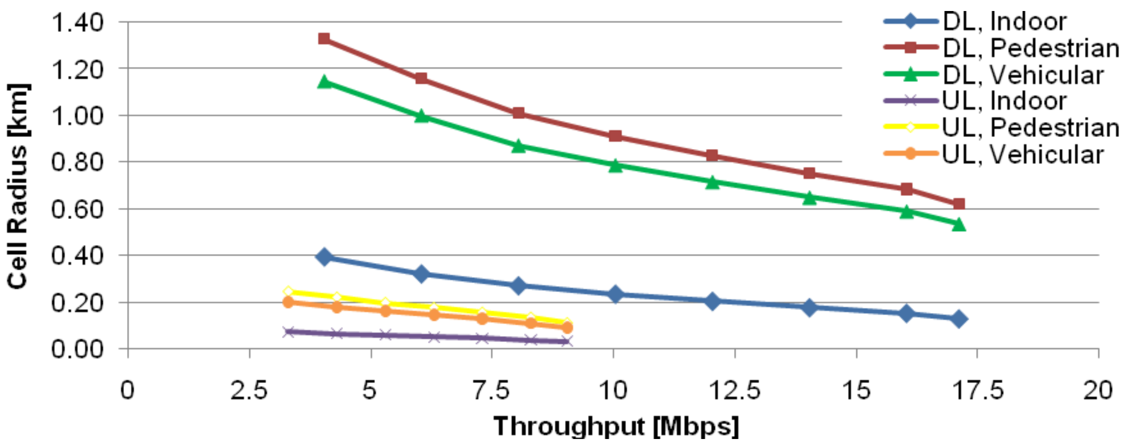
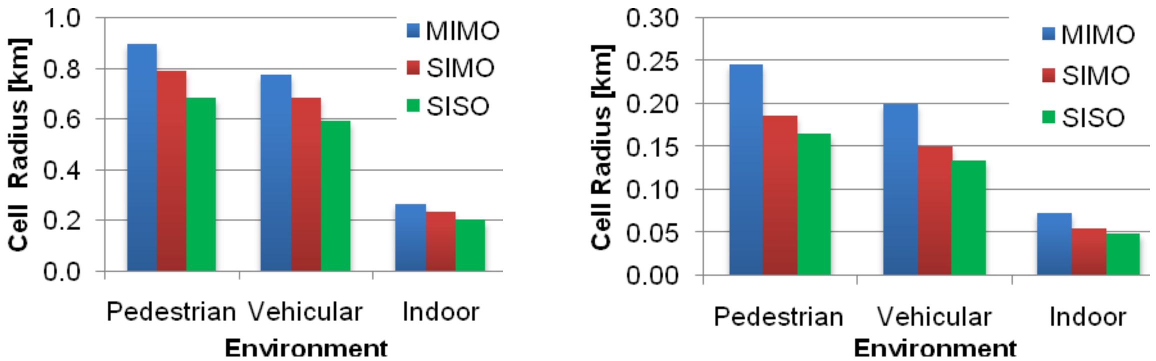


Figure 4.1. HSPA+ cell radius for DL and UL considering different environments.

In respect to the different environments, the cell radius is higher, for the same throughput, in pedestrian environments and lower in indoor ones. The cell radius, for vehicular the environment, is, considering the same throughput, lower than the pedestrian and higher than the indoor ones. Attenuation margins, listed in Table 4.2, are responsible for the variation described in (A.15) and (A.16). In DL, from 4 to 17 Mbps, the radius decreases from 1.33 to 0.62 km for a pedestrian environment and from 0.40 to 0.13 km for an indoor environment. For UL, the reductions observed are from 0.25 to 0.11 km, for a pedestrian environment, and from 0.07 to 0.03 km for an indoor environment of about 3.3 to 9.03 Mbps. For DL, assuming that there is a higher percentage of users requesting services in indoor scenarios, the distance between the users and BSs have to be reduced which introduces problems to the network deployment through the hypothetical necessity of introducing new BSs or reducing of the throughputs delivered to the users. In pedestrian and vehicular environments, the cell radii are more reasonable than the indoor ones. For UL, one can notice that the cell radii are excessive lower for all the environments, being lower than 0.20 km for throughputs higher than 5 Mbps which intensify the problems mentioned for DL. An asymmetric traffic has to be considered to have a more favourable trade-off between coverage and maximum throughputs associated.

The cell radius for HSPA+ for different antenna configurations, with a fixed throughput, is presented in Figure 4.2. The throughputs considered are 12.0 and 7.0 Mbps, for DL and UL respectively. The modulations selected are 64QAM, for DL, and 16QAM for UL. In terms of variation of the cell radius, one can observe that for SIMO it increases 16%, in DL and 13% in UL, compared with SISO.

However, the higher cell radius is reached with MIMO, which increases the cell radius, compared with SISO, of 30 and 49%, in DL and UL. The reason for this improvement on coverage is due to the fact that MIMO requires a lower SNR for the throughputs considered as one can verify in Figure 2.5 for DL. For UL, the increase in using MIMO is higher, because there are no expressions for this topology, therefore, it is necessary to consider that, for all ranges of throughputs, the use of MIMO reduces to a half the value of the associated SNR, i.e., the theoretical capacity gain of MIMO is considered.



(a) DL . (b) UL.

Figure 4.2. HSPA+ cell radius variation considering different environments and configurations.

The cell radius corresponding to the highest throughput achieved for different modulations and environments are presented in Figure I.1. In [Lope08] and [Salv08], one can observe the variation of a cell radius in HSDPA with the variation of transmitting power for 15 HS-PDSCH codes.

4.2.2 Mobile WiMAX

Regarding Mobile WiMAX, Figure 4.3 and Figure 4.4 represent the variation of the cell radius for different channel bandwidths, antenna configurations and environments. Since it is impossible to find a value of throughput common to all combinations, the cell radius corresponds to the maximum throughput for each combination, listed in Table I.1 to Table I.4 for TDD Split 1:1. The TDD Split 1:1 is used, for both DL and UL, and the modulation adopted, for these results, is 64QAM for DL and 16QAM for UL, since 64QAM for UL is optional in the standard. For both DL and UL, the cell radius decreases as the channel bandwidth increases, because there are more available sub-carriers, hence, the throughputs are higher and, consequently, the values of SNR also increases, which makes cell radius decrease as already explained in Section 4.2.1.

Concerning the environments, keeping the configuration and channel bandwidth fixed, the radius varies for the different scenarios due to reasons pointed out in Section 4.2.1. In terms of configuration, keeping the channel bandwidth constant for a certain environment, MIMO is associated to lower cell radius. This fact is a limitation of the model and happens because Figure 4.3 and Figure 4.4 are referred to the maximum throughput achieved for a combination of channel bandwidth, environment and configuration and the use of MIMO duplicate, in a theoretical point of view, the achieved throughput for a SNR. The values of SNR are not continuous; hence, for some throughputs the MIMO effect is more noticeable in capacity than in coverage aspects. For DL, using SIMO, for a 5 MHz channel bandwidth, in a pedestrian environment the radius is near to 0.30 km and, for a 20 MHz channel this value decays to almost 0.15 km. Still regarding the same conditions for UL, the cell radius decreases from 0.20 km to approximately 0.10 km. The increase in the resources allows higher throughputs but the cell radius also decreases to values not practicable to cover large areas as Lisbon.

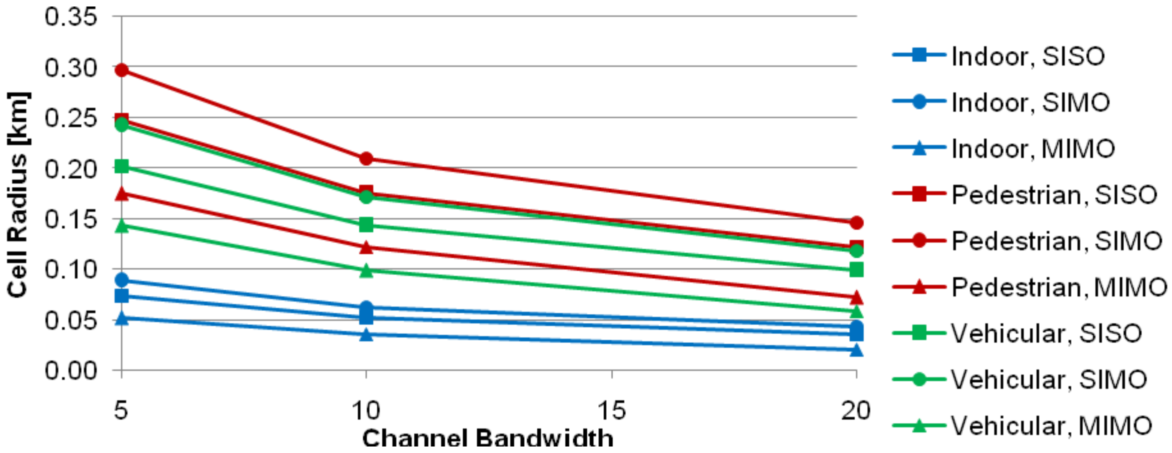


Figure 4.3. Mobile WiMAX cell radius for DL, considering different environments and configurations for the higher achieved throughput.

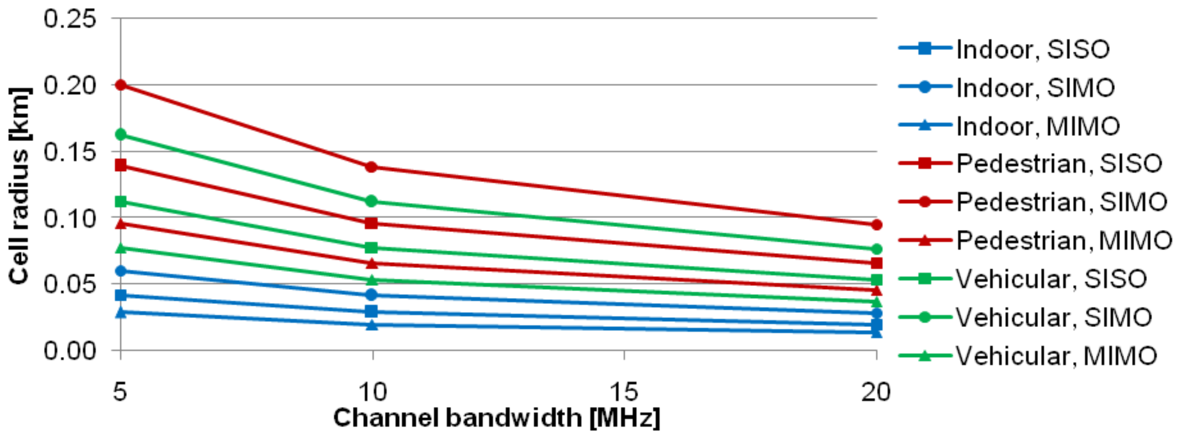


Figure 4.4 Mobile WiMAX cell radius for UL, considering different environments and configurations for the higher achieved throughput.

The frequency considered for Mobile WiMAX is always 2.5 GHz, because 3.5 and 5.8 GHz lead to lower path losses and degradation of the coverage, as one can conclude in [Salv08] where a complete analysis on the effect of the frequency is done.

The cell radius evolution is depicted in Figure 4.5 and Figure 4.6 for a pedestrian environment, varying the modulation and the channel bandwidth. For the other environments, the variation is the same, but with lower values of cell radius, as seen in Figure I.2 and I.3. The evaluated cell radius is for the highest achieved throughput, i.e., is the minimum cell radius for the range of possible throughputs. One can observe that, for less robust modulations with more symbols, the cell radius is lower, because they lead to higher maximum throughputs. A similar variation can be observed for the channel bandwidth, since it is proportional to the available throughput given that there are more resources to be used. The results were collected considering a TDD Split of 1:1 and a SISO configuration.

Finally, it is relevant to analyse the influence of varying the resources distribution for DL and UL. So, for a 64 QAM modulation, a SISO configuration, a channel bandwidth of 10 MHz, and a pedestrian environment, the variation of cell radius is examined considering several values of the TDD Split and the maximum throughputs of the available range. The results are shown in Figure 4.7. The cell radius for DL decreases from 0.18 to 0.14 km when the TDD Split varies from 1:1 to 3:1. There are more resources for DL, which guarantees higher throughput, hence, lower radius cell are obtained. The TDD Split 3:2 leads to a radius, 0.16 km, lower than the one of TDD 1:1, but higher than the others. Regarding UL, the variations are opposite to DL, because UL resources decrease when the resources allocated to DL increase, resulting in lower throughputs and higher cell radii. When UL resources increase, e.g., from TDD Split 3:1 to TDD Split 3:2, the opposite situation happens. The TDD Split 3:1 is more suitable for a deployment, where the differences between the DL and UL coverage must be lower.

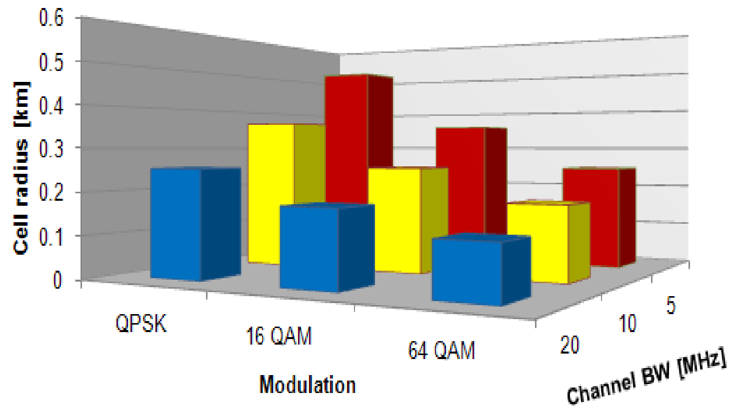


Figure 4.5. Mobile WiMAX cell radius for DL, for a pedestrian scenario, considering different modulations and channel bandwidths for the maximum throughput achieved in each situation.

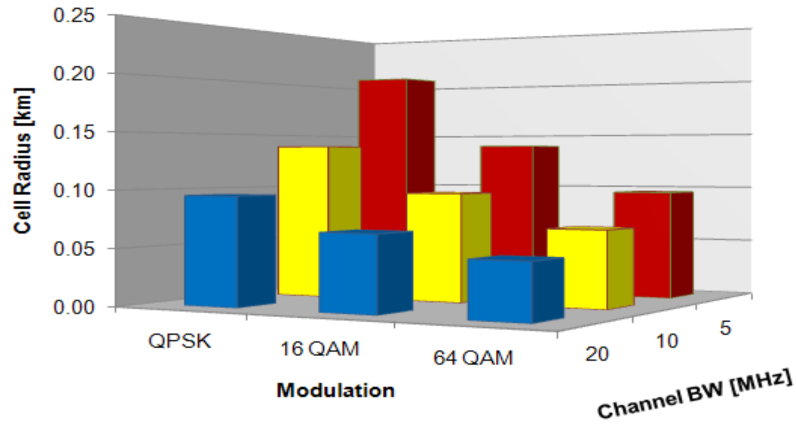


Figure 4.6. Mobile WiMAX cell radius for UL, for a pedestrian scenario, considering different modulations and channel bandwidths for the maximum throughput achieved in each situation.

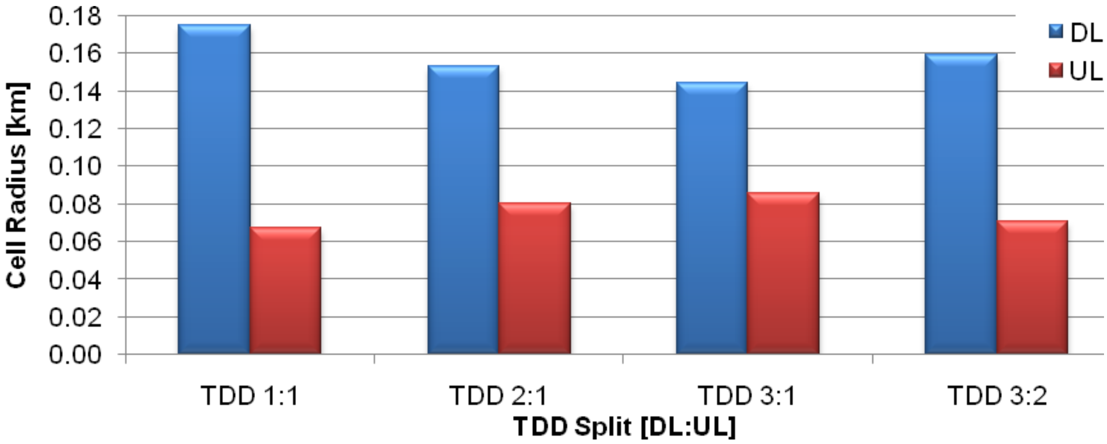


Figure 4.7. Mobile WiMAX cell radius variation considering several asymmetries of TDD Split.

4.2.3 Mobile WiMAX and HSPA+ comparison

In order to present a valid comparison for the variation of cell radius for the two systems in a single user scenario, it is important to define the interval of values to be analysed. The comparison is focused on the variation of the cell radius for different throughputs at application level.

First of all, the parameters for HSPA+ are established, such as MIMO and SIMO configurations and 16QAM and 64QAM modulations, for UL and DL respectively, which allow a reasonable range of values of throughput for a single user. Note that, if the default values for multiple users scenarios are used in this context, the capacity of the BS is excessive and improper for a unique user performing a certain service. With the purpose of comparing the same values of throughputs, a set of parameters is set up for Mobile WiMAX, such as TDD Split 3:1 and 1:1, for DL and UL respectively, SISO configuration and a channel bandwidth of 10 MHz. Regarding modulation, due to AMC, it can be changed to a certain throughput. In the comparison, QPSK and 16QAM are enough to reach the required throughputs. Concerning the environment, since its variation has consequences, the pedestrian one was chosen in order to reach a higher coverage of the cell. The obtained results are shown in Figure 4.8 where one can notice that HSPA+ is the system that guarantees a higher coverage for a fixed throughput at both sides of the connection. For UL, the cell radii are lower in the context of a larger city as Lisbon. It implies the introduction of several BSs with the purpose of cover more users, which is not advantageous in terms of implementation and complexity of the network. Mobile WiMAX, for DL, has the some problems with radius lower than 0.4 km to all the range of throughputs considered.

Regarding DL with HSPA+, the cell radius varies from 1.34 km, for 6 Mbps, to 0.72 km, for 17 Mbps, which represents a decrease of 46%. In Mobile WiMAX, the variation observed is not so noticeable, being from 0.27 to 0.16 km for the same interval of throughputs, establishing a reduction of 41%. The ratio between HSPA+ and the Mobile WiMAX radii decreases from 5.0 to 4.6, which indicates that differences occurred are slightly minimised for lower throughputs.

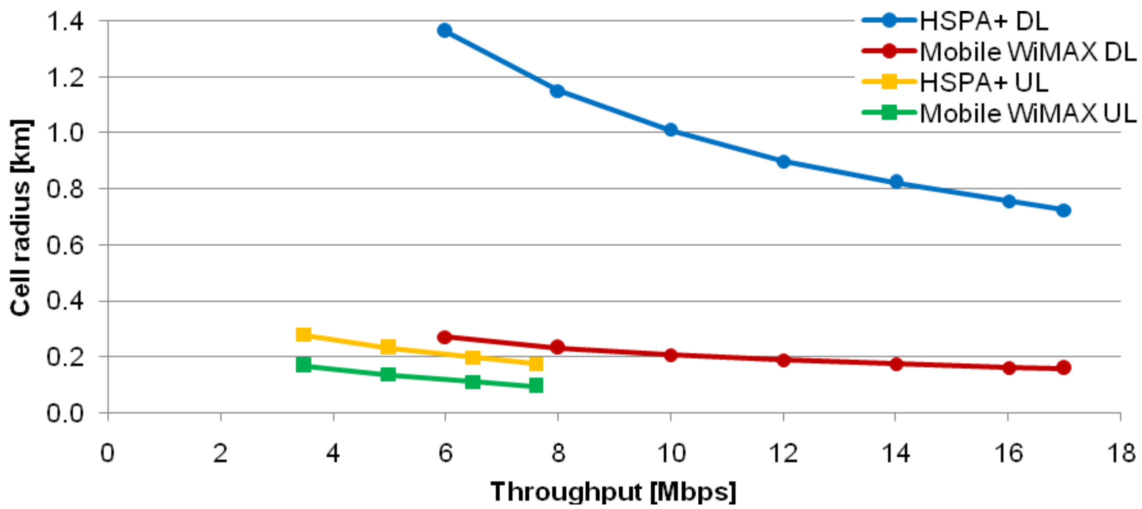


Figure 4.8. Cell radius variation, for HSPA+ and Mobile WiMAX, for DL and UL.

Relating UL, the interval of throughputs is between 3.5 and 7.6 Mbps. In HSPA+, the radius for 3.5 Mbps is 0.28 km and the lower radius achieved is 0.17 km. In Mobile WiMAX, the cell radius varies from 0.17 to near 0.09 km considering the same interval. Note that the lower radius in HSPA+ is similar to the highest radius of Mobile WiMAX, which confirms the advantage of using HSPA+ when coverage aspects are fundamental. Compared to DL, the ratio between the radii for two systems is not so notorious in UL: 1.7 for a throughput of 3.5 Mbps and 1.8 for the upper limit of the interval.

In [Salv08], a comparison between HSDPA and Mobile WiMAX is realised giving special emphasis to aspects such as TDD Split, channel bandwidth, frequencies adopted, transmission power and number of HS-PDSCH codes in HSDPA context.

4.3 DL Multiple Users Scenarios Comparison

In this section, HSPA+ and Mobile WiMAX results for the multiple users scenario are analysed in a context of a comparison focused on capacity and coverage aspects for DL.

4.3.1 Default Scenario

All the results presented in this subsection were obtained with the objective of giving a more specific insight into the impact of the systems performance in DL, concerning coverage and capacity.

The systems parameters considered for the default scenario are presented in Table 4.4 and Table 4.5. The service reference throughput is defined with the purpose of, through the single user model, obtaining the cell radius for each of the 3 sectors of a BS. The cell radius is kept constant for the whole network. The considered environment is the pedestrian one, because it provides a higher cell radius, as seen in the single user analysis. The values obtained for the cell edge, for the default parameters are 1.42 and 0.27 km for HSPA+ and Mobile WiMAX, respectively. The reference throughput is fixed based on the current trend to require more demanding services and applications, being expectable that, in a few years, market demands lead to higher throughputs. The radiation pattern of the antenna also influences the calculation of the path loss, since the BS antenna gain is not constant.

The default service profile considered was the Voice Centric, since the Mobile WiMAX contemplates all types of service and the current is that voice is still being the major service. However, HSPA+ only serves data services, which implies to analyse the same services in Mobile WiMAX with the objective to perform a fair comparison. Bearing this in mind, in Figure 4.9 one can observe the distribution of services, proportional to data services, in the Voice Centric service profile.

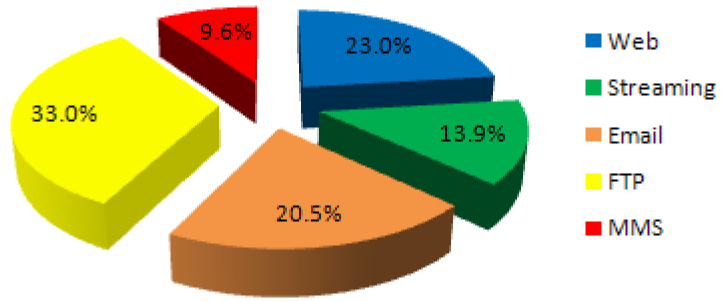


Figure 4.9. Voice centric service profile, considering only data services.

In order to highlight the distribution of users along the cell, Figure 4.10 presents, for 5 simulations, in order not to overload the figure, the served throughput for a certain distance considering all services. As expected, due to the conclusions in the single user analysis, HSPA+, compared to Mobile WiMAX, serves users placed farther away, having the capability to cover a larger area of Lisbon. One can further observe, for Mobile WiMAX, the clearly separation between voice and video-telephony users, which have a fixed throughput of 12.2 and 64.4 kbps, and the remaining services that have a minimum throughput of 0.512 or 1.024 Mbps. Users being served with the higher throughput, nearly 10 Mbps, are performing a FTP session.

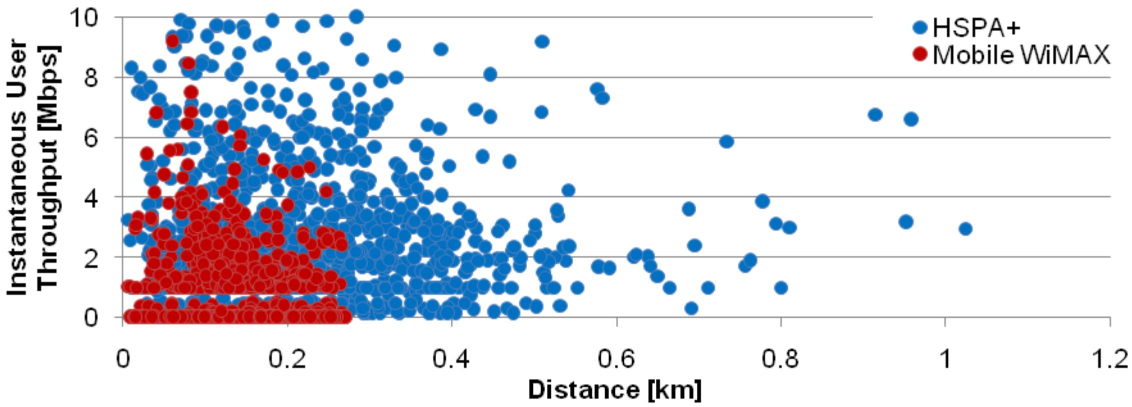


Figure 4.10. HSPA+ and Mobile WiMAX DL instantaneous throughput for all users depending on the distance, for the default scenario.

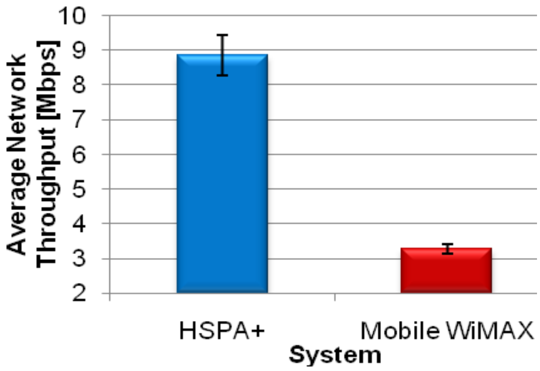
Next, one presents the most relevant network parameters in terms of capacity and coverage. In Figure

4.11 to Figure 4.13, several HSPA+ and Mobile WiMAX network parameters are presented.

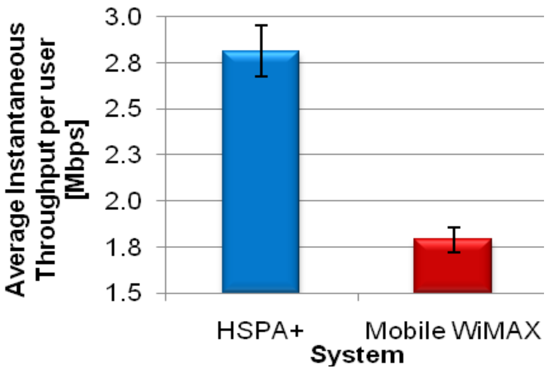
Considering Figure 4.11(a), one can notice that, in HSPA+, the average network throughput is higher than Mobile WiMAX. The difference is significant: 8.85 Mbps for HSPA+ and only 3.26 Mbps for Mobile WiMAX. In this context, one should also notice that the average number of users per BS is 3.2 and 1.8 for HSPA+ and Mobile WiMAX, respectively, which explains the fact that BSs, in HSPA+, present a higher average throughput, which influences, network results. These results are a consequence of the larger coverage that HSPA+ can provide as explained in the SU analysis, Section 4.2.

Regarding the average instantaneous throughput per user, Figure 4.11(b), it is influenced by the satisfaction grade of the network, percentage of served traffic for each service and by the application of the reduction strategy. In the case of HSPA+, users are served with a higher throughput, 3.1 Mbps, while in Mobile WiMAX, users exhibit an instantaneous throughput of 1.79 Mbps. These results suggest that HSPA+ serves users performing more demanding services and this system can achieve, for the same SNR, higher throughputs.

From Figure 4.12(a), one can notice that neither of the systems has resources enough to serve more than 70% of the covered users. Nevertheless, Mobile WiMAX presents a better performance, serving 4% more than HSPA+. In the regions with more users, since HSPA+ presents a larger coverage, the system has more users per BS, being possible that, in those zones, the capacity of a BS for the default scenario, 43.2 Mbps, is reached and, eventually, users have to be delayed or the throughputs reduced. The capacity of Mobile WiMAX, due to the lower number of users covered, is not reached. Additionally, since the slow and fast fading are described by statistical distributions, the receiver power can be insufficient for a user to perform the request service due to lower SNR values. The situation is more unfavourable to users for higher distances, because of interference margin and fading effect, the SNR values are several times under the threshold for the minimum throughput, which is the limiting factor for this case, causing the delay of users. The receiver power needed to obtain a certain throughput depends on the models considered in simulations that are different in agreement with the technology of each system.

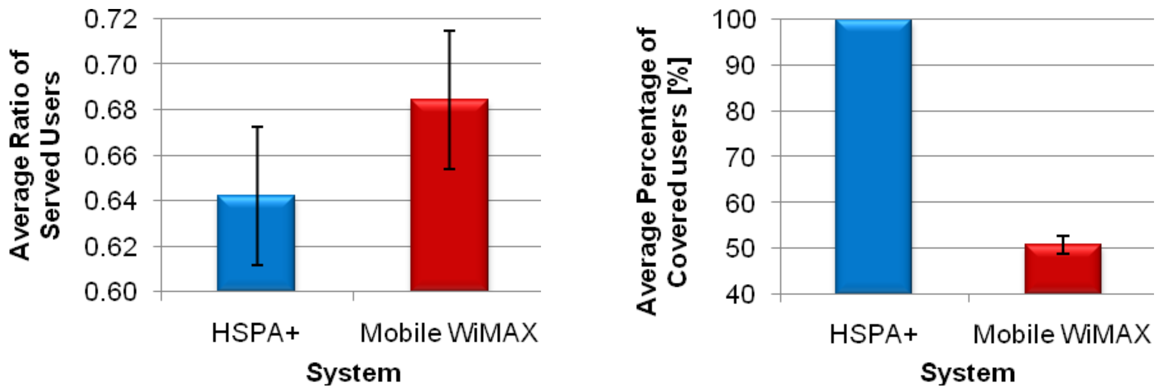


(a) Average Network Throughput.



(b) Average Instantaneous Throughput per User.

Figure 4.11. HSPA+ and Mobile WiMAX DL Average Network Throughput and Average Instantaneous Throughput per User for default scenario.

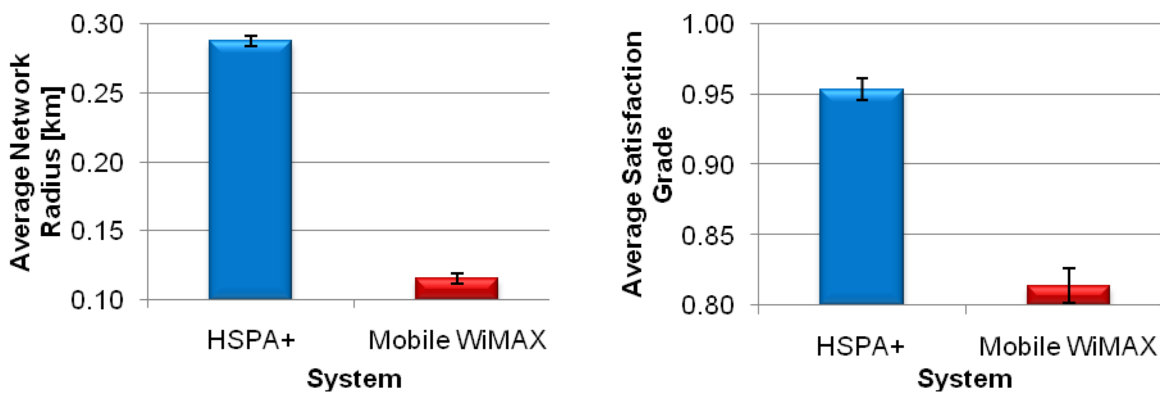


(a) Average Ratio of Served Users. (b) Average Percentage of Covered Users.

Figure 4.12. HSPA+ and Mobile WiMAX DL Average Ratio of Served Users and Average Percentage of Covered Users for the default scenario.

In fact, as seen in Figure 4.12(b), HSPA+ covers all the effective users placed in the region, while Mobile WiMAX, on average, covers nearly 51% of the users.

The average network radius, shown in Figure 4.13(a), is 0.29 km for HSPA+, being more than the double of the one for Mobile WiMAX. The differences reside mainly in the models and expressions used for calculate the cell radius for the BSs, and are inherent to the systems since the service throughput reference is common.



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

Figure 4.13. HSPA+ and Mobile WiMAX DL Average Network Radius and Average Satisfaction Grade for the default scenario

One can observe, in Figure 4.13(b), that the average satisfaction grade is approximately 0.95 for HSPA+ and is around 0.8 for Mobile WIMAX, corresponding to a reduction of 16%. For both systems, the average satisfaction grade is not unitary, due to the fact that the requested throughput cannot always be served given the slow and fast fadings and users with high indoor attenuations. Bearing this in mind, one should point out that the slow and fast fading conditions, as variable, can lead to more or less favourable conditions from the user view point. However, there is enough capacity in a BS, when the margins of slow and fast fading are higher, the radio conditions are not enough to establish the service requested. With the increase of the user´s distance to the BS, the throughput decreases, thus, the users placed farther away from the BS have more probabilities of not being served. Two situations can happen: the user is delayed and is not served, or, besides being served, the served throughput is lower than the requested one. In a general perspective, Mobile WiMAX serves more of its covered users, but with a lower quality, expressed in the satisfaction grade, comparing to the one for HSPA+.

The average network throughput, per services, is presented in Figure 4.14. With the exception of MMS, which is the less demanding service, HSPA+ has higher average throughputs compared to the ones obtained for Mobile WiMAX. This is explained by the average satisfaction grade that is also higher in HSPA+, thus, when detailing with services, the same trend is founded. The differences between the average network throughput are larger in Web and, mainly, in FTP. This can be explained by the fact that this service has the higher maximum throughput possible to be requested. Moreover, FTP is the service with the lower priority which means that, in the remote case of reduction strategy, FTP users are the first to be reduced.

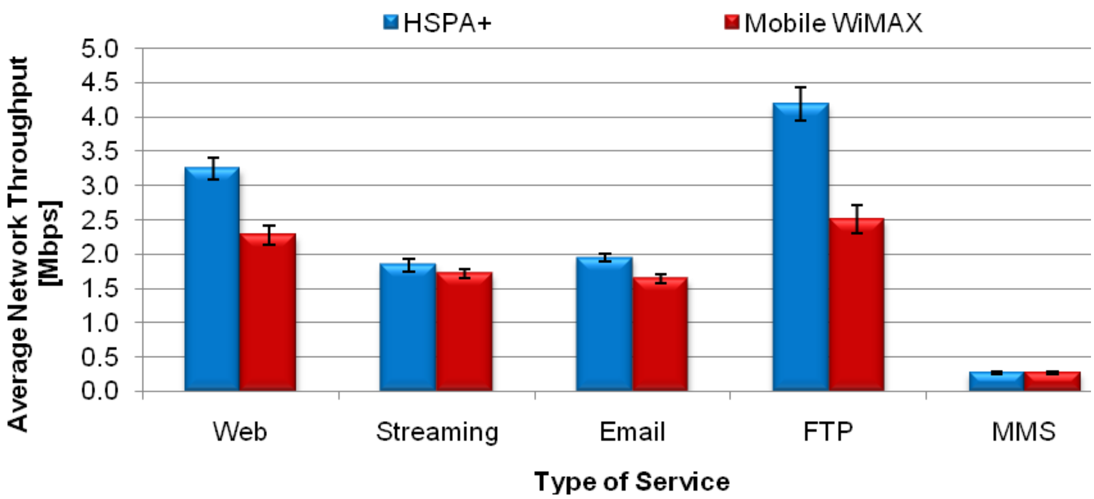


Figure 4.14 HSPA+ and Mobile WiMAX DL Average Network Throughput, per services, for the default scenario.

Regarding the satisfaction grade, its average is presented in Figure 4.15. One can notice that MMS users have a high average satisfaction grade, even though having a low average network throughput, meaning that this service has a low requested throughput. According the QoS priority list, in the remote case of lack of capacity since MIMO is considered, FTP users are the first to be reduced, and this service is the one that has a higher maximum throughput. So, the satisfaction degree is lower, for both systems, nearly 0.88 and 0.62 for HSPA+ and Mobile WiMAX respectively. Still regarding FTP, since this service is the one which higher maximum throughput, the standard deviation is also the one that presents higher values. Web is the most demanding service next to FTP, thus, despite of having the highest QoS priority, the satisfaction grade is lower compared with streaming and email, which means that the reduction strategy is not preponderant in this analysis.

Figure 4.16 presents the served traffic, being possible to compare with the offered one represented in Figure 4.9. One can notice that HSPA+ presents a served traffic almost similar to the offered one, which is very important because a good performance is characterized by not differentiate the services performed. On the other hand, in Mobile WiMAX, the differences consist in the fact that is a reduction of the most demanding services, which results in a higher percentage of MMS. It is important to remember that Mobile WiMAX serves a higher percentage of users, but the served traffic percentages are different, which should be take into account, because it is more likely that MMS users can be served rather than users that are requesting more demanding services. This happens because, due to the margins associated to the urban environment, the achieved throughputs are limited and depend strongly on the SNR than can be achieved. So, the most demanding users are delayed a higher number of times.

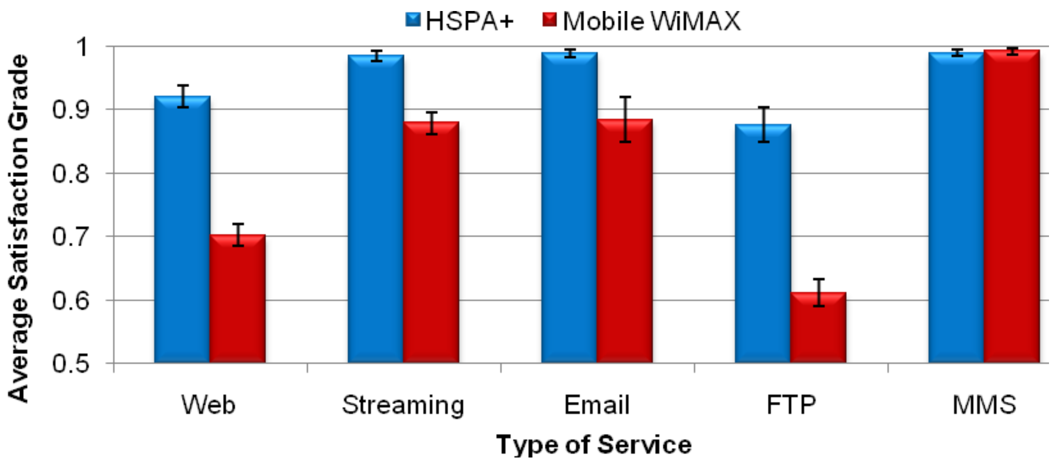
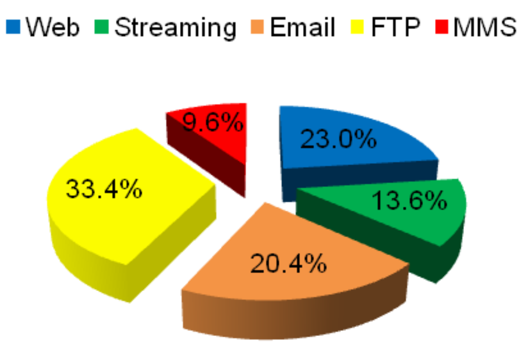
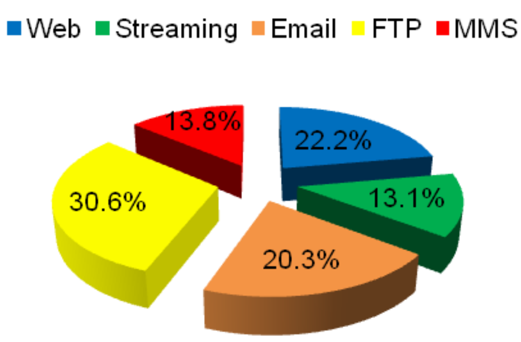


Figure 4.15. HSPA+ and Mobile WiMAX DL Average Satisfaction Grade, per services, for the default scenario.



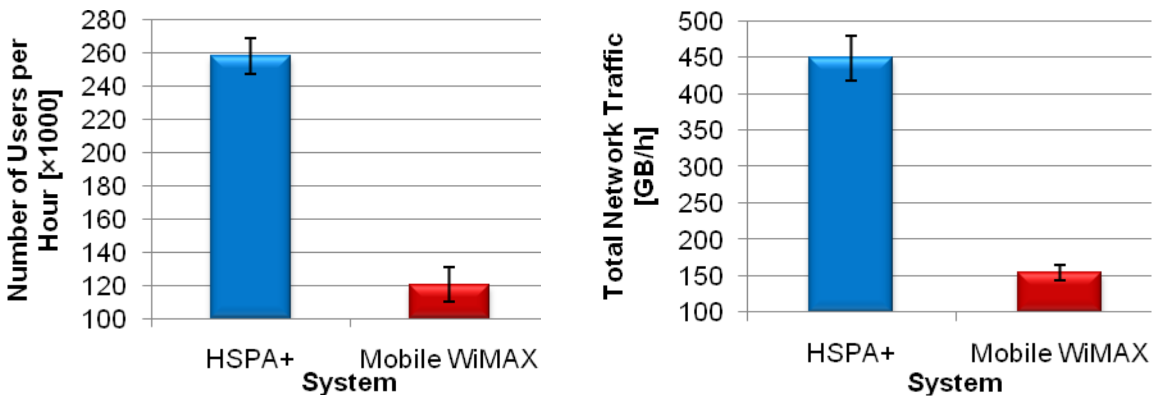
(a) HSPA+ DL.



(b) Mobile WiMAX DL.

Figure 4.16. HSPA+ DL and Mobile WiMAX DL percentage of served traffic, detailed for each service.

In what concerns the busy hour analysis, one presents, in Figure 4.17, the total number of users per hour and the total network traffic are presented. HSPA+, besides serving a lower number of users in percentage, serves them with a higher served throughput. Moreover, the number of covered users in HSPA+ is near to the double of Mobile WiMAX ones. For these reasons, HSPA+ can serve approximately 258 000 users in an hour corresponding to more 137 000 users than Mobile WiMAX. In terms of total network traffic, HSPA+ generates also a higher traffic volume, 450 GB/h, approximately the triple of the one in Mobile WiMAX. Concerning voice and video-telephony, which contribute to capacity of Mobile WiMAX, they are performed, in average, by 160 000 users in an hour contributing to traffic of a 31 MB in the same period, which are neglected.



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

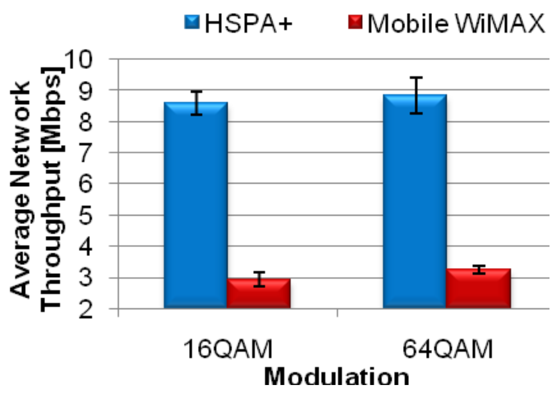
Figure 4.17. HSPA+ and Mobile WiMAX DL Number of Users per Hour and Total Network Traffic for the default scenario.

HSPA+ presents important advantages compared to Mobile WiMAX. The differences in the number of users and in the total network traffic are noticeable to define HSPA+ as the system which has a global better performance in DL.

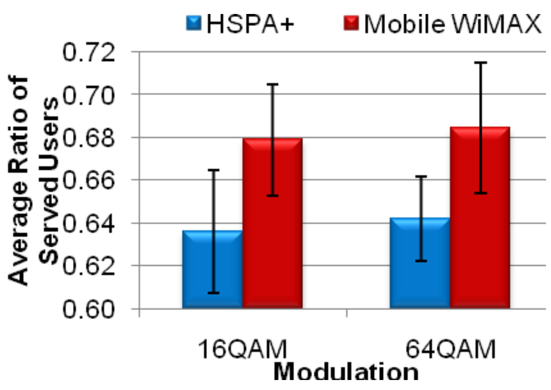
4.3.2 Modulation Impact

The introduction of HOM, brought by HSPA+, increases the achieved data rates constituting one of the most important features of Release 7, as seen in Section 2.1.5. In this subsection, one presents the effect of considering 16QAM instead of 64QAM, maintaining the remaining parameters, including MIMO. In Mobile WiMAX, the option for 16QAM not only limits the amount of data transmitted in each symbol and the achieved SNR, but also reduces the total capacity available in a BS. The last aspect is only perceptible if the number of users per BS is higher. Figure 4.18 presents the variations occurred in the average network throughput and in the average ratio of served users.

Regarding HSPA+, the use of 16 QAM causes a reduction of 3% in the average network throughput. The percentage of served users has negligible variations and the average satisfaction grade does not vary significantly. One should point out that these results are according to Figure 2.5, where the curves for HSPA+, for 16 QAM and 64 QAM, in the context of a MIMO configuration, superimpose until a SNR of 10 dB. After that point, the curves diverge and the use of 64 QAM brings the advantage of provide higher throughputs. Nevertheless, for the throughputs considered in the thesis, a 16 QAM modulation is enough for higher SNR values to achieve the considered services throughput. So, one can conclude for HSPA+, that the number of users with an SNR higher than 10 dB and the reduction in the capacity of a BS are not enough to observe several differences compared to the default scenario, maintaining the number of users and the antenna configuration.



(a) Average Network Throughput.



(b) Average Ratio of Served Users.

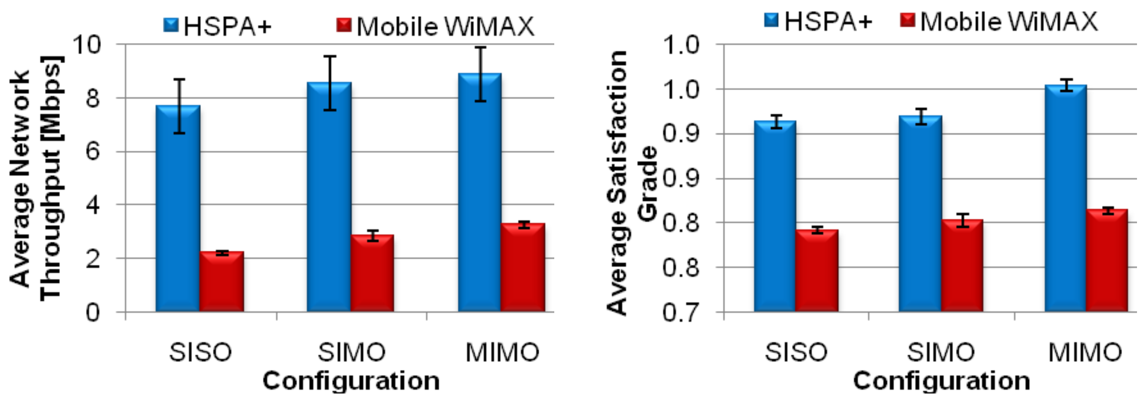
Figure 4.18. HSPA+ DL and Mobile WiMAX DL network parameters (Average Network Throughput and Average Ratio of Served Users) varying the modulation scheme.

A set of simulations were also realised for Mobile WiMAX limiting the system to 16 QAM. One can verify that the system has similar performance, compared to the default scenario, which does not introduce relevant modifications, Figure 4.18(a) and Figure 4.18(b). The justification for the lack of relevant changes is the fact that 80% of users are realising the service in indoor environments contributing to the increase of the path loss, since these users have higher indoor penetrations. So, the number of users with SNR equal or greater than 16 dB, for these conditions, is not enough to produce a notable impact on the results. In terms of the capacity of a BS, there is reduced significantly but the lower number of users covered and the support of MIMO justify the constant behaviour of the system in the percentage of served users.

4.3.3 Antenna Configuration Impact

Diversity and the MIMO configuration are introduced with the purpose of providing better coverage increasing capacity. It should be remembered that the influence diversity or MIMO is not considered in the same way for that systems. For HSPA+, one has expressions for all configurations, while for Mobile WiMAX the analysis is based on tables for a SISO configuration. So, in Mobile WiMAX, diversity is taken into account as diversity gain (A.2) and the use of MIMO is considered by modifying the maximums throughputs achieved for a certain modulation, coding rate and SNR. This approach is not an optimized one because the values of SNR are spaced and, for some throughputs, the SNR resultant is the same in SISO and MIMO, not giving emphasis to the improvements brought by MIMO in terms of coverage besides the higher throughputs considered. One of the referred throughputs is the reference one.

Concerning HSPA+, as verified in Figure 4.19(a), the average network throughput, when MIMO is not applied, decreases from 8.85 Mbps to 8.51 and to 7.69 for SIMO and SISO, respectively. This fact is associated to the variations occurred in the average satisfaction grade, according to Figure 4.19(b). The satisfaction grade of MIMO introduces an increase of 4.5% in this parameter comparing to SISO. These variations are explained by the different curves of throughput and SNR, Figure 2.5. For instance, one can observe that, for any SNR value, the use of MIMO provides a higher throughput compared to SIMO and SISO. So, the use of MIMO approximates the requested throughput to the served one. The last two configurations have similar curves for SNR higher than 20 dB, but for SNR values lower than 20 dB, SIMO provides higher throughputs. Hence, the introduction of SIMO and MIMO results in an increment of the available throughput for a certain SNR which is worthwhile to the network.



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

Figure 4.19. HSPA+ DL and Mobile WiMAX DL network parameters (Average Network Throughput and Average Satisfaction Grade) varying the antenna configuration.

For Mobile WiMAX, the trends are similar. The use of MIMO multiplies the throughput obtained in SISO by a constant given by the RMG model. Besides, the number of sub-carriers is equal, the use of MIMO increases the throughput achieved. Therefore, the average network throughput with MIMO is 3.26 Mbps, Figure 4.19(a). Without the use of two antennas, both in transmission and reception, the average network throughput decays to 2.84 and 2.21 Mbps with SIMO and SISO, respectively. The average satisfaction grade, Figure 4.20(b), also presents better results with the use of MIMO, increasing of 3% and 1% in relation to SISO and SIMO.

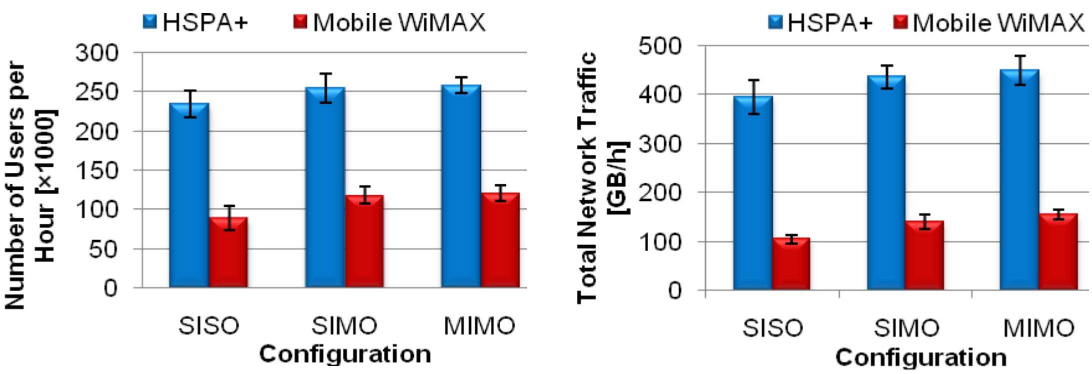
Regarding the average ratio of served users, one can conclude, by observing Figure J.1(a) that this parameter stands almost constant in HSPA+. Nevertheless, the SISO configuration exhibits a slightly decrease compared to the other configurations, because it is the one that provides lower throughputs, which increases the probability of user delayed if the available throughput is lower than the minimum established. In what regards Mobile WiMAX, the use of MIMO increases the average ratio of users in 31% and 21% comparing to the number of served users reached with the use of SISO and SIMO configurations. The use of SIMO introduces a gain that is not present in SISO, which improves the conditions of the signal receive. MIMO configuration, from a theoretical view point allows having, for same SNR, the double of throughput. However RMG model introduces a more realistic approach but the benefits of MIMO remain valid.

The average network radius does not show significant variations in HSPA+, as seen in Figure J.1(b). The reason for the constant behaviour is the fact that cell radii, obtained for a reference service, in HSPA+, can cover all users independently of the chosen configuration. Moreover, when a user is inside the cell radius of several BSs, the connection is realised with the closer one, thus, the changes in average radius are imperceptible.

Contrarily to HSPA+, in Mobile WiMAX, one can observe, also in Figure 4.21(b), significantly variations of the average BS radius. The deployment of the network fixes a cell radius for each BS for a SNR value correspondent to a certain throughput. Due to the lack of numerical expressions of SNR value as a function of throughput, the former is obtained with the use of Table 2.4 where the maximum throughputs, for a certain SNR and coding rate, are multiplied by the mean value of RMG model in the case of MIMO. So, for the service reference throughput considered, both SISO and MIMO are associated to the same SNR value because of the interval approach and the radii are approximately similar. In what regards SIMO, its use leads to an additional. Bearing this in mind, the maximum average network radius is obtained with a SIMO configuration, 0.12 km, corresponding to an increase of 21 % in relation to SISO. MIMO configuration presents an intermediate average radius network but, once its application allows the users far away from BS to have higher throughputs, its value of average network radius is near to the verified in SIMO.

Concerning with the average percentage of covered users, Figure J.2, one can observe that the use of SIMO enables the coverage of more users, representing an increase of 25% compared to the MIMO and SISO. These relations are explained by the process of attribution of a cell radius for all the BSs of the network, which one already referred in order to justify the average network radius variations.

In the context of a busy hour analysis, as one can observe in Figure 4.20(a), the variations are similar for both systems. The number of users in an hour is higher when the MIMO configuration is used. Additionally, the use of SIMO also presents better results comparing to the SISO ones. The reason for these results is the average ratio of the served users that, as seen in Figure J.1(a), presents a similar trend. Besides, the SIMO configuration has a higher coverage due to the assumptions taken in SU model, the average percentage of served users is higher with the use of MIMO explaining the results when the extrapolation for an hour is realised. The use of SISO instead of MIMO leads to a reduction in the number of users of 26% and 9.3% for Mobile WiMAX and HSPA+ respectively. One can conclude that the impact of not using MIMO has a larger importance in Mobile WiMAX.



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

Figure 4.20. HSPA+ and Mobile WiMAX DL Number of Users per Hour and Total Network Traffic varying the antenna configuration.

The total network traffic is a consequence of the number of users in an hour, if the served traffic does not present several differences compared to the offered one. So, the use of MIMO instead of SIMO represents an increase on the total network traffic of 14% in HSPA+ and 32% in Mobile WiMAX. One more time, the use of MIMO leads to a better performances with improvements being more visible in Mobile WiMAX. The use of SIMO also brings improvements relative to the situation where only one antenna is used in reception and transmission in terms of coverage.

4.3.4 Higher Throughput Impact

The present subsection analyses network behaviour when there is an enhancement in the maximum throughput that a user can require for a certain service. The randomly distributed throughput, described in Section 3.2, is also not used. Therefore, this analysis has the purpose of studying the network behaviour in more demanding throughput scenarios, maintaining constant the percentage of each service considered in the default scenario. The changes realised are marked in bold in Table 4.8.

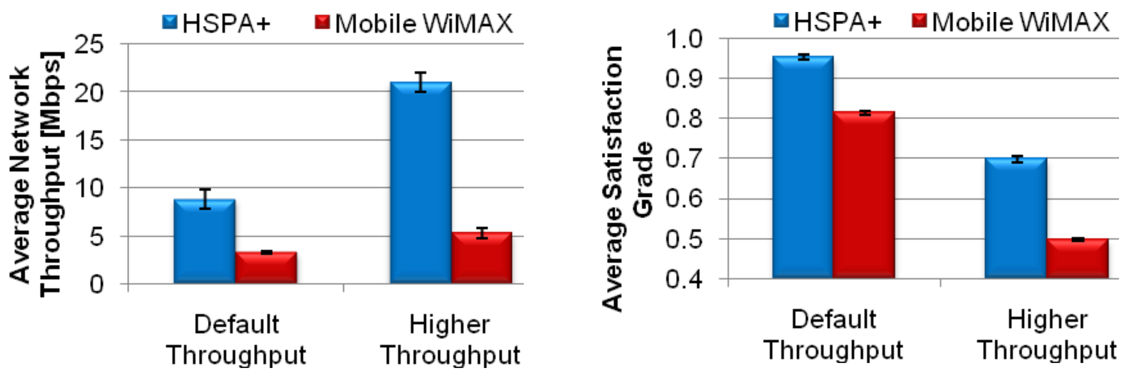
Table 4.8. New maximum throughput values for each of services for DL.

Service	Maximum Throughput [Mbps]
Streaming	**7.2**
FTP	**21.5**
HTTP/Web	**14.4**
E-mail	**7.2**

One can observe that there is an increase of the average network throughput in both systems, Figure 4.21(a). In HSPA+, the increase, compared to the default values, is of almost 140% whereas in the Mobile WiMAX this value is several lower, 62%. One can conclude that, for higher throughputs, the use of HSPA+ leads to a 15 Mbps average network throughput increase relative to the use of Mobile WiMAX. HSPA+ has a better behaviour face the enhancements verified in the throughputs, which is very important to more demanding users profile.

Regarding the average satisfaction grade, Figure 4.21(b), HSPA+ presents also better results than Mobile WiMAX. Moreover, in HSPA+, when throughputs are increased, the average satisfaction grade decays 14%. In Mobile WiMAX, the reduction is of 28%. So, one can conclude that HSPA+ has a better reaction when the users require higher throughputs for several services.

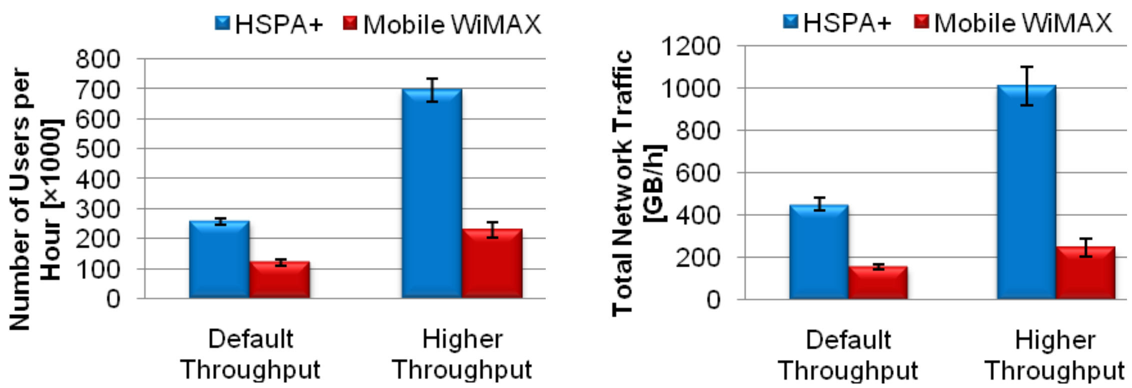
The average ratio of served users, represented in Figure J.3, is maintained constant relative to the default scenario. Users that, due to the margins associates to an urban environment, are delayed in the default scenario are also delayed when the services are more demanding. The remaining users, besides not being delayed, are served with a lower satisfaction grade. The differences between the maximum requested and the minimum possible throughputs, the latter not changed in this analysis, are important to the evaluation of the impact of enhanced throughputs. Since the differences between the lower and the higher possible throughputs are significant, they are responsible for the average satisfaction grade decrease. In the most populated areas, the maximum allowed throughput can be more easily reached. Nevertheless, the impact caused for the hypothetical reductions is lower.



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

Figure 4.21. HSPA+ and Mobile WiMAX DL Average Network Throughput and Average Satisfaction Grade for different throughput services.

In terms of number of users and total traffic, due to the increase of the major part of the services, the sessions are performed in a shorter period of time which leads to a higher number of users that create also a larger amount of transferred data, Figure 4.22. One can notice that HSPA+, for higher throughputs, serves more 466 000 users than Mobile WiMAX, with a total traffic of near to 1TB, corresponding to an increase of 310% relative to the traffic originated by the latter.



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

Figure 4.22. HSPA+ and Mobile WiMAX DL Total Number of Users per Hour and Total Network Traffic for different throughput services.

4.3.5 Data Centric Impact

In this subsection the impact of data centric profile, with different service penetration percentages, is analysed, with the results being compared with the ones from the default scenario. FTP and Web are more preponderant relative to Voice Centric and the percentage of voice is reduced, which means that are approximately 1200 effective data users in the analysis instead of the 800 for the default scenario. The Data Centric profile, representing the proportion of services in the total users performing data is presented in Figure 4.23.

Although the service profile is changed, the average satisfaction grade of the two systems is not modified, meaning that the systems have resources to serve the Data Centric users with the same satisfaction grades. In Mobile WiMAX, this fact has the consequence of a reduction of 5 % in the average ratio of served users because Mobile WiMAX, as seen in Section 4.3.1, serves essentially less demanding services with the penetration of more demanding services being lower than HSPA+. On the contrary, in HSPA+, the modification of the profile does not introduce significantly variations in the average ratio of served users, which indicates that the resources are enough for the network to receive more users performing more demanding services, without decreasing the ratio of served and requested throughput. Since the capacity of both systems is not exceeded, Mobile WiMAX is more sensible to the variations occurred in the service profile which is undesirable to the network deployment that must be robust not presenting many variations These variations are presented in Figure J.4.

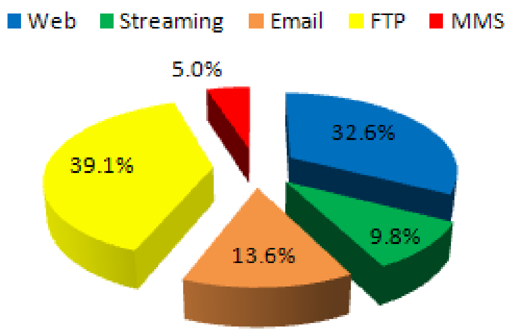


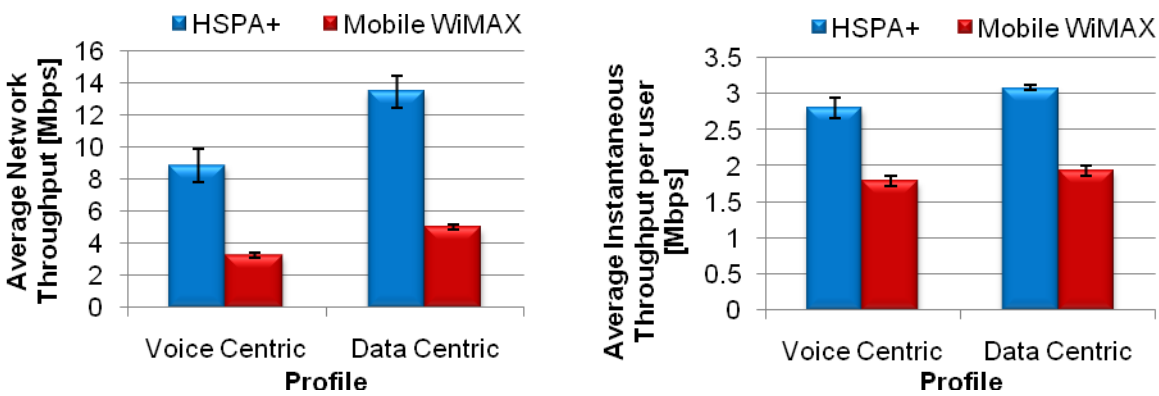
Figure 4.23 Data centric service profile, considering only data services.

For the average network throughput, it can be seen in Figure 4.24(a) that the average network throughput increases with the Data Centric profile. It is important to remember that only data services are compared in this analysis. So, since more users are introduced in the network, on average, BSs have more users connected to them contributing to this increase. Moreover, the services introduced have a higher penetration of FTP and Web that are associated to higher throughputs. For both profiles, HSPA+ presents higher values, representing an increase of 170% in the average network throughput comparing to Mobile WiMAX. This increase is independent of the profile since, as mentioned before, the average satisfaction grade has an almost constant behaviour and the ratio of served users only decreases slightly in Mobile WiMAX.

In terms of the average instantaneous throughput, Figure 4.24(b), it is possible to observe an increase with the introduction of the Data Centric profile. Besides, more users are introduced, and the offered services have different penetration percentages. So, with the preponderance of FTP and Web, there are more users performing these services, hence, due to the higher throughputs associated, instantaneously, this parameter increases.

As for the total number of users per hour, Figure J.5(a), as expected, HSPA+ can serve more users than Mobile WiMAX, because, instantaneously, HSPA+ is able to serve more users, therefore, when extrapolated to the full hour analysis, more users can be served for the same profile. However, the number of users per hour presents a decrease when considering the Data Centric profile. In fact, when compared to the Voice Centric profile, there are less 3 000 and 15 000 users being served in the period of an hour, for HSPA+ and Mobile WiMAX, respectively. There are, in relative terms, a larger number of users performing FTP and Web than in Voice Centric. The former service has larger data files, while the latter is characterised by an average time of reading the pages in the browser. As a consequence, when extrapolating for an hour, the number of users served is reduced.

Since the number of users per hour is reduced in the Data Centric profile, users are requesting services with higher volumes. So, the total traffic for the Data Centric profile increases 243 and 68 GB/h for HSPA+ and Mobile WiMAX. The total network traffic is, for the Data Centric, 692 and 223 GB/h for the two systems. The increase is higher in HSPA+ system, which means that the system has a better performance when data users have higher penetration.



(a) Average Network Throughput. (b) Average Instantaneous Throughput per User.

Figure 4.24. HSPA+ and Mobile WiMAX DL Average Network Throughput and Average Instantaneous Throughput per User, for the 2 profiles.

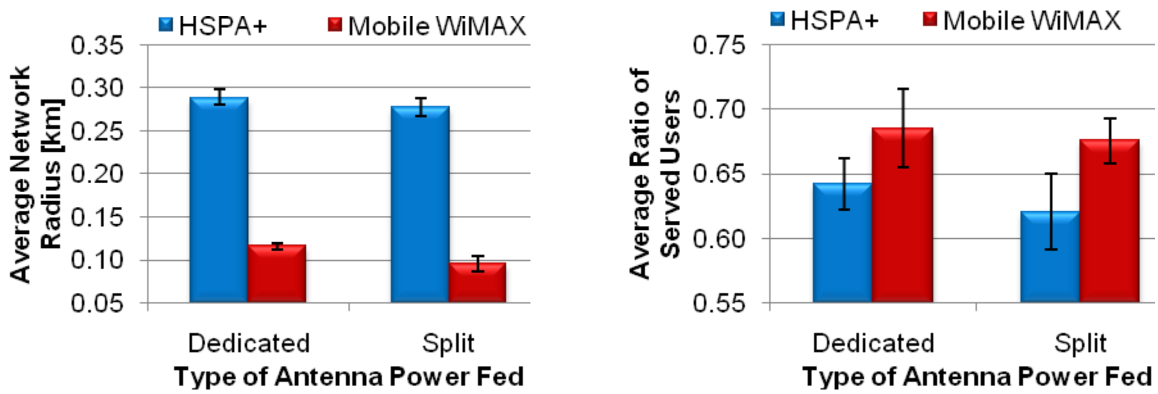
4.3.6 Split or Dedicated Power Effect

In this subsection, the effect of using split or dedicated antenna power fed is presented. This analysis is quite interesting and important, since power consumption is a very important issue to taken into account both in BS and MT. Regarding the BS, the power amplifier is an expensive feature, hence, the use of dedicated power brings additional complexity and costs to the implementation of MIMO.

It is expected that the split of power among the different antennas results in significantly lower throughputs and in a general degradation of the systems performance, as a consequence of the lower achievable SNR. However, the results presented in Figure J.6(a) show that this decrease is not expressive in respect to the average network throughput, on average being less than 0.6 Mbps in both systems. The average satisfaction grade, Figure J.6(b), has also variations lower than 1% for both systems. One can also observe, in Figure 4.25(a) that the average network radius decreases for both systems, since the cell radius of both systems decreases in the network deployment. So, users that are far away from the BS are not served any more.

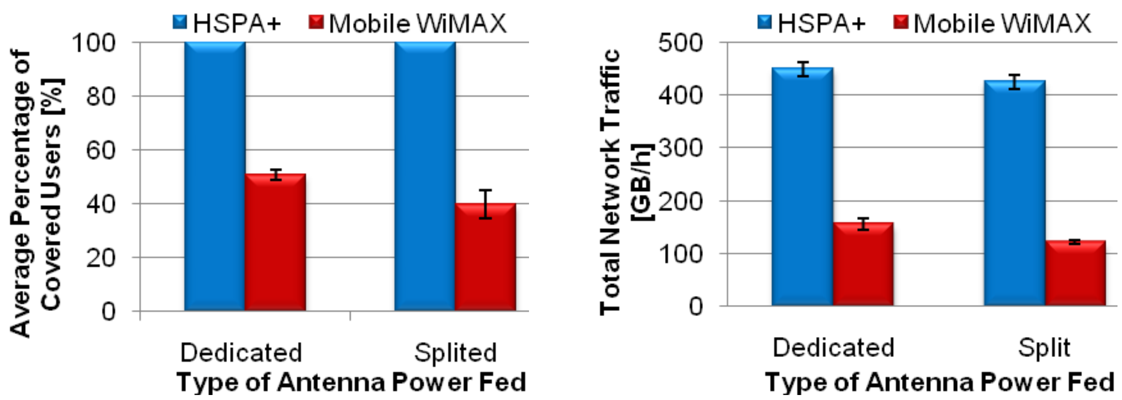
With respect to the ratio of served users, since the achievable SNR is lower due to a increase on the path loss, some users can not receive enough power to perform the requested throughput. Therefore, there are more users being delayed with the reductions observed in the number of served users of 2% in HSPA+ and only 1% in Mobile WiMAX, Figure 4.25(b).

The impact of using split antenna power fed, in terms of coverage, is more notable in Mobile WiMAX. As seen in Figure 4.26(a), HSPA+ is a system that, for a split antenna power fed, covers all the effective users, instead of Mobile WiMAX that, with the modifications effectuated, has a reduction of 10% in the covered users, covering, near to 40% of the users distributed in the area studied. For Mobile WiMAX, the split antenna power fed has negative consequences because the coverage decays even more to not optimistic values for a urban area.



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

Figure 4.25. HSPA+ and Mobile WiMAX DL Average Network Radius and Average Ratio of Served Users, for different types of antenna power fed.



a) Average Percentage of Covered Users. (b) Total Network Traffic.

Figure 4.26. HSPA+ and Mobile WiMAX DL Average Percentage of Covered Users and Total Network Traffic for different types of antenna power fed.

The variations of the average ratio of served users and, mainly the impact on the covered users, change the total traffic generated in an hour, Figure 4.26(b). So, the total network traffic decays near to 6 % in HSPA+ and almost 22% in Mobile WiMAX. One more time, HSPA+ system can react more positively to a diminution of the available resources due to its higher coverage. In terms of the number of users, as seen in Figure J.7, the decreases, in percentage, are similar to the ones verified in the total traffic, representing less 14 000 users in HSPA+ and less 26 000 users in Mobile WiMAX.

4.3.7 More Users Impact and District Analysis

In this subsection, the effect of considering a larger number of users in the network is analysed giving special emphasis to the differentiation in 3 different districts of Lisbon, with different traffic characteristics. The number for effective users introduced in the network is 4 000, representing an increase of 150%. It is important to remember that this number includes the users performing voice and video-telephony that are not taken into account in the comparison. So, the number of data users increases from 800 to 2 000.

When one increases the number of users offering traffic to the network, the average network throughput increases around 10 Mbps in HSPA+ and about 3.55 Mbps in Mobile WiMAX, Figure 4.27(a). The increases constitute, for both systems, an improvement of 110%, which means that systems react in the same way when there are more users performing data. This trend is confirmed when one considers the average ratio of served users and the average satisfaction grade where there are variations not higher than 1% when increasing the number of users, Figure J.9. These results indicate that the BSs for the default scenario are not overloaded, and the increasing in the number of users is not enough to cause the referred overloaded in a significantly way to change network results. So, on average, BSs located in the higher traffic areas and the ones located outside these areas have a large number of users inside their coverage.

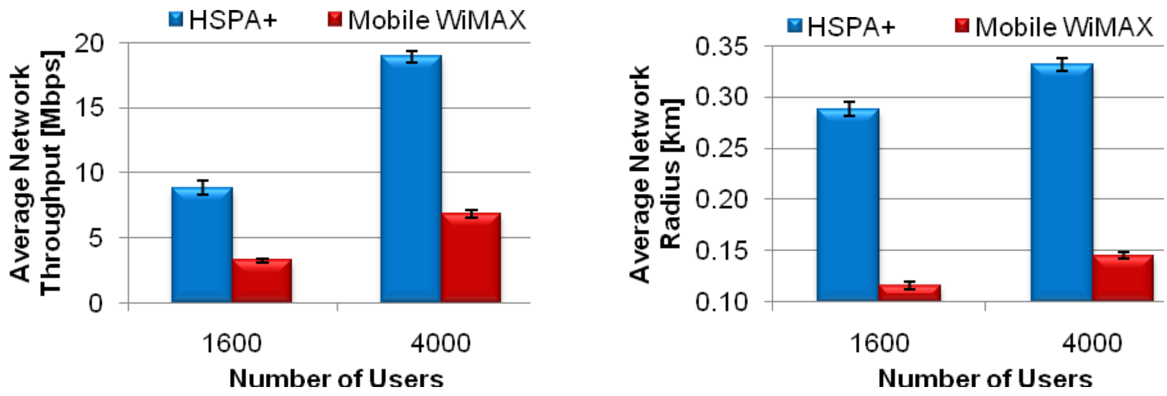
The maximum number of users per BS is, on average, near to 19 and 15 for HSPA+ and Mobile WiMAX, respectively. As services have the same interval of valid throughputs, the average instantaneous throughput per user does not differ from the one represented in Figure 4.11(b) for the default scenario, which means that is unlikely that the maximum capacity of a BS is overloaded, 43.2 Mbps for HSPA+ and 37 Mbps for Mobile WiMAX. The use of MIMO is very important to ensure that the maximum throughput per BS is enough to serve all users that have radio conditions to perform the service. Without MIMO, one should except that, for 4000 users in the network, with 2000 of them performing data services, both average ratio of served users and average satisfaction grade parameters are reduced as a consequence of capacity limitation due to not considering MIMO.

The average network radius, Figure 4.27(b), increases by 15% and 25% for HSPA+ and Mobile WiMAX, corresponding to more 40 and 30 m. Users are more spread over the coverage area, hence, the probability of the user further away from the BS being served increases. As Mobile WiMAX has a lower coverage, this effect is more perceptible for this system.

As a consequence of the average network traffic increase, the number of users per hour and the total traffic network show the same evolution trend. In fact, as seen in Figure J.9, with more users in the network, HSPA+ serves 630 000 users, more 346 000 than Mobile WiMAX. The total traffic of both systems increases 140%, with HSPA+ achieving 1TB in the period of an hour. For Mobile WiMAX, the total traffic is lower than 400 GB/h.

The introduction of more users was analysed from the view point of the network. With the purpose of having a more detailed analysis according to the different areas of the network, one analyses the results for 3 different BS, located in zones with distinct characteristics. The districts analysed are:

Coração de Jesus, Santa Maria de Belém, and Carnide. The notation used in the comparison is presented in Table 4.9.



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

Figure 4.27. HSPA+ and Mobile WiMAX DL Average Network Throughput and Average Network Radius for 1600 and 4000 users.

Table 4.9. Notation used in the reference of districts.

District	
A	Coração de Jesus (Marquês de Pombal)
B	Santa Maria de Belém
C	Carnide

As one can see in Figure J.10, the District A, where Marquês de Pombal is situated, is a region with a large number of cars and people, and where there are several offices, hotels and services. On the other hand, District B, Figure 4.28(a), is characterised by a strong impact of tourism and by the existence of several buildings with a small number of floors. Finally, the District C, Figure 4.28(b), is a residential one where blocks of flats are preponderant.

The results are associated to a higher standard deviation since the study of a unique BS depends strongly on the distribution of users in the district where the BS is located. Moreover, the average number of users in a certain BS is lower, which means that the services that are performed become important.

As one can see in Figure J.11 and Figure J.12, giving special emphasis to the standard deviation verified, the average ratio of served users and the average satisfaction grade have a significant variation in the set of simulations. Nevertheless, the average values obtained for the default scenario are within the interval of values for each district, taking standard deviations into account.

From Figure 4.29(a), one can observe that HSPA+ BSs have more users than Mobile WiMAX BSs. This fact is explained by the higher coverage of the former. For Mobile WiMAX, the number of users in the BS in Districts B and C are similar, while HSPA+ on average has more users in district C. The results are associated to a higher standard deviation since the study of a unique BS depends strongly on the distribution of users in the district where the BS is located. Moreover, the average number of users in a certain BS is lower, which means that the services that are performed become important.

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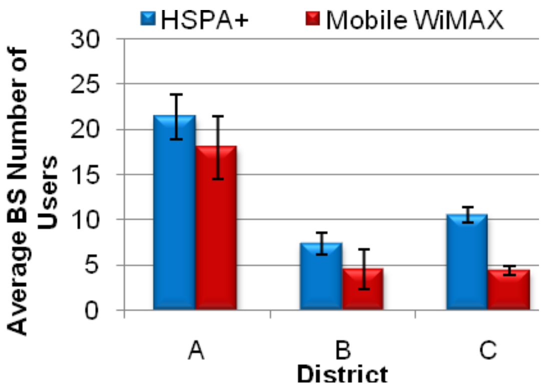
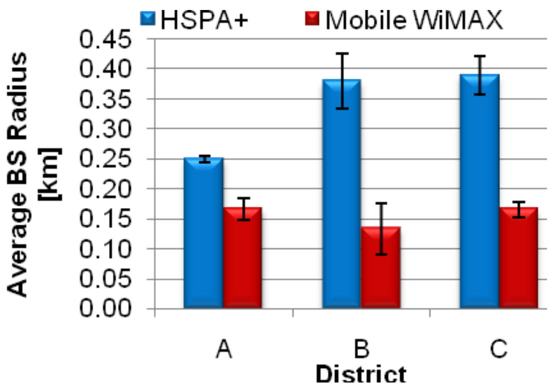
a) District B.

(b) District C

Figure 4.28 District B and District C view (extracted from [GoEa08]).



a) Average BS Number of Users.



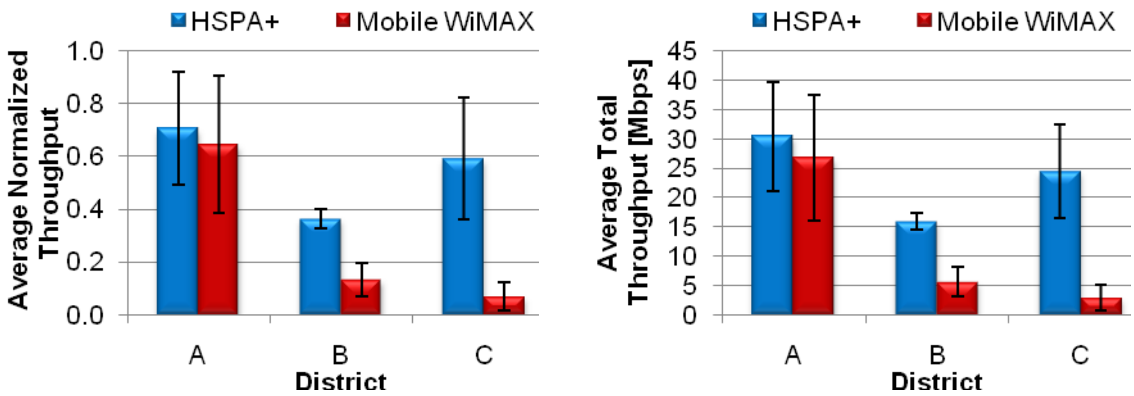
(b) Average BS Radius.

Figure 4.29. HSPA+ and Mobile WiMAX DL district analysis for Average BS Number of Users and Average BS Radius.

Concerning with the average BS radius, Figure 4.29(b), the most relevant aspect that should be pointed out is the difference, regarding HSPA+, between District A and the others. The explication for the lower BS radius in district A is that, as the area is characterised by a large amount of traffic, the BS analysed is surrounded by several BSs whose coverage areas are intersected. So, as the user is connected with the closer one, the radius is lower in this case.

The average normalised throughput, Figure 4.30(a) is an important metric to evaluate if the BS is closer to the overlaped caused by excessive throughput requested. In HSPA+, BSs are using more of their capacity compared to Mobile WiMAX. Neverthless, neither HSPA+ and Mobile WiMAX are closer of running out their capacity. The variations observed are almost similar to the average number of users in the BSs. The exception is the lower average normalised throughput for the BS placed in District C, which can be justified by the lower average satisfaction grade and average ratio of served users, as seen in Figure J.11 and Figure J.12.

In terms of the average total throughput obtained for the snapshot studied, Figure 4.30(b), one can notice that, for HSPA+, the maximum occurs in District A with 30.4 Mbps, and the minimum is established in District B being 15.9 Mbps. In relation to Mobile WiMAX, the minimum is achieved in district C with only 2.8 Mbps and the maximum, as in HSPA+, occurs in District A with 26.8 Mbps, representing a decrease of 12 % when compared to the maximum of HSPA+.



a) Average Normalised Throughput. (b) Average Total Throughput.

Figure 4.30. HSPA+ and Mobile WiMAX DL district analysis for Average BS Number of Users and Average BS Radius.

4.4 UL Multiple Users Scenarios Comparison

In this section, HSPA+ and Mobile WiMAX results for the multiple users scenario are analysed in a context of a comparison focused on capacity and coverage aspects for the UL.

4.4.1 Default Scenario

As the main objective of this thesis is to compare the capacity and coverage aspects between two different systems, for both links, a default scenario was conceived for UL in order to measure the impact of using each of the systems.

The default parameters are marked as bolt in Table 4.4 and Table 4.5. The reference service, whose function has already been explained for DL, assumes for UL the value of 3.6 Mbps, which introduces an asymmetry common in the current services and applications. Hence, the range of each sector of BSs is 0.25 km for HSPA+ and 0.16 km for Mobile WiMAX. Regarding the latter, the TDD Split 1:1 is assumed to maximise the resources allocated to UL. The SIMO configuration decreases the path loss in both systems improving their coverage, which, in theory, allow serving more users. The lack of curves for MIMO in UL was also a limiting factor. The choice of Voice Centric, and its service profile, considering only data services is explained and presented in Subsection 4.3.1.

From the served users in all simulations, Figure 4.31 can be computed, where the users´ distance and throughput are presented for both systems. The distribution verified has behaviour similar to DL. In HSPA+, there are users placed far away from the BS, 0.2 km and for Mobile WiMAX, the highest distance observed is 0.13 km, showing that coverage is lower for Mobile WiMAX. For both systems, the values are lower, which means that is difficult to cover all the area with the requested user throughputs. In spite of not being taken into account in the network parameters comparison, voice and video-telephony users are represented, for Mobile WiMAX, in this distribution as the services with lowest throughputs. The distribution of users along the cell radius, which only contemplates users that are served, suggests that the voice and video-telephony users are served in a large proportion compared to data ones. Moreover, there are no users performing services with throughputs comprised between 0.512 and 1.024 Mbps, which can be explained by the values of Table 4.6 that impose the maximum and the minimum throughputs for all users.

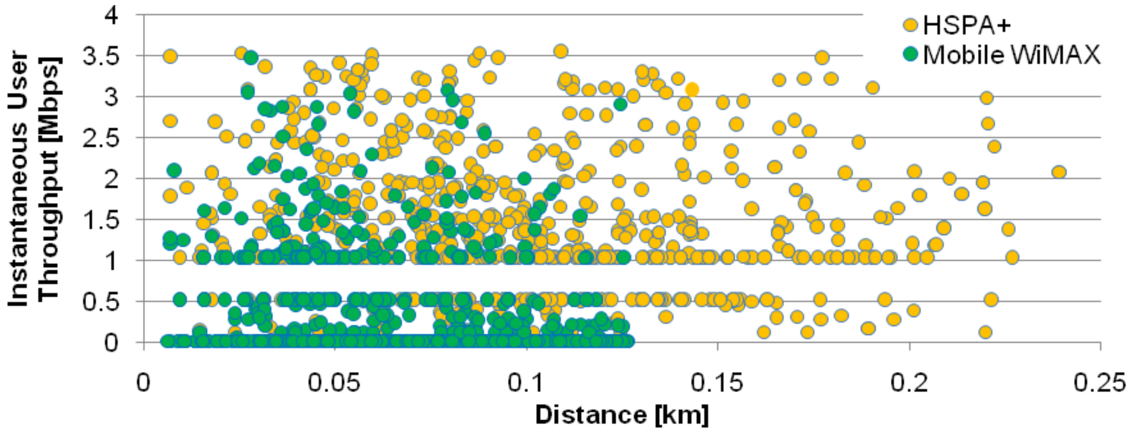


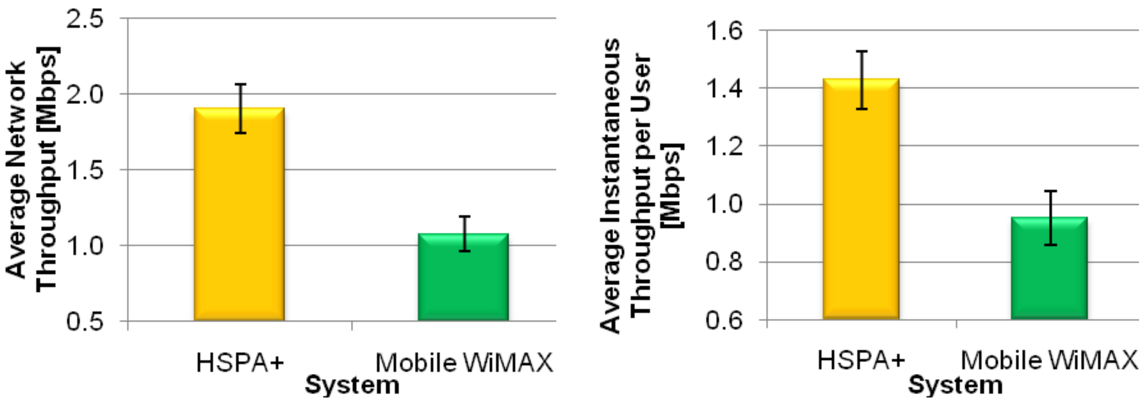
Figure 4.31. HSPA+ and Mobile WiMAX UL instantaneous throughput for all users depending on the distance.

The average network throughput, for both systems is presented in Figure 4.32(a). For HSPA+, the average network throughput is 1.90 Mbps, while for HSPA+ is around 1.08 Mbps, representing a decrease of 43%. One must have in mind that, for the calculation of this parameter, only active BSs active are kept. Underlying to this analysis, one should notice that in HSPA+, on average, 60 BSs are active while in Mobile WiMAX this number is reduced to 25. BSs in HSPA+ have, on average, 1.34 users served inside its range, 0.2 users more than Mobile WiMAX. The lower number of BSs active in Mobile WiMAX supports the idea of a more distributed traffic, which makes the analysis depend strongly on the randomness associated to the distribution of users and the percentage of served traffic per service.

Instantaneously, HSPA+, as seen in Figure 4.32(b), is able to serve users with higher throughput, 1.4 Mbps. Mobile WiMAX, which users are being served by throughputs near to 0.95 Mbps, presents, in this way, a reduction of around 34%. This parameter is, also, influenced by the satisfaction grade and the services profile, both also explained in this section.

In Figure 4.33(a), one can see that Mobile WiMAX, as observed also in Section 4.3.1 for DL, can serve 28% of the covered users. However, this is not synonymous of a better performance, since the service profile can also be changed and the satisfaction grade can also be not equivalent for both systems. HSPA+, although covering a large number of users, does not support all of them with the minimum throughput needed, being only capable of serving 23% of them.

Taking into consideration the total number of generated users, from nearly 1600 users, only 800 are performing data services in the Voice Centric profile. These users are not always inside the range of a BS. This problem grows ine UL because the MT has limitations related to the transmission power. Therefore, for HSPA+, only 43% of the users are covered by the network. Even so, in Mobile WiMAX the coverage is lower than HSPA+, thus, on average, only just 13% of the users are covered, Figure 4.33(b). Since the location of the antennas is similar, coverage areas differences can be explained by the different SNRs required to obtain a certain throughput and by the different approaches in order to calculate the receiver sensibility, Annex A.

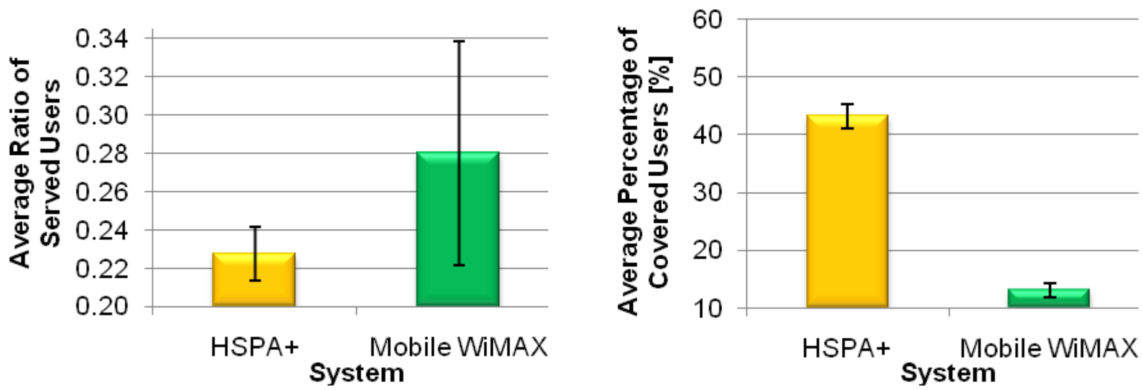


(a) Average Network Throughput. (b) Average Instantaneous Throughput per User.

Figure 4.32 HSPA+ and Mobile WiMAX UL Average Network Throughput and Average Instantaneous Throughput per User, for the default scenario.

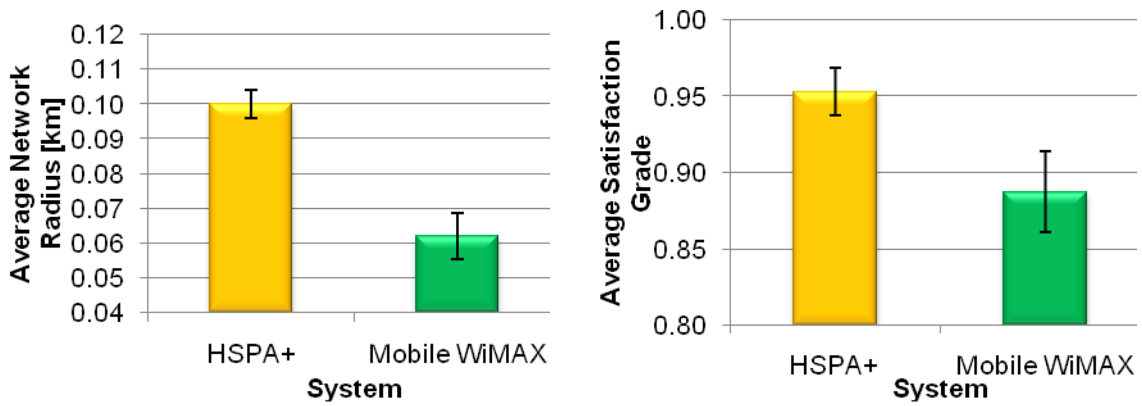
In terms of average BS radius, as already realised in DL, one can notice, observing the Figure 4.34(a), that HSPA+ presents a larger average network radius than Mobile WiMAX, representing an increase of 61% compared to the latter.

The average satisfaction degree is presented, for both systems, in Figure 4.34(b). Users served with HSPA+ have a higher satisfaction grade since the requested service is almost the served one. In Mobile WiMAX, one can notice that its average satisfaction grade, 0.89, is slightly lower than the one obtained with HSPA+, corresponding to a reduction of 7%. In HSPA+, the percentage of users covered that are served is lower, but the served throughput is closer to the requested one. The reduction strategy does not have a great impact in both systems, due to the insufficient number of user to induce a congestion of the network.



(a) Average Percentage of Served Users. (b) Average Percentage of Covered Users.

Figure 4.33 HSPA+ UL and Mobile WiMAX UL network parameters (Average Percentage of Served Users and Average Percentage of Covered Users)



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

Figure 4.34 HSPA+ and Mobile WiMAX UL network parameters (Average Network Radius and Average Satisfaction Grade).

A service analysis focused on average network throughput is presented in Figure 4.35. First of all, the superiority of HSPA+, with respect to this parameter, shown in the network average is transposed to the services detailed analysis. As expected, according to Table 4.6, the services with higher average throughputs are Email, FTP and Web. With respect to MMS, being the service with lowest penetration in the offered traffic and with lower allowed throughputs, the differences between two systems are almost imperceptible. In the case of streaming, the average network is constant and assumes the value of 512 kbps because this is the single allowed throughput for this service.

As mentioned before, the lack of resources to face the margins that increases path loss, inherent to the technology, are the causes to the reduction of the satisfaction grade. Additionally, the BS antenna gain is given by a no omnidirectional radiation pattern. The services throughputs achieved with Mobile WiMAX are lower than the HSPA+, leading to a more significantly decrease compared to HSPA+.

Since the number of covered users is not much significant, the standard deviations are higher, mainly in Mobile WiMAX, meaning that the variations occurred in the set of 10 simulations influences the results. In fact, the number of BSs active is low and there are no more than 5 and 3 users in a BS, for HSPA+ and Mobile WiMAX. It should be further pointed out that, for these reasons, simulations are more susceptible to the randomness associated with the distribution of the users along the region, hence, to the percentage of users performing each of the services.

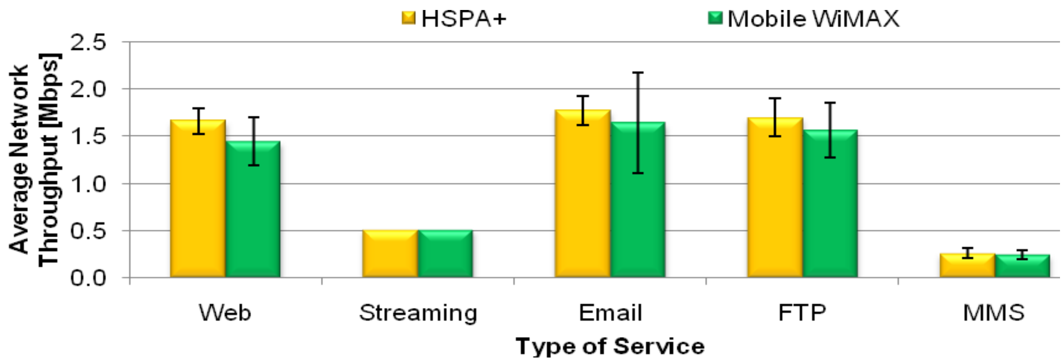


Figure 4.35. HSPA+ and Mobile WiMAX UL Average Network Throughput, per services, for the default scenario.

The average satisfaction grade, detailed per services, is presented in Figure 4.36. The explanations done in Section 4.3.1, for DL, remain valid. The referred parameter is, for all services, above 0.90 in the case of HSPA+ and above 0.80 in Mobile WiMAX, which means that, in general, the served throughputs do not differ, substantially, from the requested ones. The exception is streaming because, as the maximum and minimum throughputs are identical, when the common throughput is not achieved, users are delayed, thus, when users are performing a streaming session, the served throughput is always the requested one. The set of simulations realised are also associated to higher standard deviations, when regarding this parameter.

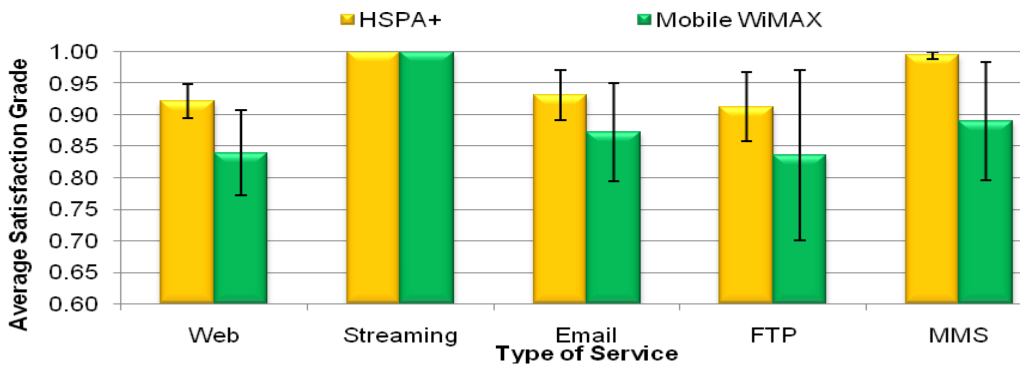
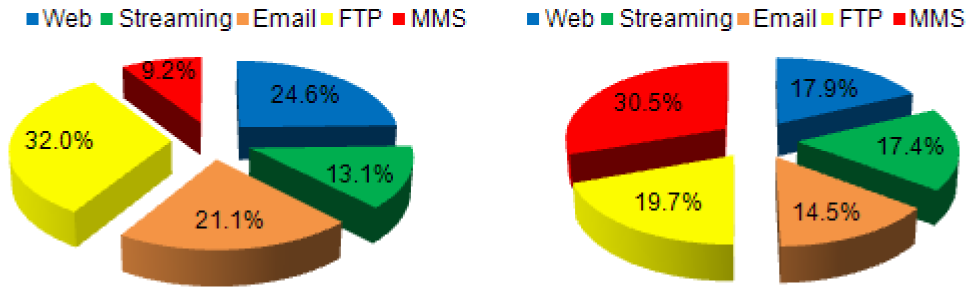


Figure 4.36. HSPA+ and Mobile WiMAX UL Average Satisfaction Grade, per services, for the default scenario.

The offered traffic contemplates the distribution of users for the entire network. Seeing that not all users are covered and the throughputs reached can be lower than the minimum requirements of each service, the served traffic is not necessarily identical to the offered one. One can notice that, through Figure 4.37, there is a higher discrepancy in the case of Mobile WiMAX comparing to the percentages referred in Figure 4.9. For instance, the percentage of FTP decreases 40 % and the percentage of MMS increases 218% which is not desirable for the network because it is advantageous that the served traffic is similar to the offered one. So, Mobile WiMAX, besides having a higher percentage of served users, serves a larger number of users performing MMS and a lower number of FTP and more demanding services users. However the average ratio of served users is higher than the HSPA+ one, the services considered are less demanding in terms of maximum and minimum throughputs that can be requested.

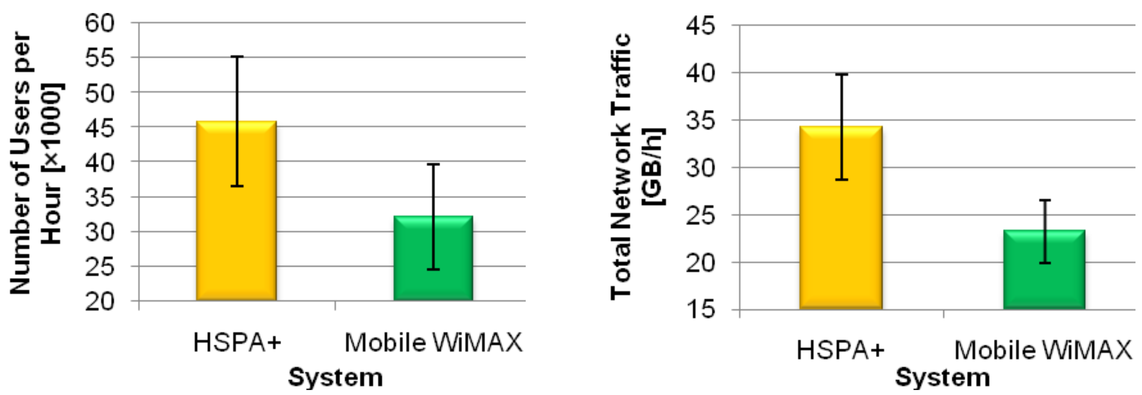
When a comparison between two systems is being performed, the number of users per hour is a fundamental parameter, since the dimensioning of the networks is done for the busy hour. The comparison, regarding the number of users in the hour period, is presented in Figure 4.38(a). One can observe that HSPA+ can serve more users in this period, because the trade-off between covered and served users is beneficial to HSPA+. Moreover, the average instantaneous throughput is also higher for HSPA+, which means that each session is realised in a shorter interval of time. HSPA+ serves 45 800 users, 13 800 more than Mobile WiMAX.



(a) HSPA+. (b) Mobile WiMAX.

Figure 4.37. HSPA+ and Mobile WiMAX UL percentage of served traffic, detailed for each service.

The total network traffic, Figure 4.38(b) depends, essentially, on the number of users in an hour and the percentage of served traffic for each service. HSPA+ serves more users and the distribution of services include more users performing sessions associated to a large volume of traffic such as FTP and Web. So, as expected, HSPA+, for the total network traffic, presents 34 GB/h, while Mobile WiMAX goes to up 23 GB/h.



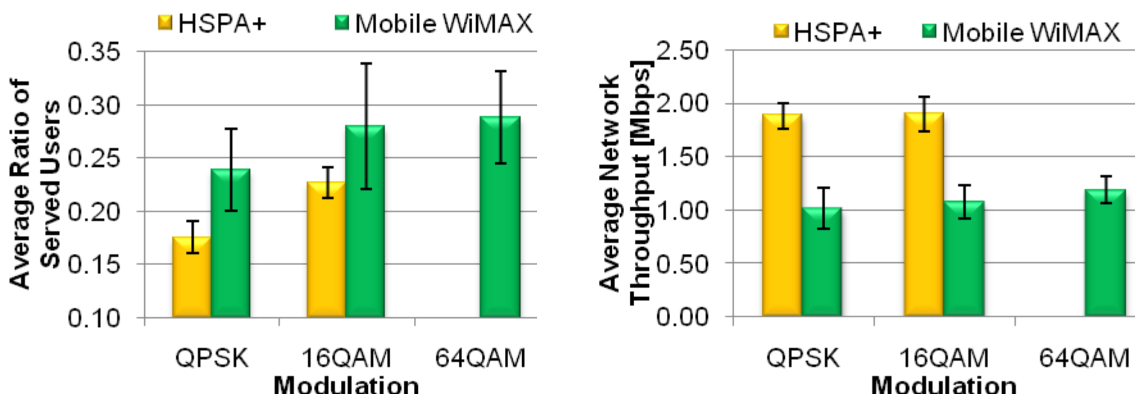
a) Number of users in a hour. (b) Total Network Traffic.

Figure 4.38. HSPA+ and Mobile WiMAX UL Number of Users per Hour and Total Network Traffic, for default scenario.

4.4.2 Modulation Impact

A set of simulations were done with the purpose of studying the importance of using different modulations. As observed in Figure 2.6, one of the most important features brought up by HSPA+ is the use of 16QAM. In this section, one evaluates the consequences of using QPSK modulation instead of 16QAM, which is considered in the default scenario. In Mobile WiMAX, the 64QAM modulation is optional, and was not considered in the default scenario. So, in addition to the study of QPSK and 16QAM, the consequences and benefits of 64QAM introduction at system level are also discussed. One should take the limitations imposed by the modulation chosen into account, which in Mobile WiMAX are similar to the ones referred to Section 4.3.2.

Supposing that all users are being served with QPSK, the average network throughput, in HSPA+, as seen on Figure 4.39(a) maintains, approximately, the value of the default scenario, around 1.9 Mbps. The QPSK use, in Mobile WiMAX, has, as a consequence, the reduction of 6.5% in this parameter. Moreover, the use of 64QAM instead of 16QAM causes an increase of 9.3%.



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

Figure 4.39. HSPA+ and Mobile WiMAX UL Average Network Throughput and Average Ratio of Served Users varying the modulation scheme.

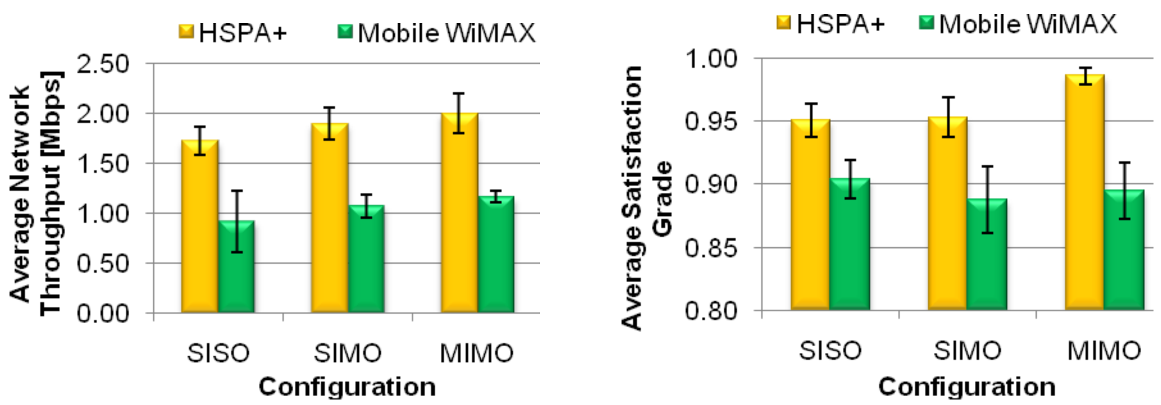
Although the changes in the average network throughput are not very expressive, the change of modulation scheme is more relevant when regarding the average ratio of served users. In fact, 16QAM, instead of QPSK, allows serving more 5% and 4% of the covered users in HSPA+ and Mobile WiMAX, respectively. Additionally, in Mobile WiMAX, when 64QAM is used instead of 16QAM, the average ratio of users increases 4% which is a good improvement to the system. The use of QPSK reduces the capacity of BSs which is undesirable if, for instance, a reasonable number of users are connected to a BS requesting demanding services. In terms of throughout, for values of E_c/N_0 lower than 2 dB, QPSK modulation presents higher throughputs, Figure 2.6. Above that value, 16QAM is the one with better performance. Therefore, the impact of modulation depends strongly on the environment type and on its conditions, such as slow and fast fading, because they influence the associated E_c/N_0 .

Concerning the average satisfaction grade, for HSPA+, Figure K.1, QPSK increases the average satisfaction grade in 2%, besides serving more users, the services requested are probably less demanding ones. Contrary to HSPA+, in Mobile WiMAX, when only QPSK is considered, the average satisfaction grade decays 3%. When one take 64QAM into account, the average satisfaction grade maintains its average value, which means that the larger number of users served is not associated with a reduction of the satisfaction grade.

4.4.3 Antenna Configuration Impact

Regarding the influence of antenna configuration, a set of simulations were realised for both HSPA+ and Mobile WiMAX. The use of MIMO is not standardised in Release 7, but once discussed in DL, it is also important to have a perspective of the performance in UL. The antenna fed power considered is the dedicated one.

The average network throughput, Figure 4.40(a), presents a variation with the configuration almost similar for both systems. The configuration that presents worse results is SISO, where the average network throughput is 1.73 Mbps for HSPA+, almost duplicating the value of the parameter obtained in Mobile WiMAX. The use of MIMO, due to improvements in terms of capacity, supporting higher throughputs, represents an increase of 16% and 27%, for HSPA+ and Mobile WiMAX, compared to SISO. The configuration used in default scenario, SIMO, has results for this parameter between SISO and MIMO. The results, mainly in Mobile WiMAX, has higher standard deviations caused by the few number of users connected to each BS.

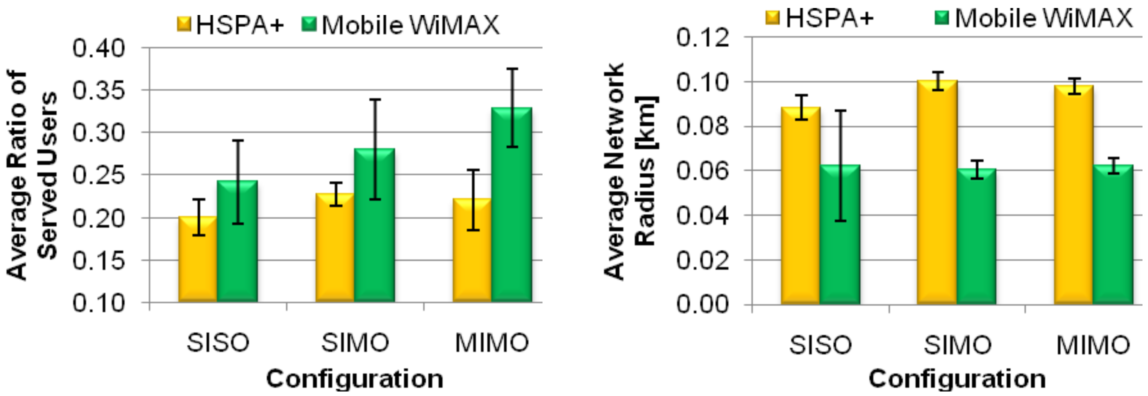


(a) Average Network Throughput. (b) Average Satisfaction Grade.

Figure 4.40. HSPA+ and Mobile WiMAX UL Average Network Throughput and Average Satisfaction Grade varying the antenna configuration.

Concerning the average satisfaction grade, Figure 4.40(b), one can notice that, in HSPA+, this parameter increases 3.5% when MIMO is applied instead of SIMO. The use of SISO leads to an identical average satisfaction grade compared to the one obtained with SIMO, near to 0.95. Relatively to Mobile WiMAX, the results are approximately 0.90 for all configurations. The type of services requested and the randomness associated to them has a major influence in the latter results, since there are few users in the coverage area.

The average ratio of served users, Figure 4.41(a), with a SISO configuration, assumes the value of 0.21 in HSPA+ and 0.24 in Mobile WiMAX, i.e., the minimum when balancing all configurations. The introduction of one more antenna in the BS, SIMO, and the use of MIMO allows a more robust and higher performance network, increasing the parameter under discussion. In the default scenario, for Mobile WiMAX, on average, 28% of the users are served but, if MIMO is implemented, this value becomes larger, 32%, representing, relative to the default scenario, an improvement of 14.3%. In HSPA+, the ratio of served users, when SIMO is not considered, is 0.21 and 0.22 with SISO and MIMO, respectively. The better performance of SIMO instead of MIMO is not common, but can be explained, one more time, by the lower penetration of users in the UL. Bearing this in mind, still considering HSPA+, one can notice that MIMO standard deviation is higher than the obtained for SISO and SIMO.



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

Figure 4.41. HSPA+ and Mobile WiMAX UL Average Ratio of Served Users and Average Network Radius varying the antenna configuration.

Regarding the average network radius, the behaviour for the two systems presents some resemblances, Figure 4.41(b). With Mobile WiMAX, the parameter is, approximately, constant not depending on the configuration. The average network radius, nearly 60 m, is lower than the obtained for HSPA+, for any configurations. This value is extremely lower in a context of a cellular planning. For HSPA+, one can notice that, for SISO, the average network radius is 0.08 km and, when SIMO or MIMO are considered, the radius increases around 20 m, which is not enough to realise a good coverage of the area. The average network radius obtained for SISO has a higher standard deviation.

The use of diversity introduces an additional gain that increases not only the cell edge of the BSs, but also the number of users covered. Contrary to DL, in UL, due to the MT transmission power limitations, the cell radius of BSs is lower and the overlapping of the covered areas of several BSs is not so common. Therefore, the use of SIMO, compared with SISO, allows covering more 8% of the effective users. The use of MIMO has not only influence in terms of capacity and average satisfaction grade, but also in the covered area, being capable of covering near to 45% of the effective users, Figure K.2. In UL, the coverage is a limitative factor for both systems, which not happens in DL, where HSPA+ provides a total coverage.

With respect to the number of users in an hour, Figure K.3(a), and the total network traffic, Figure K.3(b), one can notice that the use of SISO instead SIMO leads to a degradation of system performance and the use of MIMO allows serving more users and a higher total traffic. One should also point that the use of MIMO instead SIMO causes more impact in Mobile WiMAX than in HSPA+. For Mobile WiMAX, the use of MIMO increases the number of users from 32 000 to 38 000, compared to the default scenario and, for HSPA+, there are only more 1 000 more users served. Still regarding a comparison with the default scenario, the use of MIMO in the Mobile WiMAX system increases the traffic during an hour in 4GB/h, representing a increase of 17% while, for HSPA+, the total traffic increases only 2%.

4.4.4 Higher Throughput Impact

In this scenario, there is an enhancement in terms of throughput for certain services that modify network behaviour. The three services that suffer an increase of throughput are the ones that are more suitable of having higher throughput. MMS and Streaming are examples of services that do not need an increase, because they are based essentially on sending small amounts of data or signalling information. The modifications performed are listed, marked with bold, in Table 4.10.

The average network throughput increases, Figure K.4(a), as expected, for both systems when the maximum throughputs are changed. For HSPA+, the increase obtained is 1 Mbps whereas, in Mobile WiMAX, it becomes 0.58 Mbps higher, representing raises of 53% and 25%, relating to Default throughputs. HSPA+ has a better performance when the users are more demanding.

Table 4.10. New maximum throughput values for each of services for UL.

Service	Maximum Throughput [Mbps]
FTP	**7.2**
HTTP/Web	**7.2**
E-mail	**7.2**

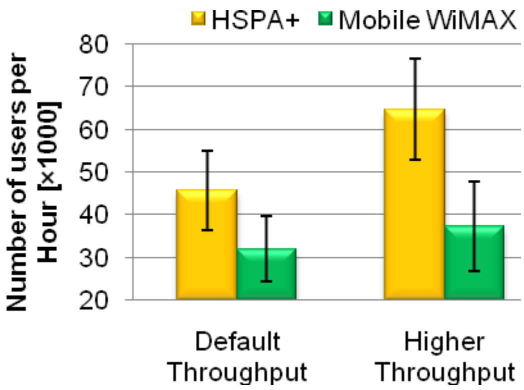
Regarding the average satisfaction grade, Figure K.4(b), the parameter decreases with the enhancement of throughputs, since the differences between the minimum and maximum allowed throughputs are higher for the same unfavourable radio conditions. Moreover, note that the services are more demanding but the total available resources are kept constant. Taking these facts into consideration, the average satisfaction grade decays near to 9% and 16% for HSPA+ and Mobile WiMAX, which means that HSPA+ system preserves a higher satisfaction grade when the throughputs considered are also higher.

Regarding the average ratio of served users, Figure K.5., for Mobile WiMAX the parameter is kept constant and for HSPA+, the parameter suffers a reduction of 6%, which can be explained by the higher number of users covered in HSPA+. With the new throughputs, summing all users' contributions, the maximum capacity of the BS can be achieved. When this happens, users are reduced, according to the priority list, and, in the BS with more traffic, there are more users delayed summing to the ones that do not have enough SNR.

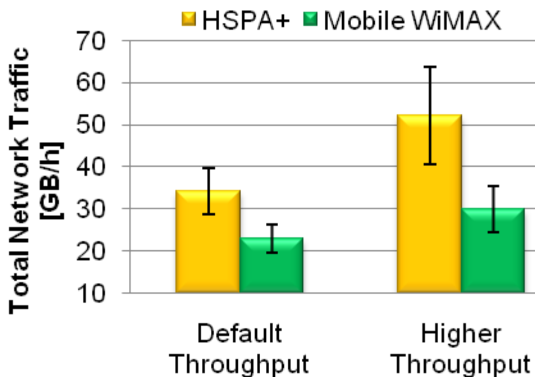
The average network throughput increases with the number of effective users, which means that, when extrapolating to an hour period, more users can be served as seen in Figure 4.42(a). For

HSPA+, 18 800 more users are served, comparing to the default scenario, while in Mobile WiMAX this number is lower, 5 000 users.

The total network traffic also increases during an hour, Figure 4.42(b). For HSPA+, the increase of total traffic is more significantly than the one occurred in Mobile WiMAX, being of 52% in HSPA+ and near to 30% in Mobile WiMAX.



(a) Number of Users per Hour.



(b) Total Network Traffic.

Figure 4.42. HSPA+ and Mobile WiMAX UL Total Number of Users per Hour and Total Network Traffic, for different throughput services.

4.4.5 Data Centric Impact

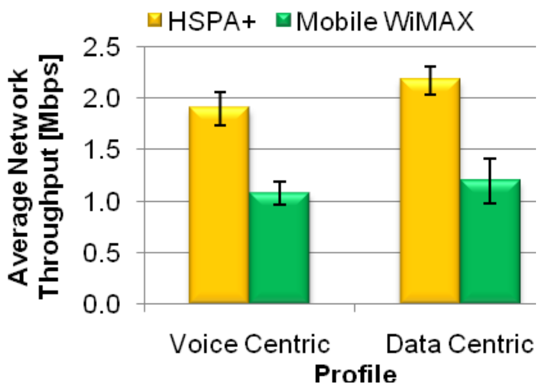
The Data Centric profile was introduced in Section 4.3.5 for DL. The objective behind this impact study is the same, and the reasons for the variations remain valid when UL is taken into account.

When introducing profiles with more users performing data services, the network is still capable of serving the same users from the default profile with HSPA+. For Mobile WiMAX, there is a slightly reduction of 2% in the number of served users, as seen in Figure K.6(a) . As one can observe in Figure K.6(b), the quality of the service given by the systems, assessed by the average satisfaction grade, is not affected with the profile change.

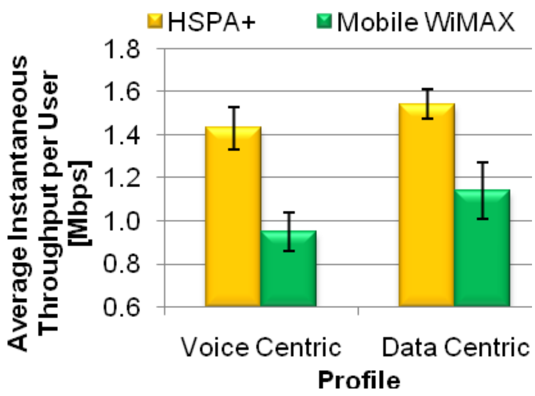
The average network throughput, Figure 4.43(a), is 1.8 times greater in HSPA+ than in Mobile WiMAX when considering the Data Centric profile. Concerning the average instantaneous throughput per user, Figure 4.43(b), due to the higher satisfaction grade, HSPA+ also presents better results corresponding to an increase of 7.7% relative to Voice Centric. For Mobile WiMAX, still regarding the average instantaneous throughput, this parameter is increased around 20%, which means that the difference between the two systems is reduced from 0.5 to 0.4 Mbps. This result, in a scenario with a small number of users covered, is irrelevant.

As for the total number of users per hour, Figure K.7(a), as expected, HSPA+ can serve more users than Mobile WiMAX as a consequence of the instantaneous trend. Nevertheless, the Data Centric profile does not causes a strong impact on the number of users, with only more 700 and 2 000 users, comparing to Voice Centric, for HSPA+ and Mobile WiMAX, respectively.

In terms of total network traffic, the same amount of users is performing services associated at a higher volume, Figure K.7(b). So, it is natural that the total network traffic is increased. HSPA+ presents 50 GB/h for Data Centric, 15 GB/h more than Voice Centric. Comparing HSPA+ and Mobile WiMAX performance with the results of Voice Centric Profile, HSPA+ corresponds to an increase of 48% in the total network traffic, while Mobile WiMAX presents a 55% higher total network traffic.



(a) Average Network Throughput.



(b) Average Instantaneous Throughput per User.

Figure 4.43. HSPA+ and Mobile WiMAX UL Average Network Throughput and Average Instantaneous Throughput per User, for the 2 profiles.

4.4.6 More Users Impact

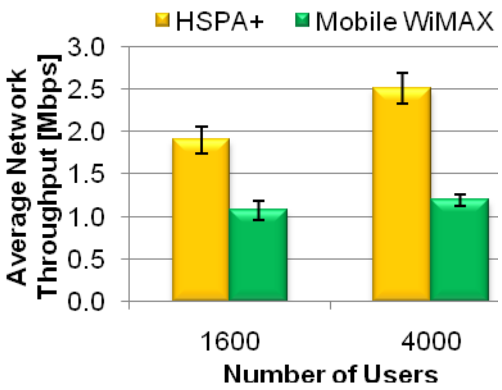
In this subsection, the effect of considering a larger number of users in the network is analysed. Contrary to DL, a district analysis is not done due to the coverage problems found in UL and, as consequence, the low number of users considered, which does not enable the analysis in a controlled environment. It is also important to remember that not all users are relevant to this analysis, because in HSPA+ voice and video-telephony users are served by Release 99 and in Mobile WiMAX they are not analysed together with the data services.

For UL, the introduction of more users in the network does not induce relevant modifications in the average satisfaction grade and in the average ratio of served users, which have variations below 0.5%. This means that the number of covered users still not being sufficient to achieve the maximum capacity of several BSs, thus, the capacity issue is overcome by aspects related to the environment, such as fading issues and indoor penetrations.

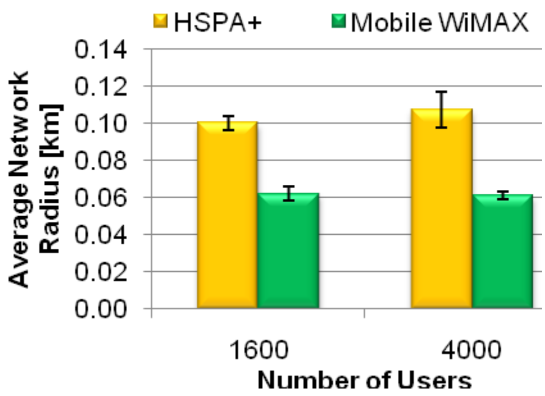
The average network throughput, Figure 4.44(a) , since more users are considered, is improved to 2.5 Mbps in HSPA+ and to approximately 1.2 Mbps in Mobile WiMAX, which denotes that HSPA+ has more than the double of the average network throughput.

Concerning the average network radius, Figure 4.44(b), there are no perceptible changes in Mobile WiMAX due to the negligible number of users in each BS. For HSPA+, an increase of 10% in the average network radius is verified which denotes that, in this system, there are more users distributed along the cell.

For the total number of users per hour, HSPA+ can serve in the hour period approximately 112 000 users, and Mobile WiMAX 50 000 users, Figure 4.45(a). Compared to the default scenario, there are more 64 000 more in HSPA+ and 18 000 more in Mobile WiMAX. The better response of HSPA+, through a higher satisfaction grade for a certain SNR, jointly with the higher coverage explains the results. The results for traffic per hour are 82 GB/h for HSPA+ and 37 GB/h for Mobile WiMAX, which denotes that the introduction of more users causes a larger impact in HSPA+ system, Figure 4.45(b).

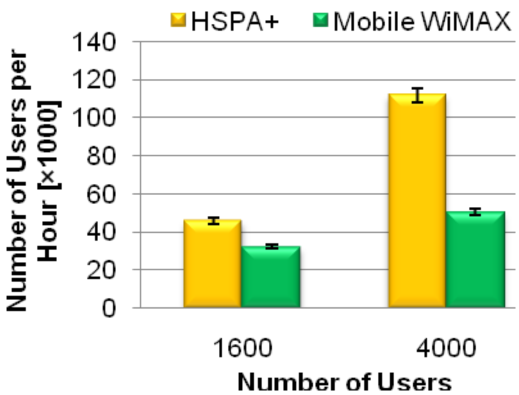


a) Average Network Throughput.

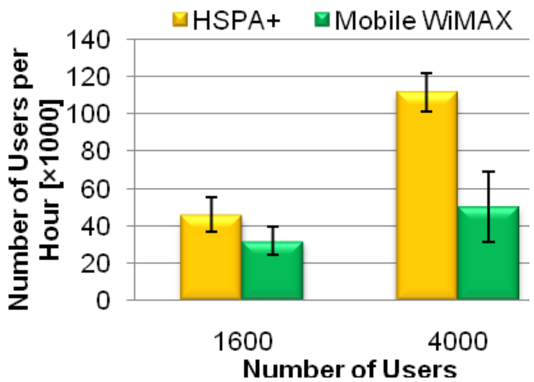


(b) Average Network Radius.

Figure 4.44. HSPA+ and Mobile WiMAX UL Average Network Throughput and Average Network Radius for 1600 and 4000 users.



a) Number of Users per Hour.



(b) Total Network Traffic.

Figure 4.45. HSPA+ and Mobile WiMAX UL network parameters Average Number of Users per Hour and Total Network Traffic for 1600 and 4000 users.

Chapter 5

Conclusions

This chappter point out the main conclusions of this thesis, as well as some suggestion for future work.

The main objective of this thesis was to make a comparison of the performance of HSPA+ and Mobile WiMAX giving special emphasis to capacity and coverage aspects. These goals were accomplished through the development and implementation of 2 models: the single user and the multiple users one. The former is intended to provide a global overview of network planning, regarding cell radius for HSPA+ and Mobile WiMAX for a single user. This model was implemented in a C++ program, with an intuitive interface, where it is possible to calculate the cell radius for a certain application throughput requested by a single user in the network, varying several parameters of each system. Since there is only one user for all the available resources, and the model does not take the interference phenomenon into account, the overheads differentiation for both systems is discussed and compared.

Afterwards, the multiple users model was adapted from the single user one. This model had the objective of studying a realistic case, where users are performing multiple services and placed randomly over the network area. There are two important differences between the single and the multiple users scenarios: the interference margin is introduced and the slow and fast fading are not longer fixed, being represented by log-normal and Rayleigh distributions. The resources available in each BS are shared among all users. 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, simultaneously. If the BS is not capable of doing that, a reduction strategy is applied, reducing the user´s throughput according to QoS requirements. If the maximum capacity is not overlapped and the throughput given by distance is higher than the minimum, and lower than the maximum service throughput, and also lower than the requested one, the satisfaction grade is reduced. The goal of this thesis is to analyse both systems together, to have a perspective of the differences and of the distinct sensitivity to variations to default scenario.

Regarding the single user scenario for HSPA+, the radio parameters considered in the analysis were: antenna configuration, environment and modulation scheme. The frequency, BS and MT antenna gains, transmission power and traffic power percentage remains constant. For all the environments, it is observed that, both for DL and UL, the cell radius decreases with the increase of the application throughput, because higher throughputs require higher SNR values, which leads to a decrease of the path loss and a reduction of cell radius. The cell radii are extremely lower being not appropriate to cover the city of Lisbon except the one obtained for HSPA+ DL that is enough to cover all users.

For the cell radius variation with the different antenna configurations, the throughputs considered were fixed, 12.0 and 7.0 Mbps for DL and UL. SIMO increases the cell radius of 16% and 13% in DL and UL when compared to SISO while, for MIMO, the improvements registered, still comparing with SISO, were 30% and 49%. MIMO has a great importance in provide higher throughputs along higher cell radius.

Considering the variation of the modulation scheme for the different environments, it can be seen that the use of 64QAM leads to higher throughputs, when comparing to 16QAM. The cell radii are, as a consequence, lower which constitutes a trade-off to be analysed careful.

Concerning the single user for Mobile WiMAX, some of the radio parameters taken into account are the same as the ones for UMTS/HSPA+ and the exclusive TDD Split and channel bandwidth. For a TDD Split 1:1 and with a 64QAM modulation for DL and a 16QAM modulation for UL, the variation of the cell radius for different channel bandwidths, antenna configurations and environments are analysed for the maximum throughput of each combination. The simulations performed allow conclude that the cell radius decreases with the increase of channel bandwidth, both for DL and UL, because, when the channel bandwidths are higher, there are more data sub-carriers and sub-channels, thus, the throughputs achieved are also greater. MIMO is the configuration that is associated to higher throughput, and in theory, duplicates the achieved throughput. The use of higher channel bandwidths, associated to higher modulation, also leads to lower cell radii, for all the environments studied.

A comparison between the two systems considered is performed for a single user scenario. For DL, the interval of throughputs analysed was from 6 Mbps to 17 Mbps and, for UL, the range of throughputs considered was the ones higher than 3.5 Mbps and lower than 7.6 Mbps. For DL, the cell radius decrease 46% in HSPA+ and 41% in Mobile WiMAX. The radius obtained for HSPA+ is, for the values considered, 4 times higher than the Mobile WiMAX one. For UL, the cell radius decreases from 0.28 to 0.17 km in HSPA+ and from 0.17 to approximately 0.09 km in the case of Mobile WiMAX. HSPA+ presents an extremely advantageous coverage in DL. For UL, the coverage is a limitative factor for both systems when considering higher service throughputs.

Concerning the multiple users scenario, the comparative study of the performance of both systems is separated for DL and UL. A default scenario is created with the objective of realise a set of simulations that are references to analyse the impact when there is a modification on one of the several parameters. The use of MIMO increases the capacity of the system and the available throughputs for a certain SNR. For HSPA+, curves with values of throughput in order to SNR are used. In Mobile WiMAX, the RMG model is used to include the MIMO enhancements. This model, besides the 2.5 GHz frequency is out of the validation interval, is not so optimistic as the theoretical one and origin more realistic results.

Concerning the default scenario, for DL, the HSPA+ system covers a large number of users than Mobile WiMAX. The average network throughput, for HSPA+, is 8.85 Mbps and, for Mobile WiMAX, is 3.26 Mbps. Instantaneously, HSPA+ also presents better results with 3.1 Mbps whereas, in Mobile WiMAX, a user is served, in average, by 1.79 Mbps. Mobile WiMAX has a average ratio of served users 4% higher than the HSPA+ but its average satisfaction grade is lower and the served services profile shows that the most demanding services, such as FTP, Email and Web, have a lower penetration. Since, in a certain instant, the trade-off of covered and served users is more advantageous for HSPA+, this system can serve 258 000 users in a hour, corresponding to more 137 000 users than the ones served by Mobile WiMAX. The users served in HSPA+, in an hour, are associated to a total traffic of 450 GB/h, corresponding to the triple of the traffic generated by the Mobile WiMAX users in an hour. In general, one can say that HSPA+ has a better performance serving more users, with higher satisfaction grade and with served penetrations almost similar to the offered ones.

A set of simulations were realised to verify the impact on the DL of considering that in HSPA+ all the users are being served with a modulation of 16 QAM and, in the case of WiMAX, the modulation of 64QAM is not used. The neglected variations observed in the average satisfaction grade, average network throughput and average ratio of users denote that, both for Mobile WiMAX and HSPA+, the number of users served by higher values of SNR is lower and the modulation scheme is not a preponderant factor in the analysis.

When the MIMO configuration is not adapted in the DL, the performance of the system is degraded. The average network throughput, when MIMO is not used, decreases, in HSPA+, from 8.85 Mbps to 8.51 and to 7.69 Mbps when comparing to SIMO and MIMO, respectively. The total number of users and the total network traffic also decreases when MIMO is not considered, which means that MIMO is a very useful enhancement brought to the systems and its use improves the performance of the systems in terms of average networks and satisfaction grade which are very important parameters in mobile communication systems.

When considering higher maximum throughputs for the DL, the average satisfaction grade decays 14% in HSPA+ and 28% in Mobile WiMAX causing more impact when considering the latter system. In terms of number of users and total traffic, the sessions are performed in shorter period of time, which increase the number of users in an hour.

Regarding the impact of Data Centric profile in the DL, there are two changes that need to be kept in account. The total number of effective users placed in Lisbon is higher and the distribution of data services is different. Since Data Centric profile has a preponderance of FTP and Web, the services that are delayed more times in Mobile WiMAX, the average ratio of served users is reduced from 0.69 to 0.65 in this system. Contrary to the Mobile WiMAX, HSPA+ presents a similar average ratio of served users, which means that the system reacts in a more favourable way face to more demanding data services.

Since the antenna power fed is an expensive feature of the BS, the use of different antenna power fed solutions was also analysed in DL. With split antenna power fed, the achievable SNR for a certain user, placed along the cell radius BS, is lower and could not be sufficient to have the minimum throughput for each service. The higher cell edge of the BSs belonging to HSPA+ network allows that covered users are not reduced because there are several intersections between the areas of influence of each BS. In Mobile WiMAX, the coverage issue is a problematic one and is accentuated with the split antenna power fed by the reduction of the average percentage of covered users.

The last set of simulations realised to evaluate the systems performance in DL was relative to the introduction of more users. A district analyse is also done in order to have a more specific overview of different BSs instead of an average one. With the introduction of more uses, the average network traffic increases around 10 Mbps and 3.55 Mbps in HSPA+ and Mobile WiMAX, respectively. Three distinct BSs, located in district A, district B and district C, are analysed to reflect the different characteristics of the area in study. The district A represents a business area, the district B is connoted to a tourism zone and the district C is merely a residential one. As expected, the BS of district A is the one with more users connected with and, as a consequence, the normalised throughput is also the highest one of the 3 BSs considered.

After the complete analysis of the DL, a similar study is done for UL for a different scenario default. When comparing to the DL, one can notice that the coverage area is lower due to the limitations of MT which constitutes a problem when the services are demanding and the environment is an urban one with intense fast fading. So, the number of users covered are also lower which introduces a strongly dependence on the type of service that is performed by the users served and on its distribution. For UL, there are several BS inactive, i.e., without any user performing data services. Since there are more users covered in HSPA+, the average network throughput, for the default scenario, is 1.90 Mbps while, for HSPA+, the value is around 1.08 Mbps, representing a decrease of 43%. Instantaneously, HSPA+ also presents better results with 1.4 Mbps, more 0.45 Mbps than a user being served by Mobile WiMAX. HSPA+ covers 43% of the users placed in the city while Mobile WiMAX covers only 13% of the total users. Mobile WiMAX, besides serving 28% of the covered users, more 5% than HSPA+, serve them with a low satisfaction grade when compared to HSPA+. One should further refer that the distribution of served traffic in Mobile WiMAX contemplates less demanding services. In what regards the number of users per hour, one can refer that HSPA+ serves 45 800 users, more 13 800 than Mobile WiMAX. The total network traffic obtained for HSPA+ is 34 GB/h, while for Mobile WiMAX the parameter assumes the value of 23 GB/h. As happens in DL, for UL the HSPA+ system has a better performance in terms of capacity resources using and coverage issues.

Still considering the UL, when the modulation scheme is changed from 16QAM to QPSK, the average network throughput is decreased of 6.5% in Mobile WiMAX and remains constant in HSPA+. The introduction of 64QAM in Mobile WiMAX causes an increase of 9.3% in the mentioned parameter comparatively to 16QAM being a optional feature to be taken into account.

Concerning the influence of the antenna configuration in the UL, it is possibly to verify that SISO is the configuration that leads to the worst results in terms of average network throughput for both systems. The use of MIMO represents an increase of 16% and 27% in the mentioned parameter, for HSPA+ and Mobile WiMAX. In what concerns the percentage of served users, for Mobile WiMAX, there are more 4% of users served with MIMO when comparing to the default scenario. The higher throughputs achieved with the use of MIMO are very important to increase the number of served users.

The enhancements applied in the maximum throughput for several services, still regarding the UL, causes an impact on the average network throughput that increases 53% and 23% for HSPA+ and Mobile WiMAX. In an hour, when comparing to the default scenario, more 18 800 users are served in HSPA+ with this number being reduced to 5 000 users when one refers to Mobile WiMAX. HSPA+ reacts in a more satisfactory way when users are more demanding.

Considering the Data Centric profile in the UL, the ratio of the average network throughput in HSPA+ over Mobile WiMAX is 1.8 and the total network traffic of HSPA+ is 50 GB/h more 15 GB/h than Mobile WiMAX. HSPA+ is the system with better results in profiles that gives more importance to data services.

The introduction of more users in the network increases the average network throughput of HSPA+ to

2.5 Mbps with this value being more than the double of the one obtained for Mobile WiMAX, 1.2 Mbps. Extrapolating to an hour, the larger number of users introduced allows serving more 64 000 users and 18 000 users for HSPA+ and Mobile WiMAX.

One can conclude that for a single user scenario, HSPA+ presents a higher cell radius than Mobile WiMAX, for the same throughput. This is due to the improvements brought by Release 7 such as HOM and the use of MIMO in collaboration with important Layer-2 enhancements. For the multiple users scenario, HSPA+ presents better results in almost every analysed parameter analysed, even in the average network radius, where the percentage of covered users is always higher than Mobile WiMAX. However Mobile WiMAX presents a better result than HSPA+ for the average ratio of served users, HSPA+ providing higher average instantaneous throughputs, because the percentages of served traffic, in HSPA+, are approximately the offered ones. So, HSPA+ reacts better to the attenuations and slow and fast fading, serving users with more demanding services and with a higher quality as seen in the average satisfaction grade. On the other hand, Mobile WiMAX has less number of users per BS and the system is not capable of serving users with the satisfaction grade achieved in HSPA+. Moreover, the higher average ratio of served users is obtained for a distribution where the percentages of FTP, Email and Web are lower than the offered ones.

For future work, it would be interesting to study DL and UL jointly, and include the possibility of performing more than one service simultaneously. The impact of variable slow and fast fading margins could be analysed separated for a common distribution of users, to have a perspective of the behaviour of the two systems without the randomness associated to the distribution of users and to the requested throughput. The introduction of AAS and beamforming could also be interesting in order to have more directive ways of transmitting data. Regarding voice and video-telephony, a temporal analysis is interesting with the purpose of study the behaviour of the systems concerning real time services. The estimation of the time necessary to serve delayed users, which is preponderant in a TDD system, is also worthwhile doing. At the RRM level, it could be interesting to analyse the optimisation of the user´s connection to the BS, not only based on distance, but also on the available resources at each instant of time. Finally, given the advances in Mobile Communications Systems, a comparison between Mobile WiMAX and LTE would also be appealing, as two systems with the same access technique, OFDMA. A parallelism between resource blocks and sub-channels could be interest together with the advantages of flexible channel bandwidth presented in both systems

Annex A – Link Budget

The link budget used throughout this thesis is based on the Release 99 one, described in detail in [CoLa06] and [Sant04], adapted to HSPA+ and Mobile WiMAX.

The path loss can be calculated by [Corr06]:

$$L_{P_{[\mathrm{dB}]}} = P_{t_{[\mathrm{dBm}]}} + G_{t_{[\mathrm{dBi}]}} - P_{r_{[\mathrm{dBm}]}} + G_{r_{[\mathrm{dBi}]}} = EIRP_{[\mathrm{dBm}]} - P_{r_{[\mathrm{dBm}]}} + G_{r_{[\mathrm{dBi}]}} \quad \text{(A.1)}$$

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.

When diversity is considered, *Gr* in (A.1) is replaced by:

$$G_{rdiv_{[\mathrm{dB}]}} = G_{r_{[\mathrm{dBi}]}} + G_{div_{[\mathrm{dB}]}} \quad \text{(A.2)}$$

where G_{div} represents the diversity gain.

Note that diversity is more suitable to be implemented in UL, because there is no space in the MT for spatial diversity, and polarisation diversity requires a duplication of the transmit equipment at the BS, which represents a disadvantage [Sant04].

The Equivalent Isotropic Radiated Power (EIRP) can be estimated for DL by (A.3), and for UL by (A.4):

$$EIRP_{[\mathrm{dBm}]} = P_{Tx_{[\mathrm{dBm}]}} - L_{c_{[\mathrm{dB}]}} + G_{t_{[\mathrm{dBi}]}} - P_{Sig_{[\mathrm{dBm}]}} \quad \text{(A.3)}$$

$$EIRP_{[\mathrm{dBm}]} = P_{Tx_{[\mathrm{dBm}]}} - L_{u_{[\mathrm{dB}]}} + G_{t_{[\mathrm{dBi}]}} - P_{Sig_{[\mathrm{dBm}]}} \quad \text{(A.4)}$$

where:

- P_{Tx}: total BS transmission power;
- L_c: cable losses between transmitter and antenna;
- P_{Sig}: signalling power;
- L_u: user losses.

The received power can be calculated by (A.5) for DL, and (A.6) for UL:

$$P_{Rx_{[\mathrm{dBm}]}} = P_{r_{[\mathrm{dBm}]}} - L_{u_{[\mathrm{dB}]}} \quad \text{(A.5)}$$

$$P_{Rx_{[\mathrm{dBm}]}} = P_{r_{[\mathrm{dBm}]}} - L_{c_{[\mathrm{dB}]}} \quad \text{(A.6)}$$

where P_{Rx} represents the received power at receiver input.

The HSPA+ receiver sensitivity, can be approximated by:

$$P_{Rx\min_{[\mathrm{dBm}]}} = N_{[\mathrm{dBm}]} - G_{P_{[\mathrm{dB}]}} + SNR_{[\mathrm{dB}]} \quad \text{(A.7)}$$

where:

- N: total noise power given by (A.10);
- G_p: processing gain,Table A.1;
- SNR: signal to noise ratio, Table A.1;
- R_b: bit rate;
- R_c: WCDMA chip rate;
- E_b/N_0: energy per bit to noise spectral density ratio.

Table A.1. HSPA+ DL and HSPA+ UL processing gain and *SNR* definition.

System	Processing Gain	*SNR*
HSPA+ DL	Fixed and equal to 16	SINR
HSPA+ UL	R_c/R_b	E_b/N_0

The total noise power is:

$$N_{[\mathrm{dBm}]} = -174 + 10 \cdot \log(\Delta f_{[\mathrm{Hz}]}) + N_{F[\mathrm{dB}]} + M_{I[\mathrm{dB}]} \quad \text{(A.8)}$$

where:

- Δf: signal bandwidth;
- N_F: receiver's noise figure;
- M_I: interference margin.

For HSPA+ UL, the metric used for SNR is the E_b/N_0. The E-DPDCH throughput is a continuous function of the E_b/N_0 at the BS. The values for E_c/N_0, energy per chip to noise spectral density ratio, as function of the throughput, are calculated by interpolating the curves presented in Figure 2.6.

For the sensitivity calculation, the E_b/N_0 is necessary being obtained from E_c/N_0:

$$E_b/N_{0\,[\mathrm{dB}]} = E_c/N_{0\,[\mathrm{dB}]} + G_{P_{[\mathrm{dB}]}} \quad \text{(A.9)}$$

In HSPA+ UL, manipulating (A.7) and (A.10), the E_c/N_0 for a certain user´s distance is given by:

$$E_c/N_{0\,[\mathrm{dB}]} = P_{Rx\min_{[\mathrm{dBm}]}} - N_{[\mathrm{dBm}]} \quad \text{(A.10)}$$

For HSPA+ DL, rearranging (A.7), the SNR associated to a certain user distance is calculated by:

$$SNR_{[\mathrm{dB}]} = P_{Rx_{[\mathrm{dBm}]}} - N_{[\mathrm{dBm}]} + G_{p_{[\mathrm{dB}]}} \quad \text{(A.11)}$$

For Mobile WiMAX, the MT receiver sensitivity is given by [IEEE06]:

$$P_{Rx\min[\text{dBm}]} = -114 + SNR_{[\text{dB}]} + 10 \cdot \log\left(F_{S[\text{MHz}]} \cdot \frac{N_{DSC}}{N_{TSC}} \cdot \frac{N_{SCH}}{16} \right) + I_M N_{F[\text{dB}]} \quad \text{(A.12)}$$

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:

$$F_{s[\text{MHz}]} = n \cdot \Delta f_{[\text{MHz}]} \quad \text{(A.13)}$$

where:

- n: sampling factor
- Δf_c : channel bandwidth

The interference margin, is spite of not being considered in the single user mode, has to be calculated to use in the multiuser scenario. The margin is calculated based on the number of users of the BS coverage area. Since the BS with higher number of users in its coverage area has, also, more served users, the margin calculation is done through the number of served users. Therefore, a maximum margin value is assigned to the BS with higher number of users connected to and the margin of other BSs is calculated considering a proportional relationship. Both for HSPA+ and Mobile WiMAX, the interference margin to the users associated with BS_j is given by:

$$M_{I_j[\text{dB}]} = \frac{N_{u_j}}{N_{u_{max}}^{NodeB}} \cdot \xi_{[\text{dB}]} \quad \text{(A.14)}$$

where:

- ξ: maximum interference margin considered;
- N_{u_j} : number of users in the BS *j*;
- $N_{u_{max}}^{BS}$: number of users of the most populated BS.

Some margins must be taken into account, to adjust additional losses due to radio propagation and others. For HSPA+ and Mobile WiMAX:

$$M_{[\text{dB}]} = M_{SF_{[\text{dB}]}} + M_{FF_{[\text{dB}]}} + L_{int_{[\text{dB}]}} \quad \text{(A.15)}$$

where:

- M_{SF}: slow fading margin;

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

The total path loss is calculated by:

$$L_{p\,total_{[\text{dB}]}} = L_{p_{[\text{dB}]}} - M_{[\text{dB}]} \tag{A.16}$$

The total path loss is used as input in the COST 231 Walfisch-Ikegami propagation model, described in [DaCo99], to calculate the cell radius, r, for the single user model as explained in a simple way, in Section 3.1.

Considering that frequency bands for HSPA+ DL and UL are similar to those used by HSDPA and HSUPA respectively, one can state that DL frequency values used [2110,2170] MHz exceed the frequency validation values and it is also possible that the cell radius are outside the respective validation interval. Nevertheless, the model was used, since it is adjusted to urban non-line of sight propagation as the better model for this type of environment. The same conclusions are valid for Mobile WiMAX in the 2.5 GHz band.

The COST 231 Walfisch-Ikegami propagation model is valid for [DaCo99]:

- $f \in [800, 2000]$ MHz ;
- $r \in [0.02, 5]$ km ;
- BS height between 4 and 50 m;
- MT height between 1 and 3 m.

In Table A.2, the values for the propagation model's parameters are listed. For the parameter that represents the frequency losses dependence due to diffraction by a set of knife-edges, k_f, only the urban centre case was considered.

Table A.2. Default values used in the COST 231 Walfish-Ikegami 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

For Mobile WiMAX, the number of sub-carries necessary to provide the requested throughput is obtained by:

$$R_{b\,[\text{bps}]}^{PHY} = \frac{N_{DSC} \cdot N_{SB} \cdot \beta \cdot N_{DS}}{T_{F[\text{s}]}} \Leftrightarrow N_{DSC} = \frac{R_b^{PHY} \cdot T_{F[\text{s}]}}{N_{SB} \cdot \beta \cdot N_{DS}} \tag{A.17}$$

where:

- R_b^{PHY} : physical layer throughput,

- N_{DSC} : number of data sub-carriers,
- N_{SB} : number of symbol bits,
- β : effective code rate,
- N_{DS} : number of data symbols,
- T_F : frame duration (for Mobile WiMAX it is considered 5 ms).

The number of sub-carriers necessary to form a sub-channel is different for DL and UL transmission. Table 2.3 lists the values for 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. In order to include the MAC layer overhead, the number of OFDM symbols should be 37 considering that all resources are allocated to DL or UL.

The application throughputs for different TDD splits are presented in Table A.3 to Table A.6. In addition of considering a maximum of 37 data symbols, the reductions in the physical throughput caused by the application overhead and the BLER are applied multiplying the throughput by 0.95 and 0.90 respectively.

The values presented are the maximum for the respective SNR, [TaCh07], code rate and channel bandwidth. For DL and UL, the values are obtained through the physical values for TDD Split 1:0 and 0:1, presented in Table 2.4. For TDD Split 1:1, TDD Split 2:1, TDD Split 3:1 and TDD Split 3:2, for DL, the number of data symbols is multiplied, approximately, by 1/2, 2/3, 3/4 and 3/5 and, for UL, the same parameter is multiplied by 1/2, 1/3, 1/4, 2/5.

In a multiple user perspective, it is necessary to calculate the throughput due to the distance between the user and the BS. The first step is to determine the path loss associated to the user distance, described in [CoLa06] and [Sant04]. After the path loss calculation, the received power is determined, resulting:

$$P_{Rx_{[\mathrm{dBm}]}} = EIRP_{[\mathrm{dBm}]} - L_{P_{[\mathrm{dB}]}} + G_{r_{[\mathrm{dBi}]}} - L_{u,c_{[\mathrm{dB}]}} \quad (A.18)$$

Table A.3. Mobile WiMAX application throughputs for 5, 10 and 20 MHz channels for DL and UL considering TDD split 1:1 (adapted from [WiMF06a]).

Modulation	SNR [dB]	Code Rate	5 MHz Channel		10 MHz Channel		20 MHz Channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
QPSK	8	3/4	1.71	1.23	3.42	2.54	6.83	5.15
16QAM	10.5	1/2	2.28	1.64	4.55	3.38	9.11	6.86
	14	3/4	3.42	2.46	6.83	5.07	13.67	10.29
64QAM	16	1/2	3.42	2.46	6.83	5.07	13.67	10.29
	18	2/3	4.55	3.29	9.11	6.77	18.22	13.73
	20	3/4	5.13	3.70	10.25	7.61	20.50	15.44

Table A.4. Mobile WiMAX application throughputs for 5, 10 and 20 MHz channels for DL and UL considering TDD split 2:1 (adapted from [WiMF06a]).

Modulation	SNR [dB]	Code Rate	5 MHz Channel		10 MHz Channel		20 MHz Channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
QPSK	8	3/4	2.17	0.88	4.34	1.81	8.69	3.68
16QAM	10.5	1/2	2.90	1.17	5.79	2.42	11.58	4.90
	14	3/4	4.34	1.76	8.69	3.62	17.39	7.35
64QAM	16	1/2	4.34	1.76	8.69	3.62	17.39	7.35
	18	2/3	5.79	2.35	11.59	4.83	23.18	9.80
	20	3/4	6.52	2.64	13.04	5.43	26.07	11.02

Table A.5. Mobile WiMAX application throughputs for 5, 10 and 20 MHz channels for DL and UL considering TDD split 3:1 (adapted from [WiMF06a]).

Modulation	SNR [dB]	Code Rate	5 MHz Channel		10 MHz Channel		20 MHz Channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
QPSK	8	3/4	2.48	0.71	4.97	1.45	9.93	2.94
16QAM	10.5	1/2	3.31	0.94	6.62	1.94	13.24	3.93
	14	3/4	4.97	1.41	9.94	2.90	19.88	5.89
64QAM	16	1/2	4.97	1.41	9.94	2.90	19.88	5.89
	18	2/3	6.62	1.88	13.25	3.87	26.49	7.85
	20	3/4	7.45	2.11	14.90	4.35	29.80	8.83

Table A.6. Mobile WiMAX application throughputs for 5, 10 and 20 MHz channels for DL and UL considering TDD split 3:2 (adapted from [WiMF06a]).

Modulation	SNR [dB]	Code Rate	5 MHz Channel		10 MHz Channel		20 MHz Channel	
			DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]	DL Data Rate [Mbps]	UL Data Rate [Mbps]
QPSK	8	3/4	2.02	1.06	4.04	2.18	8.07	4.42
16QAM	10.5	1/2	2.69	1.41	5.38	2.90	10.76	5.89
	14	3/4	4.04	2.11	8.08	4.35	16.16	8.83
64QAM	16	1/2	4.04	2.11	8.08	4.35	16.16	8.83
	18	2/3	5.38	2.82	10.77	5.81	21.54	11.78
	20	3/4	6.06	3.17	12.11	6.53	24.23	13.25

For Mobile WiMAX, the throughput associated to a certain distance is determined through several steps. The maximum values of sensitivity for each SNR and bandwidth are calculated for both DL and UL using (A.8). The results obtained are list in Table A.7.

Table A.7. Sensitivity for each value of SNR for 5, 10 and 20 MHz channels.

SNR [dB]	Receiver Sensitivity [dBm]					
	5 MHz		10 MHz		20 MHz	
	DL	UL	DL	UL	DL	UL
8	-92.20	-95.88	-86.23	-89.65	-80.29	-83.71
10.5	-89.70	-93.38	-83.73	-87.15	-77.79	-81.21
14	-86.20	-89.88	-80.23	-83.65	-74.29	-77.71
16	-84.20	-87.88	-78.23	-81.65	-72.29	-75.71
18	-82.20	-85.88	-76.23	-79.65	-70.29	-73.71
20	-80.20	-83.88	-74.25	-77.65	-68.29	-71.71

The values of Table A.7 are references used to be compared with the values for the received power given by (A.18). If the user receiver sensitivity is higher than the first position in Table A.7, then it is compared with the next position. The process is repeated until the user sensitivity calculated is lower than one of the values of Table A.10. If the condition is not verified, the user can not be served because the technology is insufficient. When the process is finished, the correspondent value of SNR, σ, is used to calculate the number of data sub-carriers, in DL, by:

$$N_{DSC} = \sqrt{\frac{N_{TSC} \cdot 24 \cdot 16 \cdot 10^{\frac{(P_{r\,x\min[\mathrm{dBm}]} + 114 - \sigma_{[\mathrm{dB}]} - I_M N_{F[\mathrm{dB}]})}{10}}}{F_{S[\mathrm{MHz}]}}} \quad \text{(A.19)}$$

For UL, the number of data sub-carriers is calculated by:

$$N_{DSC} = \sqrt{\frac{N_{TSC} \cdot 16^2 \cdot 10^{\frac{(P_{r\,x\min[\mathrm{dBm}]} + 114 - \sigma_{[\mathrm{dB}]} - I_M N_{F[\mathrm{dB}]})}{10}}}{F_{S[\mathrm{MHz}]}}} \quad \text{(A.20)}$$

The user throughput due to the distance to the BS is calculated by (A.17).

Annex B – Expressions for Models

Figure 2.9 represents the 90th percentile throughput in Pedestrian A channel for HOM and MIMO for HSPA+ DL. The values for SNR, ρ, and throughput are collected in order to create real curves in the figure. The values of SNR as function of the throughput at physical layer, R_b^{PHY}, are calculated by polynomial interpolation, using Matlab and Excel. The interpolated functions are stepwise in order to minimise errors. The relative mean error, for all the curves collected, is, on average, below 3%. The values of relative mean error are shown in Table B.1 and B.2 for different interpolations.

The relative mean error, $\bar{e}$, is given by:

$$\bar{e} = \left| \frac{z_r - z_i}{z_r} \right| \tag{B.1}$$

where:

- z_r: reference value.

Considering 1×1 configuration with 16 QAM, for DL, one has:

$$\rho_{[\text{dB}]} = \begin{cases} -0.0541 \times {R_b^{PHY}}_{[\text{Mbps}]}^{6} + 0.9496 \times {R_b^{PHY}}_{[\text{Mbps}]}^{5} - 6.7214 \times {R_b^{PHY}}_{[\text{Mbps}]}^{4} \\ +24.6466 \times {R_b^{PHY}}_{[\text{Mbps}]}^{3} - 49.805 \times {R_b^{PHY}}_{[\text{Mbps}]}^{2} + 55.0299 \times {R_b^{PHY}}_{[\text{Mbps}]} - \\ 31.1894, \quad 0.7 \le {R_b^{PHY}}_{[\text{Mbps}]} < 4.5 \\ -0.0319 \times {R_b^{PHY}}_{[\text{Mbps}]}^{2} + 1.7534 \times {R_b^{PHY}}_{[\text{Mbps}]} - 6.9882, \quad 4.5 \le {R_b^{PHY}}_{[\text{Mbps}]} < 9.7 \\ 0.1529 \times {R_b^{PHY}}_{[\text{Mbps}]}^{3} - 5.1218 \times {R_b^{PHY}}_{[\text{Mbps}]}^{2} + 57.816 \times {R_b^{PHY}}_{[\text{Mbps}]} - 211.471, \\ 9.7 \le {R_b^{PHY}}_{[\text{Mbps}]} \le 14.4 \end{cases} \tag{B.2}$$

For a SISO configuration with 64 QAM, for DL, the SNR is given by:

$$\rho_{[\text{dB}]} = \begin{cases} -0.0541 \times {R_b^{PHY}}_{[\text{Mbps}]}^{6} + 0.9496 \times {R_b^{PHY}}_{[\text{Mbps}]}^{5} - 6.7214 \times {R_b^{PHY}}_{[\text{Mbps}]}^{4} \\ +24.6466 \times {R_b^{PHY}}_{[\text{Mbps}]}^{3} - 49.805 \times {R_b^{PHY}}_{[\text{Mbps}]}^{2} + 55.0299 \times {R_b^{PHY}}_{[\text{Mbps}]} \\ -31.1894, \quad 0.7 \le {R_b^{PHY}}_{[\text{Mbps}]} < 3.7 \\ 1.3691 \times {R_b^{PHY}}_{[\text{Mbps}]} - 5.8516, \quad 3.7 \le {R_b^{PHY}}_{[\text{Mbps}]} < 8.7 \\ 0.9565 \times {R_b^{PHY}}_{[\text{Mbps}]} - 2.3371, \quad 8.7 \le {R_b^{PHY}}_{[\text{Mbps}]} < 20 \\ 0.0396 \times {R_b^{PHY}}_{[\text{Mbps}]}^{2} + 0.0799 \times {R_b^{PHY}}_{[\text{Mbps}]} + 1.9286, \quad 20 \le {R_b^{PHY}}_{[\text{Mbps}]} \le 21.5 \end{cases} \tag{B.3}$$

In a 1×2 configuration with 16 QAM modulation, for DL, the SNR can be calculated by:

$$\rho_{[\mathrm{dB}]} = \begin{cases} -0.0012 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{6} - 0.0171 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{5} + 0.0476 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} \\ +0.4255 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - 3.251 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 10.0299 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 17.1838, \\ \quad 1.0 \le R_{b\,[\mathrm{Mbps}]} < 1.8 \\ -0.4437 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 4.3888 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 13.5340, \quad 1.8 \le R_{b\,[\mathrm{Mbps}]} < 3.2 \\ 0.0661 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} - 1.2758 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} + 8.8721 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} \\ -24.7943 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 19.3601, \quad 3.2 \le R_{b\,[\mathrm{Mbps}]} < 5.9 \\ -0.1323 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} + 2.7646 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 17.8122 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 36.0243, \\ \quad 5.9 \le R_{b\,[\mathrm{Mbps}]} < 8.3 \\ 0.0208 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - 0.6278 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 7.276 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 26.0464, \\ \quad 8.3 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 13.5 \\ 3.3333 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 87.6667 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 585, \quad 13.5 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} \le 14.4 \end{cases} \tag{B.4}$$

Considering 1×2 configuration with 64 QAM, for DL, one has:

$$\rho_{[\mathrm{dB}]} = \begin{cases} -0.0012 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{6} - 0.0171 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{5} + 0.0476 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} \\ +0.4255 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - 3.251 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 10.0299 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 17.1838, \\ \quad 1.0 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 2.2 \\ -0.1349 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 2.7519 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 11.4313, \\ \quad 2.2 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 5.9 \\ -0.0148 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} + 0.2876 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - 1.6684 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} \\ +2.8789 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 0.07, \quad 5.9 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 7.4 \\ -0.0148 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} + 0.2876 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - 1.6684 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} \\ +2.8789 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 0.07, \quad 5.9 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 7.4 \\ -0.0381 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 1.7802 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 9.1641, \\ 7.4 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 12.4 \\ -0.0158 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 1.4815 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 9.0373, \quad 12.4 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 18.5 \\ 0.6466 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 23.7609 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 230.2882, \quad 18.5 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} \le 21.5 \end{cases} \tag{B.5}$$

For a MIMO 2×2 configuration, with 16 QAM, for DL, the SNR is given by:

$$\rho_{[\mathrm{dB}]} = \begin{cases} -0.0052 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{6} + 0.1479 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{5} - 1.7114 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} \\ +10.2135 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - 33.3531 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 58.6222 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} \\ -50.9322, \quad 1.7 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 3.4 \\ -0.0642 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 1.9468 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 10.8835, \quad 3.4 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 5.6 \\ -0.0579 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 2.1091 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 12.0231, \quad 5.6 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 7.0 \\ -0.0704 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 2.3595 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 13.1371, \quad 7.0 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 12.0 \\ -0.0043 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} + 0.1489 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 0.8793 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} \\ +1.6067, \quad 12.0 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 14.2 \\ -0.0170 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 1.1714 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 6.3410, \quad 14.2 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 19.3 \\ -0.0016 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} + 0.1082 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 1.6755 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 13.4935, \\ 19.3 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 25.8 \\ 0.5533 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 28.4577 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 381.012, \quad 25.8 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 28.8 \end{cases} \tag{B.6}$$

In a MIMO 2×2 configuration with 64 QAM, for DL, the SNR can be calculated by:

$$\rho_{[\mathrm{dB}]} = \begin{cases} -0.0673 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{6} + 1.5397 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{5} - 14.3404 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} \\ +69.4089 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - 184.0043 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 255.3831 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} \\ -154.7503, \quad 1.7 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 3.5 \\ -0.0202 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} + 0.5189 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - \\ 4.7933 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 20.2255 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 37.2841, \quad 3.5 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 6.4 \\ -0.0202 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{4} + 0.5189 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} - \\ -0.0579 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 2.1091 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 14.0231, \quad 6.4 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 7.0 \\ -0.0817 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 2.4592 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 13.2108, \quad 7.0 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 7.8 \\ -0.0933 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{3} + 2.5064 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 21.18938 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 57.9987, \\ 7.8 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 9.5 \\ 0.8613 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 5.1806, \quad 9.5 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 14.1 \\ -0.0042 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} + 0.7262 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} - 2.4267, \quad 14.1 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 34.5 \\ 0.0482 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 2.879 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 60.0064, \quad 34.5 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} < 42.5 \\ 0.2984 \times {R_b^{PHY}}_{[\mathrm{Mbps}]}^{2} - 21.9131 \times {R_b^{PHY}}_{[\mathrm{Mbps}]} + 417.3976, \quad 42.5 \le {R_b^{PHY}}_{[\mathrm{Mbps}]} \le 43.2 \end{cases} \tag{B.7}$$

Interpolations for MIMO, which are the curves with higher SNR values, are represented in Figure B.1.

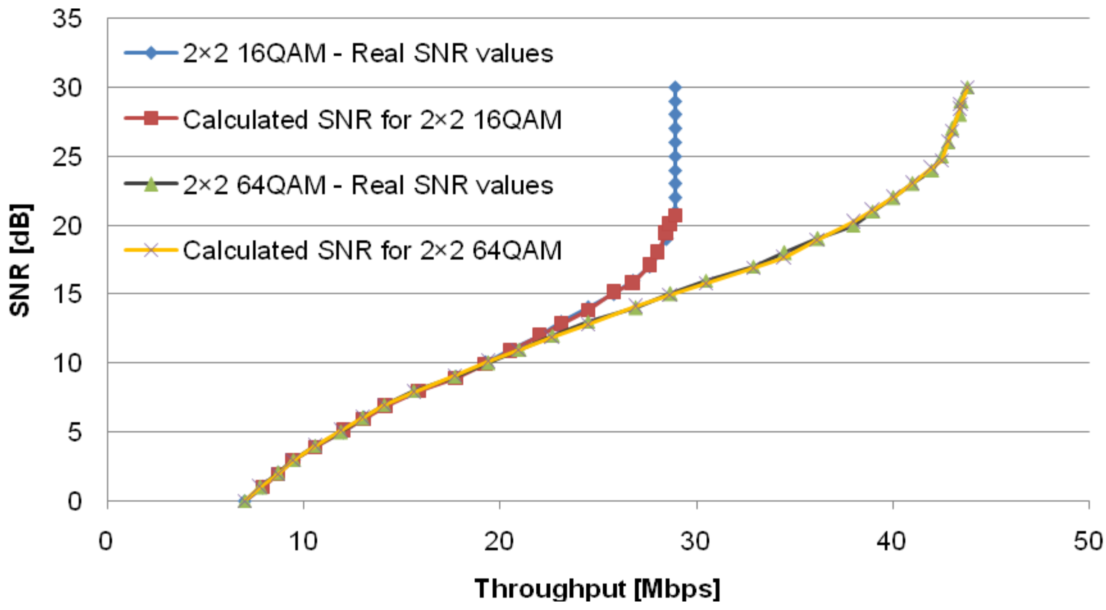


Figure B.1. Interpolations for HSPA+ DL for MIMO – SNR as function of physical throughput.

For QPSK, for UL, one has:

$$(E_c/N_0)_{[\mathrm{dB}]} = \begin{cases} -3.33 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} - 10.0, \quad 0 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} < 1.5 \\ -0.5998 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^2 + 5.0194 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} - 11.1447, \quad 1.5 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} < 2.7 \\ -5.2083 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^3 + 62.5 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^2 - 244.7917 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} + 313.5, \\ 2.7 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} < 4.2 \\ 0.8613 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} - 5.1806, \quad 4.2 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} < 5.5 \end{cases} \tag{B.8}$$

Considering 16 QAM, for UL, the E_c/N_0 is given by:

$$(E_c/N_0)_{[\mathrm{dB}]} = \begin{cases} -1.5432 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^3 + 6.9444 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^2 - 6.9444 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} - 3, \\ 0.6 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} < 1.8 \\ 2 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} - 6, \quad 1.8 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} < 3.5 \\ 0.1307 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^4 - 3.041 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^3 + 26.0522 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^2 \\ -95.8265 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} + 129.0191, \quad 3.5 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} < 7.7 \\ 0.1386 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^3 - 3.5025 \times R_b^{PHY}{}_{[\mathrm{Mbps}]}{}^2 + 30.979 \times R_b^{PHY}{}_{[\mathrm{Mbps}]} \\ -87.2192, \quad 7.7 \le R_b^{PHY}{}_{[\mathrm{Mbps}]} \le 11 \end{cases} \tag{B.9}$$

The interpolation realised for HSPA+ UL with 16 QAM is shown in Figure B.2.

As mentioned in Section 3.1, although the results are obtained considering 15 HS-PDSCH codes, the results are valid for 14 HS-PDSCH codes, since there are no available simulations for the latter number of codes.

The relative mean errors for the interpolated curves of E_c/N_0 as a function of the physical throughput are also listed in Table B.1. The values are acceptable, which gives consistence to the approximations done.

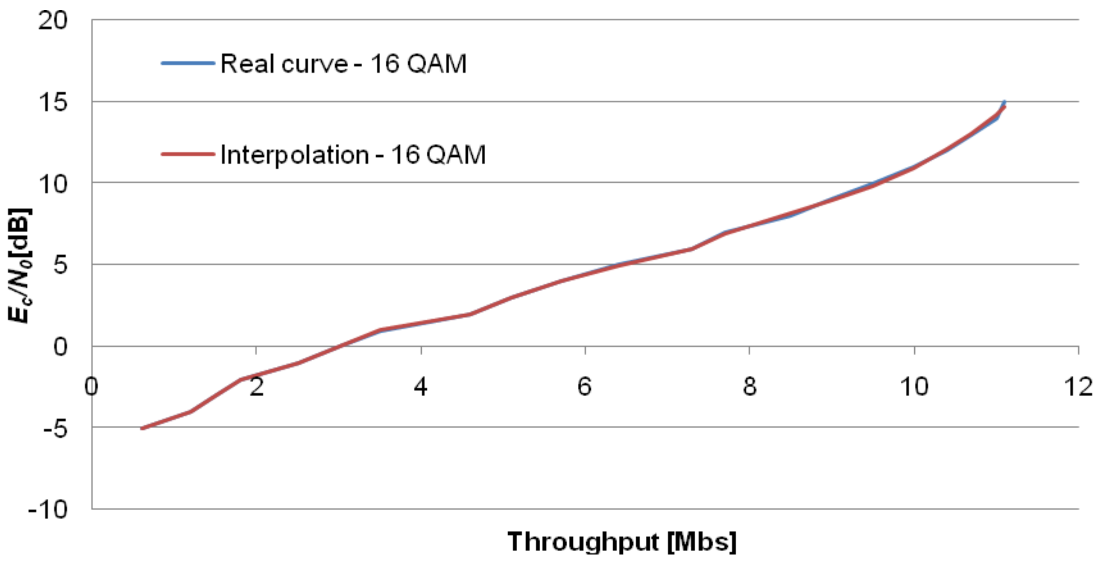


Figure B.2. Interpolation for HSPA+ UL with 16 QAM – E_c/N_0 as a function of physical throughput.

Table B.1. Relative Mean Error for interpolated curves of SNR and E_c/N_0 as function of throughput.

	Configuration and Modulation	Relative Mean Error [%]
DL	1×1 , 16QAM	1.22
	1×1 , 64QAM	2.31
	1×2 , 16QAM	0.99
	1×2 , 64QAM	2.98
	2×2 , 16QAM	2.17
	2×2 , 64QAM	1.64
UL	1×1 , QPSK	0.32
	1×1 , 16QAM	0.71

Using Figure 2.9, the expressions of physical throughput as a function of SNR are obtained for HSPA+ DL.

Considering 1×1 configuration with 16 QAM, one has:

$$R_b^{PHY}{}_{[\text{Mbps}]} = \begin{cases} 0.0143 \times \rho_{[\text{dB}]}{}^2 + 0.3486 \times \rho_{[\text{dB}]} + 2.7657, & -10 \le \rho_{[\text{dB}]} < -6 \\ 0.05 \times \rho_{[\text{dB}]}{}^2 + 0.85 \times \rho_{[\text{dB}]} + 4.5, & -6 \le \rho_{[\text{dB}]} < -1 \\ 0.0223 \times \rho_{[\text{dB}]}{}^2 + 0.631 \times \rho_{[\text{dB}]} + 4.3203, & -1 \le \rho_{[\text{dB}]} < 10 \\ -0.05 \times \rho_{[\text{dB}]}{}^2 + 1.5757 \times \rho_{[\text{dB}]} + 1.9286, & 10 \le \rho_{[\text{dB}]} < 18 \\ 14.4, \quad 18 \le \sigma_{[\text{dB}]} \le 30 \end{cases} \tag{B.10}$$

For a SISO configuration with 64 QAM, the physical throughput is given by:

$$R_b^{PHY}{}_{[\text{Mbps}]} = \begin{cases} 0.0143 \times \rho_{[\text{dB}]}{}^2 + 0.3586 \times \rho_{[\text{dB}]} + 2.7657, & -10 \le \rho_{[\text{dB}]} < -6 \\ 0.0005 \times \rho_{[\text{dB}]}{}^3 + 0.0208 \times \rho_{[\text{dB}]}{}^2 + 0.6167 \times \rho_{[\text{dB}]} + 4.3131, & -6 \le \rho_{[\text{dB}]} < 11 \\ -0.0652 \times \rho_{[\text{dB}]}{}^2 + 2.85 \times \rho_{[\text{dB}]} - 9.7048, & 11 \le \rho_{[\text{dB}]} < 20 \\ 21.6, \quad 20 \le \rho_{[\text{dB}]} \le 30 \end{cases} \tag{B.11}$$

In a 1×2 configuration with 16 QAM, the physical throughput can be calculated by:

$$R_b^{PHY}{}_{[\text{Mbps}]} = \begin{cases} 0.03 \times \rho_{[\text{dB}]}{}^2 + 0.7823 \times \rho_{[\text{dB}]} + 5.8266, & -10 \le \rho_{[\text{dB}]} < 3 \\ -0.0626 \times \rho_{[\text{dB}]}{}^2 + 1.6205 \times \rho_{[\text{dB}]} + 3.813, & 3 \le \rho_{[\text{dB}]} < 13 \\ 14.4, \quad 13 \le \rho_{[\text{dB}]} \le 30 \end{cases} \tag{B.12}$$

Interpolations for MIMO, which are the curves with higher throughput values, are represented in Figure B.3.

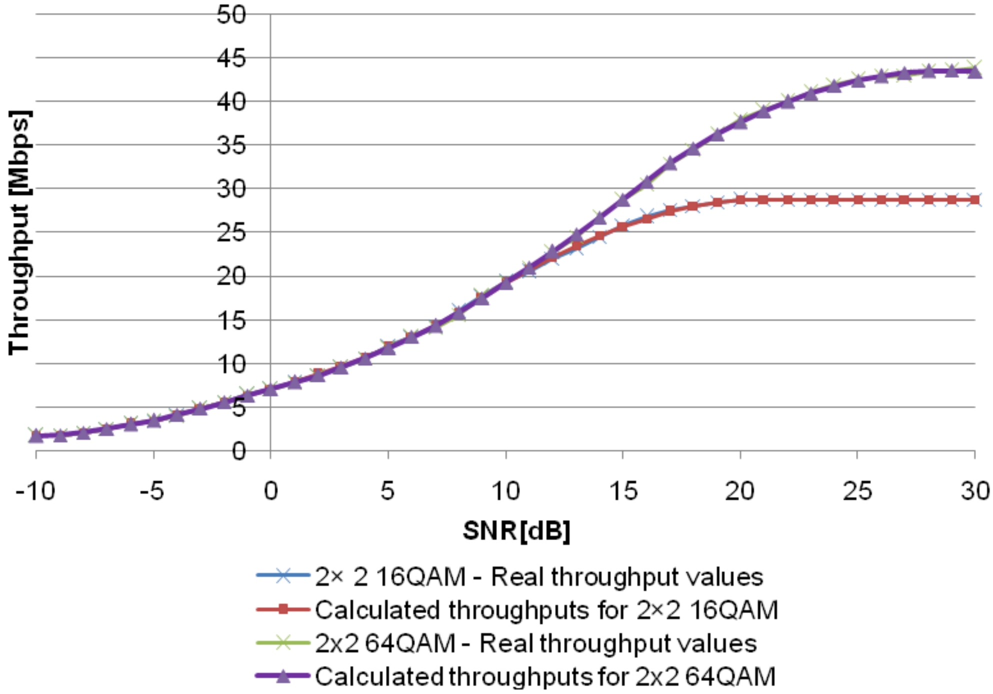


Figure B.3. Interpolations for HSPA+ DL for MIMO – physical throughput as function of SNR.

For HSPA+ UL, the values of, R_b^{PHY}, as a function of E_c/N_0, are calculated, one more time, by polynomial interpolation, using Matlab and Excel, with relative mean error below 3% for all the combinations. The interpolation functions are stepwise minimising the errors.

Considering 1×2 configuration with 64 QAM, one has:

$$R_{b\ [\mathrm{Mbps}]}^{PHY} = \begin{cases} 0.0255 \times \rho_{[\mathrm{dB}]}{}^2 + 0.7265 \times \rho_{[\mathrm{dB}]} + 5.6914, & -10 \le \rho_{[\mathrm{dB}]} < -1 \\ 0.0105 \times \rho_{[\mathrm{dB}]}{}^2 + 0.8517 \times \rho_{[\mathrm{dB}]} + 5.783, & -1 \le \rho_{[\mathrm{dB}]} < 13 \\ -0.0542 \times \rho_{[\mathrm{dB}]}{}^2 + 2.2054 \times \rho_{[\mathrm{dB}]} - 0.9696, & 13 \le \rho_{[\mathrm{dB}]} < 19 \\ 21.6, & 18 \le \rho_{[\mathrm{dB}]} \le 30 \end{cases} \tag{B.13}$$

For a MIMO configuration with 16 QAM, the physical throughput is given by:

$$R_{b\ [\mathrm{Mbps}]}^{PHY} = \begin{cases} -0.0139 \times \rho_{[\mathrm{dB}]}{}^3 + -0.2714 \times \rho_{[\mathrm{dB}]}{}^2 - 1.3004 \times \rho_{[\mathrm{dB}]} + 1.9524, \\ -10 \le \rho_{[\mathrm{dB}]} < -5 \\ 0.0021 \times \rho_{[\mathrm{dB}]}{}^3 + 0.0209 \times \rho_{[\mathrm{dB}]}{}^2 + 0.7905 \times \rho_{[\mathrm{dB}]} + 7.0537, & -5 \le \rho_{[\mathrm{dB}]} < 10 \\ -0.0722 \times \rho_{[\mathrm{dB}]}{}^2 + 3.1463 \times \rho_{[\mathrm{dB}]} - 5.2526, & 10 \le \rho_{[\mathrm{dB}]} < 20 \\ 28.8, & 20 \le \rho_{[\mathrm{dB}]} \le 30 \end{cases} \tag{B.14}$$

In a MIMO 2×2 configuration with 64 QAM, the physical throughput can be calculated by:

$$R_{b\ [\mathrm{Mbps}]}^{PHY} = \begin{cases} 0.0083 \times \rho_{[\mathrm{dB}]}{}^3 + 0.1357 \times \rho_{[\mathrm{dB}]}{}^2 - 0.2131 \times \rho_{[\mathrm{dB}]} + 4.8057, \\ -10 \le \rho_{[\mathrm{dB}]} < -6 \\ 0.0005 \times \rho_{[\mathrm{dB}]}{}^4 + 0.0018 \times \rho_{[\mathrm{dB}]}{}^3 + 0.0089 \times \rho_{[\mathrm{dB}]}{}^2 + 0.7812 \times \rho_{[\mathrm{dB}]} + 7.0784, \\ -6 \le \rho_{[\mathrm{dB}]} < 1 \\ -0.0001 \times \rho_{[\mathrm{dB}]}{}^3 + 0.0657 \times \rho_{[\mathrm{dB}]}{}^2 + 0.5792 \times \rho_{[\mathrm{dB}]} + 7.211, \\ 1 \le \rho_{[\mathrm{dB}]} < 6 \\ -0.0008 \times \rho_{[\mathrm{dB}]}{}^3 + 0.0593 \times \rho_{[\mathrm{dB}]}{}^2 + 0.8046 \times \rho_{[\mathrm{dB}]} + 6.0472, & 6 \le \rho_{[\mathrm{dB}]} < 17 \\ -0.0757 \times \rho_{[\mathrm{dB}]}{}^2 + 4.3661 \times \rho_{[\mathrm{dB}]} - 19.392, & 17 \le \rho_{[\mathrm{dB}]} < 30 \end{cases} \tag{B.15}$$

For QPSK modulation:

$$R_{b\ [\mathrm{Mbps}]}^{PHY} = \begin{cases} 0.0643 \times \left(E_c/N_{0\,[\mathrm{dB}]}\right)^2 + 0.8557 \times \left(E_c/N_{0\,[\mathrm{dB}]}\right) + 4.18, \\ -5 \le E_c/N_{0\,[\mathrm{dB}]} < -1 \\ -0.05 \times \left(E_c/N_{0\,[\mathrm{dB}]}\right)^2 + 0.31 \times \left(E_c/N_{0\,[\mathrm{dB}]}\right) + 3.77, & -1 \le E_c/N_{0\,[\mathrm{dB}]} < 2 \\ 0.0417 \times \left(E_c/N_{0\,[\mathrm{dB}]}\right)^3 - 0.5429 \times \left(E_c/N_{0\,[\mathrm{dB}]}\right)^2 + 2.5012 \times \left(E_c/N_{0\,[\mathrm{dB}]}\right) \\ +1.04, \quad 2 \le E_c/N_{0\,[\mathrm{dB}]} < 6 \\ 5.5, \quad 6 \le E_c/N_{0\,[\mathrm{dB}]} \le 11 \end{cases} \tag{B.16}$$

For 16 QAM modulation:

$$R_{b\ [\mathrm{Mbps}]}^{PHY} = \begin{cases} -0.0087\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^4 - 0.0669\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^3 - 0.0936\times \\ \left(E_c/N_{0\,[\mathrm{dB}]}\right)^2 + 0.6056\times\left(E_c/N_{0\,[\mathrm{dB}]}\right) + 3.0522,\ \ -5 \le E_c/N_{0\,[\mathrm{dB}]} < -3 \\ 0.0333\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^4 + 0.1\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^3 - 0.0333\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^2 + 0.4\times \\ \left(E_c/N_{0\,[\mathrm{dB}]}\right) + 3,\ \ -3 \le E_c/N_{0\,[\mathrm{dB}]} < 1 \\ 0.0583\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^3 - 0.575\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^2 + 2.3667\times\left(E_c/N_{0\,[\mathrm{dB}]}\right) + \\ 1.66,\ 1 \le E_c/N_{0\,[\mathrm{dB}]} < 5 \\ -0.0003\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^3 - 0.0195\times\left(E_c/N_{0\,[\mathrm{dB}]}\right)^2 + 0.9558\times\left(E_c/N_{0\,[\mathrm{dB}]}\right) + \\ 2.1899,\ 5 \le E_c/N_{0\,[\mathrm{dB}]} < 15 \\ 11,\ 15 \le E_c/N_{0\,[\mathrm{dB}]} \le 20 \end{cases} \tag{B.17}$$

Interpolation for 16QAM, which is the curve with higher throughput values, is represented in Figure B.4.

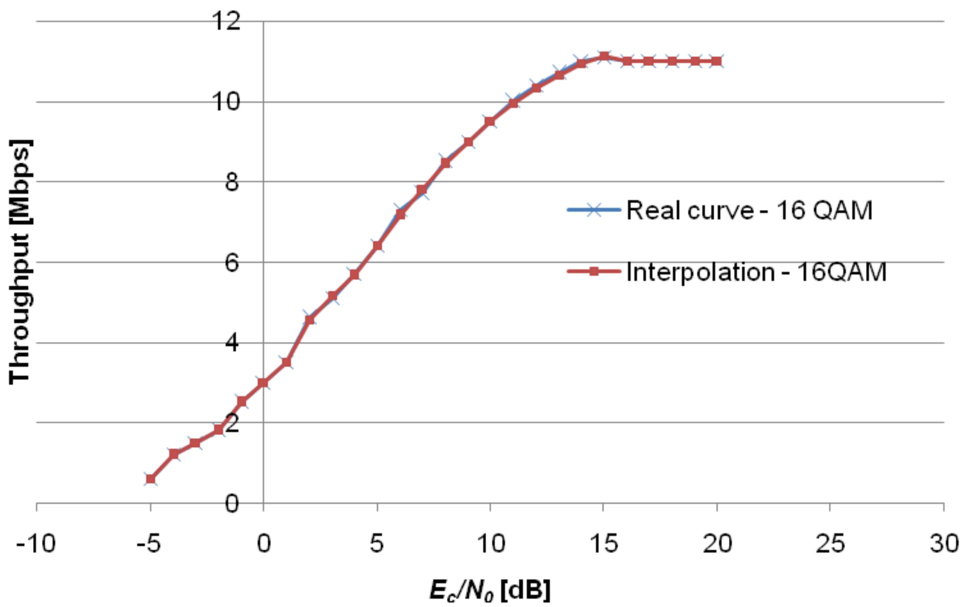


Figure B.4. Interpolation for HSPA+ UL curve for 16QAM modulation – Physical throughput as function of SNR.

The relative mean errors for all the interpolated curves of physical throughput as function of SNR and E_c/N_0 are listed in Table B.2. The values are acceptable which gives consistence to the approximations.

Table B.2. Relative mean error for interpolated curves of SNR and E_c/N_0 as function of throughput.

	Configuration and Modulation	Relative mean error [%]
DL	1×1 , 16QAM	0.60
	1×1 , 64QAM	1.74
	1×2 , 16QAM	0.56
	1×2 , 64QAM	0.70
	2×2 , 16QAM	0.57
	2×2 , 64QAM	0.78
UL	1×1 , QPSK	0.19
	1×1 , 16QAM	0.53

All the curves obtained for HSPA+ are referred to the physical throughput. The expressions for the different branches of all functions should be multiplied for a constant that takes in account all the necessary throughput reductions such as several overheads and BLER to obtain the throughput at application level.

The functions obtained for SNR and physical throughput are based on a Pedestrian A channel. It is important to have a perspective of the performance of HSPA+ in the presence of channels with different characteristics. Nevertheless, estimations for a vehicular A channel were not properly done due to the lack of simulations with the necessary assumptions for the systems in study. The comparison between the two channels is done using the curves of HSDPA, [HoTo04], for HSPA+ DL, and the curves of [GCWC07] for HSPA+ UL. For a comparison purpose, only the modulations and the configurations that present higher throughputs are considered.

The assumptions taken into account are the following:

- For HSPA+ DL, the curve of SNR as function of physical throughput for a Vehicular A channel is obtained, shifting down the Pedestrian channel A curve in 1 dB. The curve of HSDPA is limitative since its maximum value of throughput is 2Mbps. In the point of maximum throughput occurs a difference between SNR values for the two types of channel of 1 dB. Therefore, this difference is considered constant for higher throughputs for HSPA+ DL.
- For HSPA+ UL, due to the lack of coherence information, there is no distinction between the pedestrian and the vehicular channel.

Annex C – HSPA MT Categories

In Table C.1 and Table C.2, one presents the HSDPA and HSUPA MT category and capability categories. For HSDPA 12 MT categories were defined while for HSUPA, only 6 were considered.

Table C.1. HSDPA terminal capability categories (adapted from [HoTo06]).

MT Category	Maximum number of parallels codes per HS-DSCH	Modulation	Minimum inter-TTI interval	ARQ type at maximum data rate	Achievable Maximum data rate [Mbps]
1	5	QPSK & 16QAM	3	Soft	1.2
2	5	QPSK & 16QAM	3	IR	1.2
3	5	QPSK & 16QAM	2	Soft	1.8
4	5	QPSK & 16QAM	2	IR	1.8
5	5	QPSK & 16QAM	1	Soft	3.6
6	5	QPSK & 16QAM	1	IR	3.6
7	10	QPSK & 16QAM	1	Soft	7.2
8	10	QPSK & 16QAM	1	IR	7.2
9	15	QPSK & 16QAM	1	Soft	10.2
10	15	QPSK & 16QAM	1	IR	14.4
11	5	QPSK only	2	Soft	0.9
12	5	QPSK only	1	Soft	1.8

Table C.2. HSUPA Fixed reference channels (FRCs) defined for E-DCH (extracted from [HoTo06]).

FRC	TTI length [ms]	Codes	Coding rate	Maximum bit rate [Mbps]	MT Category
1	2	$2\times$ SF4	0.71	1.353	2
2	2	$2\times$ SF2	0.71	2.706	4
3	2	$2\times$ SF4+$2\times$ SF4	0.71	4.059	6
4	10	$1\times$ SF4	0.53	0.508	1
5	10	$2\times$ SF4	0.51	0.980	2 and 3
6	10	$2\times$ SF2	0.51	1.960	4 and 5
7	10	$1\times$ SF16	0.29	0.069	1

The maximum bit rate varies with the number of codes with the maximum being achieved with the FRC3 - 4.059 Mbps. This value is valid in a theoretical scenario being impossible to be reached in practical. Both factors used and presumptions taken can be consulted in [HoTo06].

Annex D – MIMO and RMG Model

The simultaneous availability of multiple antennas at the transmitter and the receiver can be used to create what can be seen as multiple parallel communications channels over the radio interface. This provides the possibility for very high bandwidth utilisation without a corresponding reduction in power efficiency [DPSB07].

The idea of using multiple receive and multiple transmit antennas has emerged as one of the most significant technical breakthroughs in modern wireless communications. In a multipath propagation environment, the Rx antenna is reached by many copies of the transmitted signal. The difference in each component propagation path results in diversity of Time of Arrival (ToA), Angle of Arrival (AoA), signal amplitude and phase.

Diversity reception, well known in various radio applications, improves only the BER statistics and reduces the probability of total outage. However, the MIMO scheme, which is the result of parallel deployment of several space-separated antennas at input and output, does not only improve Bit Error Ratio (BER) performance, but also causes an increase of channel capacity [Dziu04]. In order to achieve higher throughputs, a correspondingly higher carrier-to-interference ratio is required at the receiver.

Since the correlation of a channel is between 0 and 1, it is possible to derive the upper and lower bounds for capacity. If there is no correlation between parallel paths, i.e., Ω=0, and additionally assuming that the signal is propagating without path loss, the maximum capacity is achieved (D.1):

$$C_{MIMO_{\Omega=0}} \text{ [bps/Hz]} = N_{\min} \log_2\left(1+\frac{\rho}{N_T}\right) \tag{D.1}$$

where:

- ρ: SNR,
- C_{MIMO}: capacity gain of a MIMO system,
- $N_{\min}=\min\{N_T, N_R\}$,
- N_R: *n*umber of receiver antennas,
- N_T: *n*umber of transmitter antennas,

On the contrary, the minimum capacity of a MIMO channel occurs when all sub-channels are totally correlated, Ω=1:

$$C_{MIMO_{\xi=1}} \text{ [bps/Hz]} = \log_2\left(1+N_{\min}\frac{\rho}{N_T}\right) \tag{D.2}$$

A good way to quantify how much MIMO can increase capacity is to use the Relative MIMO Gain (D.3), since it is defined as the relation between the capacity of a MIMO system relative to the SISO one, C_{SISO}:

$$G_{M/S} = \frac{C_{MIMO}}{C_{SISO}} \tag{D.3}$$

In order to predict the improvements in capacity of using MIMO over SISO based on simulation results, the RMG Model, [KuCo07], was chosen. The description this model is next presented based on [KuCo07] and [Bati08].

The RMG is defined as the ratio between the MIMO and SISO capacity of a radio link, with the RMG model as a statistical model developed to approximate the distribution of the RMG, based on simulation results. In order to maintain a low-complexity of the model the distribution of the RMG is modelled with an inverse Sigmoid function (also known as logistic function or *S*-shape function), which is completely modelled by its mean and variance. The general sigmoid function is given by:

$$\delta(x,\mu,s)=\frac{1}{1+e^{-\frac{x-\mu_{dist}}{s}}} \tag{D.4}$$

where:

- μ_{dist}, is the mean value of the distribution;
- *s,* is the determines the slope which is related to σ^2 by:

$$\sigma^2=\frac{\pi^2}{3}s^2 \tag{D.5}$$

- σ^2 is the variance;

Both the mean value and the variance depend on the number of Tx and Rx antennas, while the mean value also depends on the distance between the Tx and the Rx. Focusing on obtaining a model that gives a realistic statistical RMG as a result, the inverse of the distribution is required, and it is given by:

$$g(u,\mu_{RMG},\sigma_{RMG})=\mu_{RMG}(d,N_T,N_R)-\frac{\sqrt{3\sigma^2_{RMG}(d,N_T,N_R)}}{\pi}\ln\frac{1-u}{u} \tag{D.6}$$

where:

- *u,* is the random value with a Uniform distribution, i.e., $u = U[0,1]$;
- *d*, is the distance between BS and MT;
- $\sigma^2_{RMG}(d,N_T,N_R)$, is the variance depending on the cell type, N_T and N_R;
- $\mu_{RMG}(d,N_T,N_R)$, is the average RMG depending on the cell type, N_T and N_R.

The values for the variance needed for this thesis are presented in Table D.1. The mean results of the RMG model for a MIMO 2×2 is 1.54. Other values for others MIMO configurations can be consulted at [KuCo07].

Table D.1. Variance for different number of Tx and Rx antennas (adapted from [KuCo07]).

$\sigma^2_{RMG}(10^{-3})$		[10 – 60] m	[100 – 600] m	[1200 – 2400] m
N_R		2	2	2
N_T	2	18.5	24.0	1.9

Annex E – Maximum Throughputs

In this annex, the maximum throughputs achieved for both systems and for several combinations of parameters are presented:

Table E.1. Variance for different number of Tx and Rx antennas (adapted from [KuCo07]).

Configuration	Modulation	Maximum Throughput at Physical Layer [Mbps] – 15 codes	Maximum Throughput at Physical Layer [Mbps] – 14 codes	Throughput at Application Level [Mbps]
1×1 (SISO)	16QAM	14.4	13.44	10.89
1×1 (SISO)	64QAM	21.6	20.16	16.33
1×2 (SIMO)	16QAM	14.4	13.44	10.89
1×2 (SIMO)	64QAM	21.6	10.16	8.23
2×2 (MIMO)	16QAM	28.8	26.88	21.77
2×2 (MIMO)	64QAM	43.2	40.32	32.66

Table E.2. Maximum application throughput for different configurations in Mobile WiMAX.

Channel Bandwidth [MHz]	Configuration		TDD split					
			1:0	3:1	2:1	3:2	1:1	0:1
5	SISO (1×1)	DL	10.25	7.46	6.52	6.06	5.13	0
		UL	0	2.11	2.64	3.17	3.70	7.39
	SIMO (1×2)	DL	10.25	7.46	6.52	6.06	5.13	0
		UL	0	2.11	2.64	3.17	3.70	7.39
	MIMO (2×2)	DL	20.51	14.91	13.04	12.12	10.25	0
		UL	0	4.23	5.28	6.34	7.39	14.78
10	SISO (1×1)	DL	20.51	14.91	13.04	12.12	10.25	0
		UL	0	4.23	5.28	6.34	7.39	14.78
	SIMO (1×2)	DL	20.51	14.91	13.04	12.12	10.25	0
		UL	0	4.23	5.28	6.34	7.39	14.78
	MIMO (2×2)	DL	41.01	29.82	26.09	24.24	20.51	0
		UL	0.00	14.91	13.04	12.12	10.25	29.56
20	SISO (1×1)	DL	41.01	29.82	26.09	24.24	20.51	0
		UL	0	8.46	10.55	12.68	14.78	14.78
	SIMO (1×2)	DL	41.01	29.82	26.09	24.24	20.51	0
		UL	0	8.46	10.55	12.68	14.78	14.78
	MIMO (2×2)	DL	82.02	59.65	52.17	48.49	41.01	0
		UL	0	29.82	26.09	24.24	20.51	59.12

Annex F – Throughput Calculation

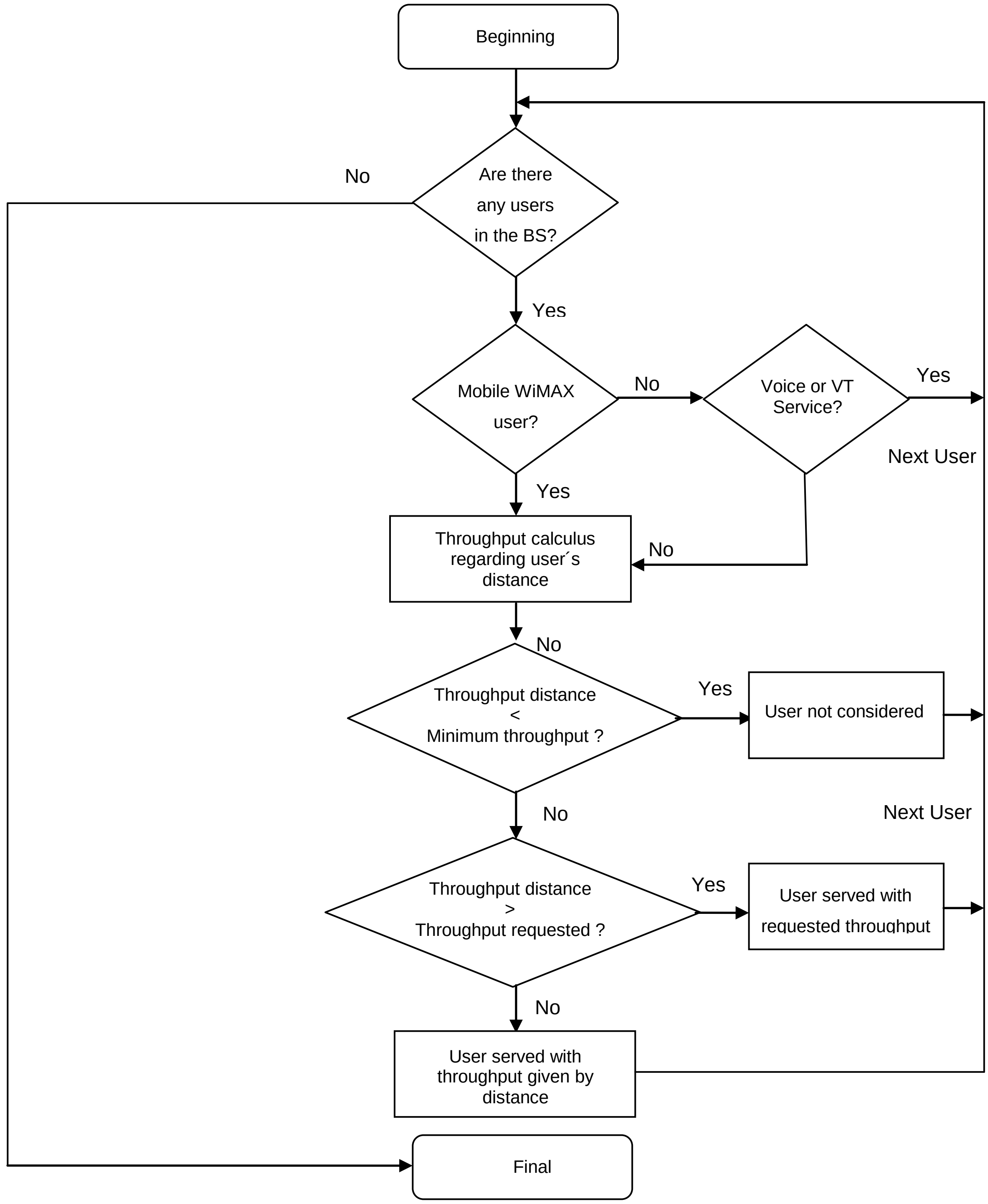


Figure F.1. HSPA+ and Mobile WiMAX user´s throughput calculation algorithm.

Annex G – Single User Model Interface

In this annex, the single user and single service model interface for HSPA+ DL, Figure G.1 and Figure G.2, and for Mobile WiMAX, Figure G.3 are shown. The interfaces for UL are similar and both are very user friendly and easy to manage.

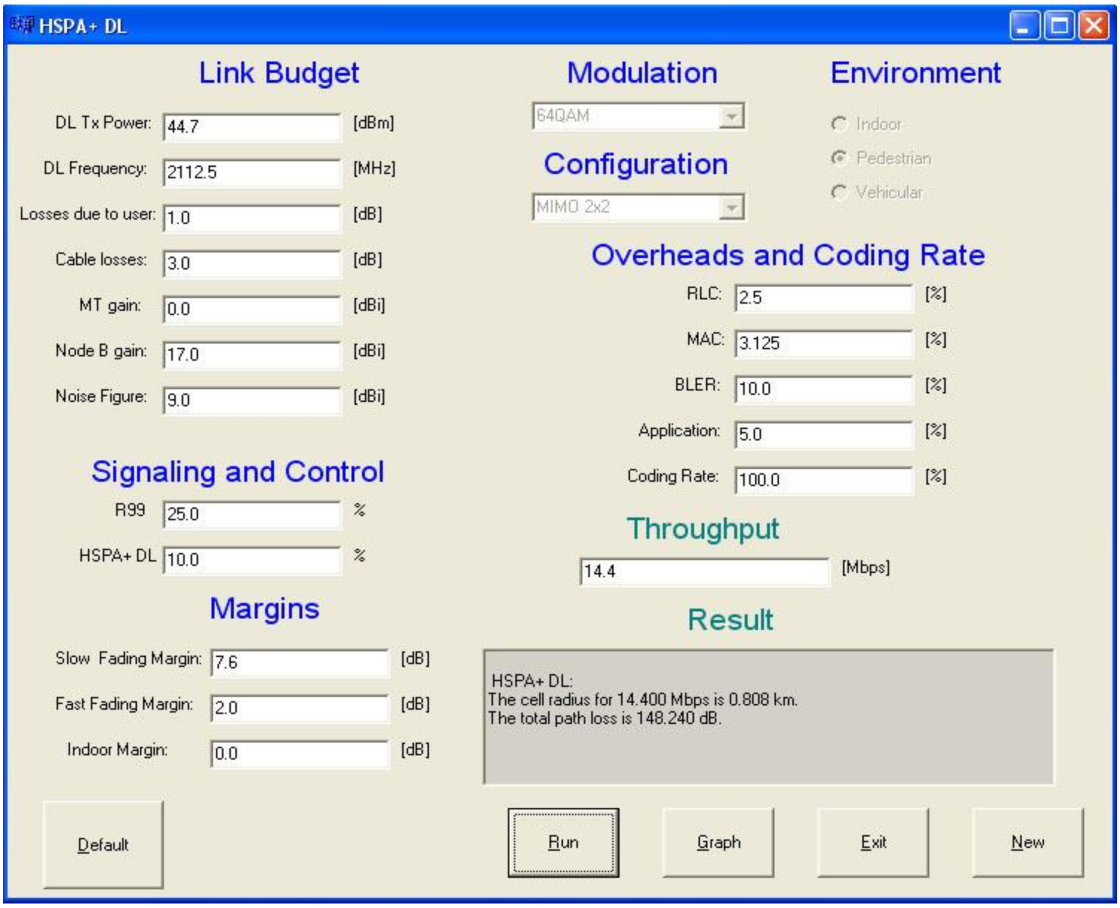


Figure G.1. HSPA+ DL single service user model interface.

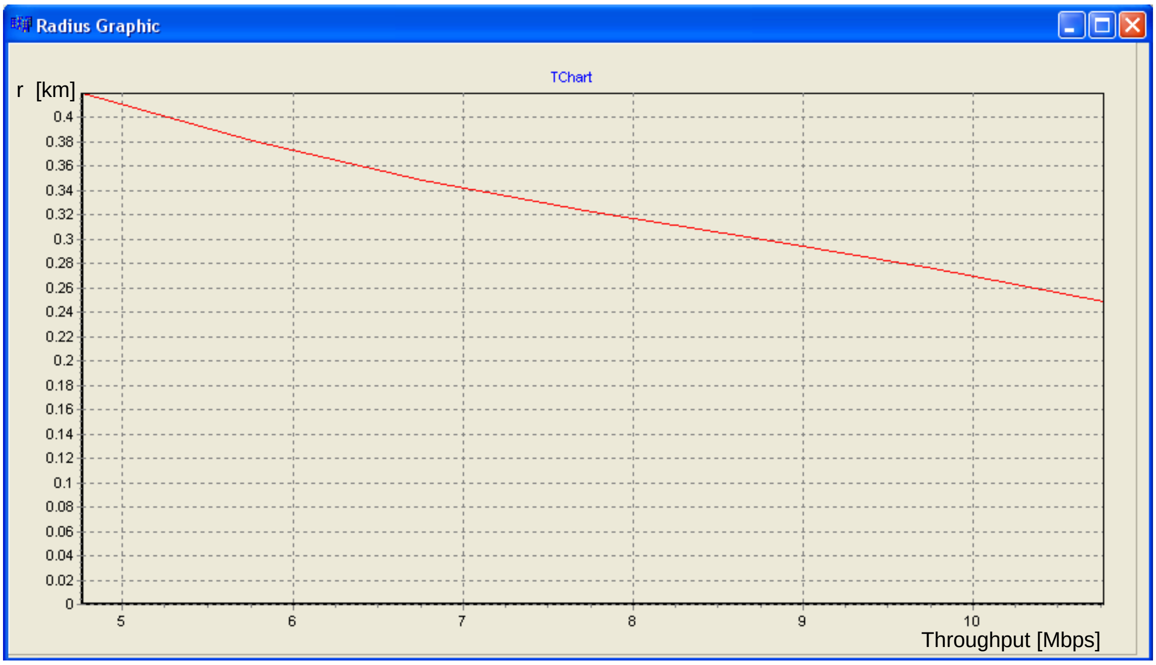


Figure G.2. HSPA+ DL single service user model graphic.

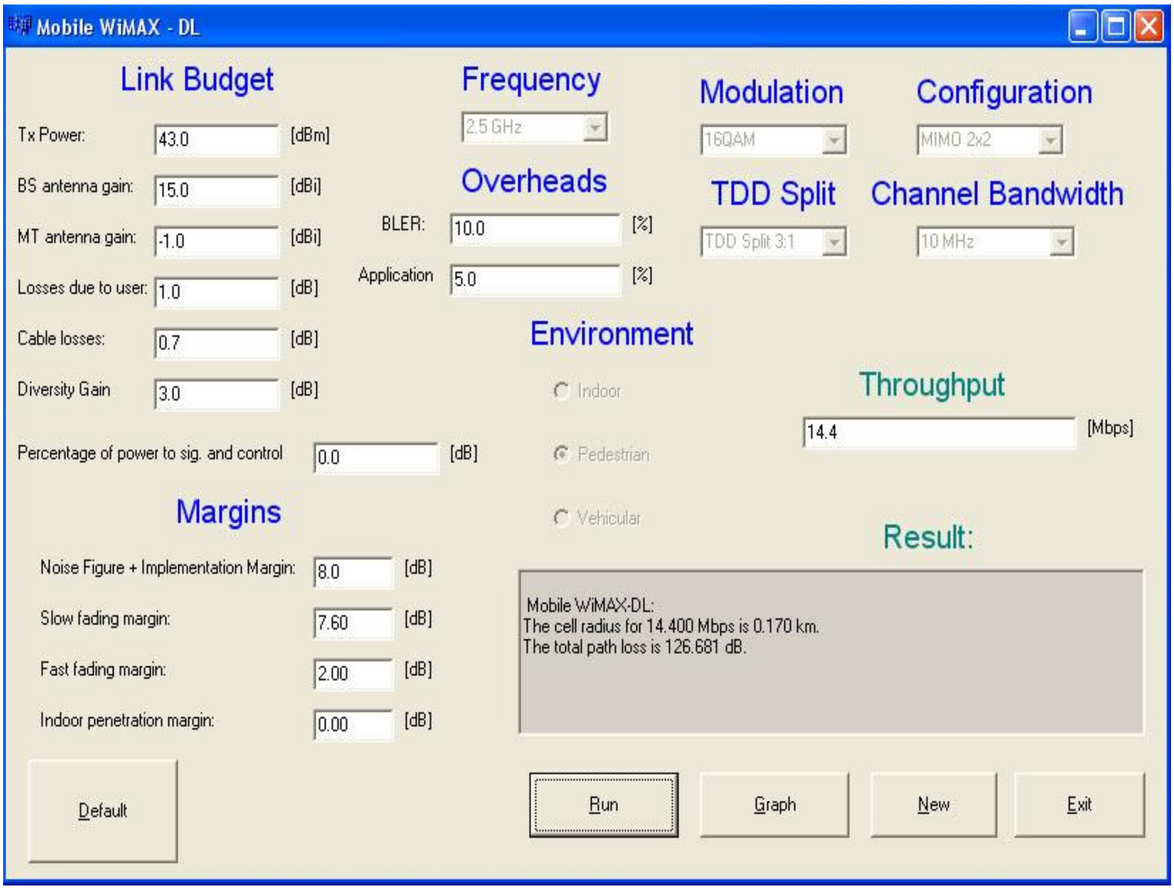


Figure G.3. Mobile WiMAX DL single service user model interface.

Annex H – User´s Manual

In this annex, one presents the simulator's user manual. To start the application, it is necessary to introduce 3 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 districts;
- "ZONAS_Lisboa.TAB", with the area characterisation, like streets, gardens along with others, Figure H.1.

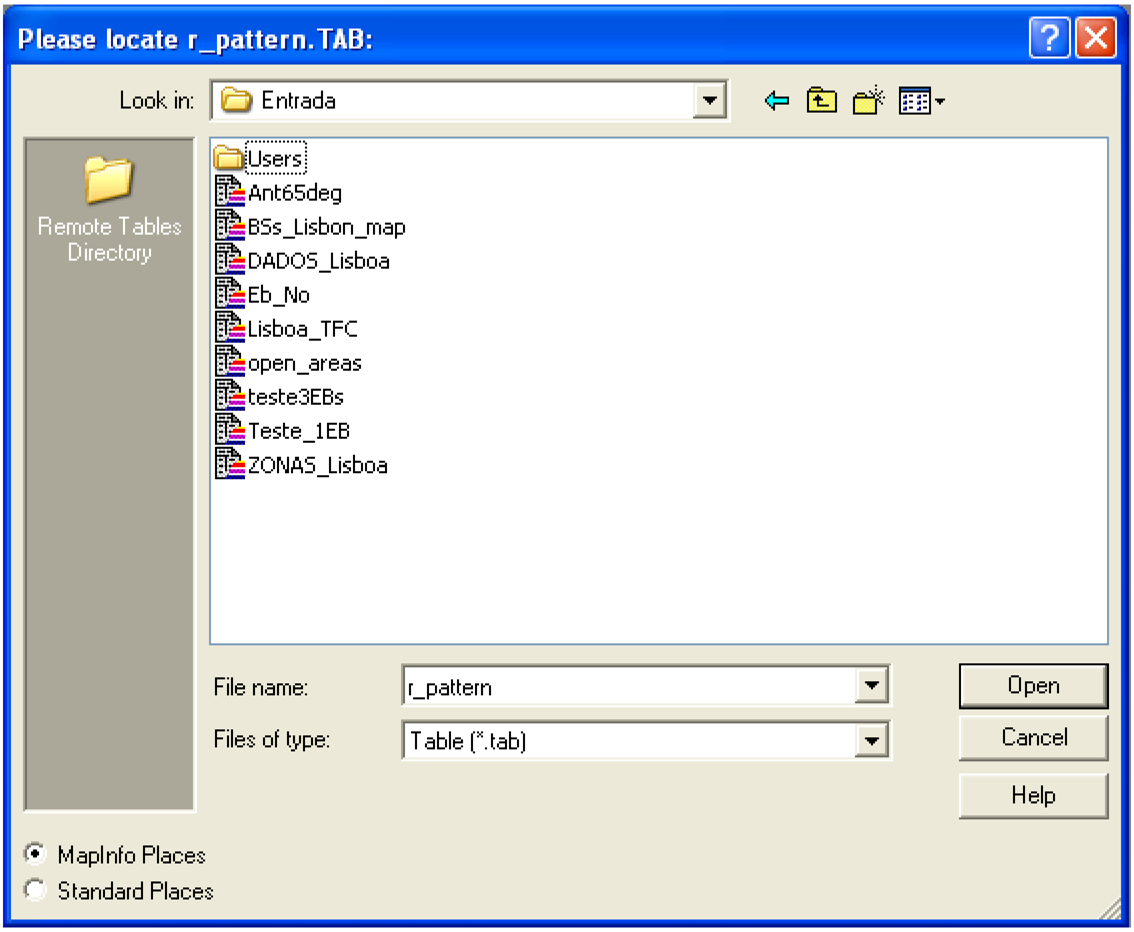


Figure H.1. Window for the introduction of ZONAS_Lisboa.TAB file.

After the introduction of the geographical information, a new options bar is displayed in MapInfo, where it is possible to choose between HSPA+ and Mobile WiMAX, Figure H.2, and define the simulation's characteristics.

Among the several options that are available for HSPA and Mobile WiMAX, the windows for the propagation model and services' colours are common for both systems, Figure H.3 and Figure H.4, respectively, since the propagation model parameters used are the same and the service's colour isonly a graphical information.

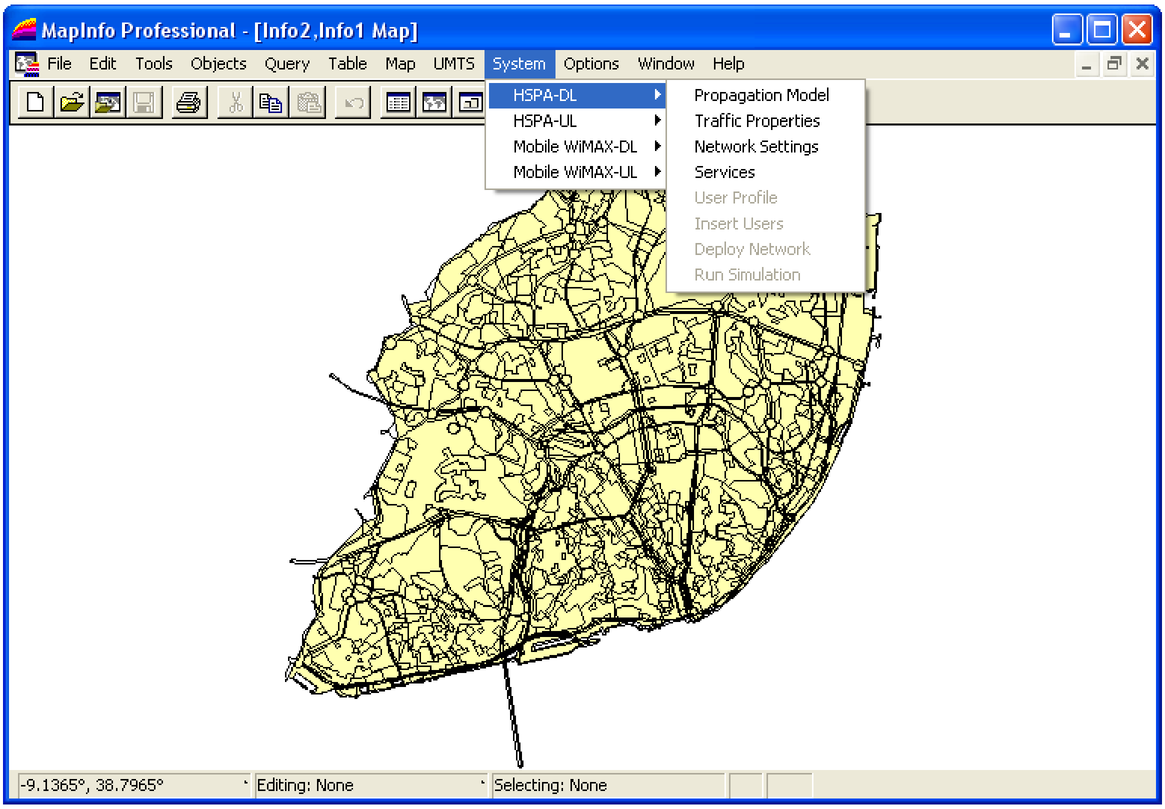


Figure H.2. View of the simulator and menu bar with the several options for each one of the systems.

For both HSPA+ and Mobile WIMAX Profile windows', Figure H.5, it is possible to change the maximum and minimum desired throughput for each service. The values for the minimum throughput are the ones presented in, not being possible to define a minimum service throughput lower than the ones presented. Traffic properties, Figure H.6., like the volume, average duration of a call and service QoS priorities, can be modified excepted the priority of voice that is always the most priority service.

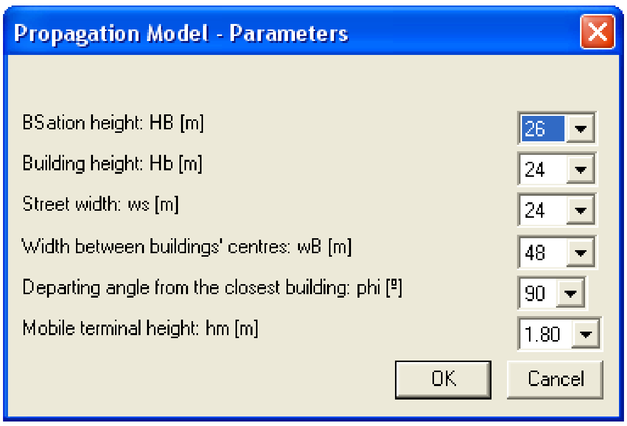


Figure H.3. View Propagation model parameters.

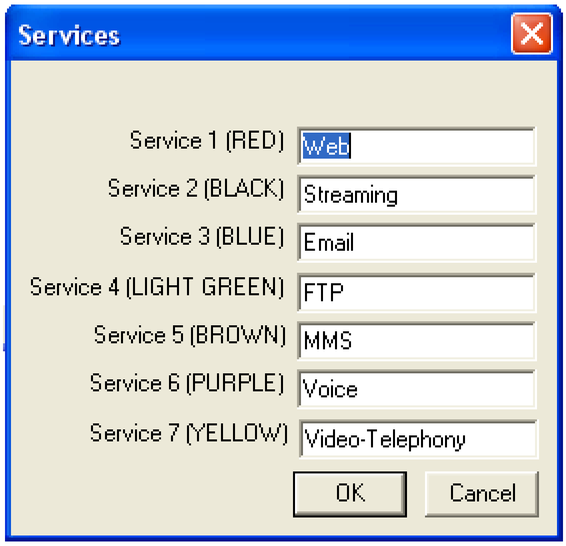


Figure H.4. Services´ colour assignment.

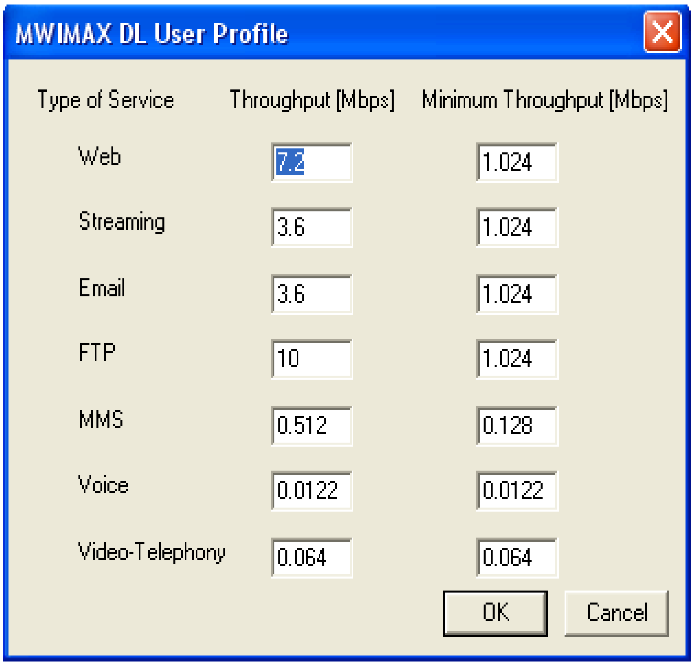


Figure H.5. Mobile WiMAX User Profile.

Regarding Mobile WiMAX and HSPA+ Settings windows, Figure H.7 and Figure H.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.

In Table H.1, one presents the relation between the number of users effectively considered and the ones that are necessary to consider as input parameter in the SIM program, as there are some users that are placed outside of the network area, not being considered in the analysis.

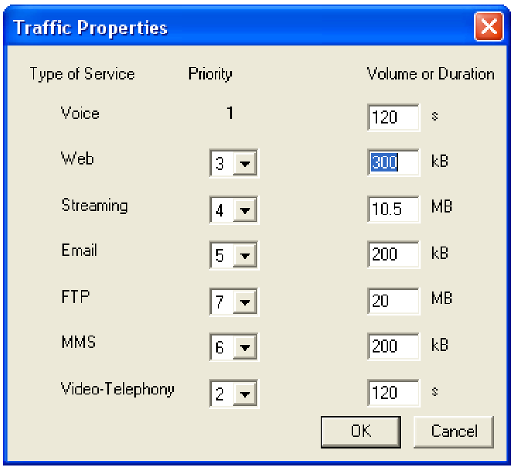


Figure H.6. Traffic Properties

Table H.1. Maximum application throughput for different configurations in Mobile WiMAX.

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

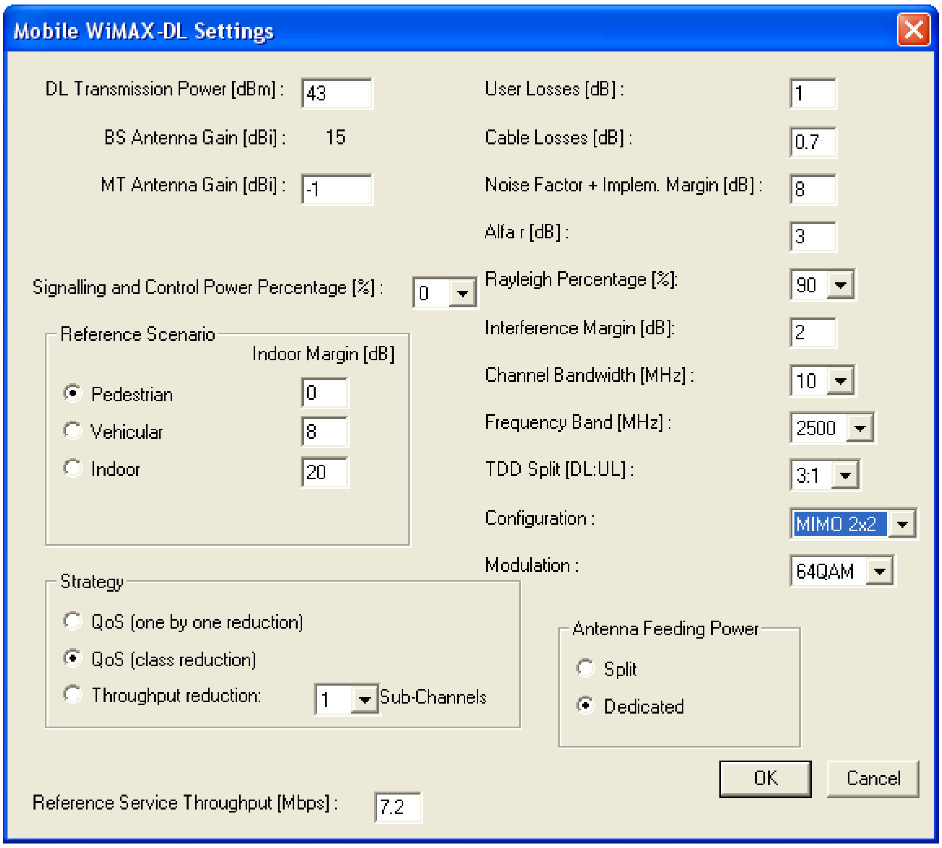


Figure H.7. Mobile WiMAX DL simulations´ parameters.

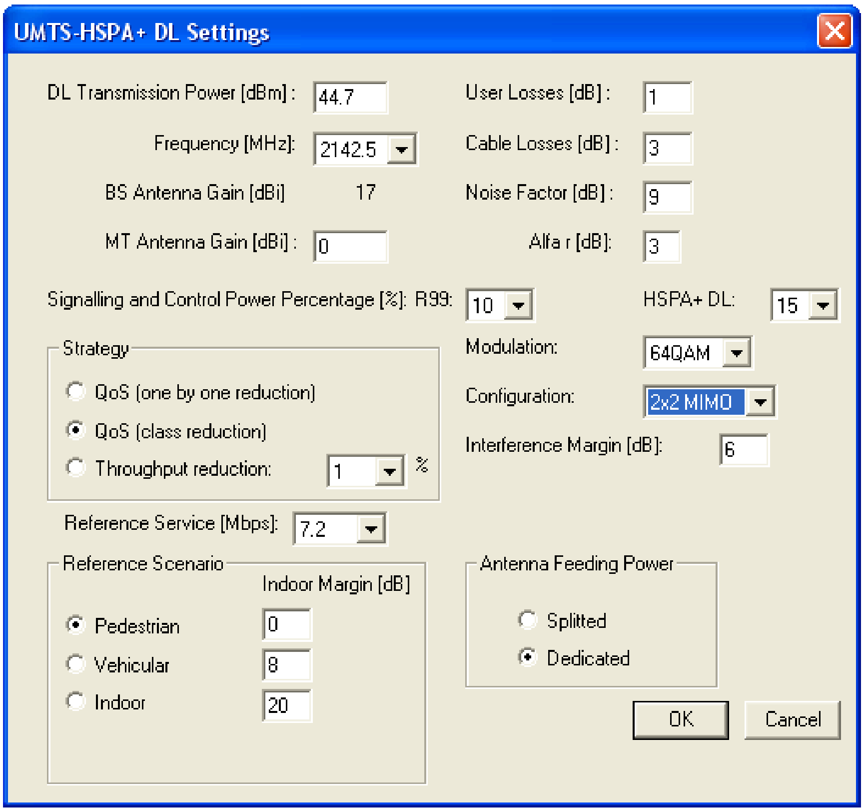


Figure H.8. HSPA+ DL simulations´ parameters.

After pressing the “OK” button, it is displayed in the “Message” window the results regarding the cell radius for the reference service and the different services considered in Figure H.9. From now on, only HSPA+ DL windows will be presented, since the procedures are identical to both systems.

Later, in the network setting window, the functionality “Insert Users” is activated, to introduce the users in the network, by choosing one of the user files from the SIM application. Afterwards, the menu “Deploy Network” becomes active, requesting a file containing the BSs’ location, so that these can be placed in the city area, Figure H.10

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 H.11, Figure H.12 and Figure H.13, the results for 194 BSs and 2000 users are presented.

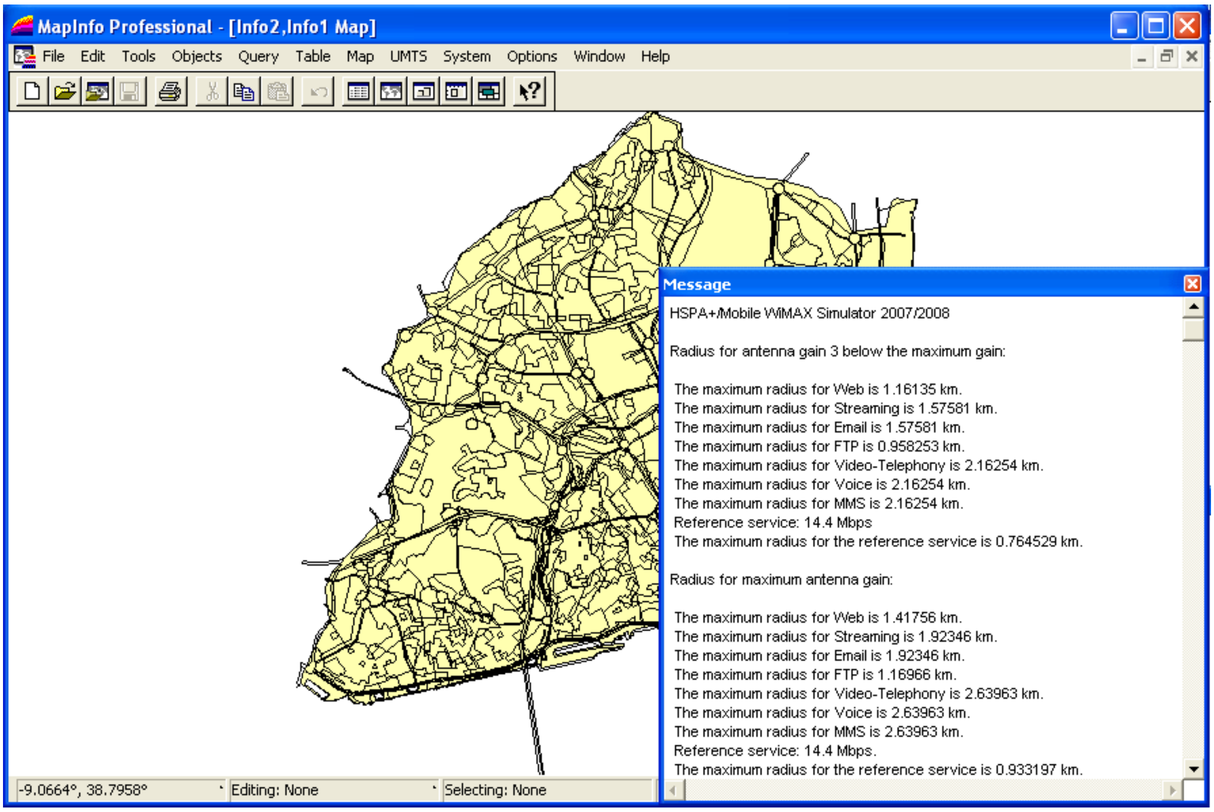


Figure H.9. Visual aspect of the application after running the HSPA+ DL settings window.

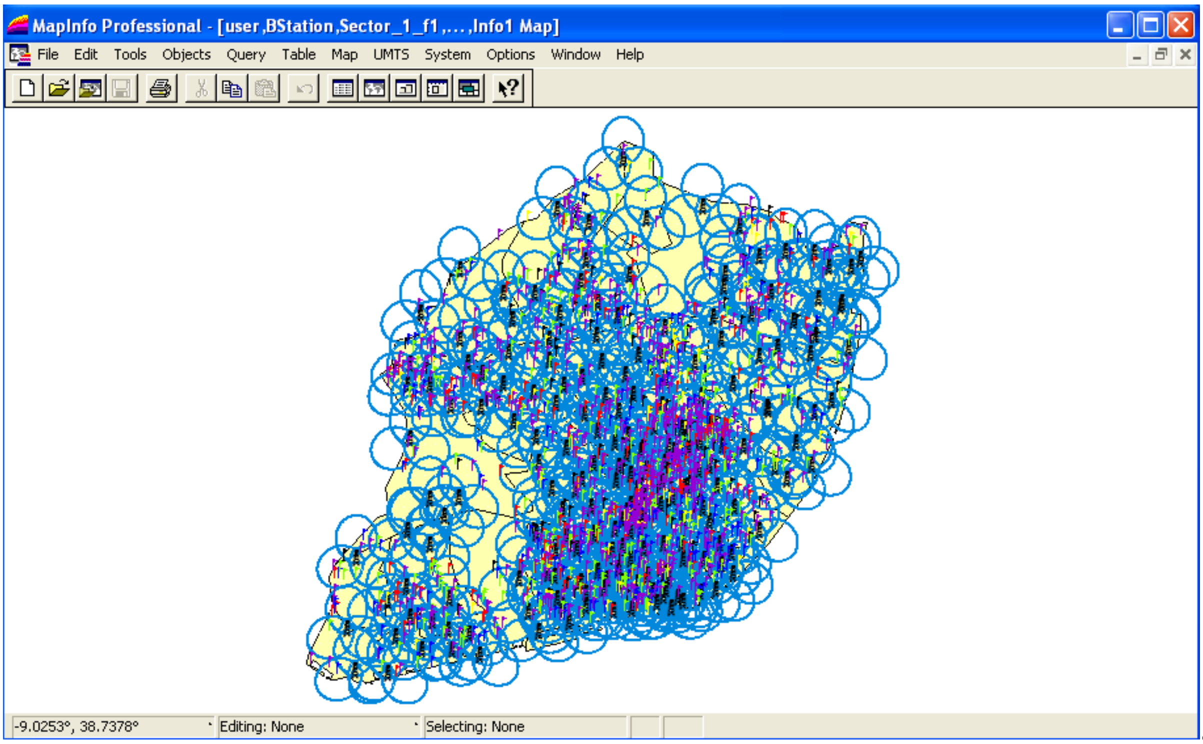


Figure H.10. Result of the “Deploy Network” menu with 194 tri-sectored BSs’ coverage area.

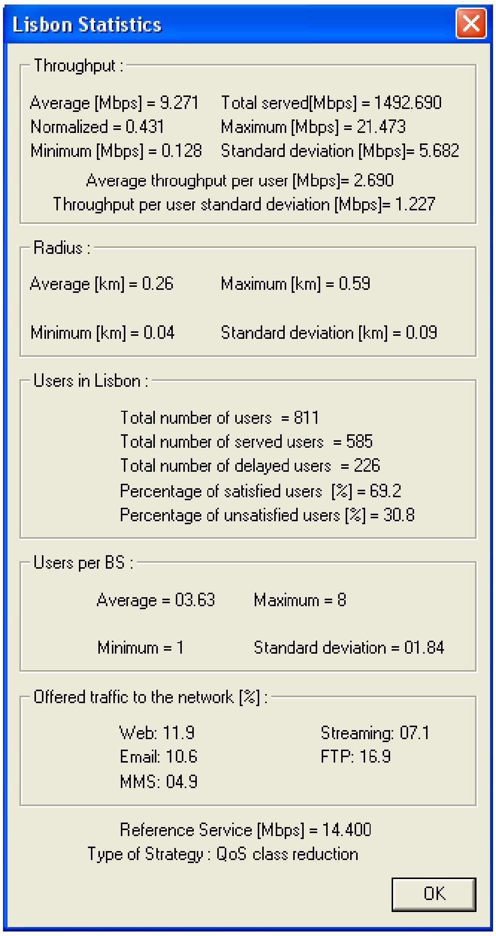


Figure H.11. HSPA+ DL instantaneous results for the city of Lisbon.

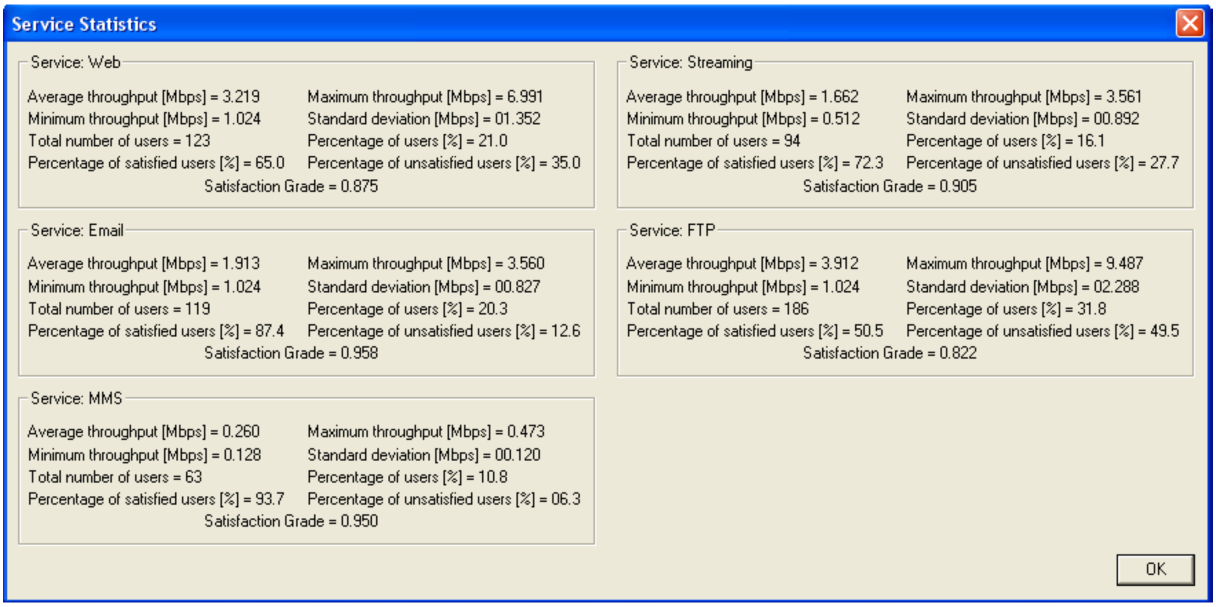


Figure H.12. HSPA+ DL instantaneous results detailed by services for the city of Lisbon.

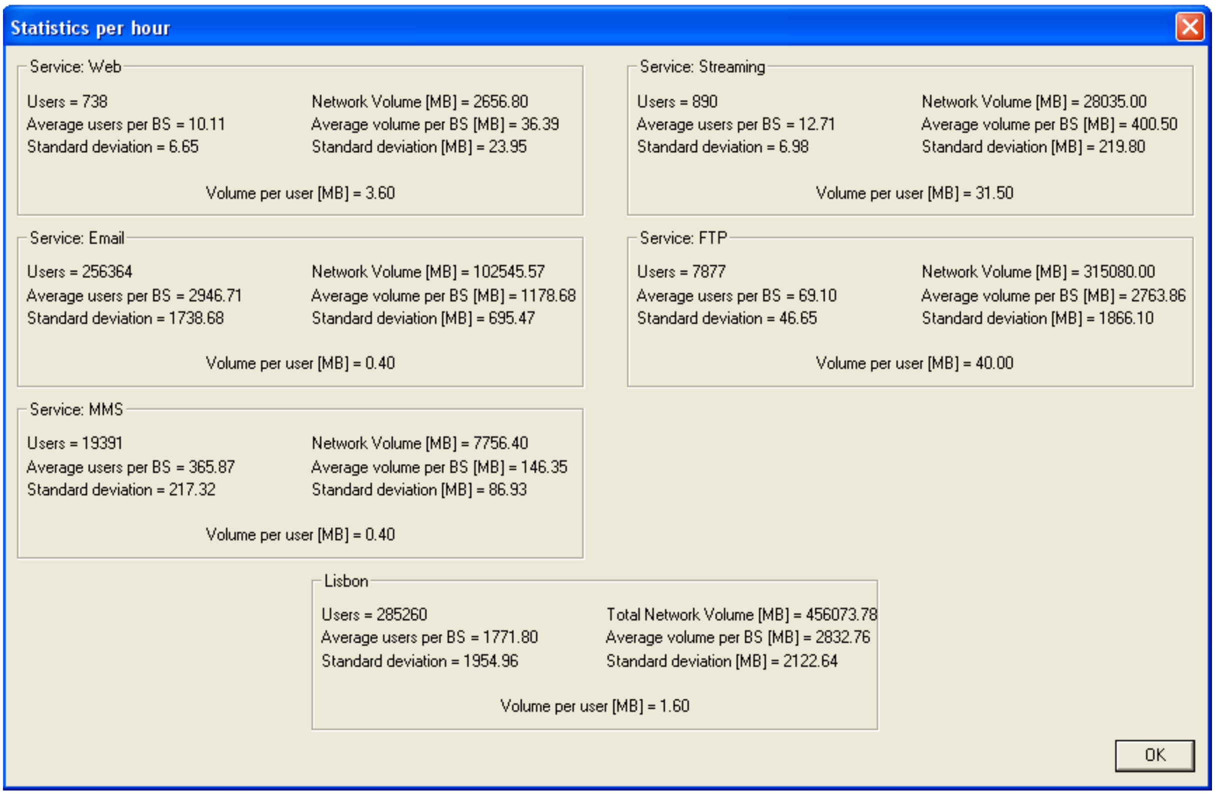


Figure H.13. HSPA+ DL extrapolation results for the hour analysis.

Annex I – Single User Model Results

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

Table I.1. Mobile WiMAX DL single user cell radius for the minimum throughput for several combinations.

Mobile WiMAX TDD Split 1:1			**DL R_{bmin} [Mbps]**			**Cell Radius [km]**		
Environment	Channel Bandwidth [MHz]	Configuration	Modulation			Modulation		
			QPSK	16QAM	64QAM	QPSK	16QAM	64QAM
Indoor	5	SISO	0.384	1.71	3.42	0.31	0.15	0.10
		SIMO	0.384	1.71	3.42	0.38	0.18	0.12
		MIMO	0.384	3.42	6.83	0.31	0.11	0.07
	10	SISO	0.384	3.42	6.84	0.31	0.11	0.07
		SIMO	0.384	3.42	6.84	0.38	0.13	0.08
		MIMO	0.384	6.83	13.68	0.31	0.08	0.05
	20	SISO	0.384	6.83	13.68	0.31	0.08	0.05
		SIMO	0.384	6.83	13.68	0.38	0.09	0.06
		MIMO	0.384	13.66	27.35	0.31	0.04	0.03
Pedestrian	5	SISO	0.384	1.71	3.42	1.05	0.51	0.33
		SIMO	0.384	1.71	3.42	1.26	0.61	0.39
		MIMO	0.384	3.42	6.83	1.05	0.36	0.23
	10	SISO	0.384	3.42	6.84	1.05	0.36	0.23
		SIMO	0.384	3.42	6.84	1.26	0.44	0.27
		MIMO	0.384	6.83	13.68	1.05	0.25	0.16
	20	SISO	0.384	6.83	13.68	1.05	0.25	0.16
		SIMO	0.384	6.83	13.68	1.26	0.30	0.19
		MIMO	0.384	13.66	27.35	1.05	0.15	0.09
Vehicular	5	SISO	0.384	1.71	3.42	0.86	0.42	0.27
		SIMO	0.384	1.71	3.42	1.03	0.51	0.32
		MIMO	0.384	3.42	6.83	0.86	0.29	0.19
	10	SISO	0.384	3.42	6.84	0.86	0.29	0.19
		SIMO	0.384	3.42	6.84	1.03	0.35	0.22
		MIMO	0.384	6.83	13.68	0.86	0.20	0.13
	20	SISO	0.384	6.83	13.68	0.86	0.20	0.13
		SIMO	0.384	6.83	13.68	1.03	0.24	0.16
		MIMO	0.384	13.66	27.35	0.86	0.12	0.08

Table I.2. Mobile WiMAX DL single user cell radius for the maximum throughput for several combinations.

Mobile WiMAX TDD Split 1:1			**DL R_{bmax} [Mbps]**			**Cell Radius [km]**		
Environment	Channel Bandwidth [MHz]	Configuration	Modulation			Modulation		
			QPSK	16QAM	64QAM	QPSK	16QAM	64QAM
Indoor	5	SISO	1.71	3.42	5.13	0.15	0.11	0.07
		SIMO	1.71	3.42	5.13	0.18	0.13	0.09
		MIMO	3.42	6.83	10.25	0.11	0.08	0.05
	10	SISO	3.42	6.84	10.25	0.11	0.08	0.05
		SIMO	3.42	6.84	10.25	0.13	0.09	0.06
		MIMO	6.83	13.68	20.51	0.08	0.05	0.04
	20	SISO	6.83	13.68	20.5	0.08	0.05	0.04
		SIMO	6.83	13.68	20.5	0.09	0.06	0.04
		MIMO	13.66	27.35	41	0.04	0.03	0.02
Pedestrian	5	SISO	1.71	3.42	5.13	0.51	0.36	0.25
		SIMO	1.71	3.42	5.13	0.61	0.43	0.30
		MIMO	3.42	6.83	10.25	0.36	0.25	0.18
	10	SISO	3.42	6.84	10.25	0.36	0.25	0.18
		SIMO	3.42	6.84	10.25	0.44	0.30	0.21
		MIMO	6.83	13.68	20.51	0.25	0.18	0.12
	20	SISO	6.83	13.68	20.5	0.25	0.18	0.12
		SIMO	6.83	13.68	20.5	0.30	0.21	0.15
		MIMO	13.66	27.35	41	0.15	0.10	0.07
Vehicular	5	SISO	1.71	3.42	5.13	0.42	0.29	0.20
		SIMO	1.71	3.42	5.13	0.50	0.35	0.24
		MIMO	3.42	6.83	10.25	0.30	0.21	0.14
	10	SISO	3.42	6.84	10.25	0.30	0.21	0.14
		SIMO	3.42	6.84	10.25	0.35	0.25	0.17
		MIMO	6.83	13.68	20.51	0.21	0.14	0.10
	20	SISO	6.83	13.68	20.5	0.21	0.14	0.10
		SIMO	6.83	13.68	20.5	0.25	0.17	0.12
		MIMO	13.66	27.35	41	0.12	0.08	0.06

Table I.3. Mobile WiMAX UL single user cell radius for the minimum throughput for several combinations.

Mobile WiMAX TDD Split 1:1			**UL R_{bmin} [Mbps]**			**Cell Radius [km]**		
Environment	Channel Bandwidth [MHz]	Configuration	Modulation			Modulation		
			QPSK	16QAM	64QAM	QPSK	16QAM	64QAM
Indoor	5	SISO	0.1	2.47	4.93	0.45	0.06	0.04
		SIMO	0.1	2.47	4.93	0.65	0.08	0.05
		MIMO	0.1	4.94	9.86	0.45	0.04	0.03
	10	SISO	0.1	5.08	10.15	0.45	0.04	0.03
		SIMO	0.1	5.08	10.15	0.65	0.06	0.04
		MIMO	0.1	10.16	20.3	0.45	0.03	0.02
	20	SISO	0.1	10.23	20.59	0.45	0.03	0.02
		SIMO	0.1	10.23	20.59	0.65	0.04	0.03
		MIMO	0.1	20.46	41.18	0.45	0.02	0.01
Pedestrian	5	SISO	0.1	2.47	4.93	0.45	0.19	0.12
		SIMO	0.1	2.47	4.93	0.65	0.28	0.18
		MIMO	0.1	4.94	9.86	0.45	0.14	0.09
	10	SISO	0.1	5.08	10.15	0.45	0.14	0.09
		SIMO	0.1	5.08	10.15	0.65	0.20	0.13
		MIMO	0.1	10.16	20.3	0.45	0.09	0.06
	20	SISO	0.1	10.23	20.59	0.45	0.09	0.06
		SIMO	0.1	10.23	20.59	0.65	0.14	0.09
		MIMO	0.1	20.46	41.18	0.45	0.07	0.04
Vehicular	5	SISO	0.1	2.47	4.93	0.45	0.15	0.10
		SIMO	0.1	2.47	4.93	0.65	0.22	0.14
		MIMO	0.1	4.94	9.86	0.45	0.11	0.07
	10	SISO	0.1	5.08	10.15	0.45	0.11	0.07
		SIMO	0.1	5.08	10.15	0.65	0.16	0.10
		MIMO	0.1	10.16	20.3	0.45	0.08	0.05
	20	SISO	0.1	10.23	20.59	0.45	0.08	0.05
		SIMO	0.1	10.23	20.59	0.65	0.11	0.07
		MIMO	0.1	20.46	41.18	0.45	0.05	0.03

Table I.4. Mobile WiMAX UL single user cell radius for the maximum throughput for several combinations.

Mobile WiMAX TDD Split 1:1			UL R_{bmax} [Mbps]			Cell Radius [km]		
Environment	Channel Bandwidth [MHz]	Configuration	Modulation			Modulation		
			QPSK	16QAM	64QAM	QPSK	16QAM	64QAM
Indoor	5	SISO	2.47	4.93	7.39	0.06	0.04	0.03
		SIMO	2.47	4.93	7.39	0.09	0.06	0.04
		MIMO	4.94	9.86	14.78	0.04	0.03	0.02
	10	SISO	5.08	10.15	15.22	0.04	0.03	0.02
		SIMO	5.08	10.15	15.22	0.06	0.04	0.03
		MIMO	10.16	20.3	30.44	0.03	0.02	0.01
	20	SISO	10.3	20.59	30.88	0.03	0.02	0.01
		SIMO	10.3	20.59	30.88	0.04	0.03	0.02
		MIMO	20.6	41.18	61.76	0.02	0.01	0.01
Pedestrian	5	SISO	2.47	4.93	7.39	0.20	0.14	0.10
		SIMO	2.47	4.93	7.39	0.29	0.20	0.14
		MIMO	4.94	9.86	14.78	0.14	0.10	0.07
	10	SISO	5.08	10.15	15.22	0.14	0.10	0.07
		SIMO	5.08	10.15	15.22	0.20	0.14	0.10
		MIMO	10.16	20.3	30.44	0.10	0.07	0.05
	20	SISO	10.3	20.59	30.88	0.10	0.07	0.05
		SIMO	10.3	20.59	30.88	0.14	0.10	0.07
		MIMO	20.6	41.18	61.76	0.07	0.05	0.03
Vehicular	5	SISO	2.47	4.93	7.39	0.16	0.11	0.08
		SIMO	2.47	4.93	7.39	0.23	0.16	0.12
		MIMO	4.94	9.86	14.78	0.11	0.08	0.05
	10	SISO	5.08	10.15	15.22	0.11	0.08	0.05
		SIMO	5.08	10.15	15.22	0.16	0.11	0.08
		MIMO	10.16	20.3	30.44	0.08	0.05	0.04
	20	SISO	10.3	20.59	30.88	0.08	0.05	0.04
		SIMO	10.3	20.59	30.88	0.11	0.08	0.06
		MIMO	20.6	41.18	61.76	0.05	0.04	0.03

Table I.5. HSPA+ DL single user cell radius for the minimum throughput for several combinations.

HSPA+		DL R_{bmin} [Mbps]		Cell Radius [km]	
Environment	Configuration	Modulation		Modulation	
		16QAM	64QAM	16QAM	64QAM
Indoor	SISO	3.64	4.04	0.41	0.40
	SIMO	4.77	4.77	0.42	0.42
	MIMO	5.65	5.65	0.42	0.42
Pedestrian	SISO	3.64	4.04	1.39	1.33
	SIMO	4.77	4.77	1.41	1.41
	MIMO	5.65	5.65	1.42	1.41
Vehicular	SISO	3.64	4.04	1.20	1.15
	SIMO	4.77	4.77	1.22	1.22
	MIMO	5.65	5.65	1.22	1.22

Table I.6. Mobile WiMAX DL single user cell radius for the maximum throughput for several combinations.

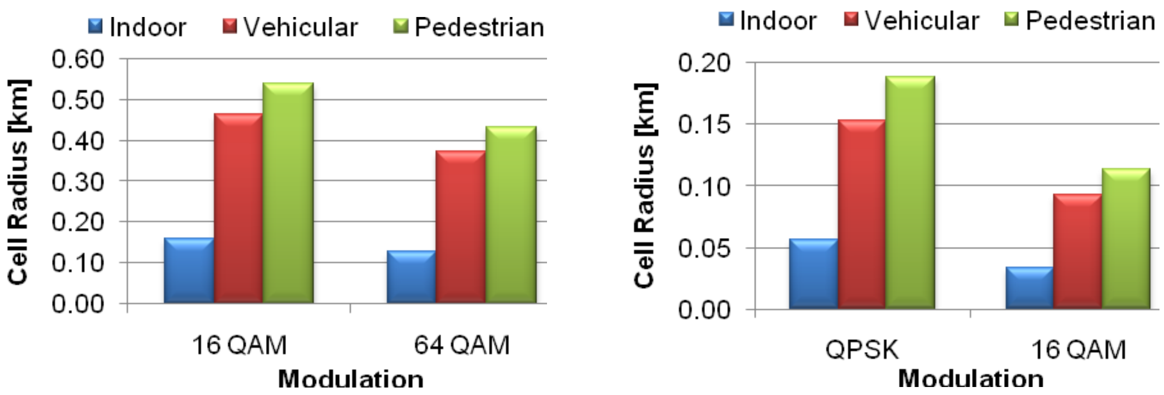
HSPA+		DL R_{bmax} [Mbps]		Cell Radius [km]	
Environment	Configuration	Modulation		Modulation	
		16QAM	64QAM	16QAM	64QAM
Indoor	SISO	11.63	17.12	0.16	0.13
	SIMO	11.63	16.56	0.18	0.17
	MIMO	23.34	35.38	0.12	0.07
Pedestrian	SISO	11.63	17.12	0.54	0.43
	SIMO	11.63	16.56	0.61	0.58
	MIMO	23.34	35.38	0.40	0.23
Vehicular	SISO	11.63	17.12	0.46	0.37
	SIMO	11.63	16.56	0.53	0.50
	MIMO	23.34	35.38	0.35	0.20

Table I.7. HSPA+ UL single user cell radius for the minimum throughput for several combinations.

HSPA+		**UL R_{bmin} [Mbps]**		**Cell Radius [km]**	
Environment	Configuration	Modulation		Modulation	
		16QAM	64QAM	16QAM	64QAM
Indoor	SISO	3.29	3.29	0.08	0.07
	SIMO	3.29	3.29	0.09	0.08
	MIMO	6.59	6.59	0.08	0.07
Pedestrian	SISO	3.29	3.29	0.25	0.25
	SIMO	3.29	3.29	0.29	0.28
	MIMO	6.59	6.59	0.25	0.25
Vehicular	SISO	3.29	3.29	0.21	0.20
	SIMO	3.29	3.29	0.23	0.23
	MIMO	6.59	6.59	0.21	0.20

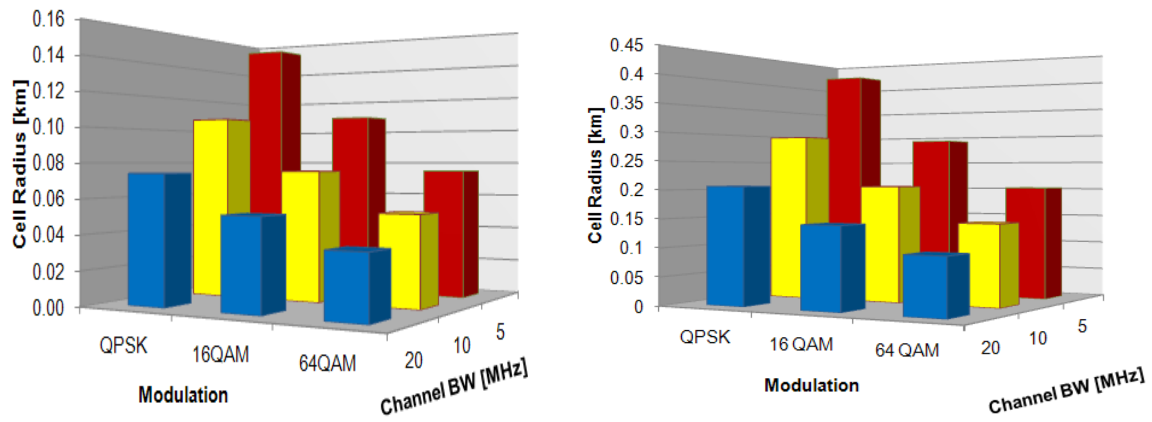
Table I.8. HSPA+ UL single user cell radius for the maximum throughput for several combinations.

HSPA+		**UL R_{bmax} [Mbps]**		**Cell Radius [km]**	
Environment	Configuration	Modulation		Modulation	
		16QAM	64QAM	16QAM	64QAM
Indoor	SISO	4.53	9.06	0.06	0.03
	SIMO	4.53	9.06	0.06	0.04
	MIMO	9.06	18.12	0.06	0.03
Pedestrian	SISO	4.53	9.06	0.19	0.11
	SIMO	4.53	9.06	0.21	0.13
	MIMO	9.06	18.12	0.19	0.11
Vehicular	SISO	4.53	9.06	0.15	0.09
	SIMO	4.53	9.06	0.17	0.11
	MIMO	9.06	18.12	0.15	0.09



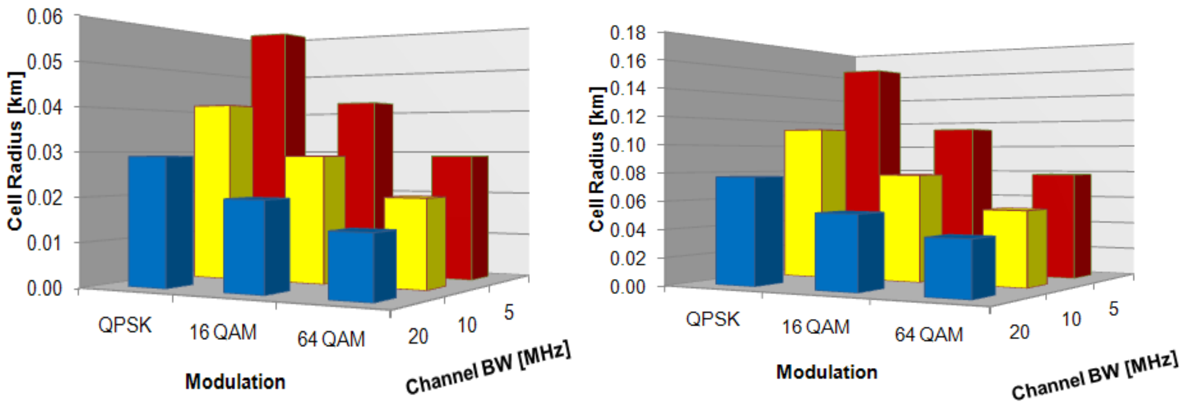
(a) HSPA+ DL. (b) HSPA+ UL.

Figure I.1. Cell radius variation for different modulations and environments for HSPA+ DL and UL considering the maximum achieved throughputs.



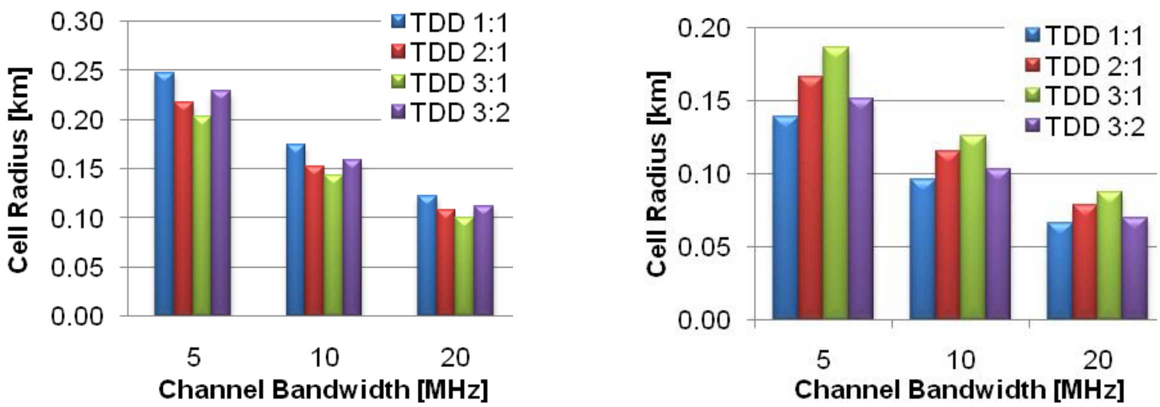
(a) Indoor. (b) Vehicular.

Figure I.2. Mobile WiMAX cell radius for DL, for different scenarios, considering different modulations and channel bandwidths for the maximum achieved throughput.



(a) Indoor. (b) Vehicular.

Figure I.3. Mobile WiMAX cell radius for UL, for different scenarios, considering different modulations and channel bandwidths for the maximum achieved throughput.

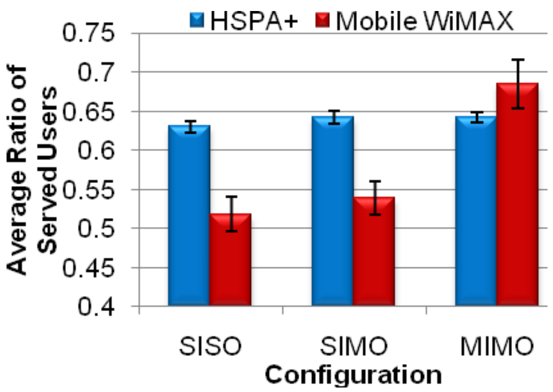


(a) DL (b) UL

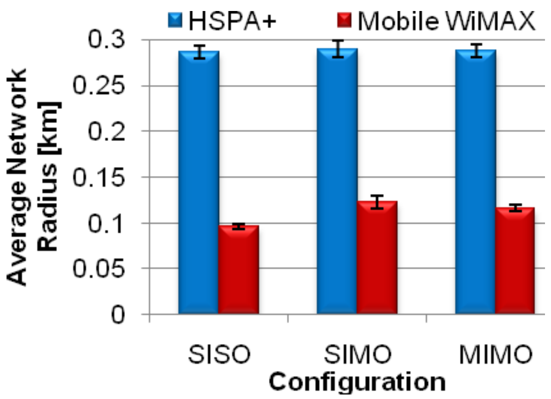
Figure I.4. Cell radius variation for different TDD Split for Mobile WiMAX DL and UL.

Annex J – DL Additional Results

In this annex, supplementary results regarding the HSPA+ and Mobile WiMAX comparison for multiple users scenario are presented for DL. Concerning the antenna configuration, the average ratio of served users and the average network radius are presented in Figure J.1, and the average percentage of covered users is presented in Figure J.2.



(a) Average Ratio of Served Users.



(b) Average Network Radius.

Figure J.1. HSPA+ and Mobile WiMAX DL Average Ratio of Served Users and Average Network Radius varying the antenna configuration.

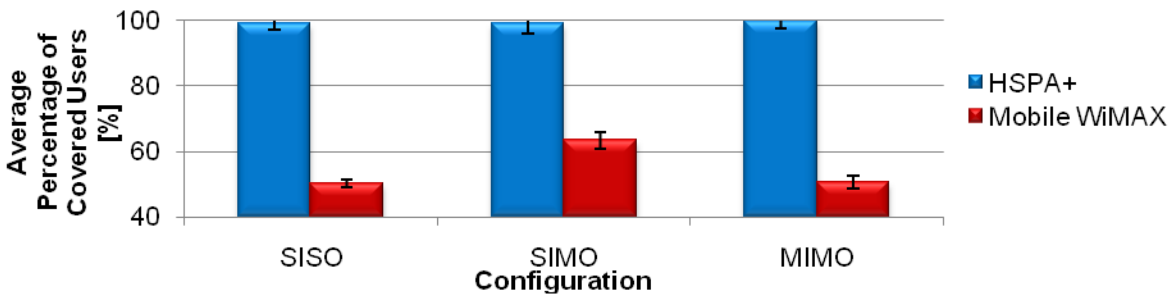


Figure J.2. HSPA+ and Mobile WiMAX DL Average Percentage of Covered Users varying the antenna configuration.

For higher services throughput variation, the average ratio of served users is presented in Figure J.3.

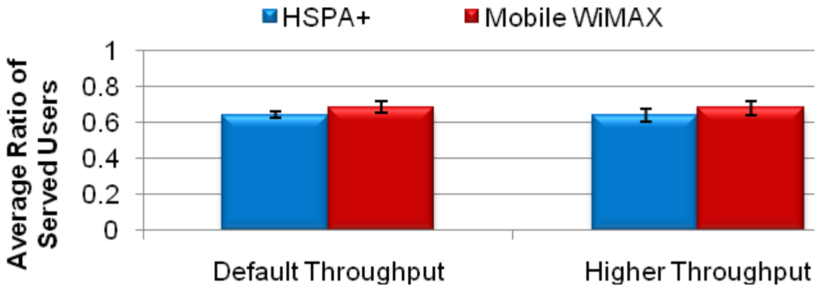
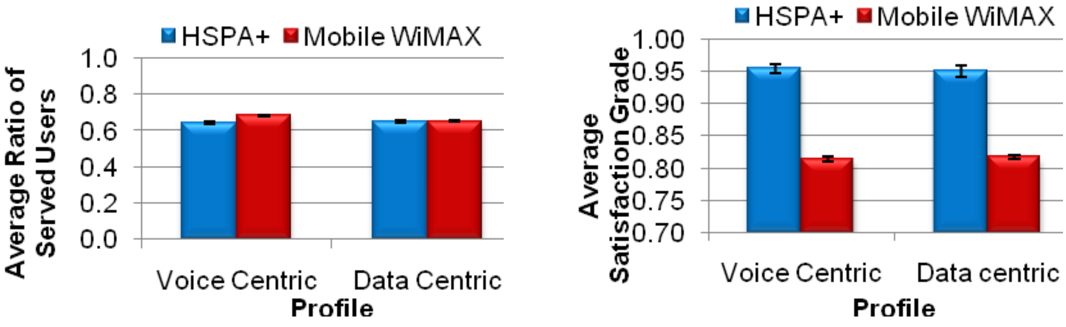


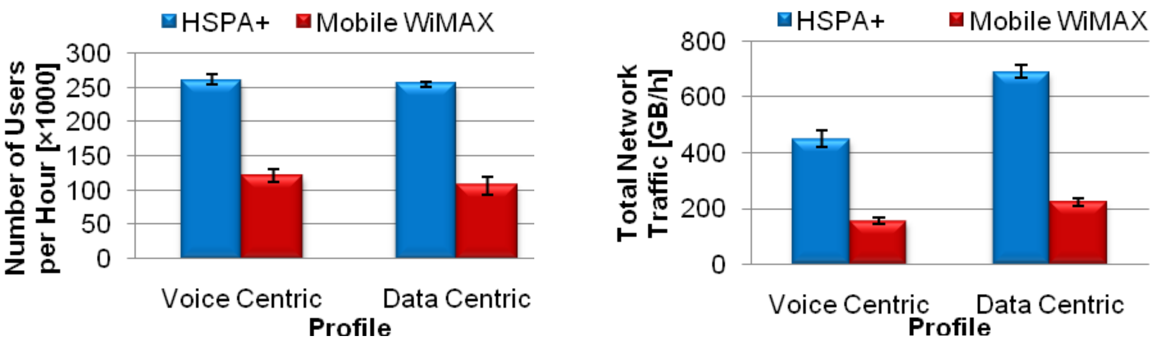
Figure J.3 . HSPA+ and Mobile WiMAX DL Average Ratio of Served Users, for different maximum services throughputs.

The average ratio of served users and the average satisfaction grade, for different profiles are presented in Figure J.4. The number of users per hour and the total network traffic are presented in Figure J.5.



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

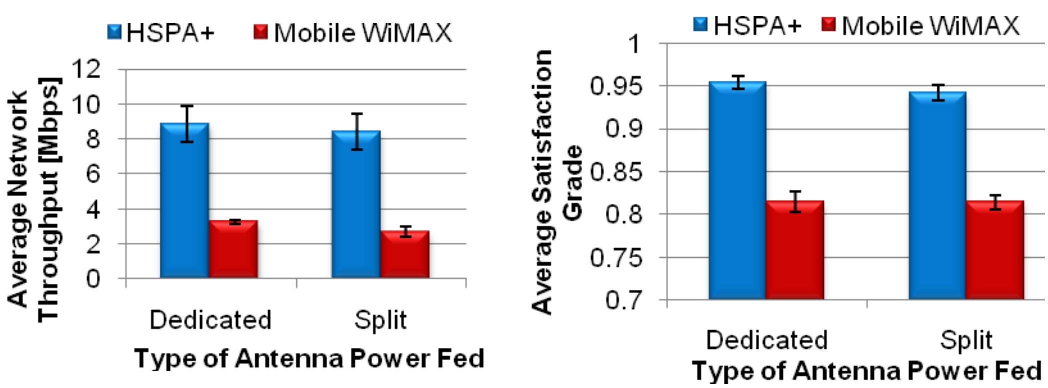
Figure J.4. HSPA+ and Mobile WiMAX DL Average Ratio of Served Users and Average Satisfaction Grade, for the 2 profiles.



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

Figure J.5. HSPA+ and Mobile WiMAX DL Number of Users per Hour and Total Network Traffic, for the 2 profiles.

For the different types of antenna power fed, the average network throughput and the average satisfaction grade are presented in Figure J.6 and the number of users per hour in Figure J.7.



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

Figure J.6. HSPA+ and Mobile WiMAX DL Average Network Throughput and Average Satisfaction Grade, for different antenna power fed.

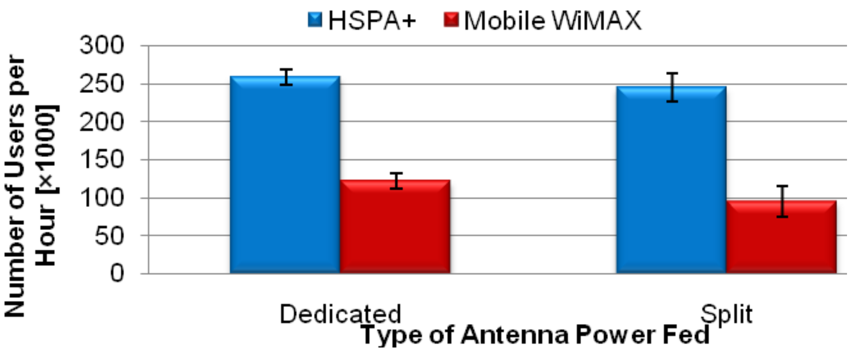
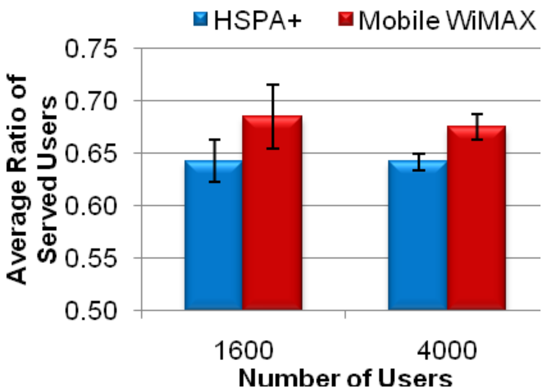
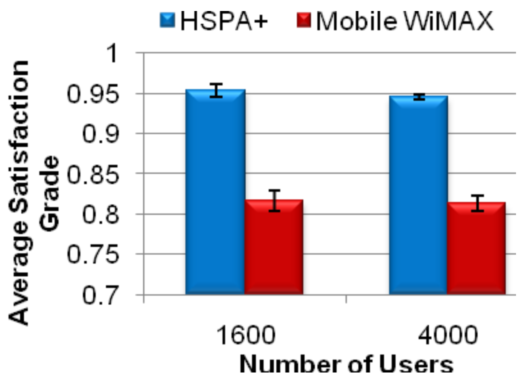


Figure J.7. HSPA+ and Mobile WiMAX DL Number of Users per Hour, for different types of antenna power fed.

In Figure J.8, one shows the variation of the average ratio of served users and the average satisfaction grade for different number of users, for both systems. Figure J.9 presents, considering the same variation, the number of users per hour and total traffic for both systems.

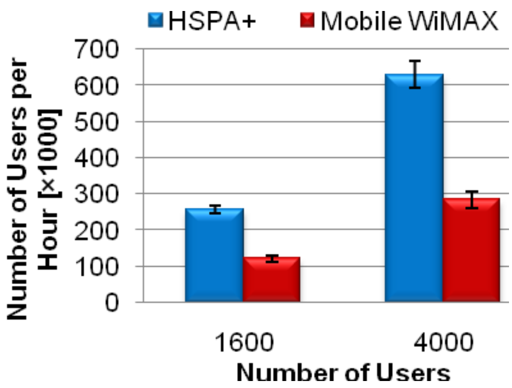


a) Average Network Throughput.

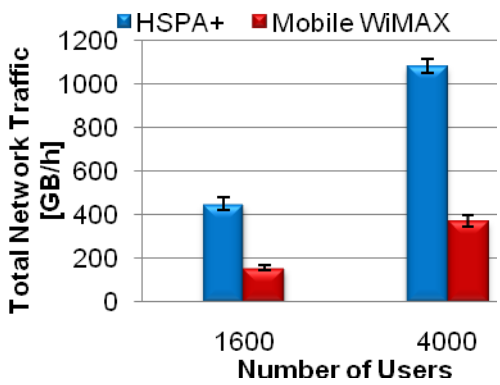


(b) Average Satisfaction Grade.

Figure J.8. HSPA+ and Mobile WiMAX DL Average Ratio of Served Users and Average Satisfaction Grade, for different number of users.



a) Total Number of Users per Hour



(b) Total Network Traffic.

Figure J.9. HSPA+ and Mobile WiMAX DL Number of Users per Hour and Total Network Traffic, for different number of users.

In Figure J.10, an overview of district A is presented.

Figure J.10. District A view (extracted from [GoEa08]).

Regarding the analysis for three different BS, located in distinct districts, the average ratio of served users is presented in Figure J.11 and the average satisfaction grade in Figure J.12.

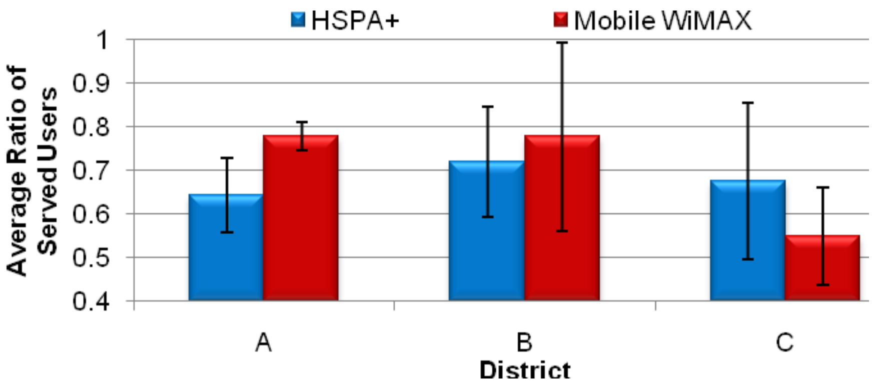


Figure J.11. HSPA+ and Mobile WiMAX DL Average Ratio of Served Users, for different districts.

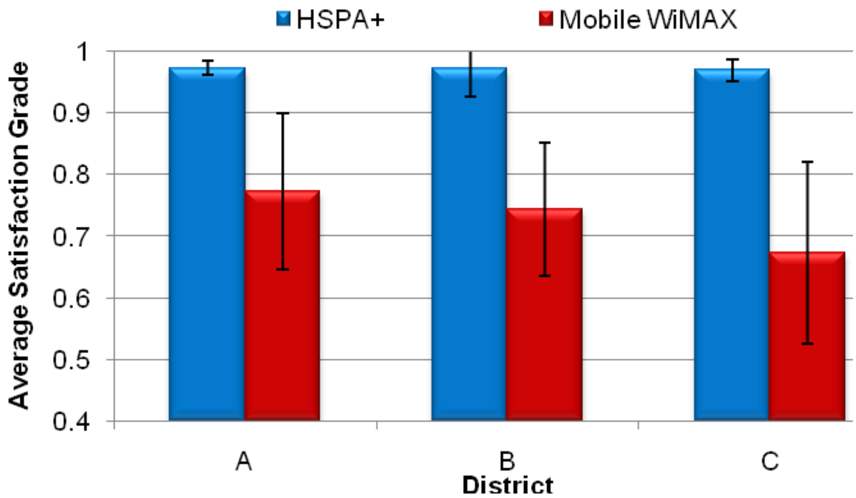


Figure J.12. HSPA+ and Mobile WiMAX DL Average Satisfaction grade, for different districts.

Annex K – UL Additional Results

In this annex, supplementary results regarding the HSPA+ and Mobile WiMAX comparison for multiple users scenario are presented for UL. Concerning the modulation scheme variation, the average satisfaction grade is presented in Figure K.1

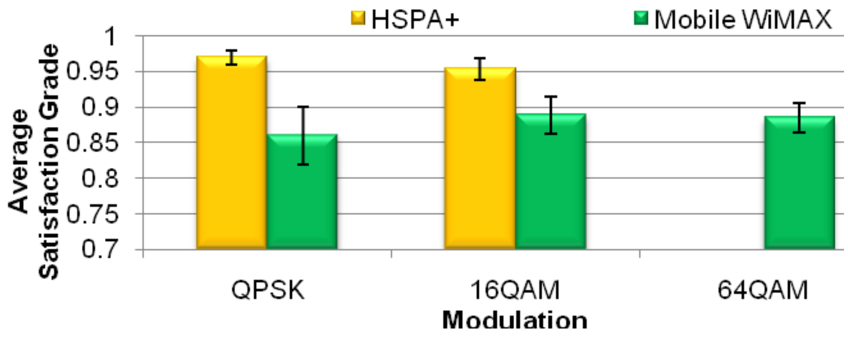


Figure K.1. HSPA+ and Mobile WiMAX UL Average Satisfaction Grade varying the modulation scheme.

For the configuration variation, one presents the average percentage of covered users, for both systems, in Figure K.2. Concerning the number of users in an hour period and the total network traffic, the results are presented in Figure K.3.

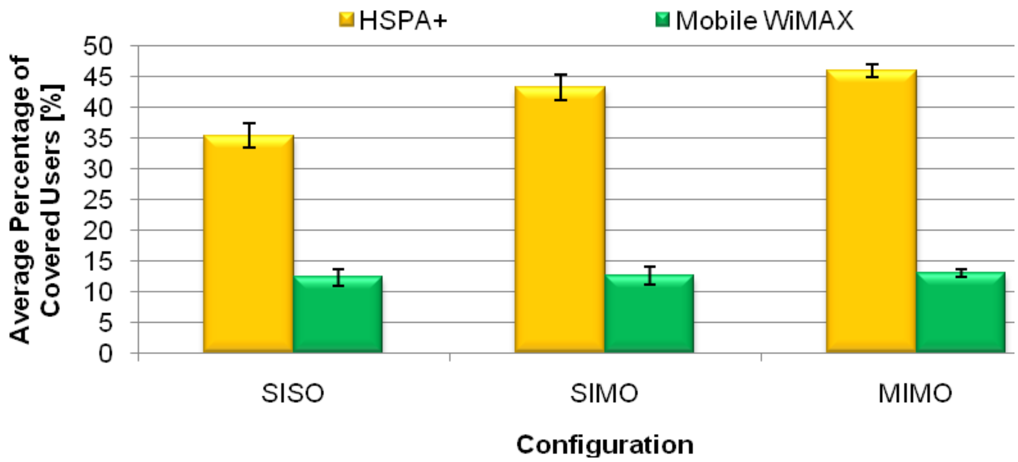
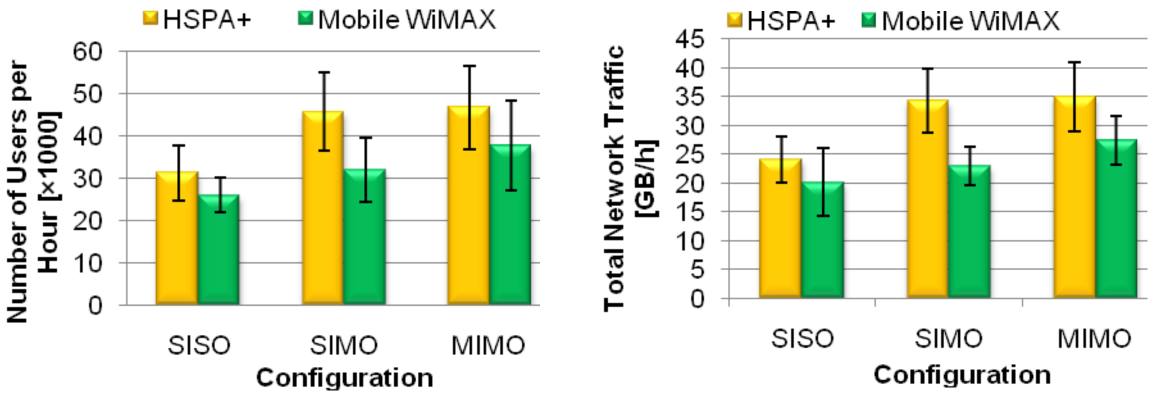


Figure K.2. HSPA+ and Mobile WiMAX UL Average Satisfaction Grade varying the antenna configuration.

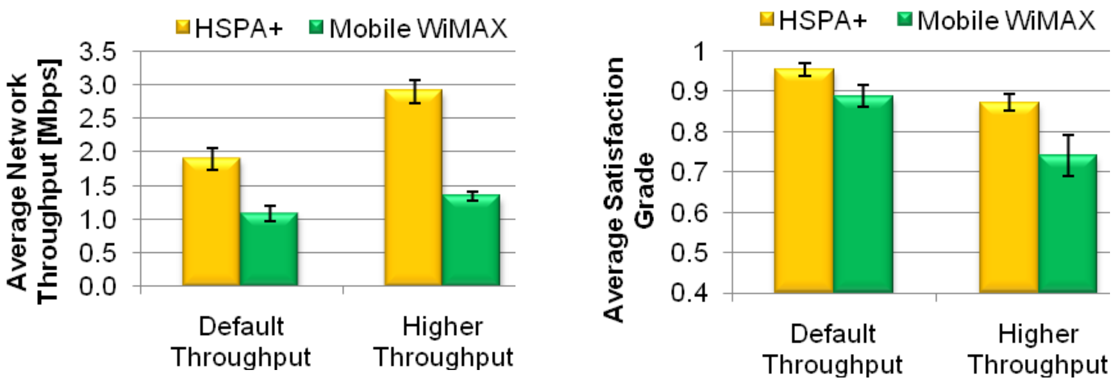
The average network throughput and the average satisfaction grade are presented in Figure K.4.

The impact of the higher throughput services is illustrated, for both systems, in Figure K.5 with respect to the average ratio of served users.



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

Figure K.3. HSPA+ and Mobile WiMAX UL Number of Users per Hour and Total Network Traffic, varying the antenna configuration.



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

Figure K.4. HSPA+ UL and Mobile WiMAX UL network parameters (Number of Users per Hour and Total Network Traffic), for different throughput services.

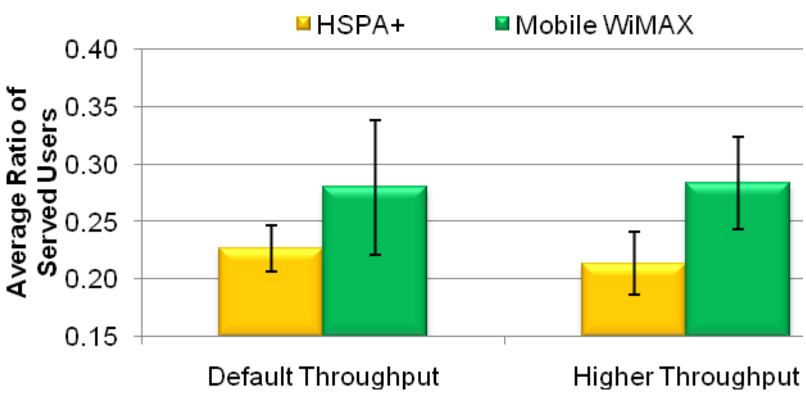
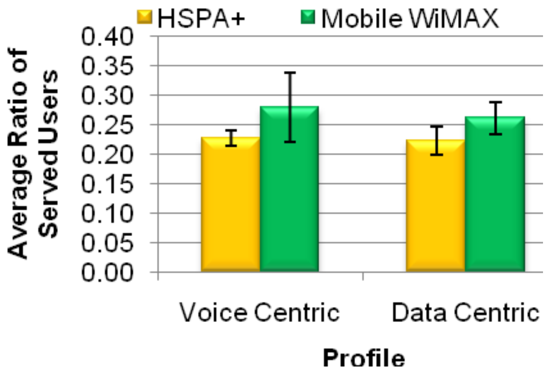
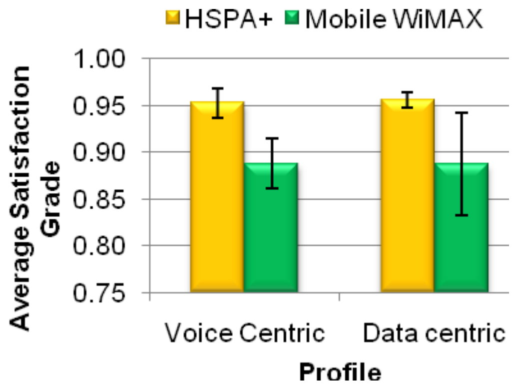


Figure K.5. HSPA+ and Mobile WiMAX UL Average Ratio of Served Users, for different throughput services.

The average ratio of served users and the average satisfaction grade are presented in Figure K.6. for different profiles considered. In Figure K.7., still regarding the different profiles, the number of users and the total network traffic are depicted.

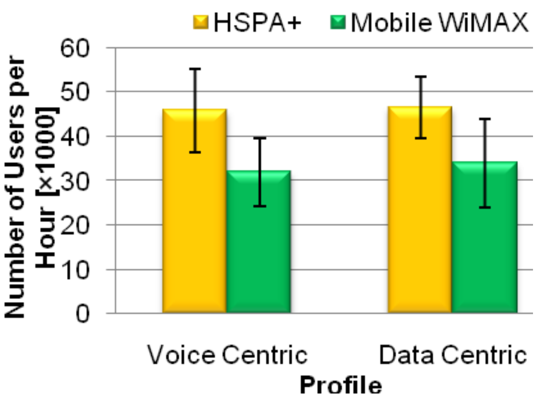


a) Average Ratio of Served Users.

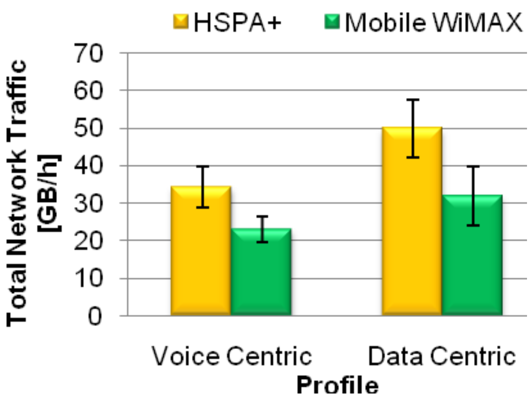


(b) Average Satisfaction Grade.

Figure K.6. HSPA+ and Mobile WiMAX UL Average Network Throughput and Average Satisfaction Grade, for 2 profiles.



a) Number of Users per Hour.



(b) Total Network Traffic.

Figure K.7. HSPA+ and Mobile WiMAX UL Number of Users per Hour and Total Network Traffic, for 2 profiles.

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