INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

WiMAX Capacity vs. Channel Bandwidth

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Dissertation submitted for obtaining the degree of
Master in Electrical and Computer Engineering

Jury

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October 2011

To Alexandra, Joana and Pedro

"Time stays long enough for anyone who will use it."

Leonardo Da Vinci

Acknowledgements

I would like to thank Professor Luis Correia for giving me a yet another chance (after the 1st try in the year 2000) to achieve an old dream of graduating on mobile telecommunications. His advices, steering, patience and support week after week were essential to complete this thesis that started back in 2008.

A Big thank you to my wife for the support and belief in me, and specially for not letting me quit in the difficult times, most of them spent travelling abroad away from home, and to my children for the time I stole away from them, that I hope to be able to compensate one day.

A special thank to my long date colleagues Conceição Dias and Jorge Costa for their availability and support, and for their friendship after all these years.

I'm also grateful to my parents and brother for their patience and support during my initial year at IST from where my fascination with mobile telecommunication systems emerged.

To all GROW members for their great reception and kindness to the group.

Abstract

The main purpose of this thesis was to study the WiMAX system capacity over different channel bandwidths. For that purpose, the maximum physical theoretical throughput was estimated, presenting values ranging from 11.67 Mbps for DL and 1.87 Mbps for UL at 5 MHz channel, up to 46.69 Mbps for DL and 7.69 Mbps for UL for 20 MHz channel. The number of users is also dependent on the traffic workload as expected, which is revealed by the variation of the traffic mix over several scenarios, showing that a 5 MHz channel could support between 2 users if only the FTP upload is considered to 216 users if only the VoIP workload is used. Results also show that by doubling the channel bandwidth the number of supported users also doubles. Considering a Residential weekdays scenario, the number of users ranges from 107 for a 5 MHz channel up to 492 users for a 20 MHz channel. To cover Lisbon's urban area, considering a Residential weekdays scenario, the range goes from 12 Base Stations providing capacity for 19,688 users for a 5 MHz channel; up to 46 Base Stations providing capacity for 356,208 users on 20 MHz channel.

Keywords

WiMAX, KPI, Capacity, Throughput, Workload

Resumo

O objectivo principal desta teste, foi estudar a capacidade do sistema WiMAX, para várias larguras de banda. Para o efeito é estimado o ritmo máximo de dados a nível físico, apresentando valores desde 11,67 Mbps para o DL e 1,87 Mbps para o UL, num canal de 5 MHz; até valores 46.69 Mbps para o DL e 7.69 Mbps para o UL num canal de 20 MHz. O número de utilizadores, dependente da carga de tráfego, tal como esperado. Isto é demonstrado pelo estudo, de vários perfis de tráfego, avaliando que para um canal de 5 MHz, a variação vai desde 2 utilizadores, se for considerado apenas a carga por FTP, até ao suporte de 216 utilizadores, se considerar apenas tráfego de VoIP. Os resultados mostram que ao duplicar a largura de banda, o número de utilizadores também duplica. Considerando o cenário “Residential weekdays”, os resultados variam desde 107 utilizadores por canal de 5 MHz, até 492 utilizadores por canal de 20 MHz, e para cobrir a área urbana de Lisboa, seriam necessárias 12 estações base, para canais de 5 MHz, com capacidade para 19.688 utilizadores, até 46 estações base, para canais de 20 MHz, com capacidade para 356.208 utilizadores.

Palavras-chave

WiMAX, KPI, Capacidade, Débito, Carga.

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List of Acronyms

16-QAM	16 Quadrature Amplitude Modulation
2G	Second-Generation cellular system
3G	Third-Generation cellular system
3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
4G	Fourth Generation
64-QAM	64 Quadrature Amplitude Modulation
AAA	Authentication Authorisation and Accounting
AAS	Adaptive Antenna System
ACK	Acknowledgements
AMC	Adaptive Modulation and Coding
ARPU	Average Revenue Per User
ASN	Access Service Network
ASN-GW	ASN Gateway
ASP	Application Service Providers
BCG	WiMAX Forum's Bandwidth Certificaton Group
BE	Best Effort
BS	Base Station
BWA	Broadband Wireless Access
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
CID	Connection Identifier
CNIR	Carrier to Noise and Interference Ratio
CPE	Consumer Premises Equipment
CQI	Channel Quality Indication
CRC	Cyclic Redundancy Check
CSN	Connectivity Service Network
DAS	Data Analysis Server
DC	Direct Current
DHCP	Dynamic Host Control Protocol
DL	Downlink
DLFP	DL Frame Prefix
DL-MAP	DL - Multiple Access Part
DSL	Digital Subscriber Line

DVB-H	Digital Video Broadcast-Handheld
EDGE	Enhanced Data rates for Global Evolution
EMS	Element Management Server
ertPS	Extended Real-time Polling Service
1xEV-DO	1x Evolution-Data Optimised
FCH	Frame Control Header
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FTP	File Transfer Protocol
GPRS	General Packet Radio Service
GPS	Global Positioning System
GRE	Generic Routing Encapsulation
GSM	Global System for Mobile Communications
GUI	Graphic User Interface
HARQ	Hybrid Automatic Repeat Request
HDTV	High Definition Television
H-NSP	Home NSP
HSPA	High Speed Packet Access
HSPA+	HSPA Evolution
HTTP	Hypertext Transfer Protocol
HO	Hand Over
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMT-2000	International Mobile Telecommunications-2000
IMS	IP Multimedia Subsystem
INS	Internal Network Server
IP	Internet Protocol
IR	Incremental Redundancy
ITU	International Telecommunications Union
KPI	Key Performance Indicators
LCP	Local Collection Point
LDCP	Low density Parity Check
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advance
MAC	Medium Access Control
MAP	Multiple Access Part
MBS	Multicast and Broadcast Service
MCS	Modulation and Coding Scheme

MIMO	Multiple Input Multiple Output
MMS	Multimedia Message Service
MOS	Mean Opinion Score
MPEG	Moving Pictures Experts Group
MPLS	Multiprotocol Label Switching
MS	Mobile Station / Mobile Subscriber
MSS	Mobile Subscriber Station
NAP	Network Access Provider
NE	Network Element
NI	Noise and Interference
NRM	Network Reference Model
nrtPS	Non-real-time Polling Service
NSP	Network Service Provider
NTP	Network Time Protocol
NWG	WiMAX Forum's Network Working Group
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operacional Expenditure
PDA	Personal Data Assistant
PDU	Protocol Data Unit
PHY	Physical Layer
PHS	Payload Header Suppression
PM DB	Performance Management Data BAse
PM	Poll-Me bit
PMP	Point-to-Multipoint
PUSC	Partial Utilised SubChannels
Q1	First Quartile of the sample
Q2	Second Quartile of the sample
Q3	Third Quartile of the sample
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RP	Reference Point
ROHC	Robust Header Compression
ROI	Return On Investment
RSSI	Received Signal Strength Indication
RTG	Receive/transmit Transition Gap
RTP	Real Time Protocol
RTT	Round-Trip Time

rtPS	Real-time Polling Service
SA	Smart Antennas
SDU	Service Data Unit
SFID	Service Flow Identifier
SI	Slip Indicator
SIM	Subscriber Identification Module
SNR	Signal-to-Noise Ratio
SOFDMA	Scalable OFDMA
SS	Subscriber Station
Std. Dev.	Standard Deviation
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TTG	Transmit to receive Transition Gap
UDP	User Datagram Protocol
UGS	Unsolicited Grant Service
USB	Univeral Serial Bus
UL	Uplink
UL-MAP	Uplink Multiple Access Part
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
VLAN	Virtual Local Area Network
V-NSP	Visited NSP
VoIP	Voice over IP
VPN	Virtual Private Network
WCDMA	Wideband Code Division Multiple Access
WiBro	Wireless Broadband
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

List of Symbols

$\overline{\Delta T_f}$	Average variation in the time required for the packet to physically travel the distance from the user equipment to the test server
ΔT_{JBT}	Bearer Traffic Jitter
$\overline{\Delta T_p}$	Average variation in the time required by the test server to process the packet
μ	Average (arithmetic mean) of a sample
σ	Standard Deviation of a sample
σ_μ	Average Standard deviation of a group of samples
σ_i:	Standard Deviation of average i
τ_{BT}	Bearer traffic Latency
τ_f	Latency due to the time required for the packet to physically travel the required distance from the user equipment to the test server
τ_{NAi}	Initial Network Access Latency
τ_p	Latency incurred by the packet being processed by the test server
τ_b	Latency due to the time required for the packet to physically travel the required distance from the test server back
A	Coverage area
D_{DL/UL_user}	Data size (per frame) including overheads
$F_{Duration}$	Frame duration
H	Header size
M_{SDU}	MAC SDU size
N	Number of samples
N_{bps}	Number bits per symbol
$N_{BytesFrameUser}$	Number of bytes per frame per user
$N_{DLactive\ DataSub}$	Number of DL active Data Subcarriers
$N_{DL/ULFrameSize}$	Number of DL and UL symbols per frame
$N_{bMCSUL/DL}$	Number of bytes per slot for each MCS
$N_{bMCS_iUL/DL}$	Number of bytes per slot for the *i*th MCS
N_{DL/UL_slots}	Total of Slots per Subframe for the total of subchannels
N_{DL/UL_slots_sub}	Number of slots per subchannel in one subframe
N_{DL/UL_sub}	Number of subchannels
N_{DL/UL_users}	Number of DL or UL users
$N_{PArrived}$	Total number of packets arrived
N_{PSent}	Total number packets sent

N_{SSslot}	Number of Subcarrier-Symbols per slot
$N_{ULactive\ DataSub}$	Number of DL active Data Subcarriers
$N_{ULFrameSize}$	Number of DL symbols per frame
N_{user}	Number of users served in a sector
N_{users}	Number of users
$P_{\%MCS_i}$	Percentage of users with the *i*th MCS
P_{PLBT}	Bearer Traffic Percentage of Packet loss
Q_{VoIP}	VoIP Quality
R	Application data rate
R_c	Cell range
R_{bDLMAX}	Maximum physical DL throughput
$R_{bSDL/UL}$	Sector Peak sustained throughput DL/UL
R_{bSDL_i}	DL instantaneous throughput of user i
R_{bSUL_i}	UL instantaneous throughput of user i
$R_{bUDL/UL}$	Single User DL/UL Peak sustained throughput
R_{bUDL_i}	DL throughput obtained on measurement i
R_{bULMAX}	Maximum physical UL throughput
R_{bUUL_i}	UL throughput obtained on measurement i
$R_{Codding}$	Coding Rate
R_{Frame}	Frame rate
$R_{with\ Header}$	Data rate
S_{MOS}	Mean Opinion Score
$T_{deadline}$	Deadline for the scheduler
t_{start}	Time of scanning start
t_{stop}	Time of scanning stop
Z_i	Sample i

List of Software

Microsoft Excel	Calculation tool
Microsoft Word	Text editor tool
Microsoft Visio	Flow Chart tool
Microsoft Internet Explorer	Internet browsing tool
Adobe Acrobat Reader	Text editor tool

Chapter 1

Introduction

This introductory chapter presents a brief overview of the work. It provides the background and scope in which this thesis fits in. At the end of this chapter, the main motivations and the work structure are provided.

1.1 Overview

The swiftly growing success of data networks usage in the last decades of the twentieth century and the advances on personal communications devices, created the need for high-speed wireless data access. This is the main driver for the initial decades of twenty first century mobile wireless data networks evolution.

An (r)evolution is in progress on the wireless communications industry, with the major standard organisations specifically the 3rd Generation Partnership Project (3GPP), the 3rd Generation Partnership Program 2 (3GPP2) and Institute of Electrical and Electronics Engineers (IEEE) competing to define new broadband standards, for the next-generations of wireless communication platforms. The explosion of Global System for Mobile Communications (GSM) in the early 1990s that became the most popular worldwide 2nd Generation (2G) standard promptly added the packet data support via the General Packet Radio Service (GPRS) to support higher data rates, this initial evolution from less than 9.6 kbps circuit switched to data rates in the order of 171 kbps packet switch, also called 2.5G, that were no match compared with the fixed communication infrastructures.

In the early 2000s one assisted to the rise of the standards fulfilling the International Mobile Telecommunications-2000 (IMT-2000) from the International Telecommunications Union (ITU), like the Enhanced Data rates for Global Evolution (EDGE) with data speeds in the order of 473.6 kbps evolving from GSM and the new Third-Generation (3G) standards, like the Code Division Multiple Access 2000 (CDMA2000) and the Wideband Code Division Multiple Access (WCDMA) based Universal Mobile Telecommunications System (UMTS) that could provide data speeds of around 153kbps and 384kbps respectively. These new standards offered enough data speed and improved reliability to directly compete with the fixed communications infrastructures in regards to the previous wireless standards, specially when applied to small communication devices like Laptops or handheld Personal Data Assistants (PDAs).

The exponential growth thirst for wireless mobile data availability in the mid 2000s soon required a 3.5G evolution for which the answer came in the form of the 1x Evolution-Data Optimised (1xEV-DO) and the High Speed Packet Access (HSPA) with data speeds of 3.1 Mbps and 14.4 Mbps respectively, which extended and improved the performance of existing 3G protocols.

The transition years to the 2010s decade brought another level of evolution to the standards that opened to the wireless devices the remaining applications that required very high levels of data speed such as High Definition Television (HDTV), and could now become alternatives to the fixed data transmission industry. In parallel to this the Fixed Worldwide Interoperability for Microwave Access (WiMAX) that evolved based on the IEEE experience over the 802.11 standards, most popularly known as Wireless Fidelity (Wi-Fi) rapidly evolved to Mobile WiMAX also known Wireless Broadband (WiBro) in South Korea, like the other 3.9G protocols such as HSPA Evolution (HSPA+) with data speed of over 40 Mbps and Long Term Evolution (LTE) with data speed of 100 Mbps, these are currently the most popular candidates in the race to become the basis of next global 4G standard, for which the LTE Advanced (LTE-A) is the best candidate. The data rates presented are related to the maximum theoretical on the Downlink (DL), and were extracted from [ZTE08].

LTE-A is currently aligned to be the merger of the two major streams of Wireless Communication Networks standards; the ones based on the GSM/UMTS and CDMA2000 that come from a mobile telecommunications background; and the Wi-Fi and WiMAX ones that comes from a Computer Science driven stream. A visual reference to this wild battle is presented in Figure 1.1, where the evolution paths of a few other standards are also shown.

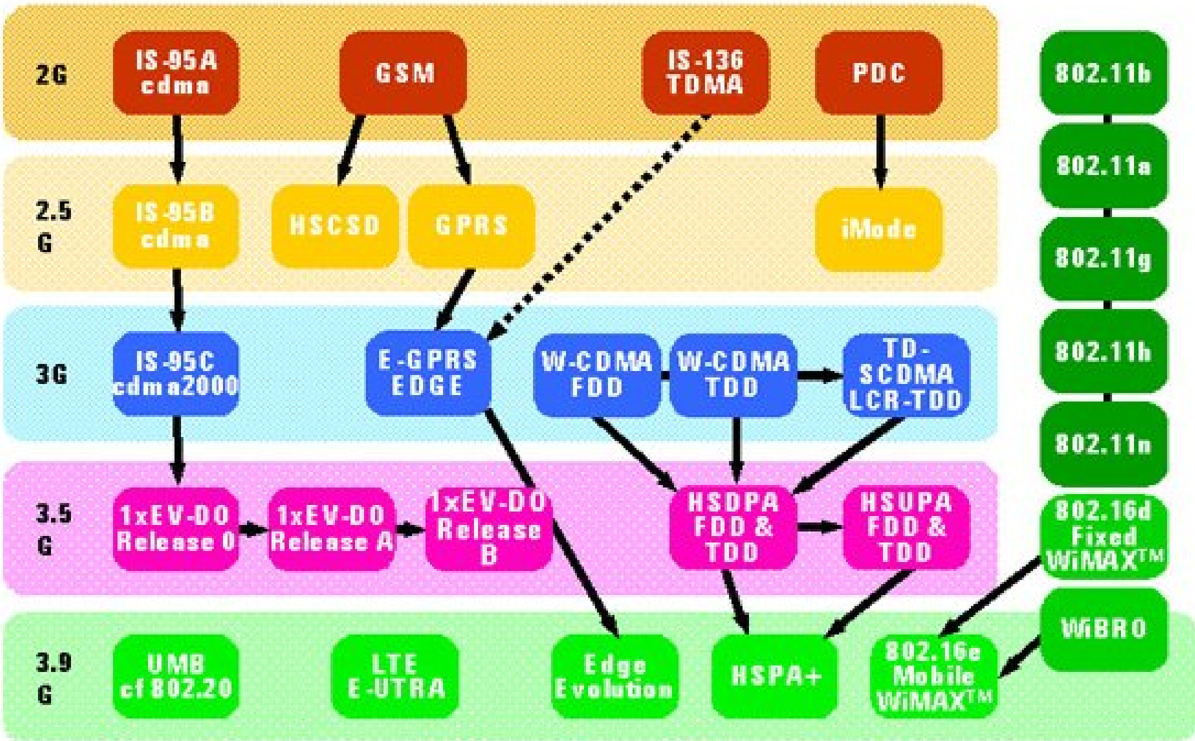

Figure 1.1. Digital Wireless Evolution 1990 to 2010, (extracted from [Agil11])

Going back to the theme of this thesis, WiMAX that provides a solution of Broadband Wireless Access (BWA), one should start by looking at its standard evolution.

WiMAX most distinctive characteristics are based on the IEEE 802.16 standards, which are continually being updated and improved. A very brief background on these standards starts by mentioning that it was first introduced in 2001 as IEEE 802.16. The standard dealt initially with fixed equipment and line of sight operations, especially to become an alternative to the copper and cable access to the data and voice network also know as the “last mile”.

In 2004, the IEEE 802.16d standard was introduced, as an improvement to the previous versions. This standard is typically referred to as “fixed” WiMAX and was effectively adopted by several equipment manufacturers for BWA either conforming to the standard or basing their proprietary system on it. In 2005, the working group began working on IEEE 802.16e. This revision is an update to IEEE 802.16d and adding mobility [Nuay07], this brought WiMAX to the picture to compete with the other standards to directly provide wireless data communications for small devices like Laptops or handheld Personal

Data Assistants (PDAs) and Smartphones.

In Table 1.1, WiMAX related standards can be observed. There are additional revisions to the standard in committee today. When a new revision is released, the standard is appended with a new “suffix”.

Table 1.1. IEEE 802.16 standards (adapted from [WiMX10]).

Standard	Status	Description
802.16-2001	Superseded	Fixed Broadband Wireless Access (10–63 GHz)
802.16.2-2001	Superseded	Recommended practice for coexistence
802.16c-2002	Superseded	System profiles for 10–63 GHz
802.16a-2003	Superseded	Physical layer and MAC definitions for 2–11 GHz
P802.16b	Withdrawn	License-exempt frequencies (Project withdrawn)
P802.16d	Merged	Maintenance and System profiles for 2–11 GHz (Project merged into 802.16-2004)
802.16-2004	Superseded	Air Interface for Fixed Broadband Wireless Access System (rollup of 802.16-2001, 802.16a, 802.16c and P802.16d)
P802.16.2a	Merged	Coexistence with 2–11 GHz and 23.5–43.5 GHz (Project merged into 802.16.2-2004)
802.16.2-2004	Active	Recommended practice for coexistence (Maintenance and rollup of 802.16.2-2001 and P802.16.2a)
802.16f-2005	Superseded	Management Information Base (MIB) for 802.16-2004
802.16-2004 / Cor 1-2005	Superseded	Corrections for fixed operations (co-published with 802.16e-2005)
802.16e-2005	Superseded	Mobile Broadband Wireless Access System
802.16k-2007	Active	Bridging of 802.16 (an amendment to IEEE 802.1D)
802.16g-2007	Superseded	Management Plane Procedures and Services
P802.16i	Merged	Mobile Management Information Base (Project merged into 802.16-2009)
802.16-2009	Active	Air Interface for Fixed and Mobile Broadband Wireless Access System (rollup of 802.16-2004, 802.16-2004/Cor 1, 802.16e, 802.16f, 802.16g and P802.16i)
802.16j-2009	Active	Multihop relay
802.16h-2010	Active	Improved Coexistence Mechanisms for License-Exempt Operation
P802.16m	Active	Advanced Air Interface with data rates of 100 Mbit/s mobile & 1 Gbit/s fixed. Also known as Mobile WiMAX Release 2 or WirelessMAN-Advanced. Aiming at fulfilling the ITU-R IMT-Advanced requirements on 4G systems.
P802.16n	Pre-Draft	Higher Reliability Networks
P802.16p	Pre-Draft	Enhancements to Support Machine-to-Machine Applications

The IEEE 802.16 standards family only provides for the Physical (PHY) and Medium Access Control (MAC) layers, the network architecture and radio interface is described on recommendations of WiMAX Forum [WiMX10]. Along with the bandwidth dependency, the impact of the main data applications and the specific WiMAX performance parameters on the user capacity are studied.

A brief comparison with other wireless networks is useful to understand the positioning of Mobile WiMAX, since Fixed WiMAX is destined to a completely different market. The main characteristics of each system are presented in Table 1.2.

In opposition to HSPA+ and LTE, which are the natural evolutions for the existing GSM and CDMA based networks; WiMAX positioned itself as an initial system for new comers to the wireless communications market. Among these new comers, the ones to highlight are the traditionally fixed voice and data communication providers searching for new markets to expand their businesses, or communities and public institutions providing broadband access to citizens for which some examples can be found at [FSHo09]. WiMAX is based on Orthogonal Frequency Division Multiplexing (OFDM) and has a spectral efficiency typically in the order of magnitude of 3.5–5 b/s/Hz, although dependent on the environment and other parameters, being usually greater than the CDMA based standards, like UMTS and CDMA2000 [Nuay07]. This spectral efficiency is similar to LTE that also uses OFDM.

Table 1.2. Some comparison elements between major wireless systems (adapted from [Nuay07], [NSN10] and [Moto10b]).

Standard	Operating frequency	Licensed	Channel bandwidth [MHz]	Users per channel	Data Rate (DL) [Mbps]
GSM/ GPRS/ EDGE	0.9 GHz, 1.8 GHz, Other	Yes	0.2	2 to 8	0.167 (GPRS) 0.463 (EDGE)
UMTS (FDD)	850 MHz, 1.9 GHz, Other	Yes	5	Order of Magnitude of 25.	0.375
CDMA 2000	450 MHz, 800 MHz, 1.8 GHz, 1.9 GHz, 2.1 GHz	Yes	1.25	Up to 64	0.149
UMTS/ HSPA+ (Rel. 5)	700 MHz, 850 MHz, 1.7/2.1 GHz	Yes	5	Order of Magnitude of 40.	14
CDMA2000/ EV-DO (Rev. A)	450 MHz, 850 MHz, 900 MHz, 1.7/2.1 GHz	Yes	1.25	Up to 64	3.1
LTE	700 MHz, 850 MHz, 1.7/2.1 GHz, 2.3 GHz, 2.6 GHz	Yes	1.25 to 40	> 200 (5 MHz channel)	100 (20 MHz channel)
WiMAX	2.3 GHz, 2.5 GHz, 3.3 GHz, 3.5 GHz, 5.8 GHz	Licensed and unlicensed	1.25 to 20	> 100 (5 MHz channel)	100 (20 MHz channel)

The values presented are indicative and for the purpose of comparison between the different standards; they show peak theoretical rates and consider some particular releases or revisions of each standard. Moreover, the values are not normalised (by physical channel size) and this hides the spectral efficiency, and possible real data rate capabilities of each standard. Nevertheless they provide a good indication that higher capacities come at the expense of wider channel bandwidth.

Among many of the financial considerations that a wireless communications operator faces when studying the business case for any new network, one of the main, and usually very expensive, is the RF spectrum license which, along with the chosen technology capabilities, delineates the possibilities regarding the channel bandwidth, this together with service offerings and applications workload, conditions the capacity both in terms of subscriber volume and services that can be provided.

1.2 Motivation and Contents

The main motivation for this thesis is to provide a bridge between the business world and the academic one, by clearly describing the dependency between the number of users - that condition the revenue of the operator of the network - and the Radio Frequency (RF) channel bandwidth. The liberalisation and agnosticism of spectrum poses the challenge of what technology should be used to maximise the Return On Investment (ROI) and future revenue. Since time is the greatest asset for mankind and due to the well known bond with frequency (f=1/t), it is clear that RF spectrum correlation is always present.

The focus on WiMAX comes from being the fastest growing 4G candidate system in the start of the 2010 decade. As of May 2011, the WiMAX Forum claims there are over 583 WiMAX (fixed and mobile) networks deployed in over 150 countries; this clearly competes with the other standards evolved from traditional mobile cellular standards.

In addition to the current chapter, four more are presented on this thesis.

Chapter 2 starts with an overview of the WiMAX system mainly focusing on the network architecture, the radio interface. Then, a summary of the main services and applications is presented. Finally, the main performance parameters are examined and a brief “State of the Art” is presented.

Chapter 3 initiates by presenting the theoretical model that is used to calculate the maximum channel throughput, followed by the discussion on the impact of the application workload. Then, the capacity and coverage estimations are described. Finally, the database from were the experimental results values are retrieved is illustrated.

Chapter 4 begins with the description of the live network and the theoretical scenarios. Afterwards, the theoretical results are analysed followed by the experimental ones. Finally a comparison between the theoretical and experimental results is performed.

The conclusions of this thesis are drawn in Chapter 5; where future work suggestions are also mentioned.

Some annexes with additional information are included, being referenced in the thesis when necessary to form a better understanding, containing antenna techniques and results.

Chapter 2

Basic Concepts

This chapter provides an overview of the WiMAX system, mainly focussing on the architecture, capacity aspects of the radio interfaces, services and applications followed by an examination of the main performance parameters, and concluding with a brief “State of the Art”.

2.1 Network Architecture

WiMAX Forum's Network Working Group (NWG) [WiMX10] is responsible for developing the end-to-end network requirements, architecture, and protocols for WiMAX, using the air interface provided by IEEE 802.16, in this thesis we will be following the ones in IEEE 802.16e. The WiMAX architecture is based on the standardised Internet Protocol (IP), is compatible with service frameworks, such as the IP Multimedia Subsystem (IMS), and has been created considering several requirements [Nuay07]:

- High-performance packet-based network with functional split, based on IEEE and Internet Engineering Task Force (IETF) protocols;
- Support of a full range of services and applications:
  - Voice over Internet Protocol (VoIP), IMS and others, like emergency calls;
  - Access to application service providers;
  - Interface with interworking and media gateways for translation of legacy services, such as: circuit voice, Multimedia Messaging Service (MMS) to IP, and transport them over WiMAX radio access networks;
  - IP Multicast and Broadcast Services (MBS).
- Roaming and interworking support with other networks.
  - Loose coupling with existing wired or wireless networks;
  - Global roaming between WiMAX operators;
  - Various user authentication methods: username/password, digital certificates, Subscriber Identification Module (SIM) based.

The Network Reference Model (NRM) can be divided into: Components, Reference Points (RPs) and Actors is shown in Figure 2.1.

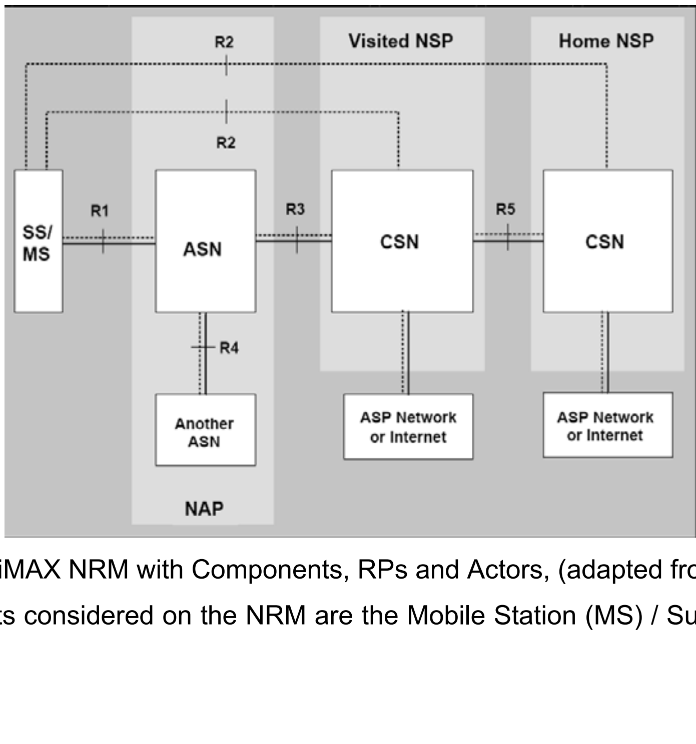

Figure 2.1. WiMAX NRM with Components, RPs and Actors, (adapted from [WiMF06]).

The main Components considered on the NRM are the Mobile Station (MS) / Subscriber Station (SS);

the Access Service Network (ASN) and the Connectivity Service Network (CSN). Then the standard RPs provides the Interoperability between equipments from different vendors. The WiMAX Release 1 network architecture defines six mandatory RPs (R1 to R6) and two informative ones (R7 and R8). Finally on the NRM one can find the Actors consisting on the Network Access Provider (NAP), Network Service Providers (NSP) and Application Service Providers (ASP). These high level functionalities can be provided by diverse and independent companies / vendors, or all by the same company / vendor, or even a mix.
The three main components perform a variety of functionalities:

- MS / SS or Customer Premise Equipment (CPE) – is the equipment providing connectivity between subscribers and WiMAX network.
- ASN – Provides the set of functionalities that allow radio access connection to WiMAX subscribers and is shown in Figure 2.2. The ASN can comprise one or more Base Stations (BSs) and one or more ASN gateways (ASN-GW) that form the Radio Access Network (RAN).

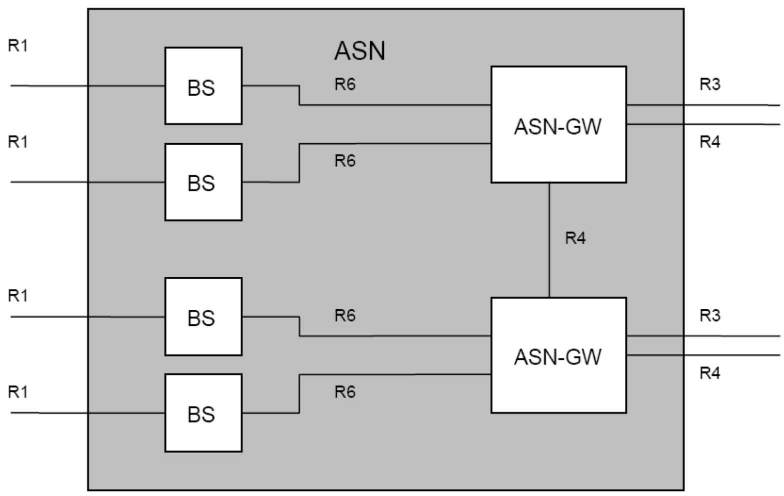

Figure 2.2. ASN reference model, (adapted from [WiMF06]).

  - o BS: Further functions to the air interface can be performed by the BS, such as: micro-mobility management functions (like handoff triggering and tunnel establishment), radio resource management, Quality of Service (QoS) policy enforcement, traffic classification, Dynamic Host Control Protocol (DHCP) proxy, key management, session management, and multicast group management.
  - o ASN-GW: Typically acts as layer 2 traffic aggregation point inside the ASN. Additional functions can be performed, like: intra- ASN location management and paging, radio resource management and admission control, caching subscriber profiles and encryption keys, Authentication Authorisation and Accounting (AAA) client functionality, establishment and management of mobility tunnel with BSs, QoS and policy enforcement, foreign agent functionality for mobile IP, and routing to the selected CSN.
  - o One or several ASN-GW, interconnected through reference point R4, and the

connectivity to CSN is provided by R3. ASN may be deployed by a NAP. A NAP provides radio access infrastructure to one or several NSP.

  - Three profiles are available for the ASN: A, B and C. Depending on the profiles, some functionality may be implemented by the BS or the ASN-GW, or by any box in the case of a profile B.

- CSN: The CSN provides connectivity from ASN to: Internet, ASP, other public networks, and corporate networks. The CSN is deployed by a NSP and includes: AAA servers that support authentication (for the devices and users) and specific services, provides policy management per user of QoS, security, IP address management, support for roaming between different NSPs, location management, mobility and roaming between ASNs [Nuay07].

Regarding the application side, WiMAX services are delivered by ASP and/or through direct connection to the Internet.

Home NSP (H-NSP) and Visited NSP (V-NSP) are required for roaming between NSPs in different countries or networks. A WiMAX subscriber may be attached to a H-NSP or to a V-NSP with whom its home NSP has a roaming agreement.

Normative RPs [Nuay07] defines a set of interfaces:

- Reference point R1 defines the radio interface between the MS and the ASN including all the physical and MAC features from the IEEE 802.16 standard. By R1 both user traffic and user control plane messages flows.
- Reference point R2 defines a logical interface between the MS and the CSN. It includes all protocols and procedures involved with: authentication for device and user, service authorisation, and IP host configuration management. R2 is established between the MS and H-NSP, and in the case of roaming some protocols, like the IP host address management, may be performed by the visited NSP.
- Reference point R3 defines a logical interface between ASN and CSN. It transports control plane messages, such as AAA methods and policy enforcement methods for end-to-end QoS, mobility management messages and data plane information using tunnelling.
- Reference point R4 provides interconnection between two ASNs (ASN profile B) or two ASN-GWs (ASN profiles A or C), It transports both control and data plane messages, especially during handover between ASNs/ASN-GWs or location update procedures in Idle mode. R4 is currently the only interoperable point between ASNs from different vendors. IP in IP tunnelling mode based on the Generic Routing Encapsulation (GRE) protocol is the recommended method to use for R4.
- Reference point R5 provides connectivity between two CSNs. It implements a set of control and data plane methods between the CSN in the visited NSP and the home NSP.
- Reference point R6 is defined in the context of specific ASN profiles A and C. These two profiles decompose the ASN into BS and ASN GW. R6 provides connectivity between BS and ASN-GW and is not applicable to profile B. It transports control messages for data path establishment, modification, control and release in accordance with MS mobility as well as

data plane (intra-ASN data path between BS and ASN-GW information). Tunnelling methods used are GRE, Multiprotocol Label Switching (MPLS), Virtual Local Area Network (VLAN) or other to be proposed. In combination with R4, this interface can also transport the MAC state information that could be carried by R8 when interoperability between BSs is not available.

For the ASN, there are two additional interfaces (R7 and R8) currently defined for further interoperability points, thus they are only informative in WiMAX architecture Release 1 [Nuay07]:

- Reference point R7: optional logical interface between decision function and enforcement function in ASN-GW.
- Reference point R8: optional logical interface between BSs. It transports control plane flow exchange used for enabling fast and efficient handover between BSs. Optionally, it may also transport data plane information during handover. R8 methods can be executed through the ASN-GW as an example.

The Motorola example of the WiMAX network architecture is shown in Figure 2.3. All components of the NRM can be identified, and many of them are implemented by individual entities (servers, routers, hosts,…).

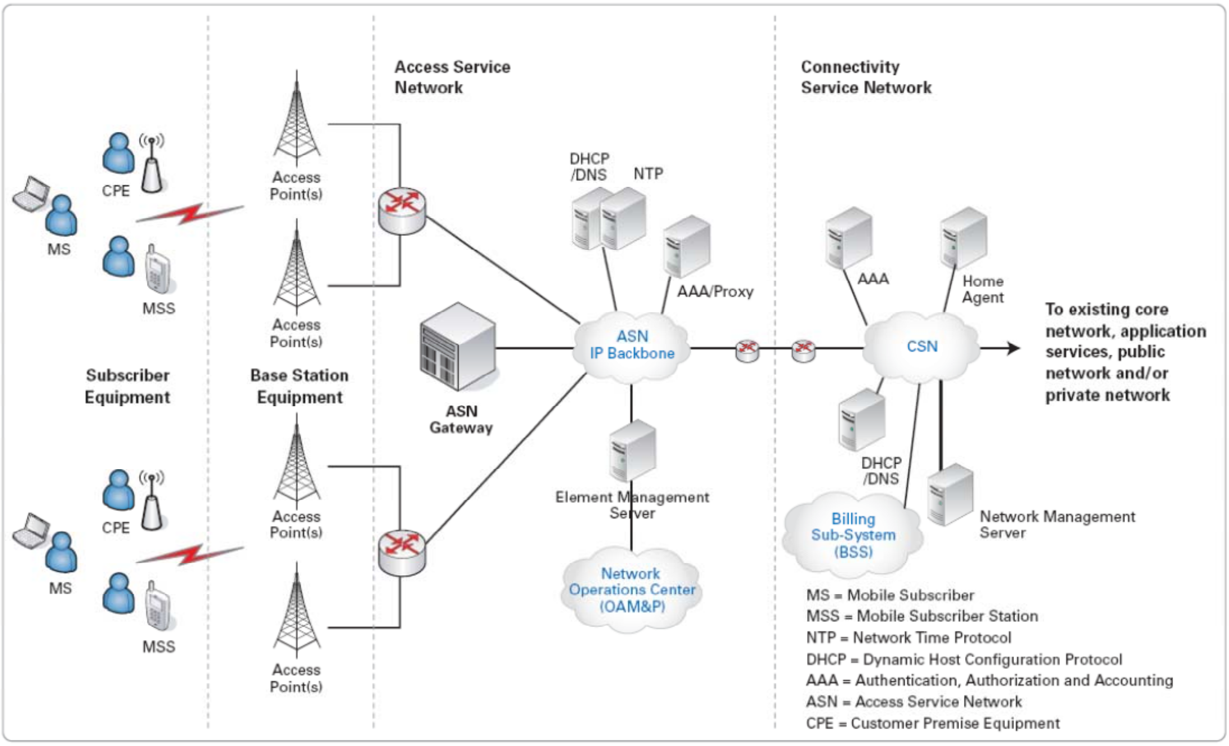

Figure 2.3. Motorola approach to reference model, (extracted from [Moto10a]).

Although two topologies are available on the standard, Point-to-Multipoint (PMP) and Mesh (where the BS is no longer the centre, as in the classical PMP mode), the focus is on the PMP one, since this is the mostly commonly implemented [Nuay07].

2.2 Radio Interface

The WiMAX physical layer has undergone an evolution from the OFDM in IEEE 802.16d to the Orthogonal Frequency Division Multiple Access (OFDMA) in IEEE 802.16e to add the support for multiple user transmissions. OFDM is the transmission scheme of choice to enable high-speed data, video, and multimedia communications. Used by a variety of commercial broadband systems, including Digital Subscriber Line (DSL), Wi-Fi, Digital Video Broadcast-Handheld (DVB-H), and MediaFLO, it is an efficient scheme for high data rate transmission in a non line-of-sight or multipath radio environment.

The focus for the physical interface in this thesis is on a variant of OFDMA, the Scalable Orthogonal Frequency Division Multiple Access (SOFDMA) as defined in IEEE 802.16e-2005 [Nuay07] that provides the required scalability of channels from 1.25 to 20 MHz which is part of the analysis of this thesis. Both licensed and un-license frequency bands are possible. The WiMAX Forum Bandwidth Certification Group (BCG) [Nuay07], based on market requirements and spectrum suitability, provides specific channel bandwidths for product support and certification [EtKa08]. Table 2.1 summarises the channel and licences band classes for Time Division Duplexing (TDD) in Release 1.0.

Table 2.1. Mobile WiMAX TDD band classes for release 1.0, (extracted from [EtKa08]).

Band class	Spectrum range [GHz]	Bandwidth [MHz]	BCG
1 (Korea, South Asia)	[2.3, 2.4]	8.75	1.A
		5 10	1.B
2 (USA/Canada)	[2.305, 2.320] [2.345, 2.360]	3.5	2.A
		5	2.B
		10	2.C
3 (International: USA/Europe,IMT2000)	[2.496, 2.690]	5 10	3.A
4 (China/India)	[3.3, 3.4]	5	4.A
		7	4.B
		10	4.C
5 (International: Europe/Asia)	[3.4, 3.8]	5	5.A
		7	5.B
		10	5.C

Up to date the 20 MHz channels have not been assigned by BCG. Both TDD and Frequency Division Duplexing (FDD) operations are supported by IEEE802.16e PHY specifications [Nuay07]. A half duplex FDD mode is also defined for lower-complexity terminals, where the radio front unit is time-shared between Uplink (UL) and DL. From Mobile WiMAX Release 1.5 both TDD and FDD are supported. The OFDMA frame structure for TDD is illustrated in Figure 2.4, each 5 ms radio frame being divided flexibly into DL and UL subframes, which are separated by transmit/receive and receive/transmit transition periods in order to prevent transmission collisions [EtKa08].

Most of the transitions between modulations and coding take place on slot boundaries in the time domain, and on subchannels within an OFDMA symbol in the frequency one, with the exception of the

Adaptive Antenna Systems (AAS) zone. Frame Control Header (FCH) is transmitted using the Quadrature Phase Shift Keying (QPSK) ½ rate with four repetitions using the mandatory coding scheme, and the FCH information is sent on four adjacent subchannels with successive logical subchannel numbers in a Partial Utilised Subchannels (PUSC) zone. The FCH also contains the DL Frame Prefix (DLFP), which specifies the length and the repetition coding of the DL - Multiple Access Part (DL-MAP) message that follows immediately after [Nuay07].

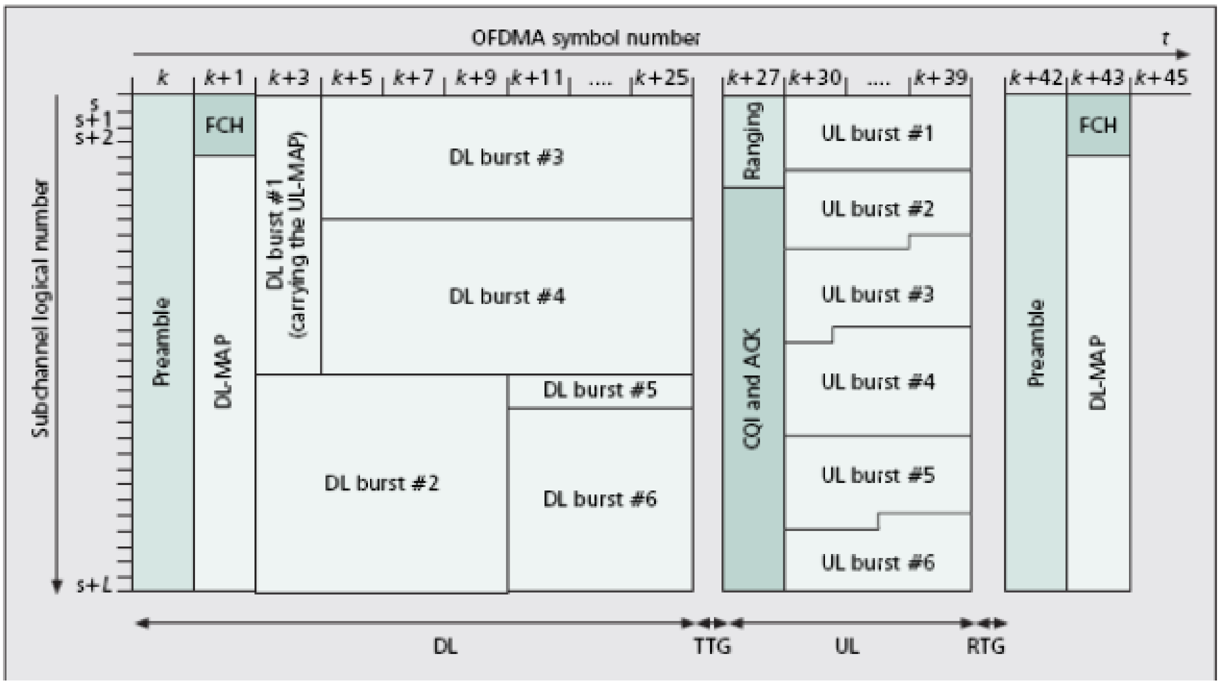

Figure 2.4. Example of an OFDMA frame in the TDD mode, (extracted from [KiYu09]).

Several PHY modes are defined in the IEEE 802.16 standard; Mobile WiMAX only uses OFDMA PHY, which has been the main focus of standardisation since 2004.

WiMAX OFDMA uses three types of subcarriers, as shown in Figure 2.5 [WiMF06]:

- Data subcarriers for data transmission.
- Pilot subcarriers for estimation and synchronisation purposes.
- Null subcarriers for no transmission; used for guard bands and Direct Current (DC) carrier.

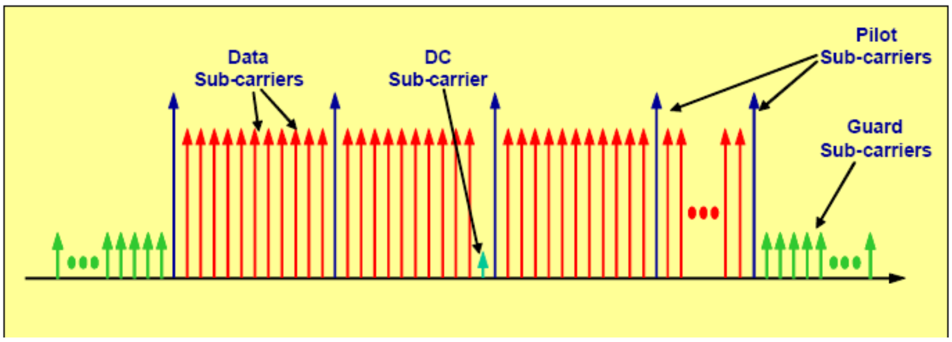

Figure 2.5. OFDMA Subcarrier Structure, (extracted from [WiMF06]).

Active subcarriers (data and pilot) are grouped into subsets of subcarriers called subchannels. WiMAX OFDMA supports subchannelisation in both DL and UL. The minimum frequency-time resource unit of subchannelisation is one slot, which is equal to 48 data tones (subcarriers).

The scalability concept is introduced by SOFDMA, which is capable to scale the Fast Fourier Transform (FTT) size to the channel bandwidth with the purpose to keep the carrier spacing constant across various channel bandwidths [WiMF06a]. FFT supported sizes are 2048, 1024, 512 and 128, but only 1024 and 512 are mandatory for Mobile WiMAX profiles, [Nuay07]. Typical parameters are presented in Table 2.2.

Table 2.2. SOFDMA parameters and subcarriers, (adapted from [WiMF06] and [SJTa09]).

Parameter	DL	UL	DL	UL	DL	UL
System Bandwidth [MHz]	5		10		20	
Sampling factor	28/25					
Sampling frequency [MHz]	5.6		11.2		22.4	
Sample time [ns]	178.6		89.3		44.6	
Null subcarriers (Guard and DC)	92	104	184	184	368	368
Pilot subcarriers	60	136	120	280	240	560
Data subcarriers ($N_{DL/ULactive\ DataSub}$)	360	272	720	560	1440	1120
Number of used subcarriers (Pilot plus Data)	420	408	840	840	1680	1680
Number of subcarriers	512		1024		2048	
Subchannels (N_{DL/UL_sub})	15	17	30	35	60	70
Subcarrier spacing [kHz]	10.93					
OFDMA symbol duration [μs]	102.8					
Guard Time [μs]	11.4					
Usefull symbol time [us]	91.4					
Number of OFDMA symbols in 5ms frame	48					

The 802.16 standards specify several channel coding schemes that includes convolutional coding, convolutional turbo coding, and Low density Parity Check (LDPC) coding combined with both Hybrid Automatic Repeat Request (HARQ) Chase and Incremental Redundancy (IR). The system profile requires only convolutional and convolutional turbo coding combined with asynchronous HARQ Chase. Table 2.3 shows the user data rates for the 5 MHz and 10 MHz bandwidth extracted from [WiMF06], and the values for 20 MHz based on [SJTa09] for the QPSK and Quadrature Amplitude Modulation (QAM) modulations.

Table 2.3. WiMAX IEEE 802.16e throughputs, (adapted from [WiMF06] and [SJTa09]).

Modulation	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	3/4	4.75	3.43	9.50	7.06	17.64	6.05
16-QAM	1/2	6.34	4.57	12.67	9.41	23.52	8.06
	3/4	9.50	6.85	19.01	14.11	35.28	12.10
64-QAM	1/2	9.50	6.85	19.01	14.11	35.28	12.10
	2/3	12.67	9.14	25.34	18.82	47.04	16.13
	3/4	14.26	10.28	28.51	21.17	52.92	18.14
	5/6	15.84	11.42	31.68	23.52	58.80	20.16

Beamforming is defined in both IEEE 802.16-2004 and 802.16e. For Mobile WiMAX profiles, this feature is mandatory only to the MS and optional for the BS. Mobile WiMAX provisions several mechanisms to enhance beamforming performance and operation. Extensive support for Multiple Input Multiple Output (MIMO) is provided by IEEE 802.16e. The spectral efficiency of Mobile WiMAX is achieved in great extent by beamforming and MIMO, making it superior in comparison to other existing systems. MIMO and beamforming have different complementary benefits, especially due to the choices made by the WiMAX Forum. Annex A provides more details about beamforming and MIMO.

2.3 Services and Applications

A summary of QoS classes (or scheduling services as defined on the 802.16 standard MAC Layer) are presented in Table 2.4. Originally only four were created, but later on 802.16e the Extended Real-time Polling Service (ertPS) was added.

Table 2.4. 802.16e-2005 QoS classes, (adapted from [Nuay07]).

Service	Abbrev	Definition
Unsolicited Grant Service	UGS	Real-time data streams comprising fixed-size data packets issued at periodic intervals
Extended Real-time Polling Service	ertPS	Real-time service flows that generate variable-sised data packets on a periodic basis
Real-time Polling Service	rtPS	Real-time data streams comprising variable-sised data packets that are issued at periodic intervals
Non-real-time Polling Service	nrtPS	Delay-tolerant data streams comprising variable-sised data packets for which a minimum data rate is required
Best Effort	BE	Data streams for which no minimum service level is required and therefore may be handled on a space-available basis

WiMAX supports all services that are available on any such type of wireless data network. A classification according to QoS of the most common services available today is in Table 2.5.

Table 2.5. WiMAX Services vs. QoS, (adapted from [Nuay07] and [JoAg07]).

Class description	Typical Applications	Real time?	QoS	Data rate
Streaming media	VoIP without silence suppression	Yes	UGS	5—128 kbps
VoIP, video conference	VoIP Video phone	Yes	ertPS	4—64 kbps 32—384 kbps
Streaming media	Music/speech MPEG Vídeo; Streaming	Yes	rtPS	5—128 kbps 20—384 kbps > 2 Mbps
Interactive gaming	Interactive gaming	Yes	ertPS	40—85 kbps
Media download	Bulk data, movie download	No	rtPS	> 1 Mbps
Information technology	Filet Transfer Protocol (FTP) Web Browsing	No	nrtPS	> 500 kbps > 500 kbps
	Instant messaging E-Mail (with attachments) P2P	No	BE	< 250 byte messages > 500 kbps > 500 kbps

QoS classes have a mandatory set of QoS parameters that are summarised in Table 2.6. Service Flow Identifier (SFID), Connection Identifier (CID), and traffic priority are mandatory for QoS classes. Other mandatory service flow parameters depend on the used class. The BS provides radio resources for the different SS taking the QoS parameters of the different service flows into count [Nuay07].

Table 2.6. Main parameters of a service flow, (extracted from [BeNu08]).

Parameter	Description
SFID	Primary reference of a service flow.
CID	Identifier of the connection.
QoS Class Name	Refers to a predefined BS service configuration.
Traffic Priority	Priority assigned to the service flow.
Maximum Sustained Traffic Rate	Peak information rate of the service flow.
Minimum Reserved Traffic Rate	Minimum reserved rate of the service flow.
Service Flow Scheduling Type	Scheduling type of the service flow (one of the five defined QoS classes).
Tolerated Jitter	Maximum delay variation of the connection.
Maximum Latency	Maximum latency between the reception of a packet and the forwarding of this packet.

As a comparison, in Table 2.7, one can see the split of QoS classes and the mandatory set of QoS parameters.

Table 2.7. Mandatory QoS parameters of the scheduling services defined in 802.16-2004, (extracted from [Nuay07]).

Scheduling service	Maximum sustained traffic rate	Minimum reserved traffic rate	Request/transmission policy	Tolerated jitter	Maximum latency	Traffic priority
UGS	✔	possible	✔	✔	✔	
rtPS	✔	✔	✔		✔	
nrtPS	✔	✔	✔			✔
BE	✔		✔			✔

The design of UGS leads to support real-time data streams of fixed-size data packets issued at periodic intervals, ergo VoIP without silence suppression. Using this service, the BS provides fixed-size data grants at periodic intervals, which eliminates the overhead and latency of SS requests. Based on the maximum sustained traffic rate of the service flow, the BS provides Data Grant Burst Information Elements (IEs) over the UL MAP (UL-MAP_IEs) to SS at periodic intervals. Taking the generic MAC header and grant management subheader into account, the grants size is sufficient to hold the fixed-length data associated with the service flow. Grant management subheader is used to pass status information from the SS to the BS on the state of the UGS service flow. When the Slip Indicator (SI) bit of grant management field is set, the BS may grant up to 1% additional bandwidth for clock rate mismatch compensation. Unless set the Poll-Me (PM) bit in the grant management subheader (of a packet on the UGS connection), the BS does not poll individual SSs that have an active UGS connection [Nuay07]. Figure 2.6 shows the UGS mechanism.

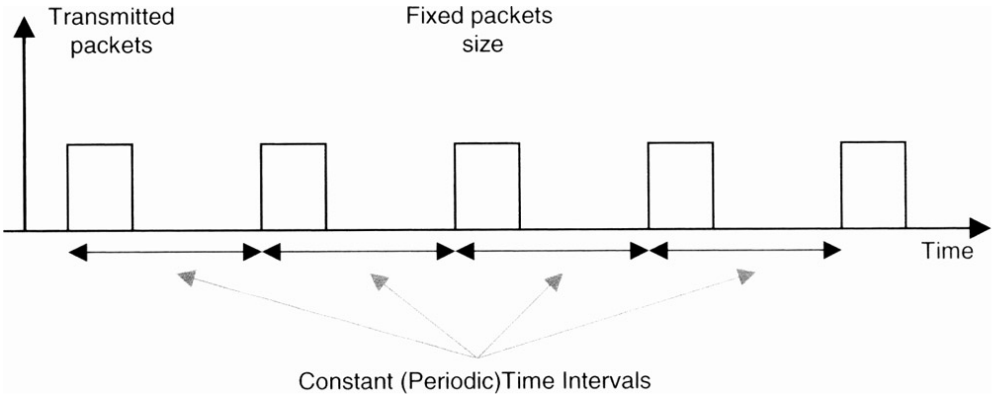

Figure 2.6. UGS scheduling service uplink grants allocation mechanism, (extracted from [Nuay07]).

The ertPS, added by the 802.16e amendment [Nuay07], is a scheduling mechanism that enhances the efficiency of both UGS and rtPS. BS provides unicast grants unsolicited, like in UGS, saving the latency of a bandwidth request. UGS allocations are fixed in size, whereas ertPS allocations are dynamic. ertPS is more suitable for real-time applications with variable rate with specific requirements for data rate and delay. As an example, one has VoIP without silence suppression.

The rtPS was designed to support real-time data streams, which may consist of variable-sised data packets issued at periodic intervals. As an example, one could consider Moving Pictures Experts Group (MPEG) video transmission for which the BS provides periodic unicast (UL) request opportunities that meet the flow's real-time needs, and allow the SS to specify the size of the desired grant. More request overheads than UGS are required for this service, but as an advantage it supports optimum real-time data transport efficiency over variable grant sizes [Nuay07]. Figure 2.7 illustrates the rtPS mechanism.

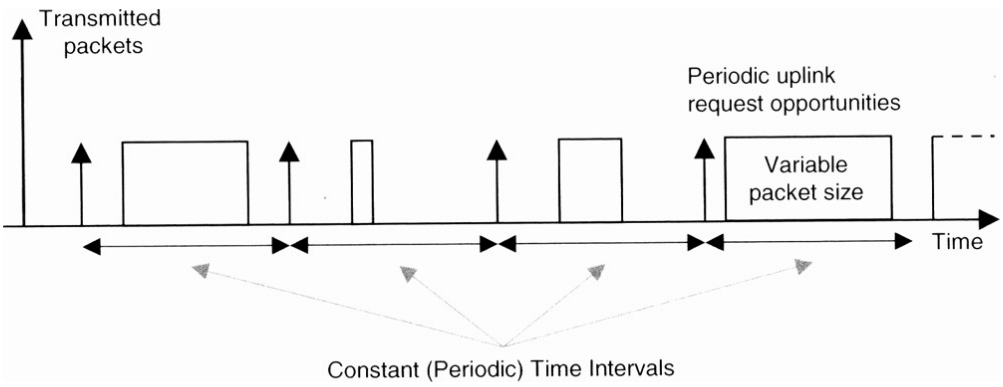

Figure 2.7. rtPS scheduling service uplink grants allocation and request mechanism, (extracted from [Nuay07]).

The nrtPS was designed to support delay-tolerant data streams with minimum data rate consisting of variable-size data packets. FTP transmission is suggested by the standard. For this service, the BS provides unicast UL request polls on a ‘regular’ basis, which guarantees that even during network congestion the service flow receives request opportunities. BS typically polls nrtPS CIDs on an interval of the order of 1s or less, according to the standard. SS is also allowed to use contention request opportunities, which means that SS may use unicast request and contention request opportunities [Nuay07]. Figure 2.8 illustrates the nrtPS mechanism.

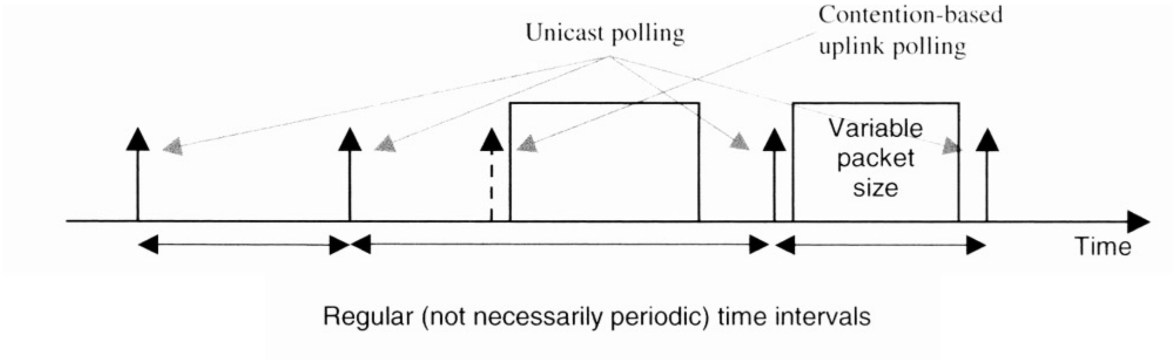

Figure 2.8. nrtPS scheduling service uplink grants allocation and request mechanism, (extracted from [Nuay07]).

The BE service was designed to support data streams for which no minimum service guarantees. SS may use contention request and unicast request opportunities when the BS sends any of them. For BE SSs, the BS does not have any unicast UL request polling obligation. Typically, when the network is in the congestion state, a long period can run without transmitting any BE packets [Nuay07]. Figure 2.9 illustrates the BE mechanism.

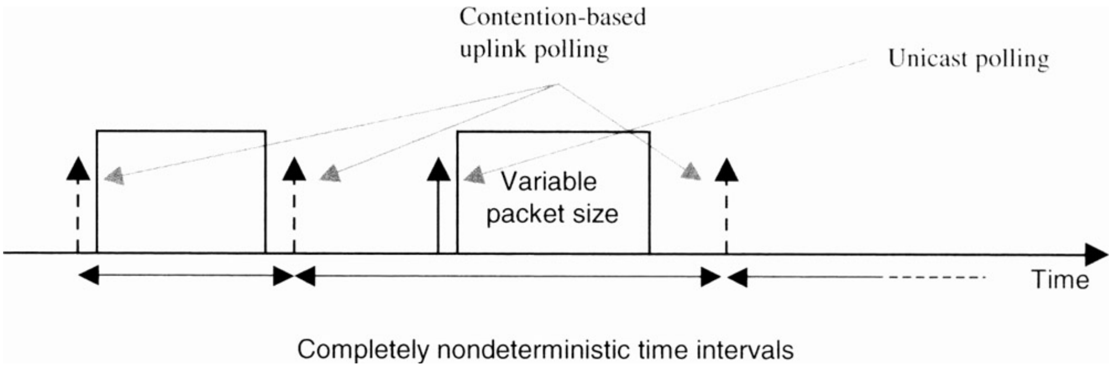

Figure 2.9. BE scheduling service uplink grants allocation and request mechanism, (extracted from [Nuay07]).

Link adaptation is used by the BS to deliver QoS. The Signal-to-Noise Ratio (SNR) value of a SS determines the Modulation and Coding Scheme (MCS) which depends on two values [BeNu08]:

- Minimum entry threshold: the minimum SNR required for using a more efficient MCS.
- Mandatory exit threshold: the SNR below which the usage of a more robust MCS is required.

Receiver SNR assumption values are presented in Table 2.8.

Table 2.8. Receiver SNR assumptions, (extracted from [BeNu08]).

Modulation	Coding	Receiver SNR [dB]
QPSK	1/2	6.0
	3/4	8.5
16-QAM	1/2	11.5
	3/4	15.0
64-QAM	2/3	19.0
	3/4	21.0

2.4 Performance Parameters

The most relevant performance parameters are usually referenced as Key Performance Indicators (KPIs), being intended to measure aspects of system performance, capacity, coverage, throughput and others. Many of the KPIs focus on the network performance that a subscriber will experience, being the most common KPI categories the followings:

- Throughput.
- Latency.
- Jitter.
- Packet Loss.

A detailed description of the most common KPIs is given in the following paragraphs:

- Sector Peak sustained throughput DL/UL ($R_{bSDL/UL}$) is the maximum achieved throughput over a sector, either DL or UL, and indicates the aggregated ability of the sector (or cell) to serve multiple users at the same time. Simultaneous throughput measurements of several users in one sector are added to get the cell throughput, and the maximum value is registered.

$$R_{bSDL[\text{Mbps}]} = \sum_{i=0}^{N_{user}} R_{bSDL_i[\text{Mbps}]} \quad (2.1)$$

$$R_{bSUL[\text{Mbps}]} = \sum_{i=0}^{N_{user}} R_{bSUL_i[\text{Mbps}]} \quad (2.2)$$

where:

  - N_{user}: number of users served in a sector.
  - R_{bSDL_i}: DL instantaneous throughput of user i.
  - R_{bSUL_i}: UL instantaneous throughput of user i.

- Single User DL/UL Peak sustained throughput ($R_{bUDL/UL}$) is the maximum achieved throughput that a subscriber can at any moment achieve in either DL or UL, being measured via User Datagram Protocol (UDP) traffic with static subscribers for specific traffic profiles. It is the maximum value achieved over a large number of sample measurements, usually more than 10.

$$R_{bUDL[\text{Mbps}]} = \max_i\left\{R_{bUDL_i[\text{Mbps}]}\right\} \quad (2.3)$$

$$R_{bUUL[\text{Mbps}]} = \max_i\left\{R_{bUUL_i[\text{Mbps}]}\right\} \quad (2.4)$$

where:

  - i: number of measurements.
  - R_{bUDL_i}: DL throughput obtained on measurement i.
  - R_{bUUL_i}: UL throughput obtained on measurement i.

- Bearer traffic Latency (τ_{BT}) is an expression of how much time it takes for a packet of data to get from one designated point to another and back. It is defined in terms of round trip, i.e., from the user equipment, through the radio access network, through the core to a test server usually residing in the core, and return over the same path, and averaged over a defined period of time. Packets are sent over a BE or ertPS WIMAX Service Flow.

$$\tau_{BT[s]} = \tau_{f[s]} + \tau_{p[s]} + \tau_{b[s]} \quad (2.5)$$

where:

- o τ_f is the latency due to the time required for the packet to physically travel the required distance from the user equipment to the test server.
- o τ_p is the latency incurred by the packet being processed by the test server.
- o τ_b is the latency due to the time required for the packet to physically travel the required distance from the test server back.

- Bearer Traffic Jitter (ΔT_{JBT}) is the average variation in the time between voice type UDP packets arriving from one designated point to another, caused by dynamic changes in the data packet's path. It is defined in terms of one way jitter, i.e., from the user equipment, through the radio access network, through the core and transport components, to a test server residing in the VoIP core. Packets are sent over eRTPS WIMAX Service Flow.

$$\Delta T_{JBT[s]} = \overline{\overline{\Delta T_{f[s]}} + \overline{\Delta T_{p[s]}}} \quad (2.6)$$

where:

- o $\overline{\Delta T_f}$ is the average variation in the time required for the packet to physically travel the distance from the user equipment to the test server.
- o $\overline{\Delta T_p}$ is the average variation in the time required by the test server to process the packet.

- Bearer Traffic Percentage of Packet loss (P_{PLBT}) is the average percentage of voice type UDP packets not arriving from one designated point to another. In this case, one defines it in terms of a percentage of packet loss, i.e., from the CPE input, through the radio access network, through the core and transport components to a test server residing in the core at same point as the SBC. Packets are sent over a BE or an eRTPS WIMAX Service Flow.

$$P_{PLBT[\%]} = \overline{\left[1 - \frac{N_{PSent[packets]} - N_{PArrived[packets]}}{N_{PSent[packets]}}\right]} \times 100 \quad (2.7)$$

where:

- o N_{PSent}: is the total number packets sent.
- o $N_{PArrived}$. is the total number of packets arrived.

- Initial Network Access Latency (τ_{NAi}) is defined as the time taken for a CPE to access the network, measured from the start of scanning to the default flow setup.

$$\tau_{NAi[s]} = t_{start[s]} - t_{stop[s]} \quad (2.8)$$

where:

- o t_{start}: is the time of scanning start.
- o t_{stop}. is the time of scanning stop.

- Coverage Measurements are related to the measurement of both Received Signal Strength Indication (RSSI) and Carrier to Interference and Noise Ratio (CINR):
    - RSSI Value: the threshold for outdoor coverage based on the link budget for the base station. An indoor allowance of 15 dB can be considered, i.e. the indoor RSSI will be 15 dB less than the measured outdoor one.
    - CINR Value: In this case, the indoor allowance cannot be added to this value, as both the carrier and the possible interferer signals might be decreased due to the penetration losses. This means that the measured CINR measured outdoor mimics the indoor one.
- VoIP Quality (Q_{VoIP}) is assessed by the average Mean Opinion Score (MOS) for a simulated voice call. For test purposes special VoIP test calls will be initiated from a VoIP performance tool to a server in the core. A tool can produce the corresponding reports to get the MOS score of the test calls.

$$Q_{VoIP[MOS]} = \overline{MOS} \quad (2.12)$$

where:

- MOS: is the Mean Opinion Score.

In order to test these KPIs, several possible scenarios are available. In Table 2.9, a summary of possible scenarios and values for the KPIs are presented, [WiMF08a], [THAI07] and [AJMCB09].

Table 2.9. Summary of the most common KPI with the test scenario and reference values.

KPI	Threshold	Assumptions
Sector Peak sustained throughput DL (R_{bSDL}) [Mbps]	7.7	UDP, MAC Layer @ 5MHz 64-QAM5/6; 75/25, BE
	15.5	UDP, MAC Layer @ 10MHz, 64-QAM5/6; 75/25, BE
Sector Peak sustained throughput UL (R_{bSUL}) [Mbps]	1.28	UDP, MAC Layer @ 5MHz 16-QAM3/4; 75/25, BE
	2.4	UDP, MAC Layer @ 10MHz 16-QAM3/4; 75/25, BE
Single User DL Peak sustained throughput (R_{bUDL}) [Mbps]	6.0	UDP, MAC Layer @ 5MHz 64-QAM5/6; 75/25, BE
	15.3	UDP, MAC Layer @ 10MHz, 64-QAM5/6; 75/25, BE
Single User UL Peak sustained throughput (R_{bUUL}) [Mbps]	1.26	UDP, MAC Layer @ 5MHz 16-QAM3/4; 75/25, BE
	1.9	UDP, MAC Layer @ 10MHz 16-QAM3/4; 75/25, BE
Bearer traffic Latency (L_{BT}) [ms]	120 90	Roundtrip, BE Roundtrip, ertPS
Bearer traffic jitter (ΔL_{JBT}) [ms]	40	Jitter, UDP– ertPS
Bearer Traffic Percentage of Packet loss (PL_{BT}) [%]	1 2	Packet Loss, UDP – ertPS Packet Loss, UDP - BE
Network Access Latency (initial) (L_{NAi}) [s]	44	CPE Indoor
Received Signal Strength Indication (RSSI) [dBm]	-75	Mimics Indoor RSSI of -90dBm
Carrier to Interference and Noise Ratio (CINR) [dB]	12	Corresponds to the indoor CINR, achieved 95% of the time
VoIP Quality (Q_{VoIP}) [MOS]	3.8	G.729A, CINR ≥7dB, ertPS

2.5 State of the Art

In this section, the state of art concerning both the study of this thesis and also the worldwide WiMAX deployments is presented.

For WiMAX capacity and bandwidth studies, only a few papers can be found, and although they refer the 20 MHz channel possibility none provides a study with it.

The WiMAX system is extensively described in [Nuay07], where one can find a large number of details that makes easier the grasp of other WiMAX documents. The main procedures of WiMAX are covered, including: topologies, protocol layers, MAC layer, MAC frames, WiMAX multiple access, the physical layer, QoS Management, Radio Resource Management, Bandwidth allocation, Network Architecture, Mobility and Security. It highlights the changes of the standards, needed for Mobile WiMAX and includes a technical comparison of WiMAX vs. Wi-Fi and cellular 3G technologies.

More recently in [Ahmad11], one finds a description of the underlying functional components of radio access networks required for system operation and design principles. According to the author, this is the most up-to-date technical reference book for the design of 4G cellular systems; the radio access and core networks of IEEE 802.16m and 3GPP LTE-Advanced are described with details of the protocol layers and functional elements. This book provides a comprehensive description of the operation of the end-to-end IEEE 802.16m system; and of the 3GPP LTE Release 9 and 3GPP LTE-Advanced Release 10 systems; that allows a better understanding of the similarities and differences between both. From what is presented, one can conclude that the 3GPP LTE and mobile WiMAX systems are technically equivalent and similar in performance as far as user experience is concerned.

The most relevant paper related to capacity and channel bandwidth estimation is presented in [SJTa09], where a simple analytical method for Mobile WiMAX networks is presented. Especially, it takes into account the various overheads that have a relevant impact on the capacity and usually are not considered on simple studies. The simple model presented has the advantage that one can easily see the effect of each decision and sensitivity to various parameters. The model is illustrated by estimating the capacity over a 10 MHz channel for three sample applications: Mobile TV, VoIP.

A comparative study on capacity between WiMAX, 3G and LTE is presented on [Intel09], where the spectral efficiency is presented as a key element of comparison and factor of choice for cost effectiveness wireless network capacity deployment.

A performance evaluation of the basic minimal configuration based on the WiMAX Forum Release-1 system profiles is presented in [WiMF06]. It shows that Mobile WiMAX can provide tens of megabits per second of capacity per channel. Again, this study does not go beyond a 10 MHz channel. A brief discussion on the advanced features, such as AAS, which can significantly improve the performance, is presented. In this study, the essential attributes facilitated by the high data throughput are analysed, such as efficient data multiplexing and low data latency; they enable broadband data services including data, streaming video and VoIP with high QoS.

The AAS suitability for WiMAX is analysed in [ZhaLi09], where the mobile WiMAX system is evaluated regarding downlink capacity and coverage. For this array antenna, the link budget model is also analysed. From the results presented, one can assume that the capacity and coverage of mobile WiMAX improve when using the AAS.

The close relation between the capacity and the factors such as user throughput and radio channel conditions of the Mobile WiMAX system is studied on [AshTa10], where methodologies to calculate actual throughput are presented. The algorithm to determine the maximum number of subscribers that each specific BS may support is described step-by-step. An analytical study using COST-231 Hata Model for the propagation channel of WiMAX is also presented.

The coverage and performance characteristics of the IEEE 802.16 standard are studied on [MVC11], where a detailed analysis is presented. A study using a software simulation tool with suitable propagation models like ITU-R 525/526, or COST231-HATA is performed in urban and suburban environments. The higher data rates offered to the users with the QAM modulation is possible at 52% of the total coverage of the area that was estimated to be 67%.

In [MCG08], the comparison of six different reuse patterns for WiMAX network is presented. It shows that without beamforming an acceptable value of outage probability is only achieved by a reuse type of 3x3x3. If using beamforming, the rest of the reuse patterns show acceptable results, but if considering a reuse of 1 with loaded systems (meaning all available subchannels in use) this will result in significant system outage. The method of PUSC reduces the outage to acceptable levels and still maintains the highest level of average throughput. It also shows that if 80% of total subchannels is used then the reuse type 1x3x1 will provide good results, for throughput and radio quality parameters. If using beamforming over loaded systems, it concludes that the reuse type 3x3x1 provides the best performance.

The next-generation Mobile WiMAX capabilities are presented in [Intel09], where wireless data rates in over 1 Gbps are possible which enables the support of a wide range of IP-based services and applications demanding high-quality and high-capacity and still maintaining the required existing Mobile WiMAX systems backward compatibility. The potential of the next generation Mobile WiMAX for successful deployment after 2011 is also presented.

The TCP over WiMAX is discussed in [OmSa11]; where the problem of this today's dominant transport protocol not meeting the demand for fast transfers of large volume is analysed. This is because the current TCP favors reliability over timeliness and does not fully utilize the network capacity due to limitations of its conservative congestion control algorithm. More aggressive congestion control algorithms alternatives have been proposed to improve the connection's throughput. Three TCP variants are studied in this paper, namely Tahoe, New Reno and Vegas; they are compared using throughput, round-trip time (RTT) and packet loss ratio.

The VoIP capacity estimation is presented in [EZEE11], where a simple analytical method for VoIP capacity estimation in IEEE 802.16e mobile WiMAX networks taking into account the various overheads that impact the capacity is presented. It is shown that proper use of overhead reducing mechanisms and proper scheduling creates the possibility of an order of magnitude difference in performance. The maximum number of voice sessions using multiple VoIP codecs is also presented.

In [FSHo09], the relevancy of WiMAX for Municipal Network is studied, from where the main information one retrieves is that the implementers of wireless municipal network infrastructures are cautious due to cost reasons. However, they consider that a WiMAX based backbone for Wi-Fi mesh networks to be an attractive option, and when mobility is of key importance then Mobile WiMAX to be definitely a proficient solution.

A study on the WiMAX suitability for the Enterprise Mobile Network is presented on [YML11], were the short falls of WiFi as an enterprise wireless technology are addressed. A comparison between WiMAX and LTE is presented in regards of the capabilities as candidates for the next generation mobile technologies for the enterprise; the high capacity, wide coverage range, and strong QoS mechanisms are among the arguments in favor of the usage of WiMAX and LTE as the next generation mobile enterprise networks. Overall architectures that illustrate how WiMAX and LTE can fit in an enterprise network environment are also present. The analyses of the differences between WiMAX and LTE from a perspective of enterprise network requirements are also described. The key difference in favor of WiMAX is the easiness of integration with the enterprise network security mechanisms in use today.

Details on the status of WiMAX worldwide deployments are presented in Annex B. The main information to take into account is, WiMAX Forum currently tracks 583 WiMAX deployments in 150 Countries, the number of people covered by WiMAX is estimated by WiMAX Forum to reach up to 1 Billion in 2011 [WiMX11]. Also to have a better conception of the state of WiMAX generalisation in the technology marked one can refer to the WiMAX Forum numbers for Certified Products and vendors which reaches up to 260, from were 62 are Base Stations and 198 are Subscriber/Mobile Stations products. On the Subscriber/Mobile Station the Intel laptop [Intel11] is of most importance since in parallel to the commonly available Wi-Fi support, the microprocessors giant, also makes WiMAX available on their chipset.

Chapter 3

Models and Algorithms

This chapter describes the theoretical model that is used to calculate the maximum physical channel throughput, followed by the discussion on the impact of the application workload required to estimate the capacity and coverage. This chapter concludes with the database description from where the experimental results values are retrieved.

3.1 Theoretical Model

One starts by defining the model that allows estimating the maximum physical throughput.

Unlike many cellular technologies with fixed width channels, WiMAX is flexible enough to allow a variety of channel bandwidths from 1.25 to 20 MHz [SJTa09]. In this thesis, one considers the values of allowed bandwidth and frame duration as follows:

- 5, 10 and 20 MHz bandwidth.
- Mobile WiMAX TDD system.
- 5 ms frame duration.
- PUSC subchannelisation mode.
- DL:UL frame ratio of 3:1.

Although these are the default values recommended by the Mobile WiMAX forum system evaluation methodology, they are among the most common values used in practice.

According to [WiMF06] and [SJTa09], the channel is divided into equally spaced subcarriers grouped for distinct usages: data transmission; pilot subcarriers for monitoring the channel quality; guard subcarriers for providing safety zone between adjacent channels; or a DC subcarrier as a frequency reference. Several MCSs are available to modulate data and pilot subcarriers, QPSK and QAM being among the available ones. Forward Error Correction (FEC) bits are also added, as coding is also applied. When the reference to “64-QAM 1/3” is made, it assumes 64 combinations (8 bit per symbol) modulated using QAM symbols, only 1/3 of the data bits being real data, since the error corrections bits take ⅔ of the data [SJTa09].

As shown in Figure 2.4, the Transmit to receive Transition Gap (TTG) and Receive to Transmit Gap (RTG) separated the DL and UL subframes in the frame structure. Also in Figure 2.4, the DL subframe starts with one symbol-column of preamble, followed by a 24-bit FCH, which is transmitted with QPSK ½ (the most robust MCS) for high reliability and repeated 4 times. DL-MAP is next, and specifies the burst profile for all DL user bursts. UL-MAP follows, where the burst profiles for all UL bursts are specified, as FCH QPSK ½ MCS is also used to transmit both DL-MAP and UL-MAP [SJTa09].

OFDMA is being used, hence, the user is allocated only a subset of the subcarriers grouped in a subchannel, and only for a specified number of symbols. PUSC is the most common way to group subcarriers in subchannels, but there are others, not relevant to this thesis [SJTa09]. A subchannel is formed by randomly selected subcarriers from all available ones; therefore, the subcarriers may not be adjacent within a subchannel. Other than the preamble, all other transmissions use slots. In PUSC, the number of slots allocated to a user depends on the link: DL or UL. The UL slot structure is shown in Figure 3.1, [SJTa09]. The slot is an aggregation of 6 tiles, each tile containing 4 subcarriers over 3 symbol times, so the total for a slot is 24 subcarriers over 3 symbol times. This also results on combinations of 12 subcarrier-symbols in a tile. Out of the 12 subcarrier-symbols, 4 are used for pilot and 8 for data (ratio of 2 of data to 1 of pilot). The group of 24 subcarriers in each symbol time forms a subchannel. Also to be noted that, since there are 8 data subcarrier-symbols in each of the 6 tiles, then the UL Number of Subcarrier-Symbols per slot (N_{SSslot}) is always 48. As an example, at 10 MHz removing from the total of 1024 the null subcarriers (184), the available for pilot (280) and data (560) are 840 so up to 35 UL subchannels can be formed [SJTa09]. The number of UL channels for 5 and 20 MHz can be found in Table 2.2

As shown in Figure 3.2, the DL slot formation is different from the UL one. In DL, each slot is an aggregation of 2 clusters, where each cluster consists of 14 subcarriers over 2 symbol times. This also results on combinations of 28 subcarrier-symbols in a cluster. Out of the 28 subcarrier-symbols, 4 are used for pilot and 24 for data (ratio of 6 of data to 1 of pilot). The set of 28 subcarriers in each symbol time forms a subchannel. Similar to UL, there are 24 data subcarrier-symbols in each of the 2 clusters, thus the DL N_{SSslot} is also 48. As an example, at 10 MHz from the 840 available for pilot plus data subcarriers, 30 DL subchannels can be formed [SJTa09]. The number of DL channels for 5 and 20 MHz can be found in Table 2.2

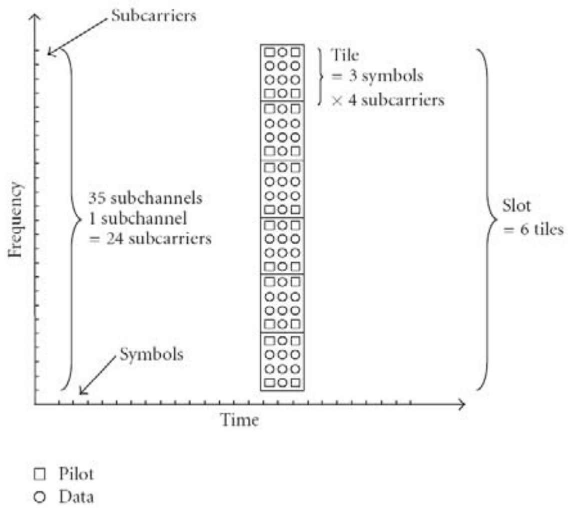

Figure 3.1. UL PUSC, (extracted from [SJTa09]).

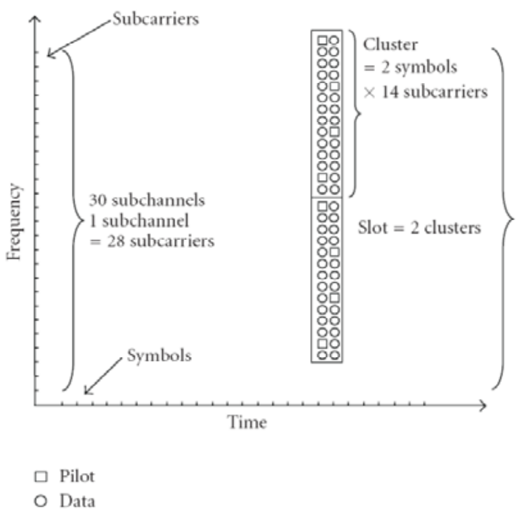

Figure 3.2. DL PUSC, (extracted from [SJTa09]).

In Table 2.2, Table 3.1 and Table 3.2, key parameters and the number of data; pilot and guard subcarriers for various channel bandwidths are summarised. From Table 2.2, a relation to be taken notice is that the product of subcarrier spacing and FFT size is always equal to the product of channel bandwidth and sampling factor. For example, for a 20MHz channel one has 10.93kHz × 2048 = 20MHz × 28/25. For the bandwidths under consideration, the OFDMA symbol time is always 102.8µs, and so 48.6 symbols can be fit into a 5ms frame. TTG and RTG occupy 1.6 symbols, thus leaving 47 symbols for frame usage. A total of *n* symbols are used for DL leaving 47 − *n* for UL. Several ways are available to divide the available symbols per UL and DL frames. The DL-to-UL-subframe ratio may be varied from 3:1 to 1:1, in order to support different traffic profiles. For the 3:1 ratio (highest DL bandwidth) the DL subframe occupies 35 symbols and the UL one uses 12 symbols, and since the DL slot requires 2 symbols period, there are 17 slots in the DL subframe (Integer of 35 divided by 2); similarly the UL slot requires 3 symbols, so there are 4 slots in the UL subframe [SJTa09].

The total of Slots per Subframe for the total of subchannels (N_{DL/UL_slots}) can be derived from (3.1) being shown in Table 3.1.

$$N_{DL/UL\_slots[number\ of\ slots]} = N_{DL/UL\_slots\_sub[slots/Subchannel]} \times N_{DL/UL\_sub[subchannels]} \quad (3.1)$$

where:

- N_{DL/UL_slots_sub}: number of slots per subchannel in one subframe from Table 3.1.
- N_{DL/UL_sub}: number of subchannels from Table 2.2.

As an example, the DL subframe for the total of 30 subchannels contains 510 slots (17 slots per DL frame in one channel × 30 subchannels) and the total UL subframe contains 140 slots (4 slots per UL frame in one channel × 35 subchannels).

Table 3.1 Symbol and Slot for 3:1 fame ratio.

Parameter	DL	UL	DL	UL	DL	UL
Bandwidth [MHz]	5		10		20	
Symbols per frame (excluding the 1.6 for TTG+RTG)	35	12	35	12	35	12
Slots per subchannel in one subframe (N_{DL/UL_slots_sub})	17	4	17	4	17	4
Total Slots per Subframe (N_{DL/UL_slots})	255	68	510	140	1020	280

The number of bytes per slot for the relevant MCS values is shown at Table 3.2. The number of bytes per slot for each MCS ($N_{bMCSUL/DL}$) can be calculated as follows.

$$N_{bMCSUL/DL[byte/slot]} = \frac{N_{bps[bit/symbol]}}{8} \times R_{Codding} \times N_{SSslot[\text{symbols/slot}]} \quad (3.2)$$

where:

- N_{bps}: number bits per symbol (from Table 3.2).
- $R_{Codding}$: Coding Rate (from Table 3.2).
- N_{SSslot}: subcarrier-symbols per slot (always 48).

The maximum allowed MCS modulation for UL is 16-QAM 2/3 [SJTa09], while for the DL up to 64-QAM 5/6 is available.

Table 3.2. MCS configurations, (extracted from [SJTa09]).

MCS	Bits per symbol (N_{bps})	Coding Rate ($R_{Codding}$)	Bytes per slot DL (N_{bMCSDL})	Bytes per slot UL (N_{bMCSDL})
QPSK 1/8	2	1/8	1.5	
QPSK 1/4	2	1/4	3	
QPSK 1/2	2	1/2	6	
QPSK 3/4	2	3/4	9	
16-QAM 1/2	4	1/2	12	
16-QAM 2/3	4	2/3	16	
16-QAM 3/4	4	3/4	18	
64-QAM 1/2	6	1/2	18	
64-QAM 2/3	6	2/3	24	
64-QAM 3/4	6	3/4	27	N/A
64-QAM 5/6	6	5/6	30	N/A

The calculation of the number of DL and UL slots is shown in Table 3.3, based on [SJTa09].

Table 3.3. WiMAX system configurations, (adapted from [SJTa09]).

Parameters	DL	UL	DL	UL	DL	UL
Bandwidth [MHz]	5		10		20	
Number of DL and UL symbols per frame (excluding the 1.6 for TTG+RTG and preamble) ($N_{DL/ULFrameSize}$)	34	12	34	12	34	12
Ranging, CQI, and ACK (symbols columns)	N/A	3	N/A	3	N/A	3
Number of symbol columns per Cluster/Tile	2	3	2	3	2	3
Number of subcarriers per Symbol column	14	4	14	4	14	4
Symbols × Subcarriers per Cluster/Tile	28	12	28	12	28	12
Symbols × Data Subcarriers per Cluster/Tile	24	8	24	8	24	8
Number of pilot subcarriers per Cluster/Tile	4	4	4	4	4	4
Number of Clusters/number Tiles per Slot	2	6	2	6	2	6
Subcarriers × Symbols per Slot	56	72	56	72	56	72
Data Subcarriers × Symbols per Slot	48	48	48	48	48	48
Total of Slots per subframe (N_{DL/UL_slots})	255	68	510	140	1020	280
Data Subcarriers × Symbols per Subframe	12240	3264	24480	6720	48960	13440

In order to estimate the maximum physical throughput, one splits the calculations in DL and UL. Any enhancement techniques, like MIMO or others are not considered here. The frame rate (R_{Frame}) is calculated as follows, since one is only considering 5 ms for the frame duration this is then fixed to 200 frames per second (fps).

$$R_{Frame\,[fps]} = \frac{1}{F_{Duration[ms]}} \tag{3.3}$$

where:

- $F_{Duration} = 5$ ms, is the frame duration.

To estimate the maximum physical DL throughput (R_{bDLMAX}) the following calculation is performed:

$$R_{bDLMAX[Mbps]} = \frac{N_{DLactive\ DataSub[subcarriers]} \times N_{DLFrameSize[symbols/frame]} \times R_{Frame[fps]} \times N_{bit/symbol[bit/symbol]} \times R_{Codding}}{2^{20}} \quad (3.4)$$

where:

- $N_{DLactive\ DataSub}$: is the number of DL active Data Subcarriers from Table 2.2.
- $N_{DLFrameSize}$: is the number of DL symbols per frame from Table 3.3.
- $N_{bit/symbol}$: is the number bits per symbols from Table 3.2.
- $R_{Codding}$. is the Coding Rate from Table 3.2.

The maximum physical UL throughput (R_{bULMAX}) is calculated by:

$$R_{bULMAX[Mbps]} = \frac{N_{ULactive\ DataSub[subcarriers]} \times N_{ULFrameSize[symbols/frame]} \times R_{Frame[fps]} \times N_{bit/symbol[bit/symbol]} \times R_{Codding}}{2^{20}} \quad (3.5)$$

where:

- $N_{ULactive\ DataSub}$: is the number of UL active Data Subcarriers from Table 2.2.
- $N_{ULFrameSize}$: is the number of UL symbols per frame from Table 3.3.

In Annex C the maximum physical throughput calculation process flow chart is available.

3.2 Applications Workload

In order to estimate capacity, assumptions on workload must be taken. The challenge is how to take the time of day, application mix and user types into consideration. One considers the simple analytical model from [SJTa09]. The application mix consists of MPEG 2 video streaming, VoIP and web browsing – Hypertext Transfer Protocol (HTTP), FTP and Email. Apart from the application characterisation presented in Table 2.5, some more considerations need to be taken:

- VoIP consists of very small packets generated periodically with equal UL and DL data rates. The vocoder determines both packet size and period. One considers G.729A, which produces a data rate of 8 kbps with 20 bytes voice packets with 10 ms interval.
- The size and quality of display condition the highly asymmetric MPEG 2 video streaming, where almost all traffic flows in DL. For this thesis, a small screen that produces a 984 bytes packet every 30 ms is considered, which results in a 350.4 kbps average data rate.
- Web browsing model is based on the 3GPP HTTP characterisation.
- FTP is Transmission Control Protocol (TCP) based and is built on a client-server architecture that uses separate control and data connections between the client and server.
- Email messages are transferred using TCP based protocols using standard email protocols.

Overheads directly impact on the number of supported users, according to the study presented at [SJTa09], and some of the overheads also depend on the number of users. A summary of the main parameters of the three applications studied include the type of transport layer used: Real Time Transport (RTP) or TCP, and the two compression mechanisms used to reduce these upper layer overheads: Payload Header Suppression (PHS) and Robust Header Compression (ROHC), is presented in Table 3.4. While PHS is a WiMAX feature, the ROHC is specified by the IETF.

The upper layer protocol overhead is directly related to the type of transport layer. For the application under analysis, one considers: RTP (with 12 bytes overhead) over UDP (with 8 bytes overhead) over IP (with 20 bytes overhead), which relates to a total of 40 bytes overhead, or TCP (with 20 bytes overhead) over IP (with 20 bytes overhead), which also relates to a total of 40 bytes overhead. PHS works by allowing the sender to hold back fixed portions of the headers and with this the 40 byte header overhead can be reduce to 3 bytes. Applying ROHC reduces the higher layer overhead between 1 and 3 bytes. The analysis considers that ROHC-RTP is used with packet type 0 and R-0 mode; this assumes that the decompressor knows RTP sequence numbers functions resulting on 1 byte higher layer overhead. For VoIP which has small packet size workload, a significant impact on the capacity is achieved by header suppression and compression. In order to improve capacity by reducing unnecessary information, VoIP uses silence suppression. If silence suppression is implemented VoIP capacity can increase by releasing the resources during the time the user is inactive (silent). One considers this option in this analysis, thus resulting in the double of users (0.5 activity factor). The data rate is obviously limited by the network and is directly dependent to the MCS. The application characterisation one uses in this study is available in Table 3.4.

Table 3.4. Application characteristics, (adapted from [SJTa09], [Kill01], [Agui03] and [NetIn11]).

Parameters	**MPEG 2**	**VoIP**	**HTTP**	**FTP**		**Email**	
				Download	**Upload**	**Receive**	**Send**
Types of transport layer	RTP	RTP	TCP	TCP		TCP	
Average packet size [bytes]	983.5	20	1200.2	499.29		495.03	
Data rate w/o header [kbps]	350 (DL only)	8	14.5 (DL only)	500		500	
DL/UL ratio	>>1	≈1	>>1	>>1	<<1	>>1	<<1
Silence suppression	N/A	Yes	N/A	N/A		N/A	
Fraction of time user is active	N/A	0.5	N/A	N/A		N/A	
ROHC packet type	1	1	TCP	TCP		TCP	
Overhead with ROHC [bytes]	1	1	8	8		8	
Payload Header Suppression	No	No	No	No		No	
MAC SDU size with header [bytes]	984.5	21	1208.2	507.29		503.03	
Data rate after headers ($R_{with\ Header}$) [kbps]	350.4	8	14.6	507.9		508.0	
Bytes/frame per user (DL)	219	5.2	9.1	317.4	0.1	317.5	0.1
Bytes/frame per user (UL)	0.1	5.2	0.1	0.1	317.4	0.1	317.5

In order to calculate the workload data rate ($R_{with\ Header}$) taking only the ROHC into consideration, the following expression can be used.

$$R_{with\ Header[\text{kbps}]} = R_{[\text{kbps}]} \times \frac{M_{SDU[bits]} + H_{[bit]}}{M_{SDU[bit]}} \quad (3.6)$$

where:

- R: application data rate.
- M_{SDU}: MAC Service Data Unit (SDU) size.
- H: header size.

The data flow path and origin of the headers for each application can be seen in Figure 3.3.

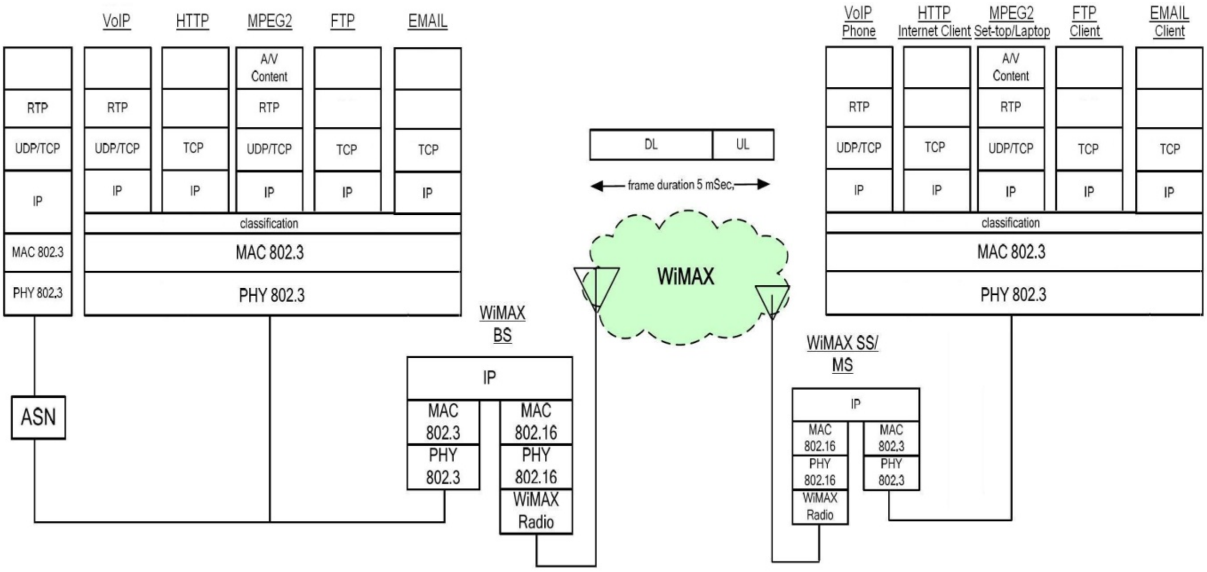

Figure 3.3. Services over WiMAX - System Model, (adapted from [OzRe08]).

The number of bytes per subframe per user ($D_{DL/UL\_user[byte]}$) can be obtained from:

$$D_{DL/UL\_user[byte/user]} = \frac{R_{with\ Header[kbps]}}{8192} \times F_{Duration[ms]} \times 1000 \quad (3.7)$$

In what follows a brief analysis of DL and UL overheads, and also MAC are presented. The overhead of PHY DL is composed of: preamble, FCH, DL-MAP and UL-MAP as presented in Figure 2.4. WiMAX Forum recommends compressed MAP for the MAP entities, both UL-MAP and DL-MAP fixes and variable parts are repeated 4 times and only use QPSK ½ MCS, thus taking up to 16 slots each per burst, since the repetition consists of repeating slots (not just the information bytes).

The UL subframe, as shown in Figure 2.4, also has fixed and variable parts that contribute to the PHY UL overhead. In the fixed part, one has Channel Quality Indication (CQI), Acknowledgements (ACK), and ranging and contention, all defined by the network administrator. The number of slots available for user data is inverse to the quantity of fixed portions allocated as expected. For the purpose of this thesis, one considers the fixed region to be contained on three OFDM symbol columns: one OFDM symbol for UL preamble at the beginning of each UL burst, another for short preamble and two for long preamble.

The MAC Protocol Data Unit (PDU) header has at least 6- bytes, and on the payload a number of optional subheaders exist; data and an optional 4- byte Cyclic Redundancy Check (CRC) as presented on Figure 3.4. Bandwidth request MAC PDUs with 6 bytes in length can also be found standalone or as alternative as a 2-byte subheader piggybacked on data PDUs.

UL preamble	MAC Bandwidth Request Header	Other Subheaders	Data	CRC (optional)

Figure 3.4. Burst preamble and MAC frame (MPDU), (extracted from [SJTa09]).

3.3 Capacity Estimation

To estimate the user capacity one starts by determining the number of users on an ideal channel (error-free), then, extending the study for channel conditions closer to reality, where the channel quality vary, one determines the closer to reality user number.

Users are allocated by a scheduler. In order to minimise the number of bursts, an optimised scheduler aggregates each user payloads. But the aggregation of payloads and minimisation of bursts has a limit. For instance, a burst may have to be scheduled even if the payload size is small to meet the delay requirements, to help reduce the number of bursts the payload for multiple users may be aggregated in one DL burst; this applies only to the downlink bursts as allowed by the IEEE 802.16e. The aggregation of the payload can only occur within the frame size is another consideration. The used scheduler is an example extracted from [SJTa09]. To calculate the number of users (N_{users}) for each individual MCS the following expressions are applied.

For UL/DL virtually symmetrical workloads where the data rates for DL/UL≈1 like VoIP one uses:

$$N_{users} = min \quad (N_{DL\_users}, N_{UL\_users}) \tag{3.8}$$

$$N_{DL/UL\_users} = \left\lceil \frac{N_{DL/UL\_Slots[slot]} \times N_{bMCSUL/DL[byte/slot]}}{D_{DL/UL\_user[byte/user]}} \times \frac{T_{deadline[ms]}}{F_{Duration[ms]}} \right\rceil \tag{3.9}$$

where:

- $N_{bMCSUL/DL}$ number of bytes per slot for the *i*th MCS from Table 3.2
- N_{DL/UL_slots} : total Slots per Subframe from Table 3.1
- $T_{deadline}$: deadline for the scheduler from Table 4.5

For the calculation of number of users for VoIP, a 0.5 activity factor needs to be added, when silence suppression is considered, thus, doubling VoIP capacity.

For those workloads strongly DL data rate asymmetrical, where DL/UL>>1, the user limitation comes from the DL resource capacity; this applies to workloads such as MPEG 2 Video streaming, HTTP web browsing; FTP download and Email download. To calculate the N_{users} for each individual MCS the following expression is applied.

$$N_{users} = \left\lfloor \frac{N_{DL\_Slots[slot]} \times N_{bMCSDL[byte/slot]}}{D_{DL\_user[byte/user]}} \times \frac{T_{deadline[ms]}}{F_{Duration[ms]}} \right\rfloor \quad (3.10)$$

Those workloads strongly UL data rate asymmetrical, where DL/UL<<1, the user limitation comes from the UL resource capacity; this applies to workloads such as FTP upload and Email upload. To calculate the N_{users} for each individual MCS the following expression is applied.

$$N_{users} = \left\lfloor \frac{N_{UL\_Slots[slot]} \times N_{bMCSUL[byte/slot]}}{D_{UL\_user[byte/user]}} \times \frac{T_{deadline[ms]}}{F_{Duration[ms]}} \right\rfloor \quad (3.11)$$

To refine the above user estimation and get a unique value for the number of users per channel, simulating like in real channel conditions the usage of a variety of MCS by different users, the average bytes per slot ($\overline{N_{bMCSUL/DL}}$) needs to be found; this is a function of the mix of MCS which is calculated by:

$$\overline{N_{bMCSUL/DL[byte/slot]}} = \sum_i P_{\%MCS_i[\%]} \times N_{bMCS_iUL/DL[byte/slot]} \quad (3.12)$$

where:

- $P_{\%MCS_i}$: percentage of users with the *i*th MCS. This is dependent on the scenario considered.
- $N_{bMCS_iUL/DL}$ number of bytes per slot for the *i*th MCS from Table 3.2

In Annex C the maximum user calculation process flow chart is available.

3.4 Coverage Estimation

The coverage area (A) for each cell (corresponding to one channel) is calculated by the "Hexagons" grid [Corr98]:

$$A[km^2] = \frac{\sqrt{3}}{2}\left(R_c[km]\sqrt{3}\right)^2 \quad (3.13)$$

where:

- R_c: cell range.

Typical cell range values derived from the available literature are presented in Table 3.5, this allows the number of sites to be estimated based upon the total area to be covered.

Table 3.5. Typical cell range, (derived from [Preg08], [Amir08], [ZhaLi09] and [Ahmad11])

BSs	Urban [km]	Suburban [km]	Rural [km]
Indoor	0.06 - 0.61	0.73 - 1.52	2.56 - 4.49
Outdoor	0.50 - 4.14	1.25 - 8.40	1.73 - 8.40

This is an estimation solely based on coverage requirements for a specific service. For capacity purposes more BSs might be required which is not covered in this thesis. The cell ranges are estimates of the average for the various morphologies. Individual BSs could have higher or lower range, depending on the specific environment morphology. The values for 10 and 20 MHz bandwidths are estimated based on the ones presented for 5 MHz.

3.5 Database

Due to confidentiality constraints the database is described in generic terms.

The database tool is based on Oracle and Java for displaying and analysing a WiMAX network, providing statistics and charts based on raw data and derived metrics. These data become useful when a substantial number of commercial users are on the system.

The architecture consists of a Local Collection Point (LCP) that collects and compiles statistics from the Network Elements (NEs) including user equipment from the Element Management Server (EMS). This information is then routed to the Performance Management Data Base (PMDB) through a Virtual Private Network (VPN) tunnel over the Internet. Information is stored on the PMDB where data is kept for up to 2 years. An Internal Network Server (INS) manages the data in terms of storage, backup, integrity, etc. and a Data Analysis Server (DAS) is used to generate reports and queries originated by any authorised user through a web Graphic User Interface (GUI) and exported as tables or figures to be used for reporting system performance.

A visual description of the architecture can be found in Figure 3.5.

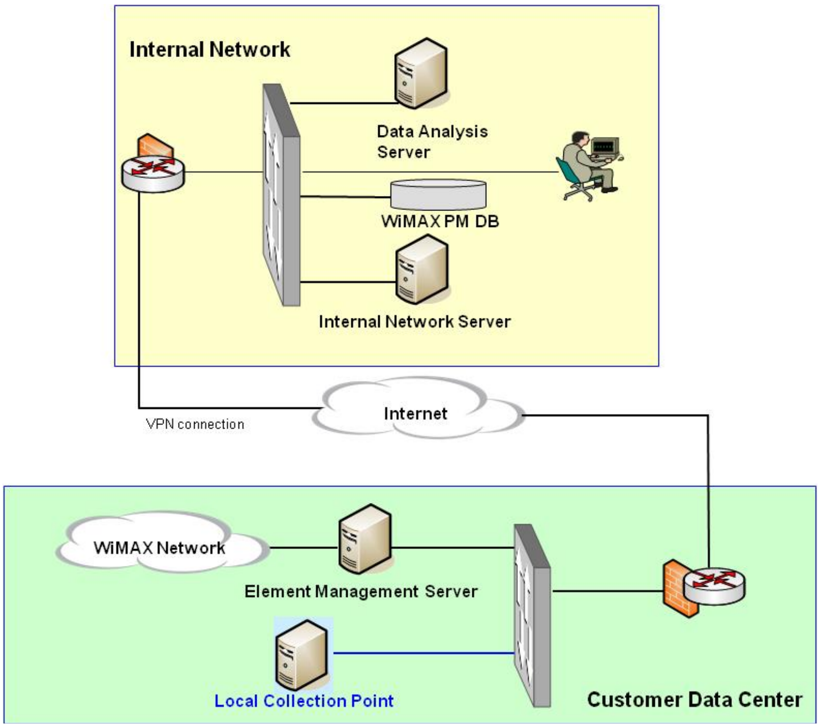

Figure 3.5. Data collection architecture.

An extensive list of available information on the Database can be found on Annex D. With relevancy to this thesis only a few are used. The matching of the available information and KPIs in Table 2.9 is summarised in Table 3.6.

Table 3.6. Database information vs. KPIs

Database information	KPI
DL Throughput	Sector Peak sustained throughput DL (R_{bSDL})
UL Throughput	Sector Peak sustained throughput UL (R_{bSUL})
(Not available)	Single User DL Peak sustained throughput (R_{bUDL})
(Not available)	Single User UL Peak sustained throughput (R_{bUUL})
DL BE Queue Latency Average	Bearer traffic Latency (τ_{BT})
(Not available)	Bearer traffic jitter (ΔT_{JBT})
DL Total Dropped Packet Rate	Bearer Traffic Percentage of Packet loss (P_{PLBT})
(Not available)	Network Access Latency (initial) (τ_{NAi})
(Not available)	RSSI
CINR	CINR
(Not available)	VoIP Quality (Q_{VoIP})

For the KPIs not available in Database one uses a special equipment setup, designed for the purpose of that specific KPI measurement. Those KPIs, although important from network performance assessment perspective, are not relevant for this thesis.

To study the information retrieved from the database, the average, μ, and Standard Deviation (Std. Dev.), σ, are used in most of the cases. In a very few cases one uses also the average Std. Dev. σ_μ to characterize the information retrieved.

$$\mu = \frac{1}{N}\sum_{i=1}^{n} Z_i \tag{3.13}$$

where:

- Z_i: sample i.
- N: number of samples.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Z_i - \mu)^2} \tag{3.14}$$

$$\bar{\sigma} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}{\sigma_i}^2} \tag{3.15}$$

where:

- σ_i: Std. Dev. of sample i.

Chapter 4

Results Analysis

This chapter starts with the description of the live network and the theoretical scenarios, followed by the results from the theoretical model presented in Chapter 3, and the experimental values from the live network for the KPIs available in the database. This chapter concluded with comparison between the theoretical and experimental results.

4.1 Scenarios

Two main scenarios are considered for this thesis; the live network scenario and the theoretical scenario for model application and analysis. Both of them consider the 3.5 GHz band.

Bearing in mind the model shown in Figure 2.3, the live network scenario follows the summary description of the Mobile WiMAX network, from where the information for this thesis was retrieved. The network consists of over 100 BSs spread mostly around urban areas in the major cities. Some BSs are also deployed on populated areas away from urban centres. The BS population consists on a mix of 4 sector SA and MIMO type using 10 MHz channel bandwidth over 3.5 GHz RF spectrum. Although mobility is possible, no specific coverage is being provided to roads, highways, train lines or other. These BSs are connected to an ASN GW through an IP network. The user traffic then flows to the CSN and from there to the Internet and other public or private data and voice networks. Several other NEs provide the remaining functions and services to the network operation.

There were over 15,000 active users by end of 2010 on the network. The spread of users across the network was carried out mainly on a slow increasing distribution over time per each BS. The users have available two types of equipment, CPEs that can be either indoor or outdoor and Universal Serial Bus (USB) type of devices mainly for Laptops (enabling mobility). The Indoor CPE is used when a good signal quality and level for the service desired is present at the end user location; for other locations where the indoor CPE is not able to provide the desired service, due to lack of enough signal quality and level, if the signal quality and level still permits an outdoor CPE installation is carried out. The USB is available to some users that whish to connect their computers (mainly Laptops) to the network. Although the coverage area will be more limited due to higher signal level requirement, it is compensated by the possibility of mobility between BSs within the coverage areas. Mobility is intended for areas within urban centres, considering mostly a walking scenario across contiguous BSs.

The most relevant services are Streaming, VoIP, HTTP, Email and FTP. These are supported by several profiles and QoS classes, the details available related to the QoS class usage are presented in Table 4.1. In relation to service profiles, the best example for CPE is: up to 12 Mbps DL speed, up to 512 kbps UL speed, unlimited quota for data download and upload, unlimited VoIP calls. For USB the best example is: up to 8 Mbps DL speed, up to 256 kbps UL speed, 20 Gbyte quota for data download and upload.

Table 4.1. Services and QoS Classes in live network.

Service	QoS
HTTP, Email, MPEG, FTP	BE
VoIP	UGS
Other	rtPS, ertPS, nrtPS

One considers Lisbon as the theoretical network scenario where the model is applied. Only the 84.8 km^2 urban centre of Lisbon is considered from which the 10 km^2 of Monsanto forest park are subtracted, due to not having enough residential or business populated areas, totalling 74.8 km^2 of coverage area. A mix of 50% outdoor and 50% indoor users is assumed as shown in Table 4.2.

Table 4.2. BSs and coverage type assumed percentages.

BSs	Outdoor	Indoor
Urban	50%	50%

Various scenarios, based on the reference one, will also be considered. In Table 4.3 the variations for each scenario are described.

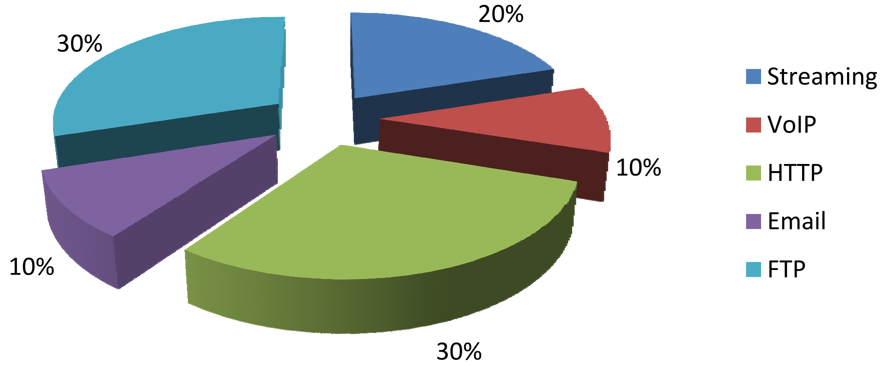

Figure 4.1. Service mix.

Table 4.3. Scenarios considered for analysis.

Scenario	Streaming [%]	VoIP [%]	HTTP [%]	Email Send [%]	Email Receive [%]	FTP Upload [%]	FTP Download [%]
Reference	20	10	30	5	5	10	20
Business	10	10	30	10	10	10	20
Residential (weekdays)	20	30	20	5	5	5	15
Residential (weekend)	30	10	30	5	5	5	15

4.2 Theoretical Results

The theoretical maximum physical throughput results from the calculations using (3.4) and (3.5) are summarised in Table 4.4. The values presented are consistent in relation with the ones already offered in Table 2.3, the differences are explained mostly by the UL:DL frame ratio differences; while the ones in Table 4.4 consider the maximum asymmetry between DL and UL allowed of 3:1, the ones in Table 2.3 consider the maximum possible values independent of the frame ratio and a estimate for the calculation, [WiMF06] and [SJTa09]. The decision to use the 3:1 frame ratio is due to fine-tune the theoretical calculations as close as possible to the real network setup. A direct relation that can be taken is that the higher the MCS N_{bps} and $R_{Codding}$ (refer to Table 3.2 for values) the higher throughput.

Table 4.4. Theoretical maximum physical throughput [Mbps].

MCS	5 MHz Channel		10 MHz Channel		20 MHz Channel	
	DL [Mbps]	UL [Mbps]	DL [Mbps]	UL [Mbps]	DL [Mbps]	UL [Mbps]
QPSK 1/8	0.58	0.12	1.17	0.24	2.33	0.48
QPSK 1/4	1.17	0.23	2.33	0.48	4.67	0.96
QPSK 1/2	2.33	0.47	4.67	0.96	9.34	1.92
QPSK 3/4	3.50	0.70	7.00	1.44	14.01	2.88
16-QAM 1/2	4.67	0.93	9.34	1.92	18.68	3.85
16-QAM 2/3	6.23	1.25	12.45	2.56	24.90	5.13
16-QAM 3/4	7.00	1.40	14.01	2.88	28.02	5.77
64-QAM 1/2	7.00	1.40	14.01	2.88	28.02	5.77
64-QAM 2/3	9.34	1.87	18.68	3.85	37.35	7.69
64-QAM 3/4	10.51	N/A	21.01	N/A	42.02	N/A
64-QAM 5/6	11.67	N/A	23.35	N/A	46.69	N/A

The clear relation between available RF channel bandwidth and the maximum physical throughput per channel is even more noticeable in Figure 4.2 and Figure 4.3 where the values for the 3 are placed side by side.

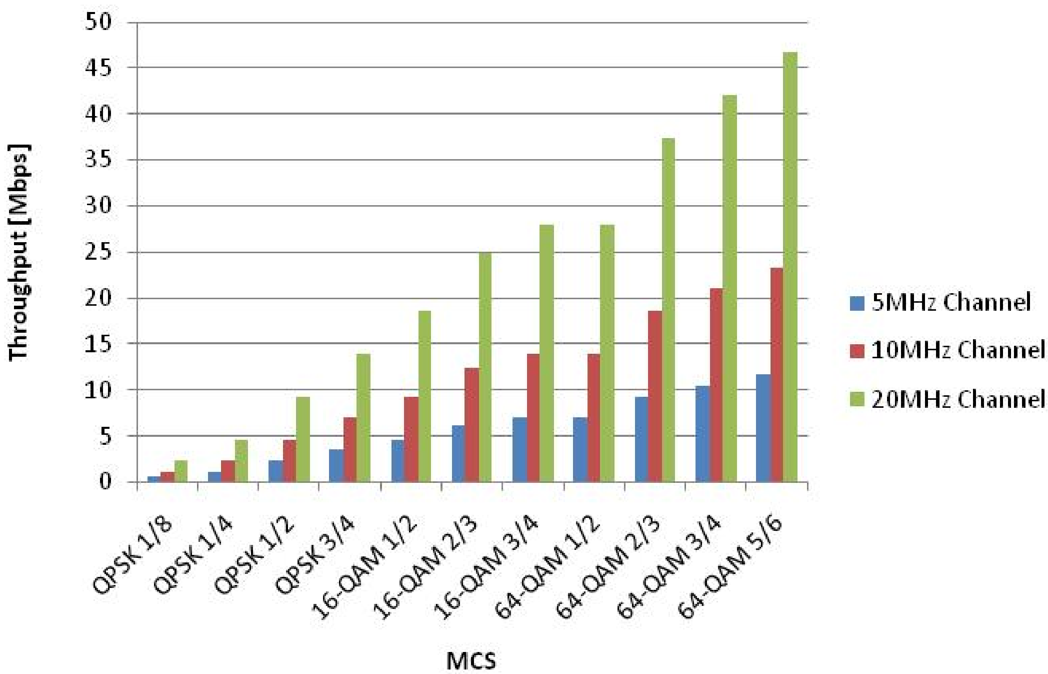

Figure 4.2. Maximum physical DL throughput.

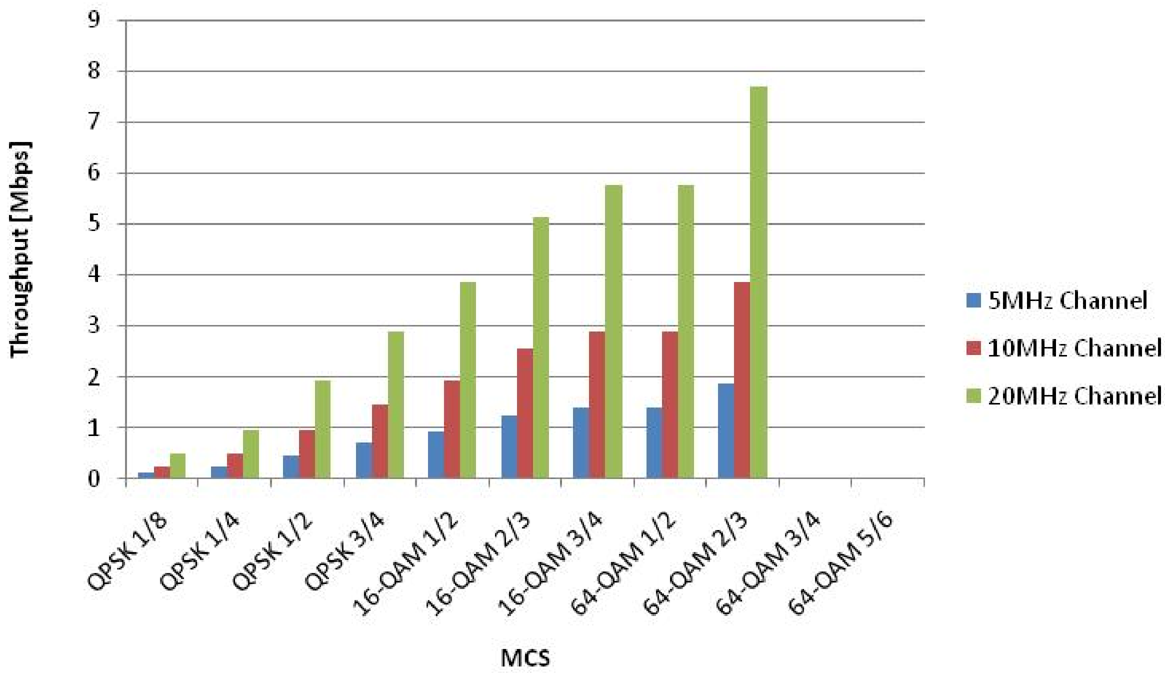

Figure 4.3. Maximum physical UL throughput.

The initial relation to be noticed is that for every time the channel bandwidth doubles the maximum available throughput also doubles for both UL and DL. This is valid with the exception to be noted that since $N_{bMCSUL/DL}$ is the same for 16-QAM 3/4 and 64-QAM 1/2 the theoretical throughput value is the same.

Although the DL:UL frame ratio is 3:1, the values for DL throughput are 5 times higher than the ones for UL, this is due to other factors to consider on the calculations like the difference at the level of available data subcarriers (a ratio of 1.3 between DL and UL) and symbols (a ratio of 3.8 between DL and UL).

For UL, 64-QAM 3/4 and 5/6 are optional and usually not implemented [SJTa09], together with the 3:1 frame ratio are the main contributors for the lower UL throughput when compared with the UL. The main reason for not implementing these optional MCSs on the UL are to save on user equipment costs, while the frame ratio is a network implementation choice of the operator to allocate the maximum resources were they mostly are needed.

Although these throughputs may seem high, they will be shared among a mix of users with different workload profiles over a variety of MCS.

Using (3.8) and the workload parameters in Table 4.5 the user capacity is calculated, this depends mostly on the MCS, bandwidth and workload considered. As an example, still in Table 4.5, the capacity for the five workloads with QPSK ½ MCS over a 10 MHz channel is analysed.

The values for the number of users for each workload presented in this example clearly show that the higher the demand for resources the less users supported. Further analysis for the full range of MCS and the 3 bandwidths follows next.

Table 4.5. Example of capacity calculation, (adapted from [SJTa09], [Kill01], [Agui03] and [NetIn11]).

Parameters	MPEG 2	VoIP	HTTP	FTP		Email	
				Download	Upload	Receive	Send
MAC SDU with header [bytes]	984.5	21	1208.2	507.29	507.29	503.03	503.03
Data rate with upper layer headers [kbps]	350.4	8.4	14.6	507.9	507.9	508.0	508.0
Deadline [ms]	10	60	250	10	10	10	10
DL							
Bytes/5 ms frame per user	437.9	62.9	456.1	634.9	0.1	634.9	0.1
Number of fragmentation subheaders	1	0	1	1	1	1	1
Fragmentation subheaders Bytes/5 ms frame	8	8	8	8	8	8	8
Number of packing subheaders	0	2	0	0	0	0	0
Packing subheaders Bytes/5 ms frame	8	8	8	8	8	8	8
DL data slots per user with MAC header + packing and fragmentation subheaders	75	14	78	108	2	108	2
Slots per user for DL-MAP IE	8	8	8	8	8	8	8
Slots per user for UL-MAP IE	0	8	8	8	8	8	8
Total slots per user (Data + DL-MAP IE + UL-MAP IE + Preamble)	83	30	94	124	18	124	18
DL Number of users	12	204	250	8	56	8	56
UL							
User Bytes/5ms Frame	0.2	62.9	2.7	0.1	634.9	0.1	634.9
Number of fragmentation subheaders	0	0	1	1	1	1	1
Fragmentation subheaders Bytes/5 ms frame	8	8	8	8	8	8	8
Number of packing subheaders	2	2	0	0	0	0	0
Packing subheaders Bytes/5 ms frame	8	8	8	8	8	8	8
UL data slots per user with MAC header + packing and fragmentation subheaders	3	14	2	2	108	2	108
UL Number of users	92	120	3500	140	2	140	2
Number of users (min of UL and DL) with silence suppression on VoIP	12	240	250	8	2	8	2

From Figure 4.4 to Figure 4.10 one shows the user capacity for each workload evaluated, the detail values can be found in the tables of Annex E. In absolute values the number of users may seem high, bear in mind that they are the maximum theoretical number of users exclusively for each MCS, i.e., if all users were allocated to the same MCS and only using a specific workload. From these figures one can assess the relative difference of users between for the different parameters under analysis: Bandwidth, MCS and Workload.

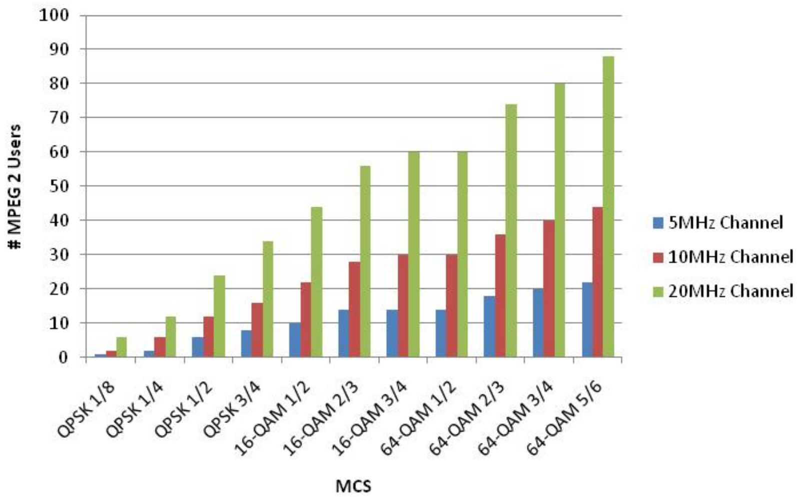

Figure 4.4. Maximum number of users for MPEG2.

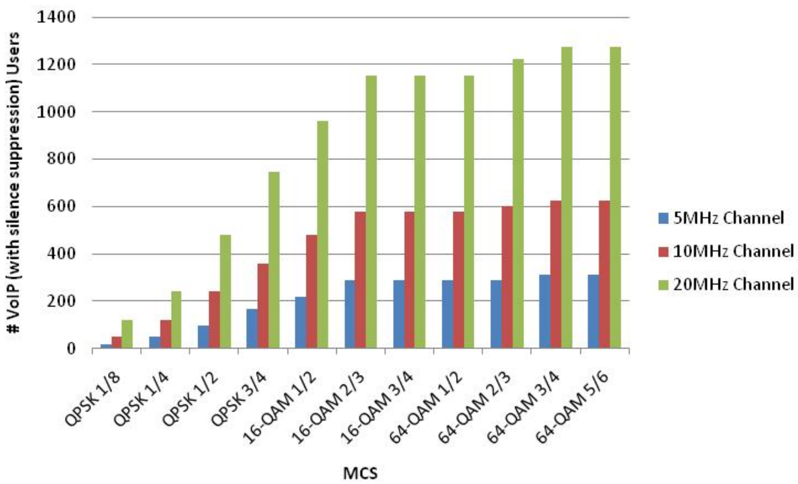

Figure 4.5. Maximum number of users for VoIP.

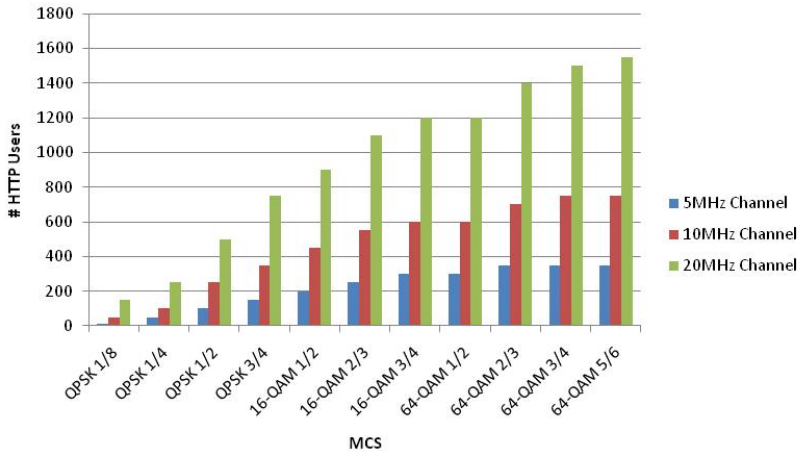

Figure 4.6. Maximum number of users for HTTP.

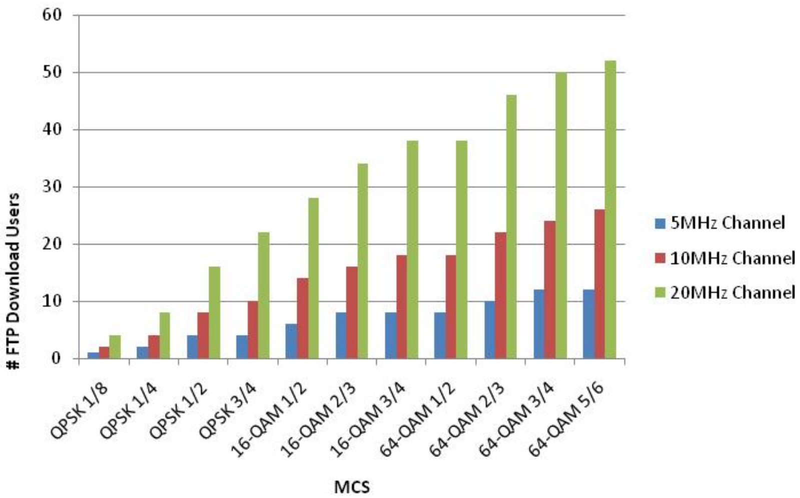

Figure 4.7. Maximum number of users for FTP Download.

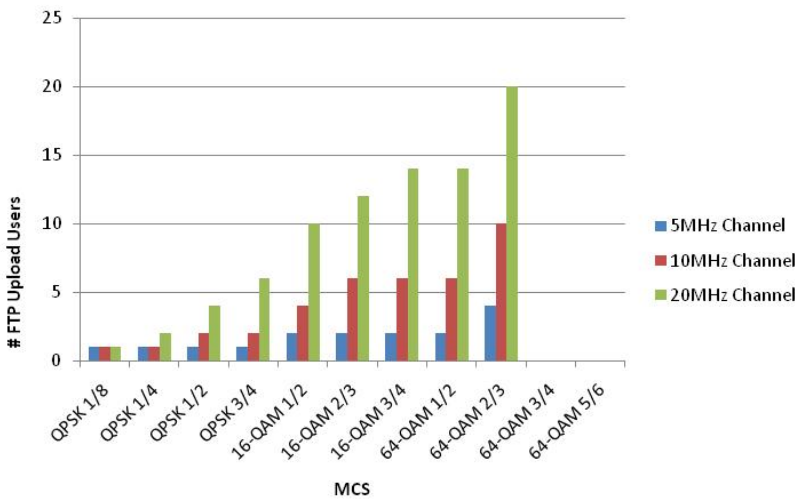

Figure 4.8. Maximum number of users for FTP Upload.

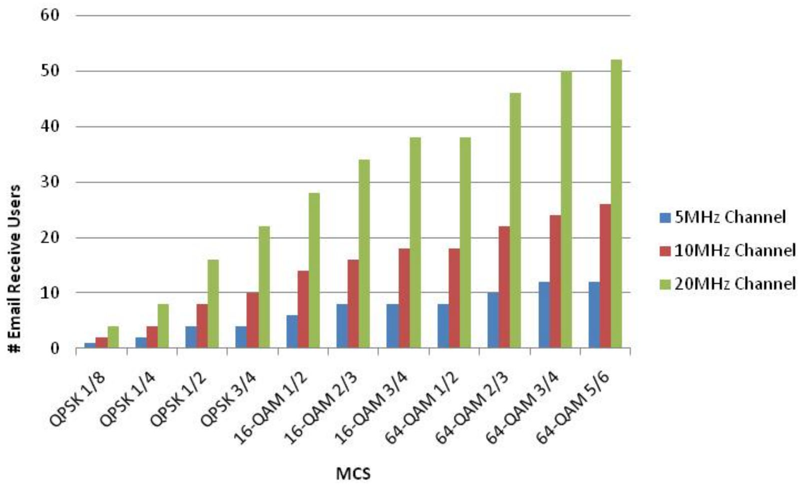

Figure 4.9. Maximum number of users for Email Receive.

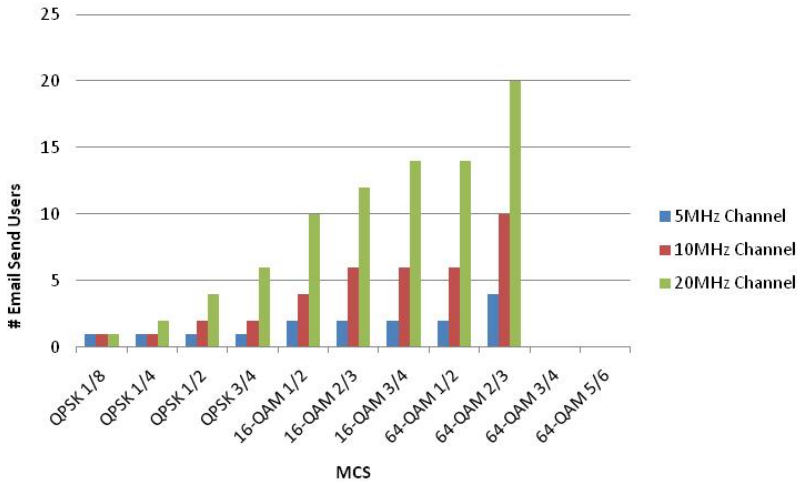

Figure 4.10. Maximum number of users for Email Send.

As shown above higher MCSs allow higher capacity when considering a perfect channel. In the real world it is not always possible to use these higher MCSs since each of them is limited by the channel quality as shown in Table 2.8. The non linearity of user increase with the MCS increase for each workload within each bandwidth is due to 2 factors: the $\mathrm{N}_{\mathrm{bMCSUL/DL}}$ being the same for 16-QAM 3/4 and 64-QAM 1/2 and the scheduler that tries to minimise the number of bursts by aggregating payloads for each user, this is more visible for VoIP workload since has the smaller packet size considered. For the workloads of FTP upload and Email Send one does not show the values for 64-QAM 3/4 and 5/6 since these workloads are strongly UL asymmetrical and the mentioned MCS are considered not to be implemented in the UL.

To have a better perception of the relative difference of maximum supported users for each workload considered, the numbers for three specific MCSs: QPSK 1/2 - the most robust one; 16-QAM 3/4 – a middle table one and 64-QAM 5/4 – the one with the highest N_{bps}, are presented in Figure 4.11, Figure 4.12 and Figure 4.13, the detail values can be found in the tables of Annex E.

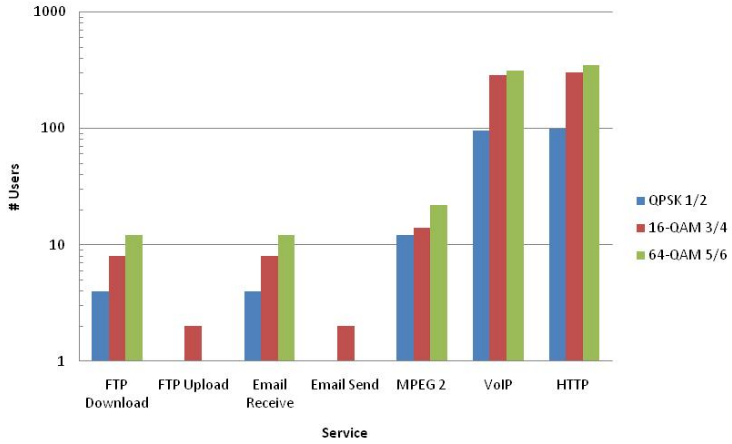

Figure 4.11. Users per service at 5 MHz.

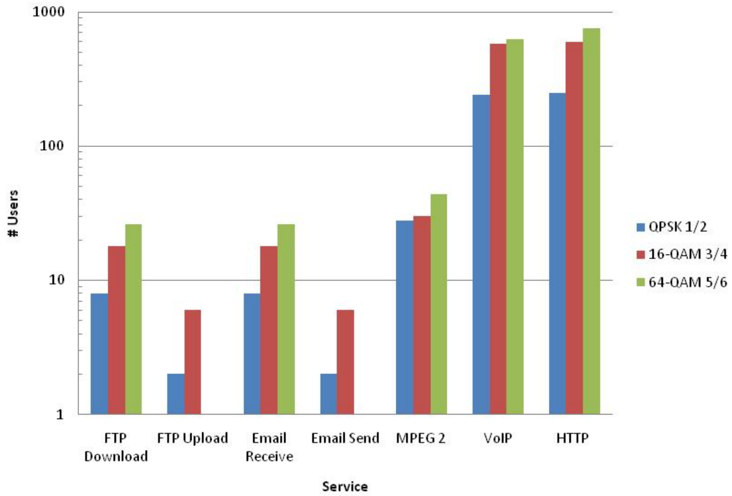

Figure 4.12. Users per service at 10 MHz.

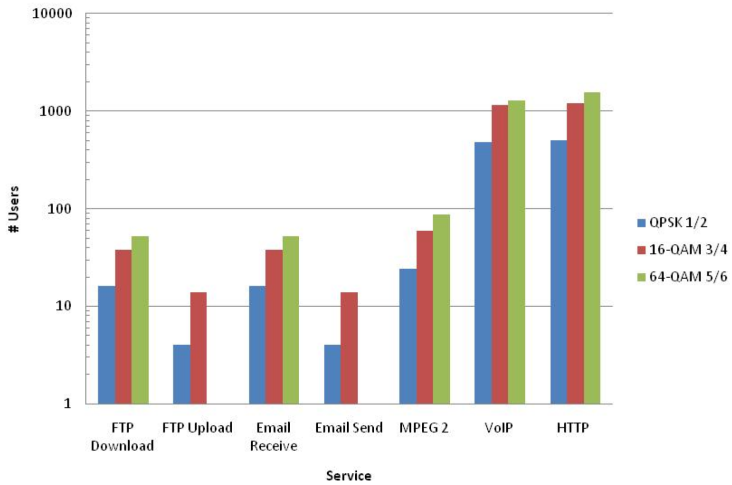

Figure 4.13. Users per service at 20 MHz.

The workloads that allow the highest number of users are HTTP closely followed by VoIP, in the other hand the ones that allow for less users are FTP Upload and Email Send, this relations is maintained irrespectively of MCS and Channel Bandwidth. The difference between maximum number of users for each workload is due to the inherent characteristics of each one and how the scheduler aggregates the payloads to minimise the bursts. For instance, HTTP has the largest packet size in analysis but since it only requires a low data rate and has the highest deadline (tolerance to delay) it is the one that allows for the highest number of users. Due to the similarities between packet size; data rate and symmetry for FTP and Email the number of users is also very similar.

To simulate a scenario closer to reality a capacity analysis assuming a variance in channel quality for different users which results in different levels of MCS is presented. The channel parameters used in a simulation by [LSHK04] are listed Table 4.6.

Table 4.6. Simulation parameters, (extracted from [LSHK04]).

Parameters	Value
Channel model	ITU Veh-B (6 taps) 120 km/hr
Channel bandwidth	10MHz
Frequency band	2.35 GHz
Forward Error Correction	Convolution Turbo Coding
Bit Error Rate threshold	10E-5
MS receiver noise figure	6.5 dB
BS antenna transmit power	35 dBm
BS receiver noise figure	4.5 dB
Path loss PL(distance)	37 × log 10(distance) + 20 × log 10(frequency) + 43.58
Shadowing	Log normal with σ= 10 dB
number of sectors per cell	3
Frequency reuse	1/3

According to [LSHK04] simulations the percentage of users which are able to achieve a particular MCS in a call is listed in Table 4.7.

Table 4.7. Average MCS for 2 × 2 antennas from [LSHK04].

MCS	Average [%]	
	DL	UL
FADE	3.00	1.2
QPSK 1/8	4.06	1.5
QPSK ¼	14.68	8.7
QPSK ½	13.15	14.1
QPSK ¾	10.28	15.3
16-QAM ½	16.12	30.0
16-QAM 2/3	0	0
16-QAM ¾	14.18	29.2
64-QAM ½	0	NA
64-QAM 2/3	24.53	NA

Although the values for the average MCSs in Table 4.7 refer to a 10 MHz bandwidth over 2.5 GHz RF spectrum and 3 sectors BSs, in opposition to 3.5 GHz RF spectrum and 4 sector BSs on the live network scenario, we will use them also for the 5 and 20 MHz bandwidths user calculations since no other could be found in the available literature. Using (3.12), one can simulate the spatial spread of users with different channel quality, and the results for $\overline{N_{bMCSUL/DL}}$ are: 11.73 bytes for UL and 12.59 bytes for DL, then the number of users supported on a closer to reality channel is calculated by (3.8), (3.10) or (3.11) depending on the workload asymmetry, and presented in Table 4.8. These values show the maximum number of users if only one workload is considered at each time but now considering a closer to reality mix of MCS

Table 4.8. Number of supported users on a closer to reality channel per workload.

Workload / Bandwidth	Number of Users		
	5 MHz Channel	10 MHz Channel	20 MHz Channel
FTP Download	6	14	30
FTP Upload	2	4	10
Email Receive	6	14	30
Email Send	2	4	10
MPEG2	10	22	46
VoIP	216	480	960
HTTP	200	450	950

In Figure 4.14 the huge difference of supported users between the workloads of HTTP and VoIP in regards to FTP, Email and MPEG 2 is noticeably outstanding.

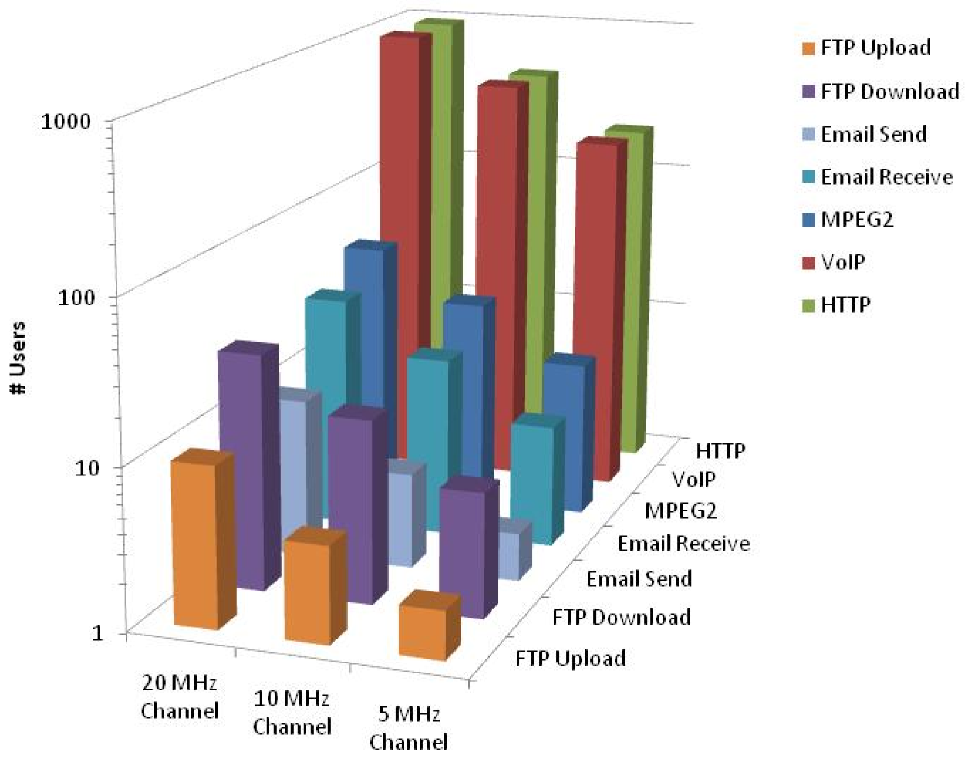

Figure 4.14. Users per service for 5, 10 and 20 MHz.

Also to be noted is the relative comparison to the values for individual MCSs in Figure 4.11, Figure 4.12 and Figure 4.13, one notes that the maximum number of users has decreased, since now one is considering an average MCS from a closer to reality mix of MCSs and not only each individual MCS.

This user capacity values derived from the average MCSs, are presented to bring the theoretical values closer to real channel conditions where each user experiences a different SNR and thus a different MCS.

The scenarios from Table 4.3 are the last influence factor under study for the total number of users, this is presented in Table 4.9.

Table 4.9. Total number of users per scenario.

Scenario	Number of Users		
	5 MHz Channel	10 MHz Channel	20 MHz Channel
Reference	85	190	397
Business	84	189	394
Residential weekdays	107	240	492
Residential weekends	85	191	399

A dependency on the channel bandwidth is clear from the results shown above; when the channel bandwidth doubles the total number of users also doubles. The variation of total number of users related to the scenario clearly shows the influence of the workloads; the Business scenario that has more data related workload (Email, FTP) than the others is the one with less users and the Residential (weekdays) scenario that has the most VoIP workload and less data is the one with more users. These are the maximum theoretical values and are consistent with the ones presented in Table 1.2, relatively to other systems currently in use, like HSPA+, they show a higher user capacity for the same channel bandwidth.

To calculate the available user capacity for the covered area of both live and theoretical scenarios one starts by showing the results of the number of required BSs to cover the respective areas. One starts by presenting in Table 4.10 the typical average urban cell ranges derived from the scenario in Table 4.2. The variation of range due to channel bandwidth increase from 5 to 10 MHz and 20MHz is mainly due to the total transmitted power remaining constant while the bandwidth increases thus reducing the received power by 3dB for each bandwidth variation. At 3.5 GHz the range variation is estimated (using the simple Free Space Loss calculation) around 29% from 5 to 10 MHz and 50% from 5 to 20 MHz.

Table 4.10. Typical average urban cell ranges.

	Cell Range [m]		
BSs	5 MHz Channel	10 MHz Channel	20 MHz Channel
Urban	1,048	741	525

The coverage for a BS is calculated using (3.13) and cell range values presented in Table 4.10. To estimate the number of BSs one simply divides the area to cover by the area of each cell and considers that each BS has 4 cells. The values are shown in Table 4.11. Note that these values are based on coverage needs only and no capacity requirements are taken into account which would increase this value.

Table 4.11. Estimated BSs number to cover Lisbon Urban area.

Band	5 MHz Channel	10 MHz Channel	20 MHz Channel
Average A [km^2]	1.65	0.83	0.41
Number of Cells	46	91	181
Number of BSs	12	23	46

The number of required BSs doubles each time the bandwidth doubles; this is expected due to the RF propagation constraints analysed before. This number of BSs can be considered small in relation to the GSM/UMTS BSs (estimated in the order of magnitude of 100s) currently deployed to cover Lisbon since the main constraint for the GSM/UMTS is capacity and not only coverage.

Applying the scenarios values from Table 4.9 to the BSs number to cover Lisbon Urban area from Table 4.11, one is able to estimates the total number of users that those BSs are able to support. Those results are presented in Table 4.12.

Table 4.12. Total number of users for Lisbon Urban Area.

Scenario	Number of Users for Lisbon Urban Area		
	5 MHz Channel	10 MHz Channel	20 MHz Channel
Reference	15,640	69,160	287,428
Business	15,456	68,796	285,256
Residential weekdays	19,688	87,360	356,208
Residential weekends	15,640	69,524	288,876

The users increase by 4 times each time the bandwidth doubles, this is due to the number of supported users as well as the number of required base stations double each time the bandwidth doubles. The same relative considerations between scenarios from Table 4.9 are still applicable. To support more than the users estimated in Table 4.12 more BSs would have to be added to the coverage area, but this either would require additional RF spectrum or would increase the interference to the network.

Applying the scenarios values from Table 4.9 to the 100 BSs like the scenario of the live network, one estimates the total number of users. Those values are presented in Table 4.13. This is especially useful to understand the level of user loading of the live network.

Table 4.13. Total number of users for Live Network.

Scenario	Number of Users for Live Network		
	5 MHz Channel	10 MHz Channel	20 MHz Channel
Reference	34,000	76,000	158,800
Business	33,600	75,600	157,600
Residential weekdays	42,800	96,000	196,800
Residential weekends	34,000	76,400	159,600

The values of supported users only double each time the bandwidth doubles instead of the 4 times in Table 4.12 since one now considers a constant value of 100 for the number of BSs. Given that, there were only around 15,000 users by end of 2010 on the live network; one is able to infer that globally the network still had available theoretical capacity to support more users at any channel bandwidth.

4.3 Experimental Results

The results presented next refer to either the full network or to two specific cells – Cell A and Cell B (one channel each) - chosen from the network by being the best examples to illustrate and compare with the full network.

The concept of sector, cell, carrier and channel are indiscriminately used as equivalent during the analysis, although these represent different things they tend to be alike, since each BS has between 1 to 4 cells and each one acts as an individual sector, with only one carrier which is chosen among the limited pool of available RF channels. Although the details of the RF planning are outside the scope of this thesis, one may assume that the RF channels distribution is planned with a reutilisation pattern that requires the most number of different RF channels, and although other patterns may be possible due to the use of subchannelisation, which would allow the operator to reduce the RF spectrum requirements, they would also reduce the overall system maximum performance.

The system also takes advantage of the Global Positioning System (GPS) synchronisation between cells, that helps avoid interference between different BS, and synchronize the DL and UL frames over the TDD system, this synchronisation ensures that all AP's are transmitting at virtually exactly the same time, thereby minimising inter-sector and inter-site interference while maintaining orthogonality within and across BSs

The values presented are averages or maximums over monthly periods unless otherwise stated, and one also has to consider that the values for 5 MHz were collected from the network some months (usually 6) prior to the upgrade for 10 MHz. Only values for 5 and 10 MHz channel bandwidths are presented since 20MHz is not yet available. Absolute and relative comparisons are provided among the experimental like network results, leaving the comparison to the theoretical to the following section.

Were possible the values for 5 MHz channels are presented using variants of blue while 10 MHz channel values are presented using variants of red. This helps to improve the visual differentiation of the channels.

Database data volume for 1 month is in the order of magnitude of 10 Gbyte and the average report creation time under one minute.

For the live network scenario retrieving from the database the values for "Modulation Schemes by Kbyte", one can find in Table 4.14 the values for the split of MCSs on the network for 5 and 10 MHz.

Table 4.14. Percent MCS for live network scenario.

MCS	Average [%]			
	5 MHz Channel		10 MHz Channel	
	DL	UL	DL	UL
QPSK	3.14	12.63	3.35	14.15
16-QAM	19.91	87.37	22.88	85.85
64-QAM	76.95	NA	73.77	NA

These values are directly related to the CINR, they show over 75% of the times the 64-QAM MCSs are used on the DL and over the UL more than 85% of the time the 16-QAM is used. This reveals that usually a good channel quality is obtained thus the highest throughputs are possible to achieve. This is expected since most of the users are in fix locations which were previously verified either by local measurements or remotely checked through service coverage predictions, to assure that the users would be in a area of enough signal quality for the desired service contracted to the operator.

The database CINR, directly related to the CINR KPI, relative distribution of UL values is presented in Figure 4.15. One can verify that there is a skew towards the highest CINR values, with more than 40% of the data for a 10 MHz channel and more than 50% of the date for a 5 MHz channel being over 36dB, one considers that the live network has a an CINR distribution which allows the usage of high MCSs and thus allowing the users to achieve the best performances possible by the system. The values from Table 4.14 and Figure 4.15 are consistent, the difference of MCS percentages when comparing between 5 and 10 MHz channels in Table 4.14 is comparable with the differences of the CINR distribution in Figure 4.15, where a slight degradation is observed when comparing between 5 and 10 MHz channels, this is mainly due to the decrease on the sub-carriers power to half because of the bandwidth doubling-up, the detail values can be found in the tables of Annex F

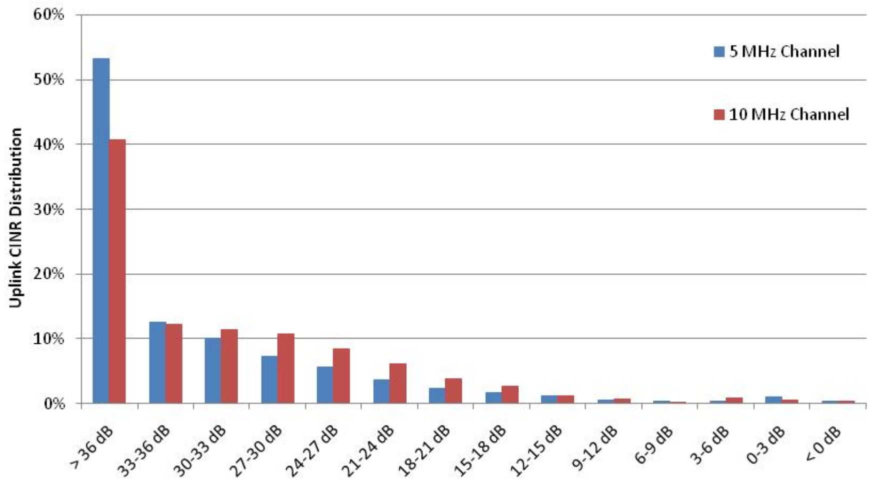

Figure 4.15. Network UL CINR distributions for 5 and 10 MHz channels.

The exact relation between the CINR level and the respective MCS is restricted information that one does not have access to; in Table 2.8 some proposed theoretical values are presented.

At individual cell level one presents in Figure 4.16 and Figure 4.17 the CINR values for the 2 cells in analysis, the detail values can be found in the tables of Annex F.

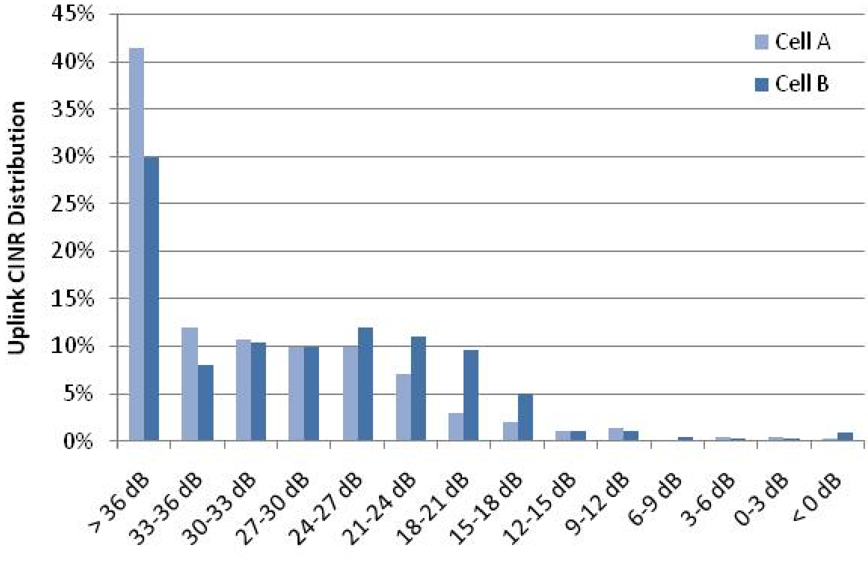

Figure 4.16. UL CINR distributions at 5 MHz for cell A and B.

Cell B is showing lower values over 30 dB and higher values between 15 and 27 dB on the distribution of UL CINR. The differences between cell A and B UL CINR values relate to the variation in the RF environment. This influences the MCS in use on that cell relating to cell A having more users with better MCS than cell B. In relation to the network CINR values for 5 MHz in Figure 4.15, these cells follow a similar distribution although they present lower values for the best CINR ranges then the network average ones.

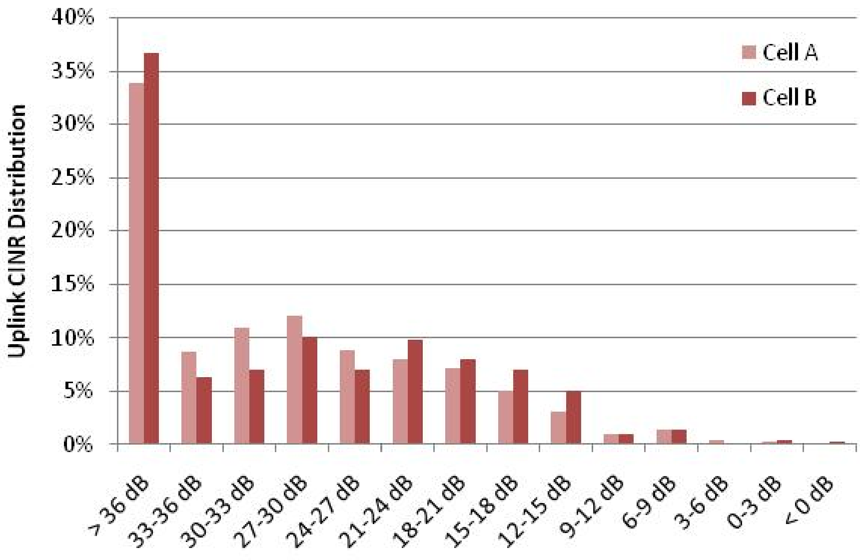

Figure 4.17. UL CINR distributions at 10 MHz for cell A and B.

At 10 MHz both cells are showing similar values over 36 dB but for the other ranges cell A is showing a better behaviour than cell B on the distribution of UL CINR. In relation to the network CINR values for 10 MHz in Figure 4.15, these cells follow a similar distribution although they present slightly lower values for the best CINR ranges then the network average ones.

The behaviour of cell A from 5 to 10 MHz is similar to the average network performance where a degradation of the highest CINR is expected as per previous analysis. In the other hand cell B shows improvements from 5 to 10 MHz upgrade, this is opposite to the average network behaviour and could be explained by a possible cell optimisation (like channel frequency change) during the upgrade from 5 to 10 MHz channels.

The UL Noise and Interference (NI) average values for the network level, at 5MHz, are shown in Figure 4.18.

The values in Figure 4.18 are the average of the daily values collected during one month period for each individual cell, and are ordered let to right on a descendent way i.e. Lower NI values on the left to the highest NI values on the right.

A detailed analysis of the NI is not in the scope of this thesis and only a brief analysis is presented to characterize in general the status of the live network in terms of NI.

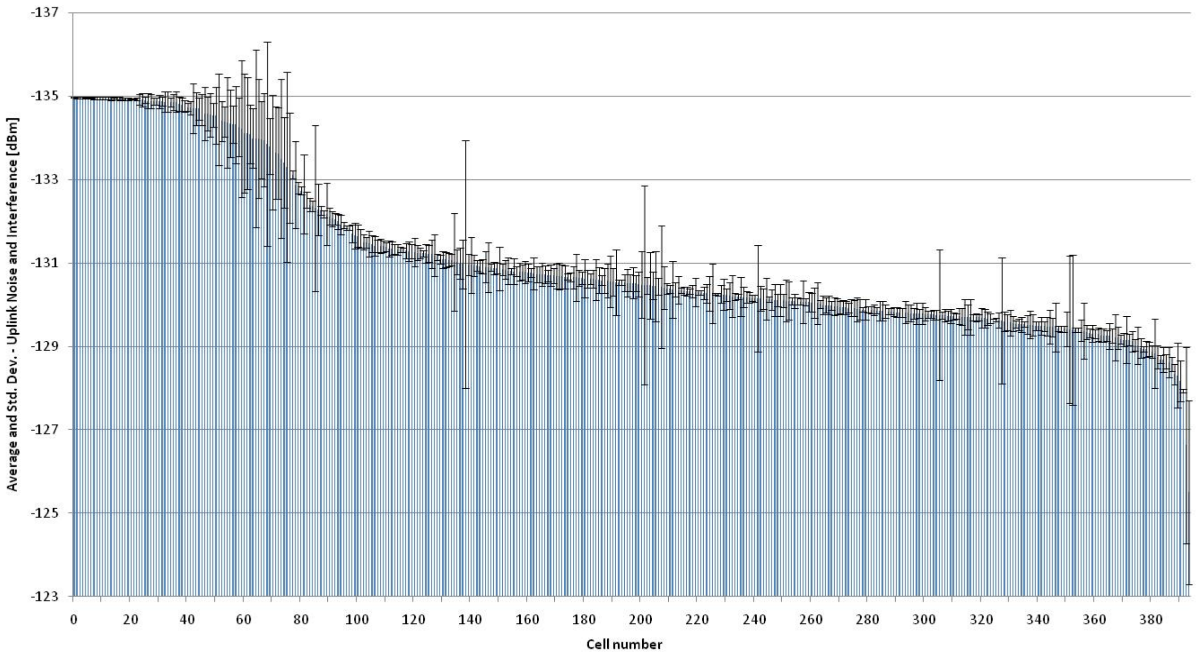

Figure 4.18. Network Average and Std. Dev. for UL NI at 5 MHz channel.

To analyse these values a histogram with the distribution of them among some NI intervals is presented in Figure 4.19, the detail values can be found in the tables of Annex F.

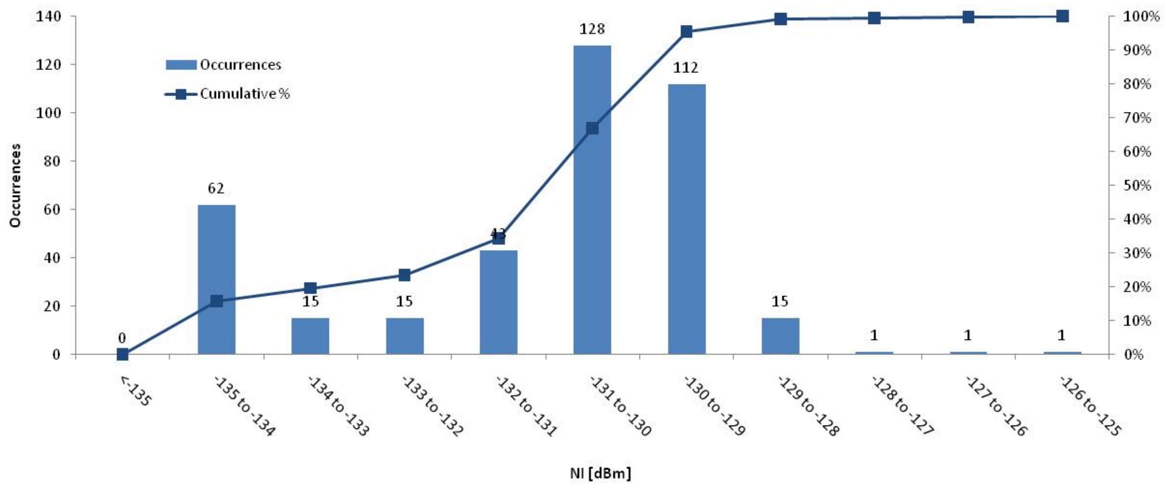

Figure 4.19. Distribution of Network Average UL NI at 5 MHz channel.

The main statistical elements used to assess the level of NI within the network are presented in Table 4.15.

Table 4.15. Network statistic values for average UL NI at 5 MHz channel.

Statistics	Uplink NI 5 MHz Channel
Count	394
Average (μ) [dBm]	-131.11
Standard Deviation (σ) [dB]	1.91
Average Standard Deviation ($\bar{\sigma}$) [dB]	0.33
Maximum [dBm]	-125.50
Median [dBm]	-130.52
Minimum [dBm]	-134.97

One considers that the channel (for that cell) suffers from noise or interference if it shows a higher value than -127 dBm. For 5MHz only 3 out of the 394 available cells fall within the considered as interfered category, if only the average is considered, which relates to 0.8% of the network. Since 15 more fall within the range of -129 to -128 dBm, and given the standard deviation of 1.91 dB, one considers a worst case of 18 out of the 394 cells potentially interfered, which relates to 4.6% of the network. From the available information one can also determine that 95% of the cells show levels lower than -129 dBm. The NI across the network follows a curve that is divided in 3 areas, the initial one with few cells showing NI values very close to -135 dBm, which is the BS hardware measurement limit, these would be the cells with virtually no NI; then follows a curve of values ranging from -135 to -129 dBm for cells with acceptable NI values, ultimately followed by the interfered cells.

The network average and Std. Dev. for UL NI at 10 MHz channel is shown in Figure 4.20.

As for the 5 MHz NI, the values in Figure 4.20 are the average of the daily values collected during one month period for each individual cell, and are ordered let to right on a descendent way i.e. Lower NI values on the left to the highest NI values on the right.

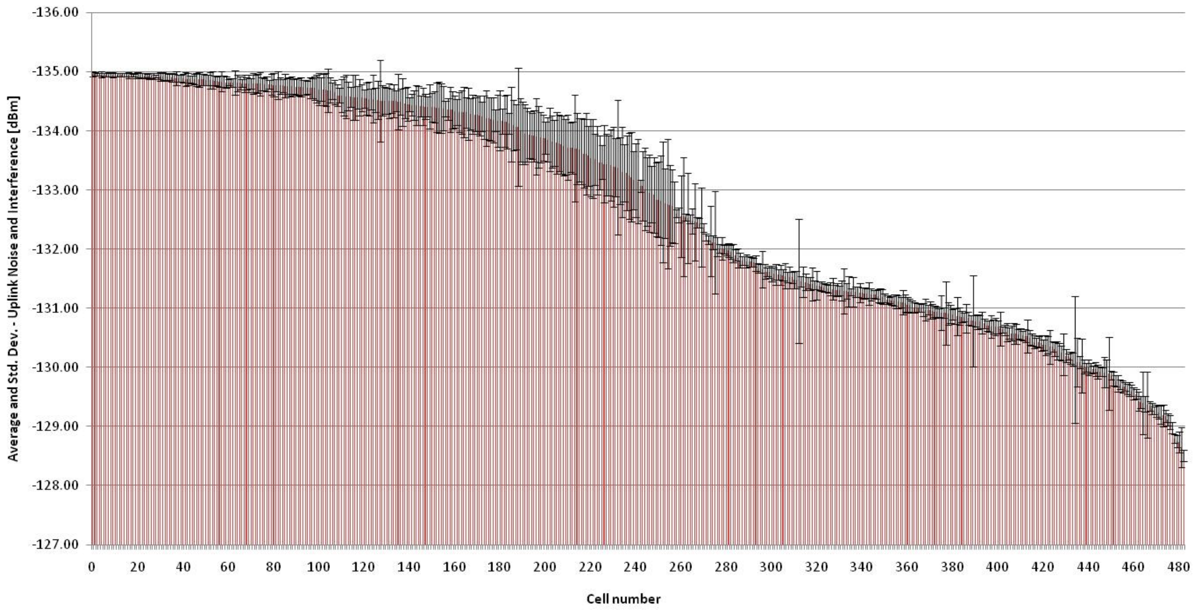

Figure 4.20. Network average and Std. Dev. for UL NI at 10 MHz channel.

Again, as for the 5 MHz NI values, a detailed analysis of the NI is not in the scope of this thesis, and only a brief analysis is presented to characterize in general the status of the live network in terms of NI. To analyse these values a histogram with the distribution of them among some NI intervals is presented in Figure 4.21, the detail values can be found in the tables of Annex F.

A similar curve shape like the 5 MHz network level is noticeable, where the main difference lies on the fact that more cells on 10 MHz network level have better NI values which influences the shape of the middle section of that curve.

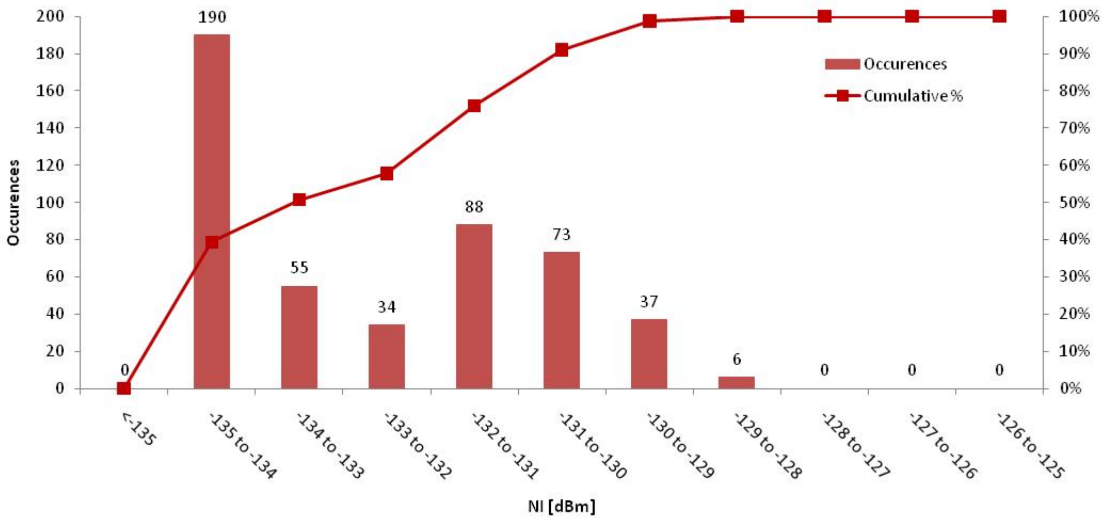

Figure 4.21. Distribution of Network Average UL NI at 10 MHz channel.

The main statistical elements to assess the level of NI within the network are presented in Table 4.16.

One considers the limit to NI of -127 dBm as well as for the 10 MHz channels to determine the threshold of cells suffering from excessive NI.

Table 4.16. Network statistic values for average UL NI at 10 MHz channel.

Statistics	Uplink NI 10 MHz Channel
Count	483
Average (μ) [dBm]	-132.71
Standard Deviation (σ) [dB]	1.89
Average Standard Deviation ($\bar{\sigma}$) [dB]	0.23
Maximum [dBm]	-128.51
Median [dBm]	-133.15
Minimum [dBm]	-134.96

For 10MHz no cells out of the 483 fall within the considered as interfered category, if only the average is considered, which shows an improvement from 5 MHz, this is not directly related to the channel bandwidth but rather to a better channel distribution across the network when of the upgrade from 5 to 10 MHz. In this case only 6 cells fall within the range of -129 to -128 dBm, and given the standard deviation of 1.89 dB, one considers a worst case of 6 out of the 483 cells potentially interfered, which relates to 1.2% of the network, again an improvement from 5 MHz channels.

Relatively to the CINR in Figure 4.15, the NI values follow the opposite expected trend. The NI values show a better values for 10 MHz compared to 5 MHz in opposition to the CINR values that show better values for 5 MHz compared to 10 MHz. Although the NI and CINR are directly linked in the inverse ratio, higher the NI lower the CINR, there are many influencing factors that could explain the apparent behaviour, and the analysis of which is out of the scope of this thesis. One can assume that this behaviour is influenced by the following 3 most probable causes: the 3 dB decrease in carrier power of the 10 MHz channel when compared to the 5MHz channel, the channel frequency changes of some of the cells when of the upgrade from 5 to 10 MHz, the increase in the number of users between the time lapsed of the collection of the samples (of around 6 months), or a mix of those.

The individual NI levels at 5 MHz for cells A and B are presented in Figure 4.22, followed by the main statistical elements to assess the level of NI for the individual cell under analysis, which is presented in Table 4.17.

From the analysis of Figure 4.22 and Table 4.17, similar trends are appreciated for both cells; clearly cell A presents better values of NI than cell B, but still within the acceptable level of less than -127 dBm. Even considering the standard deviation for the maximum values for cell B, it would still maintain the values within the -127 dBm limit. This confirms the validity of these cells at NI level as 5Mhz channel representatives for this thesis, since from a NI perspective the results would not be influenced by excessive interference or noise.

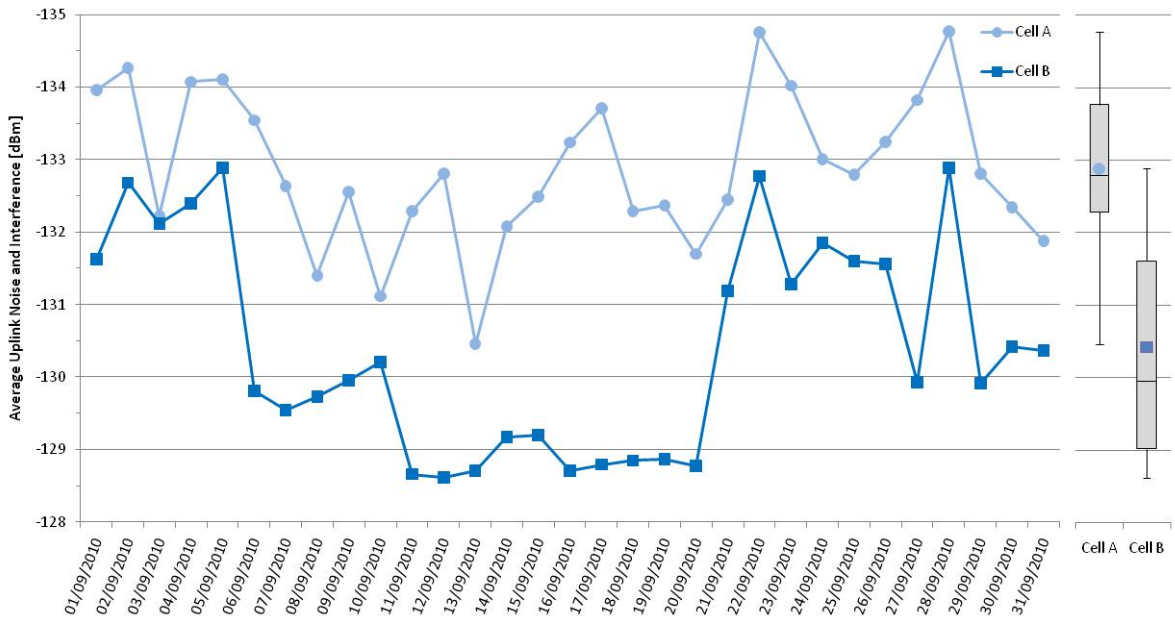

Figure 4.22. Daily Average UL NI at 5 MHz channel for Cells A and B.

Table 4.17. Statistic values for average UL NI at 5 MHz channel for Cells A and B.

Statistics	UL NI 5 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ) [dBm]	-132.88	-130.42
Standard Deviation (σ) [dB]	1.05	1.47
Maximum (=Q4) [dBm]	-130.46	-128.62
Q3 [dBm]	-132.29	-129.02
Median (=Q2) [dBm]	-132.79	-129.95
Q1 [dBm]	-133.77	-131.61
Minimum [dBm]	-134.77	-132.89

Relatively to the network NI values, cell A shows an average 1.77 dB better then the network one, and in the other hand cell B presents an average slightly worst of 0.69 dB than the network. This substantiates to the representatively of the cells under analysis.

The individual NI levels at 10 MHz for cells A and B are presented in Figure 4.23.

In the case of 10 MHz one can consider that both cells follow a similar NI value trend, although cell A presents slightly better values than cell B. Both cell values are within the acceptable level of NI, of less than -127 dBm. Even considering the standard deviation for the maximum values for both, it would still maintain the values within the -127 dBm NI limit. This confirms the validity of these cells at NI level as 10 MHz channel representatives for this thesis, since from a NI perspective the results would not be influenced by excessive interference or noise.

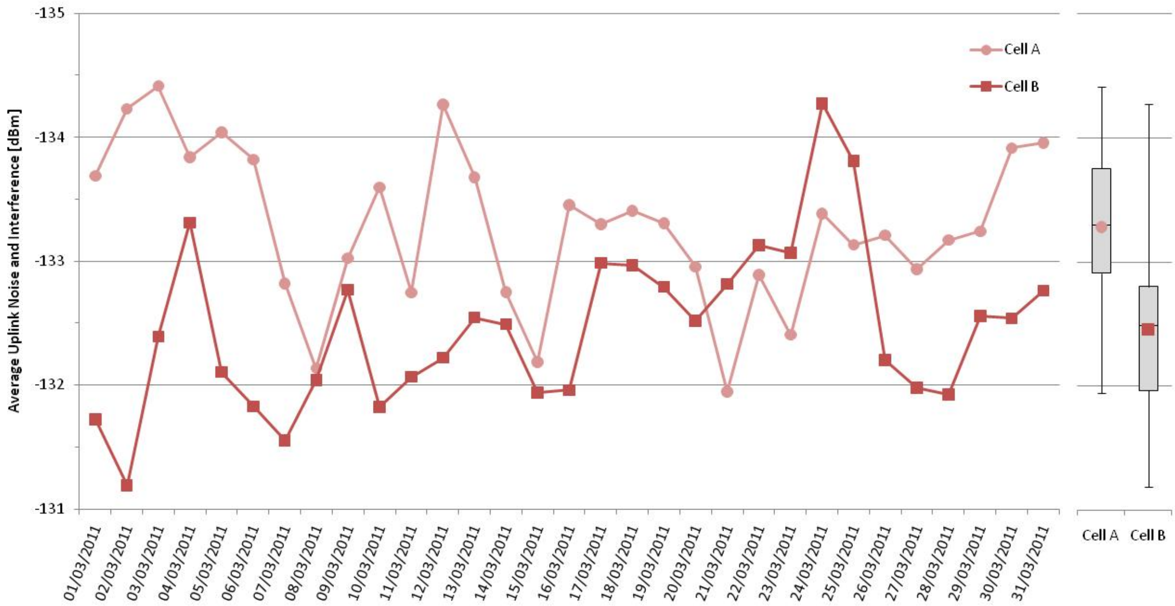

Figure 4.23. Daily average UL NI at 10 MHz channel for Cells A and B.

The main statistical elements to assess the level of NI for the individual cell under analysis are presented in Table 4.18.

Table 4.18 . Statistic values for average UL NI at 10 MHz channel for cells A and B.

Statistics	UL NI 10 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ) [dBm]	-133.28	-132.46
Standard Deviation (σ) [dB]	0.63	0.66
Maximum (=Q4) [dBm]	-131.95	-131.19
Q3 [dBm]	-132.91	-131.97
Median (=Q2) [dBm]	-133.30	-132.49
Q1 [dBm]	-133.75	-132.80
Minimum [dBm]	-134.41	-134.27

Comparatively to the network NI values, both cell show very similar values, cell A shows an average 0.57 dB better then the network one, and in the other hand cell B presents an average slightly worst of 0.25 dB than the network. This substantiates to the representatively of the cells under analysis.

The CINR values at 5 MHz and the NI values are inline, as cell A shows better results than B for both NI and CINR. For 10 MHz, and given the small difference in NI between both cells, one can still appreciate a positive correlation between CINR and NI values, where cell A has slightly better performance. The relation between 5 and 10 MHz at network level is again observed at cell level.

The network average weekly traffic patterns for DL in regards of QoS classes are presented in Figure 4.24. The pattern shows a preference to BE supported applications over the weekends, versus UGS, like VoIP, during the week days. Although not presented, the UL traffic follows the same pattern, this is important for the scenarios validation.

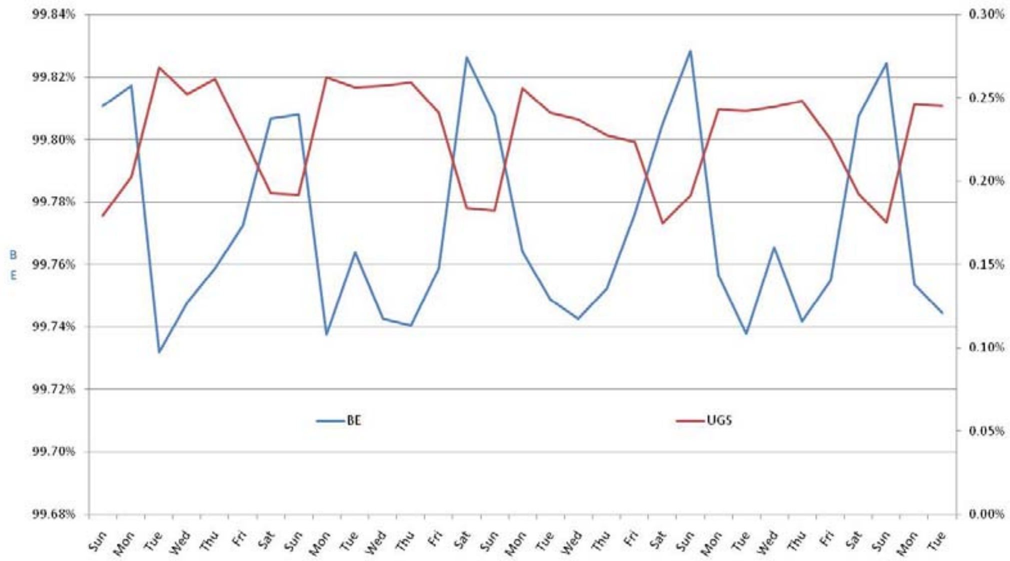

Figure 4.24. Weekly traffic pattern based on DL AP Sector Usage.

From the Database the values that are directly linked to KPIs as per Table 3.6 are presented next.

The Database network DL and UL Throughputs for 5 MHz are presented first, followed by the 10 MHz ones, all are directly related to Sector Peak sustained throughput DL (R_{bSDL}) and UL (R_{bSUL}) KPIs. The values from the database are the maximum daily peek values, sampled during one month period, and are ordered let to right on a descendent way. Since each sector is composed by one cell with only one carrier, the relation to the KPI is direct.

The network level DL Throughput at 5 MHz channels is presented in Figure 4.25.

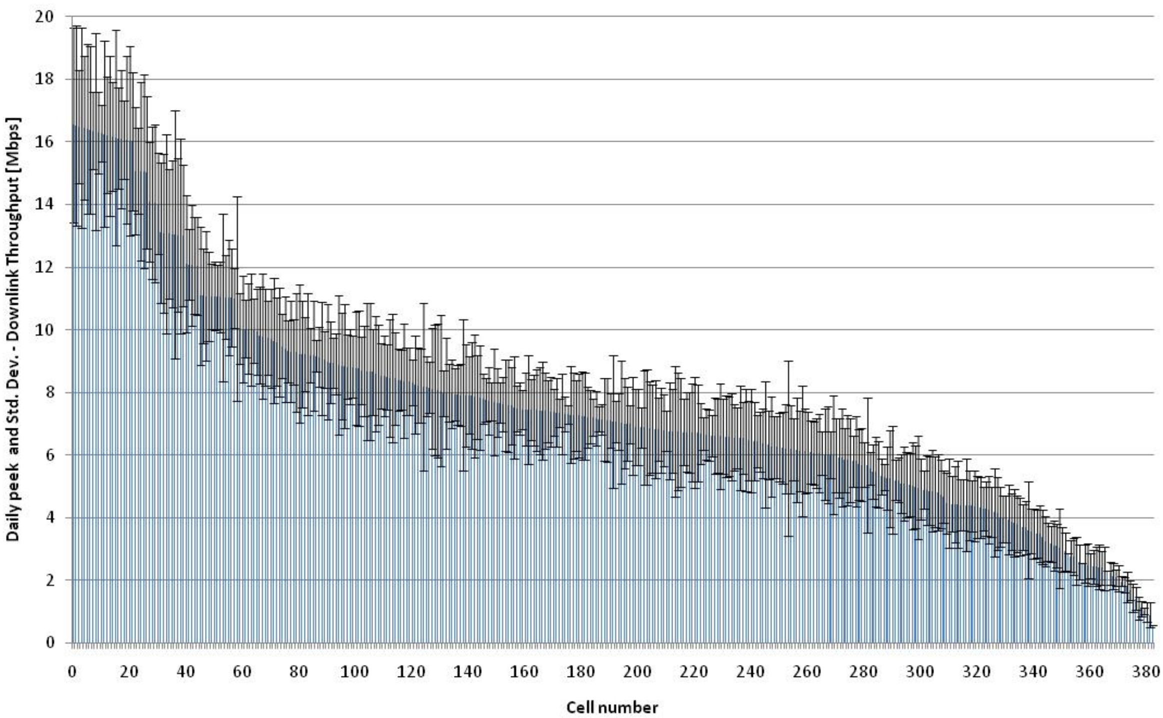

Figure 4.25. Daily peek and Std. Dev. of DL Throughput for Network at 5 MHz channel.

As for previous network level figures, the values in Figure 4.25 are the maximum of the daily peek values collected during one month period for each individual cell, and are ordered let to right on a descendent way i.e. highest values on the left to the lowest values on the right.

The main statistical elements related to Figure 4.25 are presented in Table 4.19.

Table 4.19. Network statistic values for DL throughput at 5 MHz Channel.

Statistics	DL Throughput 5 MHz Channel
Count	383
Average (μ) [Mbps]	7.50
Standard Deviation (σ) [Mbps]	3.50
Average Standard Deviation ($\bar{\sigma}$) [Mbps]	1.31
Maximum [Mbps]	16.54
Median [Mbps]	7.08
Minimum [Mbps]	0.57

From Figure 4.25 one can assess that only around 20 cells (5.2%) are near the maximum throughput; and from the statistics in Table 4.19 one verifies that both the average and the median are less than half of the maximum, therefore revealing a large potential of unused capacity in the network DL at 5 MHz.

The network level UL Throughput at 5 MHz channels is presented in Figure 4.26. As for the DL these are the maximum of the daily peek values collected during one month period for each individual cell, ordered in the same way.

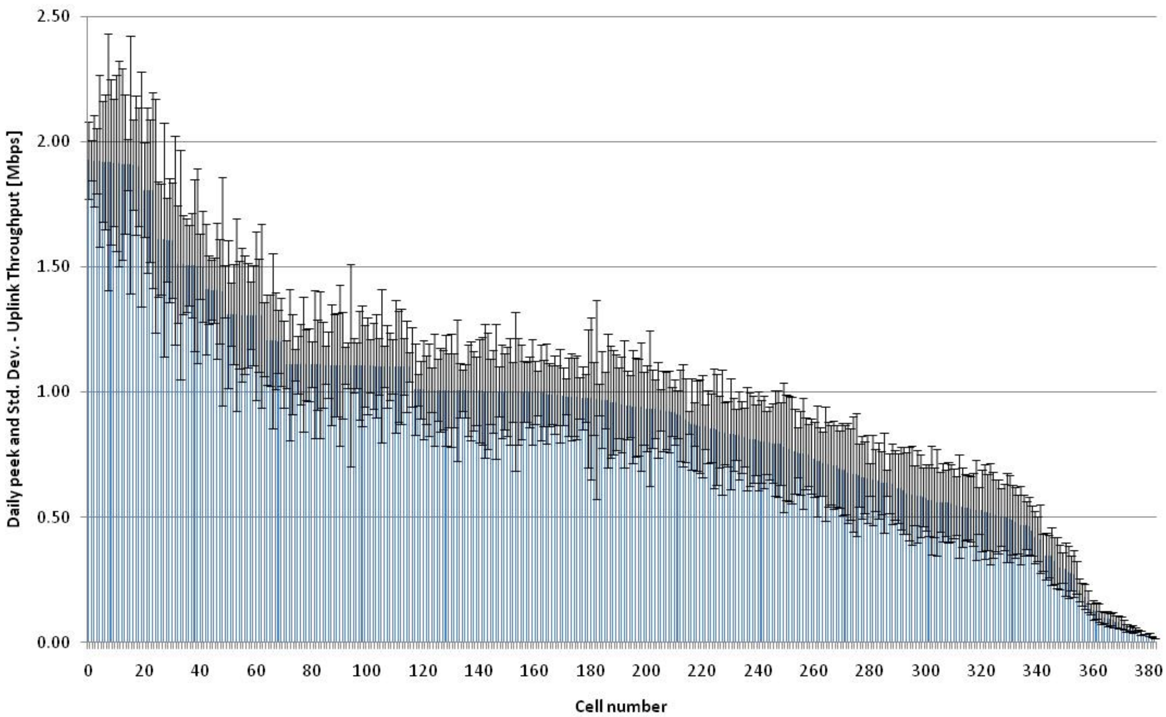

Figure 4.26. Daily peek and Std. Dev. of UL Throughput for Network at 5 MHz channel.

The main statistical elements related to Figure 4.26 are presented in Table 4.20.

Table 4.20. Network statistic values for UL throughput at 5 MHz Channel.

Statistics	UL Throughput 5 MHz Channel
Count	383
Average (μ) [Mbps]	0.91
Standard Deviation (σ) [Mbps]	0.43
Average Standard Deviation ($\bar{\sigma}$) [Mbps]	0.17
Maximum [Mbps]	1.93
Median [Mbps]	0.95
Minimum [Mbps]	0.02

As similar to DL one can consider from Figure 4.26 that only around 20 cells (5.2%) are near the maximum throughput; and from the statistics in Table 4.20 one verifies that the both the average and the median are less than half of the maximum, similarly revealing a large potential of unused capacity in the network UL at 5 MHz.

Relatively to Figure 4.25 it is also evident that around 20 cells show a very low maximum throughput indicating either a large asymmetry between UL and DL traffic for those cells (like service to users with asymmetrical traffic as MPEG 2) or a very reduced utilisation of them; apart from that both curves follow a very similar pattern. The DL average and maximum values are around 8 times higher than the UL ones, as expected, given the live network setup strong asymmetry for DL.

The network level DL Throughput at 10 MHz channels is presented in Figure 4.27. As for the 5 MHz UL, these are the maximum of the daily peek values collected during one month period for each individual cell, ordered in the same way.

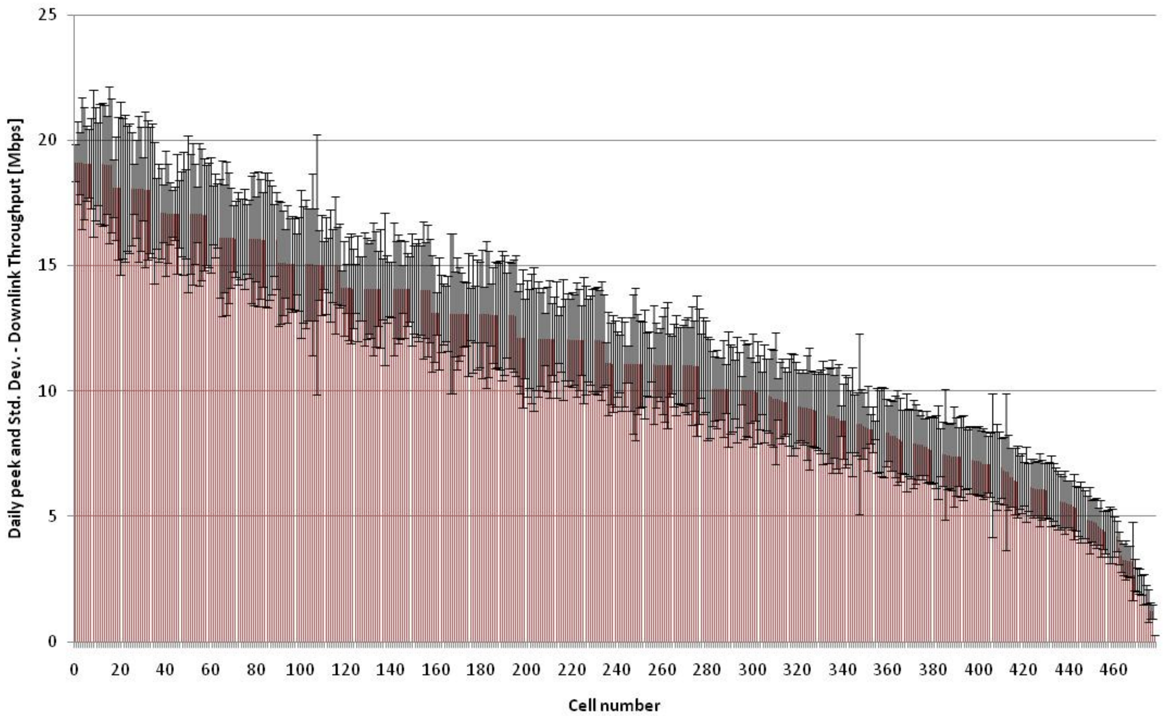

Figure 4.27. Daily peek and Std. Dev. of DL Throughput for Network at 10 MHz channel.

The main statistical elements related to Figure 4.27 are presented in Table 4.21.

Table 4.21. Network statistic values for DL throughput at 10 MHz Channel.

Statistics	DL Throughput 10 MHz Channel
Count	478
Average (μ) [ms]	11.42
Standard Deviation (σ) [Mbps]	4.18
Average Standard Deviation ($\bar{\sigma}$) [Mbps]	1.72
Maximum [ms]	19.10
Median [ms]	11.09
Minimum [ms]	0.27

From Figure 4.27 one can assess that only a few cells are near the maximum throughput denoting still as for 5 MHz a reduced usage of the available resources.

Comparing to the DL values of the maximum and average from Table 4.19 between 5 and 10 MHz one assesses that the average is 1.5 times higher, and the maximum is only 1.2 higher.

Relatively to the 5 MHz DL from Figure 4.25, one can verify that more usage is pulled out of the network since the decay of the curve is visually less steep. This is also seen by the ratio between maximum and average; on 5 MHz the ratio is 2.21 and for 10 MHz it is reduced to 1.67. This indicates a higher usage of available resources, either from an increase of usage by the subscribers since now they have higher throughput available; or by the increase of the number of users in the 6 month period between the collection of data; or even a mix of both.

The network level UL Throughput at 10 MHz channels is presented in Figure 4.28. Similar to the DL, these are the maximum of the daily peek values collected during one month period for each individual cell, ordered in the same way.

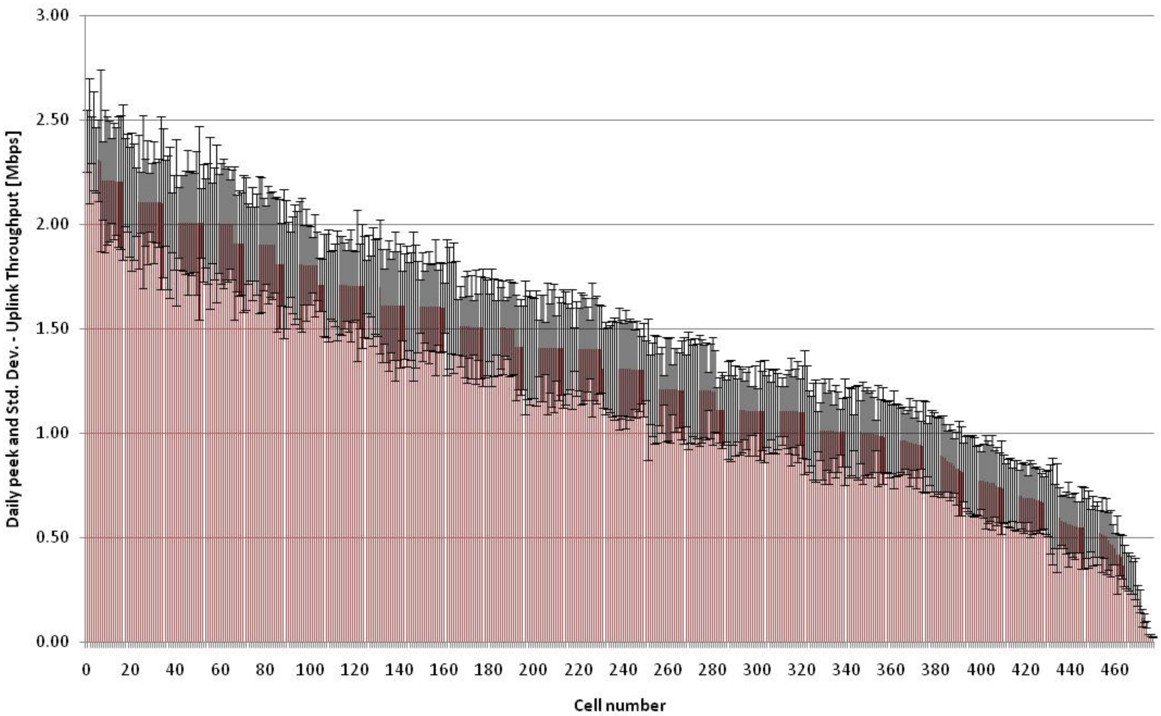

Figure 4.28. Daily peek and Std. Dev. of UL Throughput for Network at 510 MHz channel.

The main statistical elements related to Figure 4.28 are presented in Table 4.22.

Table 4.22. Network statistic values for UL throughput at 10 MHz Channel.

Statistics	UL Throughput 10 MHz Channel
Count	478
Average (μ) [Mbps]	1.32
Standard Deviation (σ) [Mbps]	0.51
Average Standard Deviation ($\bar{\sigma}$) [Mbps]	0.21
Maximum [Mbps]	2.40
Median [Mbps]	1.31
Minimum [Mbps]	0.02

Similarly to 5 MHz from Figure 4.25 one can still consider that only a few cells are near the maximum throughput, likewise revealing a large potential of unused capacity in the network at 10 MHz.

Relatively to Figure 4.26 it is also evident that the number of cells with a very low maximum throughput has decreased, indicating a regular and expected asymmetry between UL and DL traffic since both UL and DL curves for 10 MHz follow a very similar pattern. The DL average and maximum values are as well around 8 times higher than the UL ones, as expected, given the live network setup strong asymmetry for DL.

Comparing to the UL values of the maximum and average from Table 4.20 between 5 and 10 MHz one assesses that the average is 1.4 times higher, and the maximum is only 1.2 higher, this is similar to the DL values analysed before.

Relatively to the 5 MHz UL from Figure 4.26, one can verify that more usage is pulled out of the network since the decay of the curve is visually less steep. This is also seen by the ratio between maximum and average; on 5 MHz the ratio is 2.12 and for 10 MHz it is reduced to 1.82. This indicates a higher usage of available resources, for the same reasons point out for DL.

The Database cell level DL and UL Throughputs for 5 MHz are presented first, followed by the 10 MHz ones, as for the network level, these are also directly related to Sector Peak sustained throughput DL ($\mathrm{R_{bSDL}}$) and UL ($\mathrm{R_{bSUL}}$) KPIs. The values from the database are the maximum daily peek ones, which trend is presented over one month period, and since each sector is composed by one cell with only one carrier, the relation to the KPIs are direct.

The cell level DL Throughput at 5 MHz channels for cells A and B is presented in Figure 4.29; these are the maximum of the daily peek values for each cell.

Cell A shows an increase trend in the throughput values during the initial days of the sample becoming increasingly more stable towards the last days, while cell B shows a steady trend along the dates in analysis. Cell B presents consistently higher values than cell A, with the exception of the value of the very last day in the analysis, indicating a higher usage of resources from cell B when compared solely with cell A.

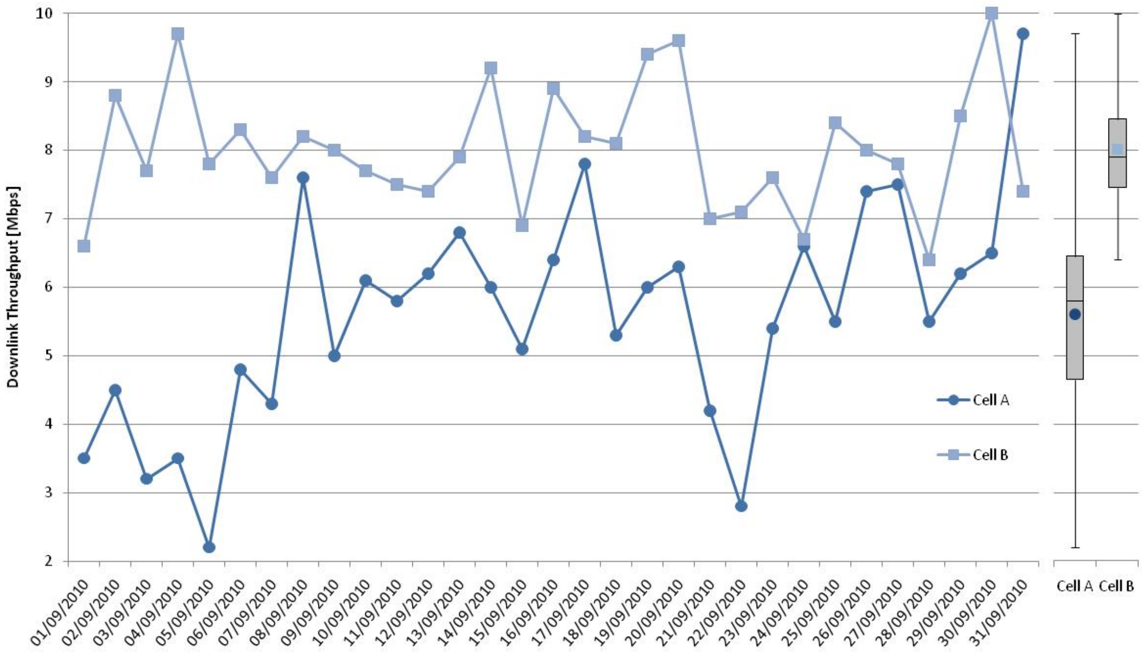

Figure 4.29. DL throughputs at 5 MHz Channel for cells A and B.

The main statistical elements related to Figure 4.29 are presented in Table 4.23.

Table 4.23. Statistic values for DL throughputs at 5 MHz Channel for cells A and B.

Statistics	DL Throughput 5 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ) [Mbps]	5.60	8.01
Standard Deviation (σ) [Mbps]	1.62	0.93
Minimum [Mbps]	2.20	6.40
Q1 [Mbps]	4.65	7.45
Median (=Q2) [Mbps]	5.80	7.90
Q3 [Mbps]	6.45	8.45
Maximum [Mbps]	9.70	10.00

All statistical elements of cell A present lower values then cell B, confirming a higher usage of the resources from cell B.

Both cells show maximum values bellow the network ones for 5 MHz, but cell B presents an average slightly higher when comparing to Figure 4.25 and the values in Table 4.19. This indicates that although cell B has a higher usage than cell A, both cells have an ample unused capacity for the period in analysis.

The individual UL Throughput at 5 MHz channels for cells A and B is presented in Figure 4.30; as for the DL these are the maximum of the daily peek values for each cell.

Both cells show very similar trends for the UL; both developing along a steady progress and not showing a tendency to an increase or decrease. Cell A shows a slightly higher dispersion of the values. This indicates a very similar resource usage level for both.

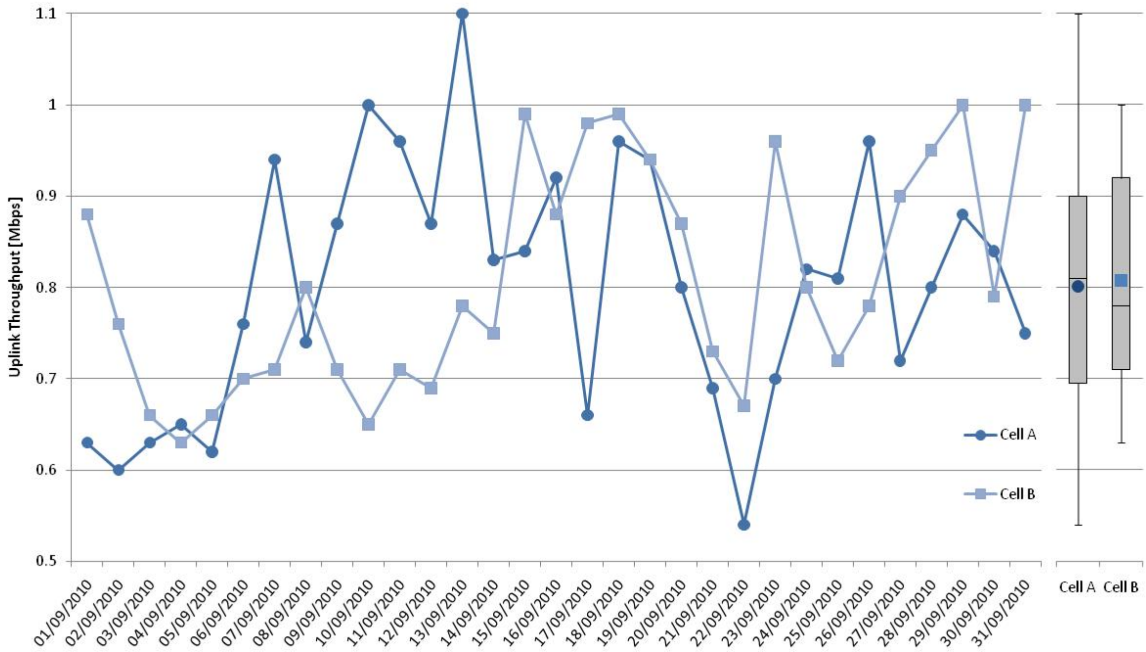

Figure 4.30. UL throughputs at 5 MHz Channel for Cells A and B.

The main statistical elements related to Figure 4.30 are presented in Table 4.24.

Table 4.24. Statistic values for UL throughputs at 5 MHz Channel for cells A and B.

Statistics	UL Throughput 5 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ) [Mbps]	0.80	0.81
Standard Deviation (σ) [Mbps]	0.14	0.12
Minimum [Mbps]	0.54	0.63
Q1 [Mbps]	0.70	0.71
Median (=Q2) [Mbps]	0.81	0.78
Q3 [Mbps]	0.90	0.92
Maximum [Mbps]	1.10	1.00

All statistical elements of both cells present similar values, confirming a very similar resource usage level for both.

Both cells show average and maximum values bellow the network ones for 5 MHz when comparing to Figure 4.25 and the values in Table 4.19. This indicates that both cells have plenty unused capacity for the period in analysis.

The DL average is 7 times higher and the maximum 9 times higher than the UL ones for cell A, and both DL average and maximum are 10 times higher for cell B in relation to the UL this is expected and already observed at the network level; this also indicates a higher asymmetry for cell B when compared to cell A, although still close to the 8 times difference observed at the network level.

The individual DL Throughput at 10 MHz channels for cells A and B is presented in Figure 4.31; these are the maximum of the daily peek values for each cell as like the 5 MHz ones.

Both cells show very similar trends for the DL; both developing along a steady progress and not showing a tendency to an increase or decrease. Cell B shows a slightly higher dispersion of the values. This indicates a very similar resource usage level for both.

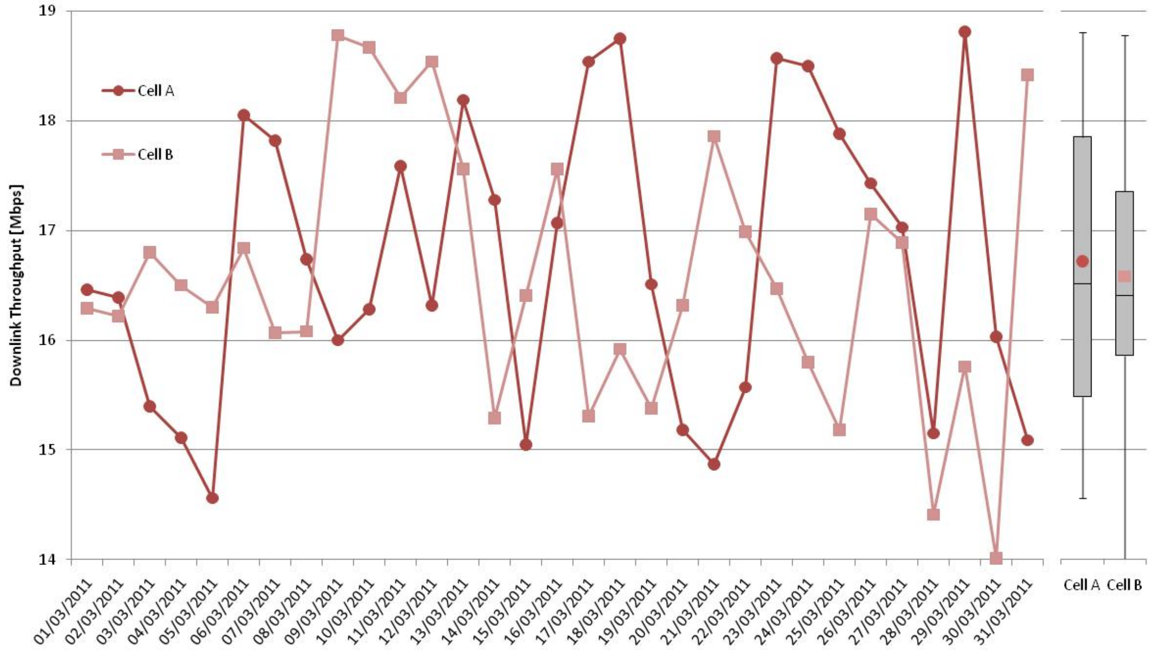

Figure 4.31. DL throughputs at 10 MHz Channel for cells A and B.

The main statistical elements related to Figure 4.31 are presented in Table 4.25.

Table 4.25. Statistic values for DL throughputs at 10 MHz Channel for cells A and B.

Statistics	DL Throughput 10 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ) [Mbps]	16.72	16.58
Standard Deviation (σ) [Mbps]	1.32	1.21
Minimum [Mbps]	14.56	14.01
Q1 [Mbps]	15.49	15.86
Median (=Q2) [Mbps]	16.51	16.41
Q3 [Mbps]	17.85	17.36
Maximum [Mbps]	18.81	18.78

All statistical elements of both cells present similar values, confirming a very similar resource usage.

Both cells show maximum values bellow, and average values higher, to the network ones for 10 MHz, when comparing to Figure 4.27 and the values in Table 4.21. This indicates similar usage levels of both cells and some degree of unused capacity for the period in analysis.

Comparing to the DL values of the average and maximum with Table 4.23 between 5 and 10 MHz one assesses that the 10 MHz average is 3 times higher for cell A and 2.1 times higher for cell B, and the maximum is 1.9 times higher for both cells. This indicates the increase in the DL capacity when moving from 5 to 10 MHz channels.

For cell A the maximum to average DL ratio is 1.1 which is lower than the same ratio of 1.7 for 5 MHz denoting a higher usage of resources at 10 MHz for that cell. For cell B the maximum to average DL ratio is 1.1 which is just slightly lower than the same ratio of 1.2 for 5 MHz denoting a slightly higher usage of resources at 10 MHz for that cell.

The individual UL Throughput at 10 MHz channels for cells A and B is presented in Figure 4.32; these are the maximum of the daily peek values for each cell as like the 5 MHz ones.

Both cells show very similar trends for the UL; both developing along a steady progress and not showing a tendency to an increase or decrease. Cell B shows a slightly higher dispersion of the values. This indicates a very similar resource usage level for both.

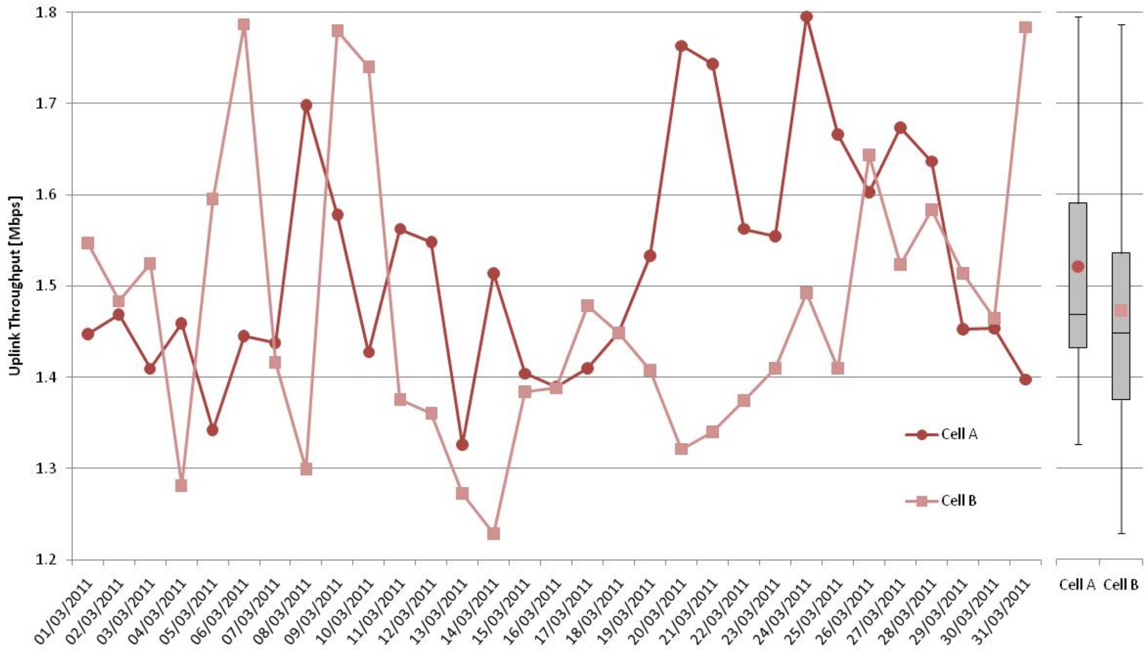

Figure 4.32. UL throughputs at 10 MHz Channel for cells A and B.

The main statistical elements related to Figure 4.32 are presented in Table 4.26.

Table 4.26. Statistic values for UL throughputs at 10 MHz Channel for cells A and B.

Statistics	UL Throughput 10 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ) [Mbps]	1.52	1.47
Standard Deviation (σ) [Mbps]	0.13	0.15
Minimum [Mbps]	1.33	1.23
Q1 [Mbps]	1.43	1.37
Median (=Q2) [Mbps]	1.47	1.45
Q3 [Mbps]	1.59	1.54
Maximum [Mbps]	1.80	1.79

Both cells present similar statistical values, confirming a very similar resource usage level for both. Also both cells show maximum values bellow, and average values higher, to the network ones for 10

MHz, when comparing to Figure 4.28 and the values in Table 4.22. This indicates similar usage levels between both cells and some degree of unused capacity for the period in analysis.

The DL average is 11 times higher and the maximum 10 times higher than the UL ones for cell A, and both DL average and maximum are 11 times higher for cell B in relation to the UL this is as expected and already observed at the network level; this also indicates a slightly higher asymmetry for cell B when compared to cell A, likely to the 10 MHz. This ratio is further away to the 8 times difference observed at the network level denoting a higher asymmetry between DL and UL than the network average for these cells when compared to 10 MHz.

Comparing the UL values of the average and maximum with Table 4.24 between 5 and 10 MHz one assesses that the 10 MHz average is 1.9 times higher for cell A and 1.8 times higher for cell B, and the maximum is 1.6 times higher for cell A and 1.8 times higher for cell B. This indicates the increase in the UL capacity when moving from 5 to 10 MHz channels.

For cell A the maximum to average UL ratio is 1.2 which is slightly lower than the same ratio of 1.4 for 5 MHz denoting a slightly higher usage of UL resources at 10 MHz for that cell. For cell B the maximum to average UL ratio is 1.2 for both at 5 and 10 MHz, denoting similar usage of resources at 5 and 10 MHz for that cell.

The database network level Maximum and Std. Dev. for Peak Single Channel Users in Active/Sleep State at 5 MHz channel is presented first, followed by the 10 MHz one. The values retrieved from the database, for the network level analysis, are the maximum of the daily peeks values of each cell sampled over one month period and are ordered let to right on a descendent way.

The network level Peak Single Channel Users in Active/Sleep State at 5 MHz channel is presented in Figure 4.33, and the main statistical elements related are presented in Table 4.27.

A much reduced quantity of cells, less than 10, presents a number of users over 150, and the maximum reaches up to 190 users. These numbers are much higher than the average of 45.63 users and median of 35 users, revealing a large unused capacity still available in the network.

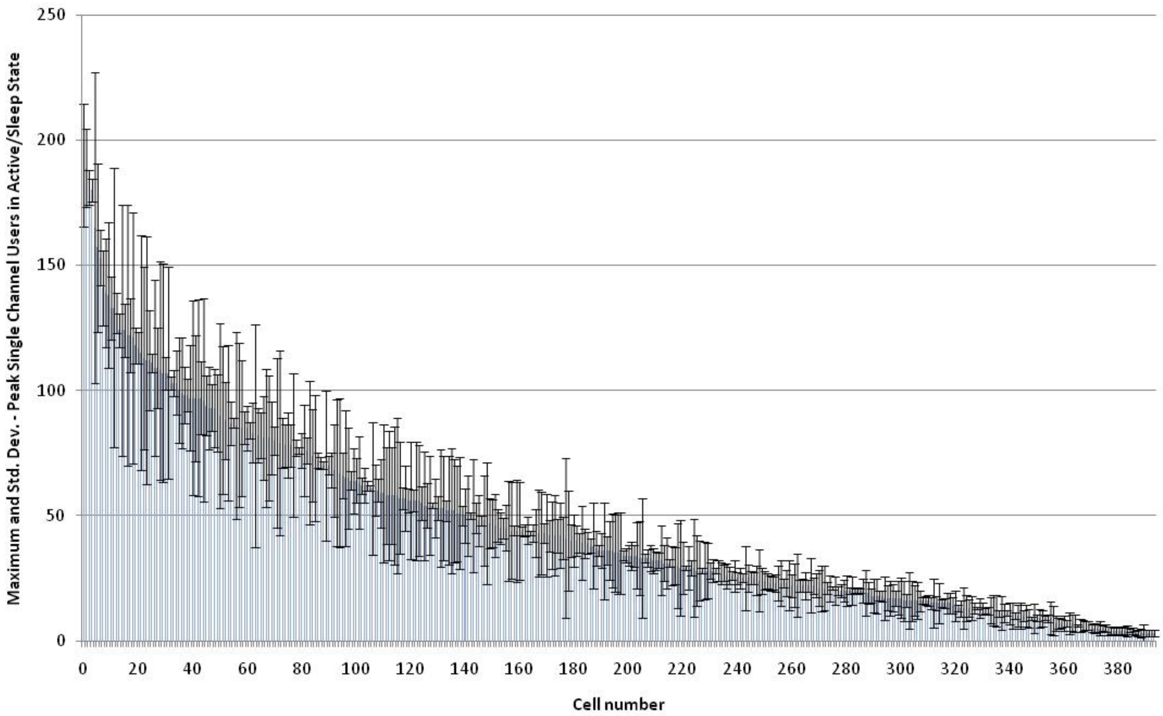

Figure 4.33. Network Maximum and Std. Dev. for Peak Single Channel Users in Active/Sleep State at 5 MHz channel.

Table 4.27. Network statistic values for Peak Single Channel Users in Active/Sleep State at 5 MHz channel.

Statistics	Peak Single Channel Users in Active/Sleep State 5 MHz Channel
Count	394
Average (μ)	45.63
Standard Deviation (σ)	36.90
Average Standard Deviation ($\bar{\sigma}$)	10.56
Maximum	190
Median	35
Minimum	3

The network level Peak Single Channel Users in Active/Sleep State at 10 MHz channel is presented in Figure 4.34, and the main statistical elements are presented in Table 4.28.

As like for 5 MHz, only a reduced quantity of cells, less than 10, presents a number of users over 150, but the maximum reaches now reaches up to 236 users. These numbers are much higher than the average of 53.50 users and median of 44 users, again revealing a large unused capacity still available in the network.

The ration between maximum values for 5 and 10 MHz is 1.24 while for the average is 1.17.

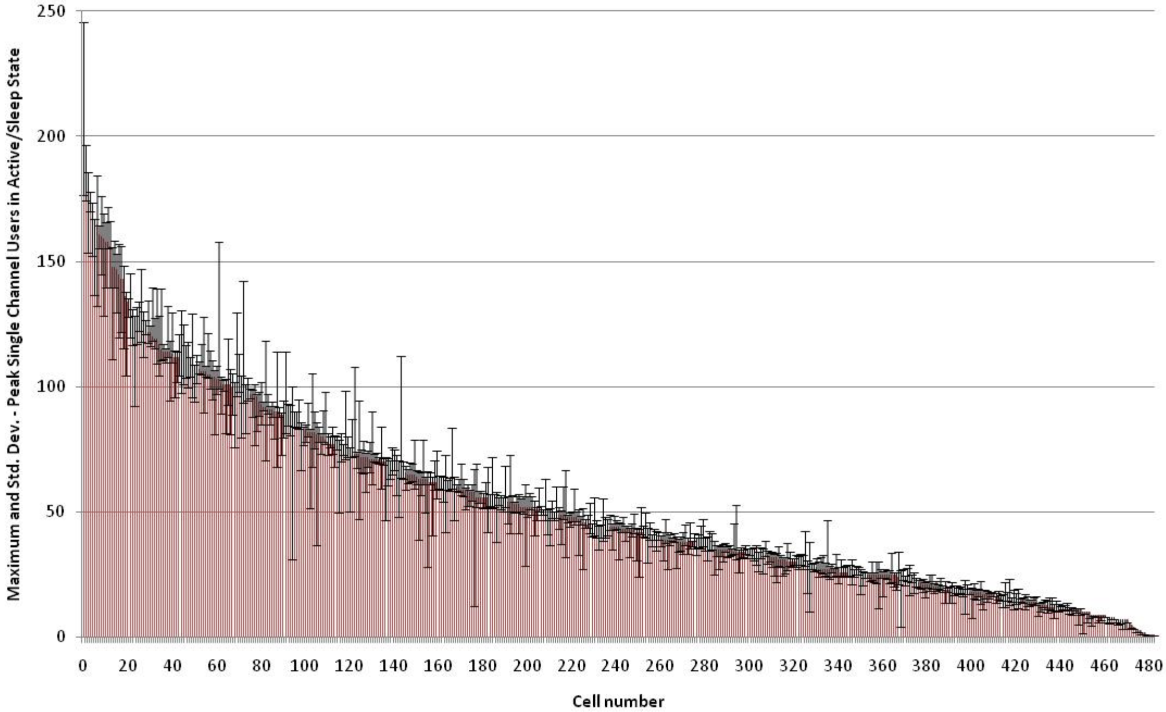

Figure 4.34. Network Average and Std. Dev. for Peak Single Channel Users in Active/Sleep State at 10 MHz channel.

Table 4.28. Network statistic values for Peak Single Channel Users in Active/Sleep State at 10 MHz channel.

Statistics	Peak Single Channel Users in Active/Sleep State 10 MHz Channel
Count	483
Average (μ)	53.50
Standard Deviation (σ)	38.96
Average Standard Deviation ($\bar{\sigma}$)	6.02
Maximum	236
Median	44
Minimum	1

The cell level Peak Single Channel Users in Active/Sleep State at 5 MHz channels for cells A and B is presented in Figure 4.35; these are the daily peak values for each cell.

The trends presented by both cells show clear increase tendency, and in general cell B presents consistently higher values than A.

The main statistical elements related to Figure 4.35 are presented in Table 4.29.

From the statistics it is clear that cell B has a higher usage level when compared to A at 5 MHz since all values are consistently higher.

Comparing with the network at 5 MHz one assesses that cell A presents a very similar average and all other statistics show lower values, while cell B shows a higher average and median but still a maximum value lower than the network one. From this one assesses that although both cells have unused capacity, cell B has a utilisation more close to the network highest.

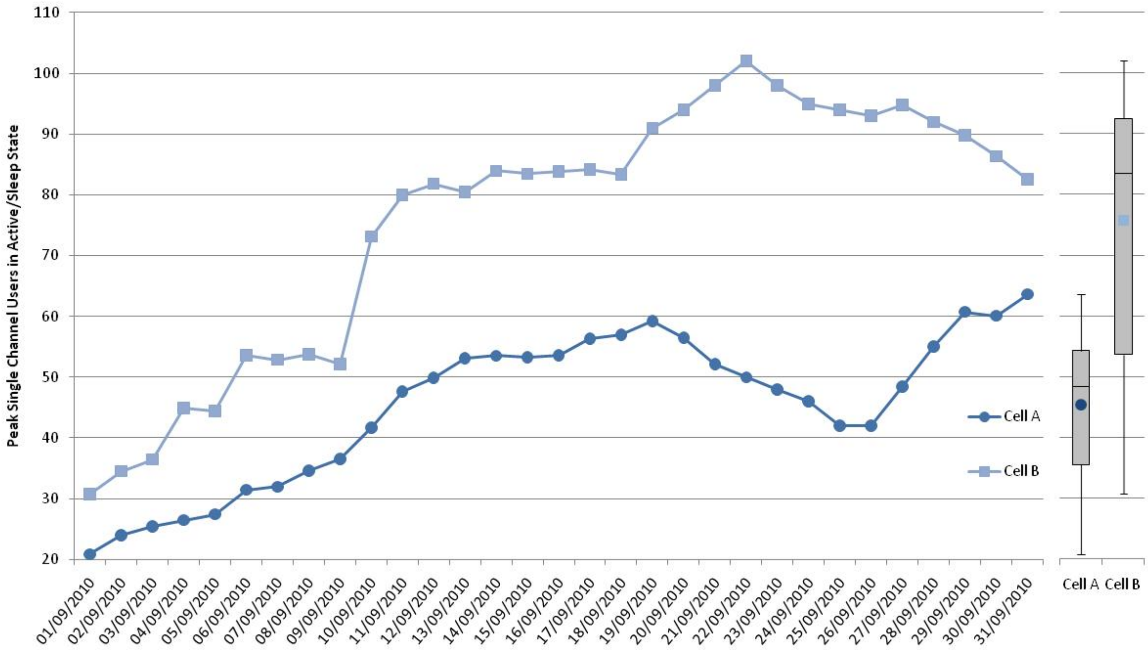

Figure 4.35 Peak Single Channel Users in Active/Sleep State at 5 MHz channel for cells A and B.

Table 4.29. Statistic values for Peak Single Channel Users in Active/Sleep State at 5 MHz channel for cells A and B.

Statistics	Peak Single Channel Users in Active/Sleep State 5 MHz channel	
	Cell A	**Cell B**
Count	31	31
Average (μ)	45.42	75.77
Standard Deviation (σ)	12.43	21.50
Minimum	21	31
Q1	35.50	54.00
Median (=Q2)	48	83
Q3	54.50	92.50
Maximum	64	102

The cell level Peak Single Channel Users in Active/Sleep State at 10 MHz channels for cells A and B is presented in Figure 4.36; these are the daily peak values for each cell.

The trends presented by both cells do not show clear increase tendency as of 5 MHz or a decrease tendency either, and in general cell B presents consistently higher values than A.

The main statistical elements related to Figure 4.36 are presented in Table 4.30.

From the statistics it is clear that cell B has a higher usage level when compared to A at 10 MHz since all values are consistently higher.

Comparing with the network at 10 MHz one assesses that both cells present higher average and median but still a maximum value lower than the network one. From this, one considers that although both cells have unused capacity, cell B has a utilisation more close to the network highest.

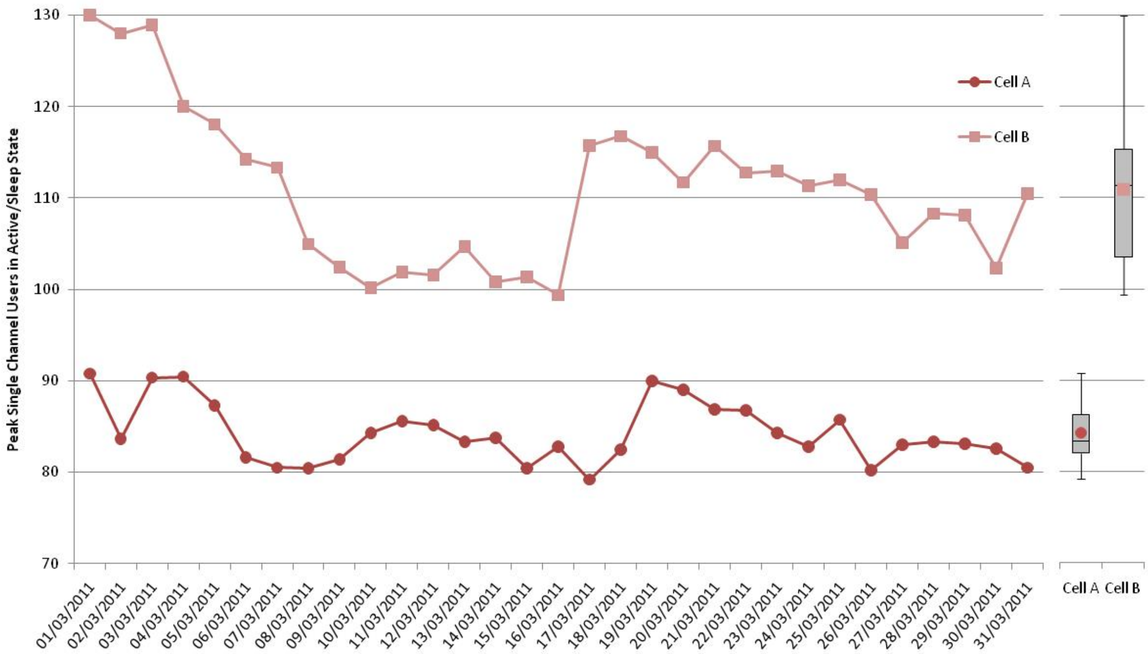

Figure 4.36 Peak Single Channel Users in Active/Sleep State at 10 MHz channel for cells A and B.

Table 4.30. Statistic values for Peak Single Channel Users in Active/Sleep State at 10 MHz channel for cells A and B.

Statistics	Peak Single Channel Users in Active/Sleep State 10 MHz channel	
	Cell A	**Cell B**
Count	31	31
Average (μ)	84.23	110.87
Standard Deviation (σ)	3.32	8.46
Minimum	79	99
Q1	82.00	103.50
Median (=Q2)	83	111
Q3	86.50	115.50
Maximum	91	130

When comparing with 5 MHz one clearly verifies that now both cells have consistently higher values for all the 10 MHz statistical elements, cell A average is 1.85 time higher and maximum 1.42 times higher; for cell B the average is now 1.46 time higher and maximum 1.34 times higher only when comparing the 10 MHz with the 5 MHz values. Thus reveals the expected increase in relative capacity and utilisation from 5 to 10 MHz.

4.4 Comparison

Following a comparison between the theoretical results and the related experimental results is presented.

Taking into account the theoretical MCS values presented in Table 4.7 and comparing them to the live network ones from Table 4.14, it is clear that more users benefit from a better MCS on the live network than the theoretical estimated one. This directly relates to the $\overline{N_{bMCSUL/DL}}$, and using (3.12) one assesses that it increases by 76% on the DL and 23% on the UL for 5 MHz; 74% on the DL and 22% on the UL for 10 MHz, thus influencing the calculated capacity in terms of maximum number of users presented on Table 4.8, that would reach up to 67% more users, depending on the workload asymmetry and frame resources consumption This approximation error is mainly due to factors like a carful distribution of the users on the network, bearing in mind that the live network users are mostly static with locations well defined and assessed previously by the service provider team for ideal signal conditions for the subscribed service, and also influenced by the usage on the live network of AAS. As assumed, the difference between 5 and 10 MHz is much reduced, confirming the validity of the relative comparisons between the different channel bandwidths in question.

The CINR KPI from Table 2.9 considers a threshold of 12 dB during 95% of the time, corresponding to the lowest value that would be considered by the network operator for a user to achieve the minimum level of service indoors. From the values presented from Figure 4.15 to Figure 4.17 one retrieves that at network level 97.4% for both 5 and 10 MHz are above the 12 dB thus achieving the KPI, and at cell level for 5 MHz one has 97.45% for cell A and 97.16 for cell B above the 12 dB thus achieving the KPI, and for 10 MHz one has 97.09% for cell A and 97.06 for cell B above the 12 dB also achieving the KPI. This confirms the validity of those cells to be good representatives of the general network for the analysis.

The Residential scenarios in Table 4.3 follow the same pattern as the QoS classes in Figure 4.24 where the preference to VoIP (UGS) is visibly shown during the working weekdays rather than weekends. The live network average QoS classes utilisation is more pronounced then the one used for the theoretical scenarios. From Figure 4.24 one assesses that the BE is higher than 99% and the UGS that supports VoIP is lower than 1%, although not shown this is valid for both UL and DL and at 5 and 10 MHz, these percentages, if used on the theoretical scenarios, would not allow for differentiations that could be noticeable when studying the variation of them, thus higher percentages were given to VoIP whole maintaining the weekly pattern. Comparing the values between Residential (weekdays) and Residential (weekends) from Table 4.9 in relation to the scenarios from Table 4.3, the change of 20% more VoIP users on the weekdays scenario also translates on around 26% more on the maximum number of the total users possible. Since the network shows a lower VoIP utilisation compared to the theoretical scenarios, and VoIP being one of the workloads that allows for more simultaneous users, this would translate that the estimated theoretical users values for each workload at each bandwidth are around 13% higher than the ones achievable by the live network, somehow partially compensating for the MCS approximation error.

The live network throughputs from 5 to 10 MHz in Figure 4.25 to Figure 4.28 are within the same order of magnitude of the theoretical results in Table 4.4, although they present a wide range of variance. The differences between the theoretical values and the live network values are shown in Table 4.31. The difference of the maximum values are explained mainly by the usage of MIMO on the live network for the 5 MHz where the theoretical maximum is lower then the measured on in the live network since this technique was not considered in the theoretical model, and for the 10 MHz ones the differences between the maximum are due to the network not being subject of enough load to reach the theoretical limits, which by the usage of MIMO and similarly to the 5 MHz ones should be exceeded. One also needs to consider that the theoretical throughput are actually the maximum physical level ones, thus not considering the overheads inherent on the values measured on the live network. The average theoretical values are determined by averaging the values from Table 4.4 by the MCS values from Table 4.14.

Table 4.31. Live and Theoretical Throughput Comparison.

Throughput Comparison	5MHz Channel		10MHz Channel	
	DL	UL	DL	UL
Theoretical				
Maximum [Mbps]	11.67	1.87	23.35	3.85
Average [Mbps]	8.66	1.09	17.07	2.22
Live				
Maximum [Mbps]	16.54	1.93	19.10	2.40
Average [Mbps]	7.50	0.91	11.42	1.32
Difference				
Maximum	41.69%	3.34%	-18.19%	-37.58%
Average	-13.37%	-16.55%	-33.08%	-40.53%

As expected an increase is seen in the live network throughput values between 5 to 10 MHz, but this less than the 2 times higher values seen in the theoretical ones. This is due to the loading of the current live network not being sufficient to take advantage of the increase in throughput capacity from 5 to 10 MHz. At cellular level the DL average is 3 times higher for cell A and 2.1 times higher for cell B, and the maximum is 1.9 times higher for both cells when comparing from 5 to 10 MHz; for the UL the average is 1.9 times higher for cell A and 1.8 times higher for cell B, and the maximum is 1.6 times higher for cell A and 1.8 times higher for cell B when comparing from 5 to 10 MHz; for the chosen cells the relation between 5 and 10 MHz is very close to the expected when comparing with the theoretical values. The ratio between DL and UL in the live network level is 8 times and at cellular level between 10 and 11 times, this is higher than the theoretical one which is around 6 times; this could be explained by a difference in the asymmetry assumption taken in the theoretical model, since from Figure 4.24 it is clear that the more asymmetrical services like MPEG2, Email, FTP are preferred to the symmetrical one of VoIP. Globally it is clear from the figures presented that the users are not achieving the maximum possible throughput available in the cells either by service offering limitations by the network operator or by the users themselves not requiring the full extent of the available resources.

In regards to the Throughput KPIs, given the thresholds from Table 2.9, one considers the following:

the 5 MHz DL KPI is set at 7.7 Mbps and the live network level presents values ranging from 0.57 to 16.54 Mbps, thus one considers that only a fraction or the cells achieves this KPI, more exactly 234 out of the 383 cells present values under this KPI threshold. In relation to the 5 MHz UL KPI is set at 1.28 Mbps, while the live network level presents values ranging from 0.02 to 1.93 Mbps, thus one considers that only a fraction or the cells achieves this KPI, more exactly 320 out of the 383 cells present values under this KPI threshold. Regarding the 10 MHz DL KPI is set at 15.5 Mbps and the live network level presents values ranging from 0.27 to 19.10 Mbps, thus one considers that only a fraction or the cells achieves this KPI, more exactly 389 out of the 478 cells present values under this KPI threshold; finally for the 10 MHz UL KPI that is set at 2.4 Mbps, the live network level presents values ranging from 0.02 to 2.40 Mbps, thus only 4 out of the 478 cells achieves this KPI.

At cell level for 5 MHz DL cell A achieves a maximum of 9.7 Mbps and B a maximum of 10.00 Mbps so one considers that both achieve this KPI. For the UL cell A has a maximum of 1.1 Mbps and cell B 1.00 Mbps thus not achieving this KPI. For 10 MHz DL cell A achieves a maximum of 18.81 Mbps and B a maximum of 18.78 Mbps so one considers that both achieve this KPI. For the UL cell A has a maximum of 1.8 Mbps and cell B 1.79 Mbps thus not achieving this KPI

These throughput KPI values were designed to verify with specific equipment that the cell meets the design potential when it is initially put into service, and not to compare directly with the database, although that would still be possible for remote sanity checks.

The latency data is available on Annex G. The live network shows average values higher than the deadline of MPEG2, FTP and Email shown in Table 4.5, which are used for the theoretical scheduler for the calculations. The live network schedule implementation is not known, thus the full impact of this can not be fully assessed. If we consider a similar implementation of the live scheduler to the theoretical one, the implication of this higher latency values are felt on the workloads that have the lower deadline requirements since they could not have the user data aggregated and reducing the maximum number of supported users for them. Since one of the main workloads is the HTTP that has a high tolerance to latency, and since the VoIP deadline if higher then the average of the latency, the impact is expected to be reduced in terms of the difference between live network capacity and the theoretical one.

In regards to the Latency KPI, the value set in Table 2.9 is 120 ms for the QoS class of BE that is used to collect the values for live network from the database, one is confronted that not all the cells achieve this KPI. At 5 MHz, although at network level the average is 39.29 ms, the maximum shows a value of 188.06 ms, this relates to 5 cells out of the 394 not achieving this KPI. At 10 MHz the average is 49.11 ms but the maximum is 220.12 ms, this relates to 10 cells out of the 483 not achieving this KPI. This again confirms the previous finding that the latency at 10 MHz is slightly worst than at 5 MHz. At cell level one verifies that both cells at either 5 or 10 MHz are able to achieve this KPI, again confirming the validity of those cells to represent the network for the analysis.

The Packet Drop data is available on Annex G. At network level the packet drop presents maximum values at both 5 and 10 MHz bellow the 2% KPI threshold, although a much reduced set of cells have standard deviations indicating the possibility that they would have reached this value over the sampled period. At cell level it is clear that both cells for both 5 and 10 MHz present values well bellow the threshold, once more confirming the validity of those cells to represent the analysis.

The live network maximum users per carrier from Figure 4.33 and Figure 4.34 are within the same order of magnitude as the theoretical ones from Table 4.9. The comparison is presented in Table 4.32 where the relative differences from the live to the theoretical maximum values are compared. The residential weekdays is the scenario closer to the live network one, even though still showing a 78% higher live network value difference in 5 MHz, but showing very close values at 10 MHz with only a 2 % higher for the theoretical one. The average is also presented to highlight the difference to the maximum, from were one verifies that to a larger extent the network has available capacity, and so the relative differences still have room to reduce.

Table 4.32. Live and Theoretical User Capacity Comparison.

User Capacity Comparison	5 MHz Channel	10 MHz Channel
Theoretical Scenarios		
Reference	85	190
Business	84	189
Residential weekdays	107	240
Residential weekends	85	191
Live Network		
Average	45.63	53.50
Maximum	190	236
Difference to Live Network Maximum		
Reference	124%	24%
Business	126%	25%
Residential weekdays	78%	-2%
Residential weekends	124%	24%

The theoretical ratio between 5 and 10 MHz is around 2 times while the live network is only 1.24 times for the maximum and 1.17 for the average. At cellular level these gaps are reduced since cell A average is 1.85 time higher and maximum 1.42 times higher; for cell B the average is now 1.46 time higher and maximum 1.34 times higher.

The differences may be explained by the loading of the current live network not being sufficient to take advantage of the increase in user capacity from 5 to 10 MHz; and the assumptions made for the theoretical scenarios not reproducing the live one, by a different scheduler than the one assumed for the theoretical calculations.

In general, for the cells not achieving some KPI it could be required a local assessment of it by specific equipment prepared for that measurement in the range of coverage of those cells. This would clear the uncertainty if it is in fact a cell performing bellow the required potential or if it is due to not having enough usage to show the achievement of this KPI from the database. But before this other database values assessment would be conducted like checking for other periods of time, or checking the exact user load for that particular cell, but this would be part of the operations and optimisation of the network excluded from the scope of this thesis.

Chapter 5

Conclusions

This chapter finalises this work, summarises the main conclusions and provides suggestions for future work.

The main objective of thesis is to analyse the overall performance of a WiMAX System in regards to the channel bandwidths of 5, 10 and 20 MHz, mainly focussing on capacity aspects of the radio interface, like the maximum user throughput and maximum number of users per channel. Theoretical models for the calculations of the maximum physical throughput and the maximum user number, are implemented using simple algorithms over excel workbooks. These models provide simple ways to estimate the throughput at different channel bandwidths for the available system MCSs, as well as the maximum number of users for a variety of workloads based on several traffic models, thus making possible the creation of scenarios to represent the real world as a secondary objective. The assessment of the accuracy of the theoretical model is performed by comparing the achieved values with the ones retrieved from the database of a live network.

Extensive literature is available on each of the individual subjects and showing several assessments, however, it does not contemplate to the full extent all of the studied constraints. Also the definition of possible KPIs for live network assessment is presented, which effectively covers the analysed system performance.

The throughput model starts by analysing the system frame in the light of some chosen system typical constraints like: TDD, 5ms frame duration, PUSC, 3:1 frame ratio and 5, 10 and 20 MHz channel bandwidths. The calculations are divided in UL and DL and the channel bandwidths, determining for each of the combinations the slots per subframe, followed by the bytes per slot, and finally determining the physical throughput.

The model for the maximum number of users is strictly related to each of the workloads analysed. It starts by a brief analysis of the main workload parameters like average packet size and data rate, then introduces the overhead, which is something usually not considered in similar analysis, thus, leading to results further away from reality, to finally estimate the capacity taking into consideration the asymmetry of the workloads.

The coverage is estimated based on the available cell ranges in the available literature, and no model apart from the usual and well known hexagon grid is presented. This coverage analysis is presented with the intent to take some conclusions in relation to the number of users that could be supported by each theoretical scenario.

The database is required to collect the live network values, used to assess the theoretical model and network KPIs. A high capacity and well organised database is required to gather all the live network values necessary to monitor and evaluate the network performance. The order of magnitude of the database size is of 10 Gbyte per each month of live network data.

Both the network and the individual cells present CINR values within the KPI threshold for both 5 and 10 MHz channel bandwidths, thus, concluding that both the network and the cells are suitable for this study in terms of CINR.

The maximum throughput values achieved by the theoretical model were at physical level for the 5 MHz channel 11.67 Mbps for DL and 1.87 Mbps for UL, for the 10 MHz channel 23.35 Mbps for DL and 3.85 Mbps for UL, and finally for 20 MHz channel, 46.69 Mbps for DL and 7.69 Mbps for UL. This equates to doubling the throughput each time the channel bandwidth doubles. This behaviour is seen at a smaller extent on the live network for the average throughputs but at a lesser extent for the maximum ones. The live network presents values for the 5 MHz channel 16.54 Mbps for DL and 1.93 Mbps for UL, for 10 MHz channel 19.10 Mbps for the DL and 2.40 Mbps for the UL. The difference to the theoretical values range from: 41.69% higher value presented by the live network for the 5 MHz DL, to -37.58% lower values presented by the live network for the 10 MHz UL. The theoretical values are assessed at physical level not accounting for the TCP/IP and MAC overheads that would decrease the theoretical values but also the MIMO gain and other features that the live network benefits from that would increase the theoretical values. Together with the previous, one also has to consider that the loading of the network is lower at 10 MHz compared to 5 MHz, which could mean that none of the cells at 10 MHz has reached the maximum on the live network; this would mostly explain the differences observed.

The conclusion about the throughput values is that the theoretical model predictions are close enough to the ones observed in the live network, thus, being a good reference to predict values for the 20 MHz channel bandwidth throughput, if one takes into account the differences observed on the 5 and 10 MHz channels.

The Throughput KPIs present mix values, at network level only a percentage of the cells are within the thresholds for both UL and DL as well as for 5 and 10 MHz channel bandwidths. At cell level both achieve the KPIs at DL for 5 and 10 MHz channel bandwidths but fail for UL 5 and 10 MHz channel bandwidths. But since the network is not loaded to the extent to have cells near the limits, the considerations of the failures of this KPI are not conclusive.

The number of users is highly dependent on the traffic workload; for single workloads the examples of FTP Upload and VoIP help understand these ranges; for a 5 MHz channel from 2 users for FTP upload up to 216 users for VoIP, for a 10 MHz channel from 4 users for FTP upload up to 480 users for VoIP and for a 20 MHz channel from 10 users for FTP upload up to 960 users for VoIP. To simulate real world use case and since users are not bound to use a single workload one considers several scenarios with mixes of them.

The maximum users are estimated by the theoretical model to be achieved by the Residential weekdays scenario, with 107 users per 5 MHz channel, 240 users per 10 MHz channel, and 492 users per 20 MHz channel. This equates to near double the users each time the bandwidth doubles. This trend is seen at a minor extent on the live network. The live network presents values for 5 MHz channel of 190 users and for 10 MHz channel of 236 users. This also shows that the Residential weekdays is the scenario closer to the live network with a difference of 78% higher live value for 5 MHz and 2% higher theoretical value at 10 MHz channel, if a deeper analysis to the workloads is performed on the live network one maybe able to create scenarios that would reproduce more accurately the like observed values, but this is out of the scope of this thesis. The maximum user model already considers the TCP/IP and MAC overheads but lacks the implications of the MIMO and AAS gain and other features that the live network benefits from, which may explain the observed difference.

The theoretical model values although exhibiting a wide variation from the live network ones, but still within the same order of magnitude, consistently predict the variations visible on the network, thus validating the theoretical model as a good tool to predict features not yet implemented in a live network. Also one should highlight that the model is predicting to a better extend at 10 MHz channel for both the maximum throughput and users, thus giving a good perception for the accuracy of the predictions of the 20 MHz channel values, and that one also takes into account the differences observed on the 5 and 10 MHz channels.

In regards to the latency KPI, only 5 cells do not achieve the required threshold at 5 MHz channel bandwidth while at 10 MHz channel bandwidth 10 cells fail to achieve the required threshold; these relate to 1.2% and 2% respectively thus concluding that the overall network presents good latency values. At the chosen cells level both are well within the threshold value also for both channel bandwidths concluding their suitability for this study.

The packet drop KPI is achieved by all the network cells at both 5 and 10 MHz channel bandwidths; thus concluding that both the network and the cells are suitable for this study in terms of packet drop rate.

The KPIs assessed in the live network reflect the typical usage of fix WiMAX network focusing on the data experience (Throughput, Latency, and Packet loss) more than the mobility or voice. Although mobility is a feature of the network it was not possible to obtain values for related KPIs like Hand Over (HO) success rate, HO attempts, or other, from the database, thus assuming that these are either inexistent or residual. Regarding voice, it was observed that the QoS class UGS supporting it had relative values of less than 0.5%, thus again considering it as of residual use, this translates in the network usage and associated KPIs to typical data network applications such as the ones analysed like MPEG2, HTTP, Email, FTP.

The network design consider many different aspects, from which one needs to mention the relevant ones to this thesis like the constraints between, maximum users per channel, and user throughput granted by the service offerings. These compete for the same network resources, the data subcarrier-symbols within each subframe, thus the increase of one means that the other need to decrease proportionally.

The network operator is tempted to promise subscribers the highest maximum throughput per user, thus if each user achieves the maxim throughput granted by the network service profile, the channel reaches the maximum channel throughput, and no more users are able to be served by that channel. For the network operator to base their revenue assumptions on the number of users per carrier, a careful traffic profile must be studied in order to determine the maximum throughput to offer on the network service profile.

Given the rapid increase of the internet speed clearly visible by the rapid increase of the worldwide average download speed in Jan 2008 of 4.1 Mbps and the upload speed of 0.88 Mbps, to download speed of 8.74 Mbps and upload speed of 2.93 Mbps in Sep. 2011, according to [NetIn11], showing a duplication in the average throughputs over the past 3 years and nine months. Facing this, network operators are also required to keep up with the demand from the users, leaving them no choice than upgrading to larger channel bandwidths to provide the increase in demand, from the subscribers for higher speeds, if this does not occur then the increase of throughput speeds, will only be done at the expenses of the decrease in the maximum number of users.

The total number of users for the Residential weekdays scenario, the one closer to the live network, and given the requirement to cover Lisbon urban area, shows that at 5 MHz channel the coverage requires 12 BSs and estimates capacity for 19,688 users; at 10 MHz channel requires 23 BSs and estimates capacity for 87,360 users, and at 20 MHz channel requires 46 BSs and estimates capacity for 356,208 users, all this given the traffic assumptions for that particular scenario.

Considering the 100 BSs of the live network and the same Residential weekdays scenario, one estimates that at 5 MHz channel a total of 42,800 users are supported, at 10 MHz channel a total of 96,000 users are supported and at 20 MHz channel a total of 196,800 users are supported. Given that only 15,000 users were active in the live network confirming the early assumptions that the network was far from the load limit.

The maximum throughput is surely a high attractive set by the network operators to subscribe users to the network, but in the end several economical aspects need to be carefully studied and planned. Larger channel bandwidths that allow for higher user capacity come at the expense of more RF spectrum – a scarce and expensive asset - this is one of the major considerations when the operator studies the Capital Expenditures (CAPEX), also the operation costs for maintaining the network and supporting the users among others also known as Operational Expenditure (OPEX) is another consideration, both of them balance with the Average Revenue Per User (ARPU) and many other financial considerations like Return on Investment (ROI), all outside the scope of this thesis. Another of the objectives of the study presented on this thesis is to show a way to estimate the link between the RF channel bandwidth and the number of users; which provides additional information on estimating the CAPEX for a possible WiMAX network viability study.

For future work, one would suggest an analysis considering the capacity differences between Mobile WiMAX scenario and a fixed one. Another suggestion would be the study of the effects of MIMO and AAS both at maximum throughput and also user capacity. The introduction of new features and capacities from the latest IEEE 802.16 releases could also be interesting. Regarding measurements in the live network, one could suggest measurements in a scenario with an appropriate mass of mobile users, and considering aspects as mobility and indoor performance. One could also suggest an improvement of the models to better fit the measurement results, and mobile users particular characteristics. A similar capacity study is also feasible to be carried out for LTE, since it is also based on the same OFDMA principles, and allows as well for both FDD and TDD multiple access techniques.

Annex A – Antenna Techniques

Follows a brief description of the two most relevant antenna techniques used on WiMAX networks Beamforming and MIMO. Regarding beamforming (or AAS), since it provides link budget gains for both the uplink and the downlink, is well suited for environments that are coverage-limited. For instance, comparing a system implementing a two-branch receive diversity with a solution for beamforming with four antenna elements can save between 40 and 50% of radio sites. Beamforming could then be recommended for the first phase of deployment of a mobile WiMAX. This corresponds to macrocell coverage where the signal at the BS side is received with really limited angular spread (no more than 20-30°), which is the preferred situation for beamforming algorithms.

Also, using beamforming may enable mobile WiMAX solutions at 3.5 GHz to be deployed since the extra gains provided by beamforming can compensate for the additional propagation losses due to transmission at a higher frequency band. As discussed previously, deploying beamforming not only increases the coverage but also increases the offered capacity.

The mobile WiMAX solution does not provide a diversity gain in the uplink (which is the weak link in WiMAX, as in most cellular systems). Consequently, MIMO solutions cannot be deployed to improve the range in areas that are coverage-limited. However, MIMO can be deployed advantageously in areas where the capacity demand is very high or where the peak rate offer to the end user is very high. This can occur in hot-spot areas (e.g. a business area) or indoor environments. Actually, these very dense environments do have the radio characteristics that are favourable to MIMO. Indeed, in very dense areas, small cells with antennas below the rooftop are usually deployed.

The benefits of beamforming are manifold: range increase and power saving at the MS side, interference mitigation and capacity increase.

First, beamforming improves the link budget for the data transmission for both the downlink and the uplink. Indeed, by concentrating the energy in one direction, the resulting antenna gain in one direction is significantly increased as presented on Figure A.1. This additional gain is beneficial for improving the coverage of the BS (less sites needed for a deployment) and/or for reducing the power needed by the MS to transmit signals (power saving).

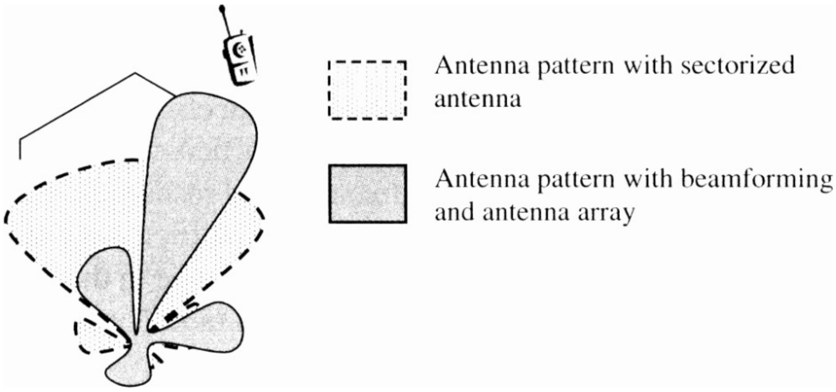

Figure A.1. Range extension with beamforming, from [Nuay07].

Theoretical gains, compared with a conventional antenna, for an N-element antenna arrays are of 10×log(N) for the uplink and 20×log(N) for the DL. For example, with a four-element antenna arrays the gains are respectively of 6 dB (12 dB) for the UL (respectively the DL). The gain in the downlink is higher since, on top of the beamforming gain, the power from each transmitter coherently increases. The value of those gains has been validated in many experiments on the field and proves to be in line with the theory [Nuay07]. Additional gains are measured in the uplink due to the additional spatial diversity gain.

Second, because the energy is focused in the direction of the user, there is a general interference reduction in a cellular system employing beamforming. Indeed, when beamforming is deployed on the BS of a given geographical area, the beams are oriented as a function of the repartition of the users served in a cell; at one moment, on a given radio resource, a single user is served. As a consequence, the interference created by the communication of this user is only in a restricted angle compared to sectorised antenna deployment as shown on Figure A.2.

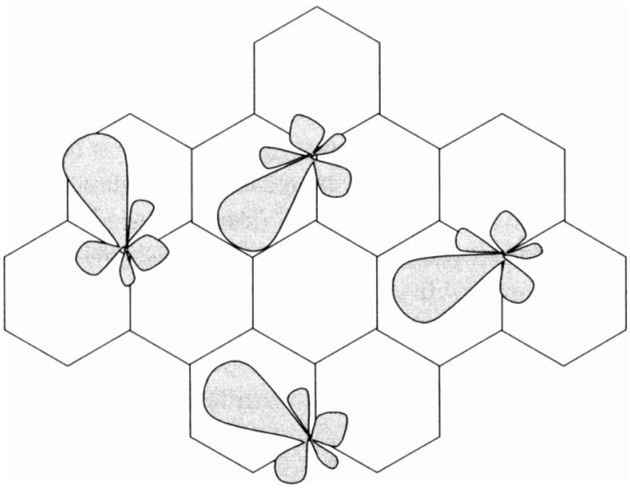

Figure A.2. Interference reduction with beamforming, from [Nuay07].

The angle spread of the main lobe is approximately the total angle of the sector divided by the number of antenna elements N. For example, with a four-element antenna array and a 90° antenna, the resulting main lobe width (at −3 dB) is around 220°. Therefore, since the users are randomly spread, the beam directions change according to the user locations, which create additional interference diversity gain. The interference reduction is further improved with the use of explicit interference cancellation algorithms.

Two direct consequences of the interference reduction are a better signal quality and availability across the cell area and a better capacity in the cell for systems using link adaptation. Indeed, since the CINR values are better, the possibility of using a better modulation and coding scheme is higher.

MIMO systems use multiple input and multiple output antennas operating on a single channel (frequency). At the transmitter side, the signal is space–time encoded and transmitted from NT antennas. At the receiving side, the signals are received from NR antennas as presented on Figure A.3 The space–time decoder combines the signal received by the NR antennas and transmitted from the NT antennas after having estimated the channel matrix (NT×NR).

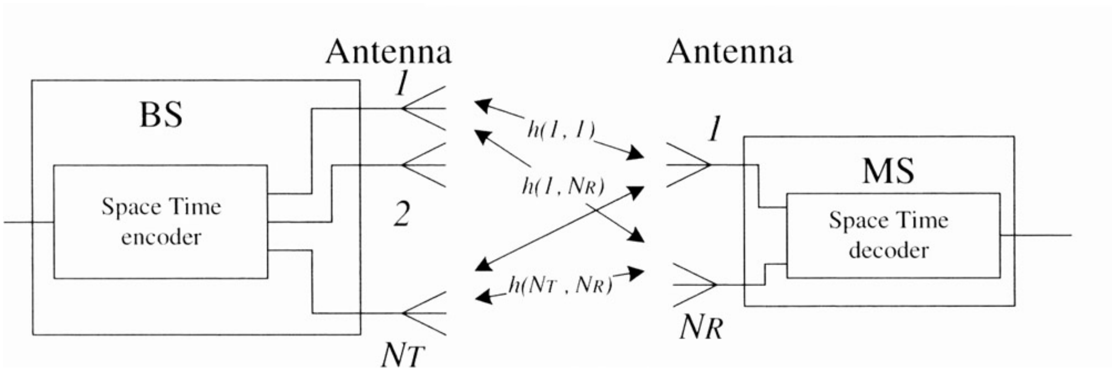

Figure A.3. Generic MIMO block diagram for the downlink, from [Nuay07].

The objective of the MIMO solution is to exploit the space and time diversity of the channels on the different radio paths between each combination of transmit/receive antennas to improve the reception sensitivity and/or to improve the channel capacity. There are several families of MIMO solutions. The two extreme ones are the spatial diversity MIMO schemes and the spatial multiplexing MIMO schemes.

Depending on the scheme, the benefits of MIMO can be to improve the receiver sensitivity and/or to multiply the capacity and the peak rates.

Annex B – Status of WiMAX

In the May 2011 WiMAX Forum Industry Research Report provided by WiMAX Forum [WiMX11], which is a monthly summary of primary and secondary research and news, the current status of WiMAX around the world is presented. WiMAX Forum currently tracks 583 WiMAX deployments in 150 Countries, this is shown in Figure B.1, where the blue markers represent Mobile WiMAX deployments and the red ones the Fixed WiMAX deployments. It is clearly visible the spread of the WiMAX all over world. These deployments use different frequency bands as shown in Table B.1. The difference between the table total and table total deployment is due to deployments' statuses unknown by WiMAX Forum.

Figure B.1. Spread of WiMAX, [WiMF08]

Table B.1. Summary of deployments by frequency band, (extracted from [WiMX11]).

Band [GHz]	Number of Deployments
2.3	48
2.5	112
3.3	10
3.5	308
5.8	21

It is clearly obvious that the most commonly used frequency bands are the 2.5 and 3.5 GHz. This is either by considerations of regulatory or equipment constraints.

The number of people covered by WiMAX is estimated by WiMAX Forum to reach up to 1 Billion in 2011 [WiMX11], the evolution of coverage through the last few years is presented in Figure B.2.

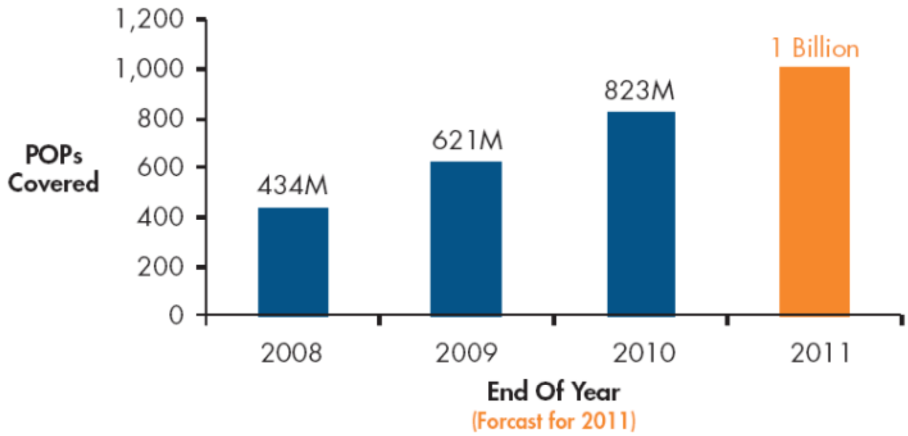

Figure B.2. Number of people covered by WiMAX, (extracted from [WiMX11])

Also to have a better conception of the state of WiMAX generalisation in the technology marked one can refer to the WiMAX Forum numbers for Certified Products and vendors which reaches up to 260, from were 62 are Base Stations and 198 are Subscriber/Mobile Stations products. These come for a variety of vendors. From the Base Station vendors one can highlight among an extensive list that the major players on the communications market are present, such as: Alcatel-Lucent, Alvarion, Cisco Systems, Harris Stratex, Huawei Technologies, Motorola, NEC, Nokia Siemens Networks, Nortel, Samsung, ZTE Corporation. On the Subscriber/Mobile Station vendors the span in the variety is also visible: Alcatel-Lucent, Alvarion, Beceem, Cisco Systems, D-Link, Fujitsu, G, Gigaset Communications, Harris Stratex, Huawei Technologies, Intel Corporation, Lenovo, Motorola, NEC, Onkyo, Panasonic, Samsung, Siemens AG, Sony, Toshiba, ZTE Corporation, ZyXEL Communications Inc… just to highlight the major ones among many others.

On the Subscriber/Mobile Station the Intel laptop [Intel11] is of most importance since in parallel to the commonly available Wi-Fi support, the microprocessors giant, also makes WiMAX available on their chipset. This is currently available on Intel chipsets such as the Intel Centrino Advanced-N + WiMAX Series, the world's first integrated WiMAX/WiFi module for laptops with Intel My Wi-Fi Technology (Intel MWT) and supporting global 2.3GHz, 2.5GHz, and 3.5GHz WiMAX frequencies.

Annex C – Flow Charts

Follows the flow charts for the theoretical models related to the calculations of the Maximum Physical Throughput and the Maximum User number.

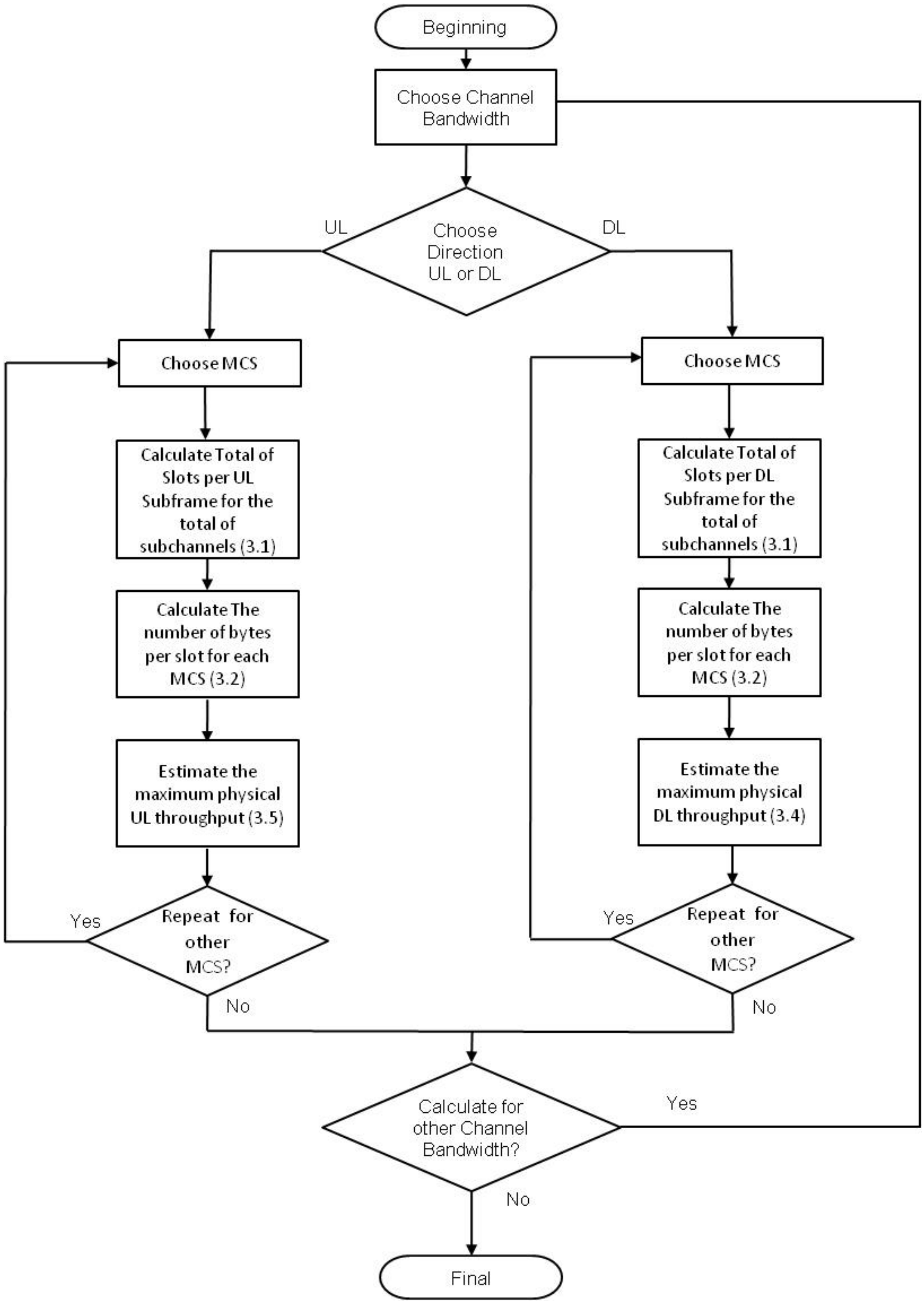

Figure C.1. Maximum Physical Throughput calculation process flow chart.

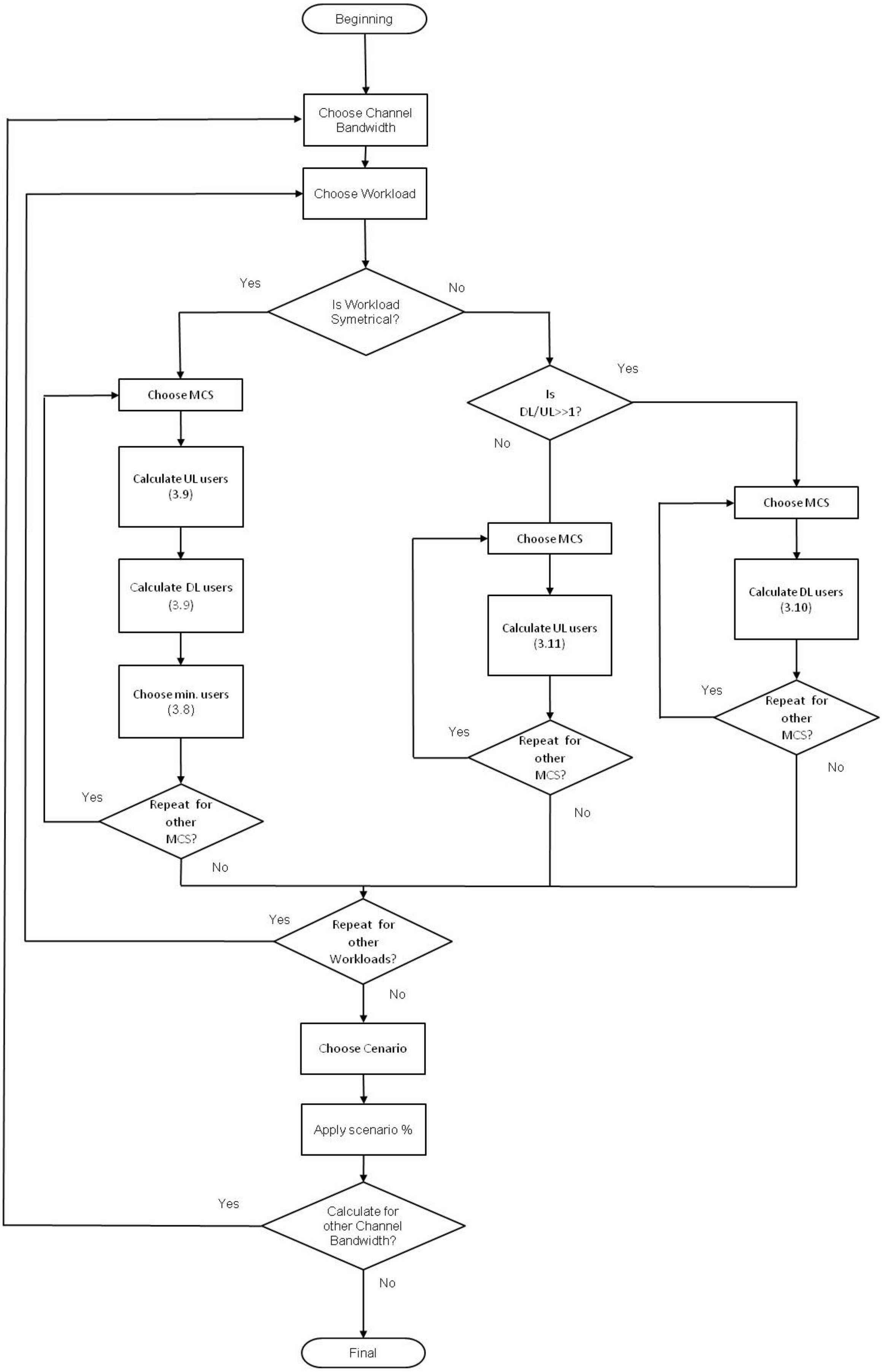

Figure C.2. Maximum user calculation process flow chart.

Annex D – Database Details

Examples of some of the available Database information:

- Subscribers
  - Max ASN Concurrent Users
  - Peak Single Channel Users in Active/Sleep State
  - Avg Channel Users in Active/Sleep State
  - Peak Channel Users Distribution in Active/Sleep State
- Throughput
  - Total DL Throughput
  - Total UL Throughput
  - DL Throughput for High Utilisation channel
  - UL Throughput for High Utilisation channel
  - Average DL MCS for UGS & BE
  - Average UL MCS for UGS & BE
  - DL RF Throughput
  - UL RF Throughput
- Packet Drops
  - DL Total Dropped Packet Rate
  - DL BE Dropped Packet Rate
  - DL UGS Dropped Packet Rate
- Users Characteristics
  - DL Throughput Per User
    - Total DL Throughput per User
    - Total DL Throughput per User for a Single Channel
  - UL Throughput Per User
    - Total UL Throughput per User
    - Total UL Throughput per User for a Single Channel
- Latency Averages
  - DL BE Queue Latency Average
  - DL UGS Queue Latency Average
- Characteristics of DL/ UL
  - DL Physical Layer MAC Overhead Ratio
  - UL Physical Layer MAC Overhead Ratio
- Utilisation
  - Total BS Channel Use
  - Total DL BS Channel Use
  - Total UL BS Channel Use

- BE DL BS Channel Use
- BE UL BS Channel Use
- UGS DL BS Channel Use
- UGS UL BS Channel Use

- RF Measurements
  - Noise (including Interference)
    - Average UL Noise
    - Count of Average UL Noise Channels > -130dbm
  - CINR
    - UL CINR <= 35 dB
    - Count of UL CINR Ratio > 5%
    - Allocation of UL CINR
- MCS
  - DL RF Quality – 64-QAM
  - DL RF Quality – 16-QAM
  - DL RF Quality – QPSK
  - UL RF Quality – 16-QAM
  - UL RF Quality – QPSK
- Network Access
  - Network Access Success Rate
  - Initial Network Access Success Rate
  - Idle Mode Access Success Rate

Annex E – Main Theoretical Results

Following the tables with the main theoretical results are presented. They contain the calculated values used to generate the figures, related to the theoretical results presented in chapter 4, for which the correspondent values are not presented alongside those figures in that chapter.

The following the tables are related to Figure 4.4 up to Figure 4.10 and also Figure 4.11, Figure 4.12 and Figure 4.13

Table E.1. Users per MCS for MPEG2 workload.

MPEG 2	QPSK 1/8	QPSK 1/4	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 2/3	16-QAM 3/4	64-QAM 1/2	64-QAM 2/3	64-QAM 3/4	64-QAM 5/6	Average MCS
Number of users (DL), 5MHz	1	2	6	8	10	14	14	14	18	20	22	10
Number of users (DL), 10MHz	2	6	12	16	22	28	30	30	36	40	44	22
Number of users (DL), 20MHz	6	12	24	34	44	56	60	60	74	80	88	46
Number of users (UL), 5MHz												
Number of users (UL), 10MHz												
Number of users (UL), 20MHz												
Number of users (min of UL and DL), 5MHz	1	2	6	8	10	14	14	14	18	20	22	10
Number of users (min of UL and DL), 10MHz	2	6	12	16	22	28	30	30	36	40	44	22
Number of users (min of UL and DL), 20MHz	6	12	24	34	44	56	60	60	74	80	88	46

Table E.2. Users per MCS for VoIP workload.

VoIP	QPSK 1/8	QPSK 1/4	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 2/3	16-QAM 3/4	64-QAM 1/2	64-QAM 2/3	64-QAM 3/4	64-QAM 5/6	Average MCS
Number of users (DL), 5MHz	36	60	96	120	132	144	144	144	144	156	156	132
Number of users (DL), 10MHz	84	132	204	240	264	288	288	288	300	312	312	264
Number of users (DL), 20MHz	168	276	408	480	528	576	576	576	612	636	636	528
Number of users (UL), 5MHz	9	24	48	84	108	156	156	156	204	204	204	108
Number of users (UL), 10MHz	24	60	120	180	240	336	336	336	420	420	420	240
Number of users (UL), 20MHz	60	120	240	372	480	672	672	672	840	840	840	480
Number of users (min of UL and DL), 5MHz	9	24	48	84	108	144	144	144	144	156	156	108
Number of users (min of UL and DL), 10MHz	24	60	120	180	240	288	288	288	300	312	312	240
Number of users (min of UL and DL), 20MHz	60	120	240	372	480	576	576	576	612	636	636	480
Number of users with silence suppression, 5MHz	18	48	96	168	216	288	288	288	288	312	312	216
Number of users with silence suppression, 10MHz	48	120	240	360	480	576	576	576	600	624	624	480
Number of users with silence suppression, 20MHz	120	240	480	744	960	1152	1152	1152	1224	1272	1272	960

Table E.3. Users per MCS for HTTP workload.

HTTP	QPSK 1/8	QPSK 1/4	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 2/3	16-QAM 3/4	64-QAM 1/2	64-QAM 2/3	64-QAM 3/4	64-QAM 5/6	Average MCS
Number of users (DL), 5MHz	10	50	100	150	200	250	300	300	350	350	350	200
Number of users (DL), 10MHz	50	100	250	350	450	550	600	600	700	750	750	450
Number of users (DL), 20MHz	150	250	500	750	900	1100	1200	1200	1400	1500	1550	950
Number of users (UL), 5MHz	400	850	1700	1700	3400	3400	3400	3400	3400	3400	3400	3400
Number of users (UL), 10MHz	850	1750	3500	3500	7000	7000	7000	7000	7000	7000	7000	7000
Number of users (UL), 20MHz	1750	3500	7000	7000	14000	14000	14000	14000	14000	14000	14000	14000
Number of users (min of UL and DL), 5MHz	10	50	100	150	200	250	300	300	350	350	350	200
Number of users (min of UL and DL), 10MHz	50	100	250	350	450	550	600	600	700	750	750	450
Number of users (min of UL and DL), 20MHz	150	250	500	750	900	1100	1200	1200	1400	1500	1550	950

Table E.4. Users per MCS for FTP Download for VoIP workload.

FTP Download	QPSK 1/8	QPSK 1/4	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 2/3	16-QAM 3/4	64-QAM 1/2	64-QAM 2/3	64-QAM 3/4	64-QAM 5/6	Average MCS
DL data slots per user with MAC header + packing and fragmentation subheaders	429	215	108	72	54	41	36	36	27	24	22	52
Total slots per user (Data + DL-MAP IE + UL-MAP IE)	445	231	124	88	70	57	52	52	43	40	38	68
Number of users (DL), 5MHz	1	2	4	4	6	8	8	8	10	12	12	6
Number of users (DL), 10MHz	2	4	8	10	14	16	18	18	22	24	26	14
Number of users (DL), 20MHz	4	8	16	22	28	34	38	38	46	50	52	30
UL data slots per user with MAC header + packing and fragmentation subheaders	6	3	2	1	1	1	1	1	1			1
Number of users (UL), 5MHz	22	44	68	136	136	136	136	136	136	136	136	136
Number of users (UL), 10MHz	46	92	140	280	280	280	280	280	280	280	280	280
Number of users (UL), 20MHz	92	186	280	560	560	560	560	560	560	560	560	560
Number of users (min of UL and DL), 5MHz	1	2	4	4	6	8	8	8	10	12	12	6
Number of users (min of UL and DL), 10MHz	2	4	8	10	14	16	18	18	22	24	26	14
Number of users (min of UL and DL), 20MHz	4	8	16	22	28	34	38	38	46	50	52	30

Table E.5. Users per MCS for FTP Upload for VoIP workload.

FTP Upload	**QPSK 1/8**	**QPSK 1/4**	**QPSK 1/2**	**QPSK 3/4**	**16-QAM 1/2**	**16-QAM 2/3**	**16-QAM 3/4**	**64-QAM 1/2**	**64-QAM 2/3**	**64-QAM 3/4**	**64-QAM 5/6**	**Average MCS**
DL data slots per user with MAC header + packing and fragmentation subheaders	6	3	2	1	1	1	1	1	1	1	1	1
Total slots per user (Data + DL-MAP IE + UL-MAP IE)	22	19	18	17	17	17	17	17	17	17	17	17
Number of users (DL), 5MHz	22	26	28	30	30	30	30	30	30	30	30	30
Number of users (DL), 10MHz	46	52	56	60	60	60	60	60	60	60	60	60
Number of users (DL), 20MHz	92	106	112	120	120	120	120	120	120	120	120	120
UL data slots per user with MAC header + packing and fragmentation subheaders	429	215	108	72	54	41	36	36	27			55
Number of users (UL), 5MHz	1	1	1	1	2	2	2	2	4	0	0	2
Number of users (UL), 10MHz	1	1	2	2	4	6	6	6	10	0	0	4
Number of users (UL), 20MHz	1	2	4	6	10	12	14	14	20	0	0	10
Number of users (min of UL and DL), 5MHz	1	1	1	1	2	2	2	2	4	0	0	2
Number of users (min of UL and DL), 10MHz	1	1	2	2	4	6	6	6	10	0	0	4
Number of users (min of UL and DL), 20MHz	1	2	4	6	10	12	14	14	20	0	0	10

Table E.6. Users per MCS for Email Receive workload.

Email Receive	QPSK 1/8	QPSK 1/4	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 2/3	16-QAM 3/4	64-QAM 1/2	64-QAM 2/3	64-QAM 3/4	64-QAM 5/6	Average MCS
DL data slots per user with MAC header + packing and fragmentation subheaders	429	215	108	72	54	41	36	36	27	24	22	52
Total slots per user (Data + DL-MAP IE + UL-MAP IE)	445	231	124	88	70	57	52	52	43	40	38	68
Number of users (DL), 5MHz	1	2	4	4	6	8	8	8	10	12	12	6
Number of users (DL), 10MHz	2	4	8	10	14	16	18	18	22	24	26	14
Number of users (DL), 20MHz	4	8	16	22	28	34	38	38	46	50	52	30
UL data slots per user with MAC header + packing and fragmentation subheaders	6	3	2	1	1	1	1	1	1			1
Number of users (UL), 5MHz	22	44	68	136	136	136	136	136	136	136	136	136
Number of users (UL), 10MHz	46	92	140	280	280	280	280	280	280	280	280	280
Number of users (UL), 20MHz	92	186	280	560	560	560	560	560	560	560	560	560
Number of users (min of UL and DL), 5MHz	1	2	4	4	6	8	8	8	10	12	12	6
Number of users (min of UL and DL), 10MHz	2	4	8	10	14	16	18	18	22	24	26	14
Number of users (min of UL and DL), 20MHz	4	8	16	22	28	34	38	38	46	50	52	30

Table E.7. Users per MCS for Email Send workload.

Email Send	QPSK 1/8	QPSK 1/4	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 2/3	16-QAM 3/4	64-QAM 1/2	64-QAM 2/3	64-QAM 3/4	64-QAM 5/6	Average MCS
DL data slots per user with MAC header + packing and fragmentation subheaders	6	3	2	1	1	1	1	1	1	1	1	1
Total slots per user (Data + DL-MAP IE + UL-MAP IE)	22	19	18	17	17	17	17	17	17	17	17	17
Number of users (DL), 5MHz	22	26	28	30	30	30	30	30	30	30	30	30
Number of users (DL), 10MHz	46	52	56	60	60	60	60	60	60	60	60	60
Number of users (DL), 20MHz	92	106	112	120	120	120	120	120	120	120	120	120
UL data slots per user with MAC header + packing and fragmentation subheaders	429	215	108	72	54	41	36	36	27			55
Number of users (UL), 5MHz	1	1	1	1	2	2	2	2	4	0	0	2
Number of users (UL), 10MHz	1	1	2	2	4	6	6	6	10	0	0	4
Number of users (UL), 20MHz	1	2	4	6	10	12	14	14	20	0	0	10
Number of users (min of UL and DL), 5MHz	1	1	1	1	2	2	2	2	4	0	0	2
Number of users (min of UL and DL), 10MHz	1	1	2	2	4	6	6	6	10	0	0	4
Number of users (min of UL and DL), 20MHz	1	2	4	6	10	12	14	14	20	0	0	10

Annex F – Main Experimental Results

Some of the main experimental results are presented in the next tables. The criterion followed is to present the tables for those figures which is not easy and direct to determine the exact values from.

Table F.1. UL CINR distributions for 5 and 10 MHz channels, matching to Figure 4.15.

CINR	10 MHz Channel [%]	5 MHz Channel [%]
> 36 dB	40.80	53.20
33-36 dB	12.30	12.60
30-33 dB	11.40	10.00
27-30 dB	10.70	7.20
24-27 dB	8.40	5.60
21-24 dB	6.20	3.70
18-21 dB	3.80	2.30
15-18 dB	2.70	1.70
12-15 dB	1.10	1.10
9-12 dB	0.70	0.60
6-9 dB	0.20	0.40
3-6 dB	0.80	0.30
0-3 dB	0.60	1.00
< 0 dB	0.30	0.30

Table F.2. UL CINR distributions at 5 MHz for cell A and B, matching to Figure 4.16.

CINR	Uplink CINR Distribution 5 MHz Channel - Cell A [%]	Uplink CINR Distribution 5 MHz Channel - Cell B [%]
> 36 dB	41.37	29.94
33-36 dB	11.98	8.00
30-33 dB	10.65	10.44
27-30 dB	10.00	10.00
24-27 dB	10.00	12.00
21-24 dB	7.00	11.00
18-21 dB	3.00	9.64
15-18 dB	2.00	5.00
12-15 dB	1.00	1.00
9-12 dB	1.44	1.00
6-9 dB	0.00	0.42
3-6 dB	0.49	0.23
0-3 dB	0.39	0.31
< 0 dB	0.23	0.88

Table F.3. UL CINR distributions at 10 MHz for cell A and B, matching to Figure 4.17.

CINR	Uplink CINR Distribution 10 MHz Channel - Cell A [%]	Uplink CINR Distribution 10 MHz Channel - Cell B [%]
> 36 dB	33.83	36.65
33-36 dB	8.64	6.25
30-33 dB	11.00	7.00
27-30 dB	12.00	10.12
24-27 dB	8.84	7.00
21-24 dB	8.00	9.86
18-21 dB	7.06	8.00
15-18 dB	5.00	7.00
12-15 dB	3.00	5.00
9-12 dB	1.00	1.00
6-9 dB	1.39	1.31
3-6 dB	0.31	0.00
0-3 dB	0.20	0.37
< 0 dB	0.00	0.26

Table F.4. Distribution of Network Average UL NI at 5 MHz channel matching to Figure 4.19.

Average Uplink Noise and Interference over 5 MHz Channel	Occurrence	Cumulative [%]
<-135	0	0.00
-135 to -134	62	15.78
-134 to -133	15	19.59
-133 to -132	15	23.41
-132 to -131	43	34.35
-131 to -130	128	66.92
-130 to -129	112	95.42
-129 to -128	15	99.24
-128 to -127	1	99.49
-127 to -126	1	99.75
-126 to -125	1	100.00

Table F.5. Distribution of Network Average UL NI at 10 MHz channel matching to Figure 4.21.

Average Uplink Noise and Interference over 10 MHz Channel	Occurrence	Cumulative [%]
<-135	0	0.00
-135 to -134	190	39.34
-134 to -133	55	50.72
-133 to -132	34	57.76
-132 to -131	88	75.98
-131 to -130	73	91.10
-130 to -129	37	98.76
-129 to -128	6	100.00
-128 to -127	0	100.00
-127 to -126	0	100.00
-126 to -125	0	100.00

Annex G – More Experimental Results

Some of the main experimental results are presented in the next tables.

The database network level DL BE Queue Latency Average for 5 MHz is presented first, followed by the 10 MHz one, both are directly related to Bearer traffic Latency (L_{BT}) KPI. The values from the database, for the network level analysis, are the averages of the daily average values of each cell sampled over one month period and are ordered let to right on a descendent way.

The network level DL BE Queue Latency Average for 5 MHz channels is presented in Figure G.1.

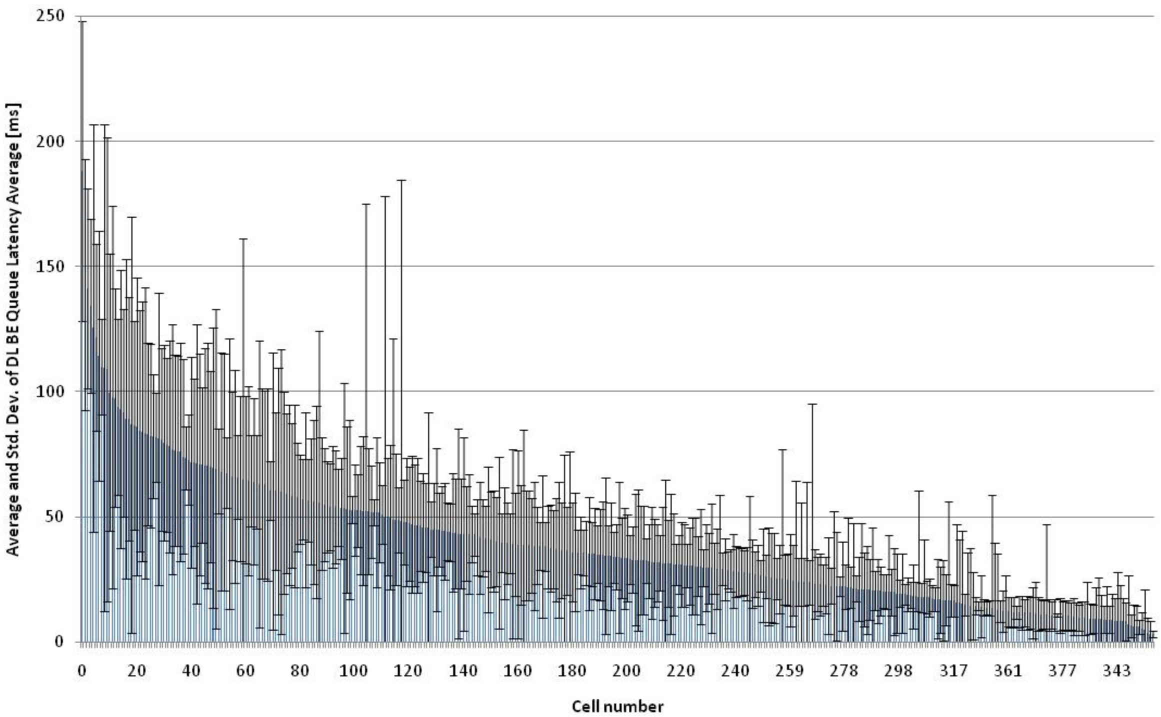

Figure G.1 Network average and Std. Dev. for BE Queue Latency Average at 5 MHz channel.

The main statistical elements related to Figure G.1 are presented in Table G.1.

Table G.1. Network statistic values for BE Queue Latency Average at 5 MHz channel.

Statistics	BE Queue Latency Average 5 MHz Channel
Count	394
Average (μ) [ms]	39.29
Standard Deviation (σ) [ms]	26.37
Average Standard Deviation ($\bar{\sigma}$) [ms]	23.21
Maximum [ms]	188.06
Median [ms]	33.78
Minimum [ms]	3.08

From the Figure G.1 one verifies that less than 20 cells present values over 100 ms and the majority are under half that value. This is also patent on the statistic values that show an average around 5 times lower than the maximum and a median even lower than the average.

The network level DL BE Queue Latency Average for 10 MHz channels is presented in Figure G.2.

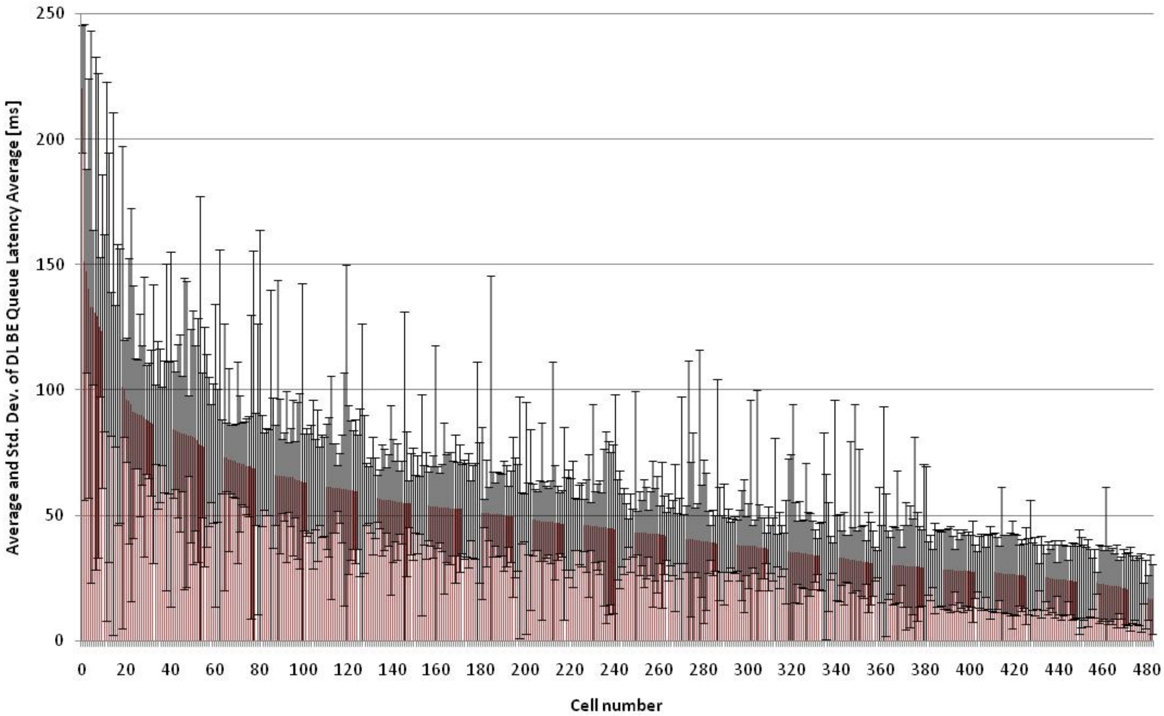

Figure G.2. Network average and Std. Dev. for BE Queue Latency Average at 10 MHz channel.

The main statistical elements related to Figure G.2 are presented in Table G.2.

As like 5 MHz less than 20 cells present values over 100 ms, and the majority are under half that value. This is also evident from the statistic values that show an average around 3 times lower than the maximum and a median even lower than the average.

Comparing with 5 MHz the network shows at 10 MHz almost all higher statistical elements, from which one highlights a 25% higher average and 17% higher maximum. This is consistent with the previous findings of higher usage of the network at 10 MHz translating from a higher sharing of resources.

Table G.2. Network statistic values for BE Queue Latency Average at 10 MHz channel.

Statistics	**BE Queue Latency Average 10 MHz Channel**
Count	483
Average (μ) [ms]	49.11
Standard Deviation (σ) [ms]	24.56
Average Standard Deviation ($\bar{\sigma}$) [ms]	25.05
Maximum [ms]	220.12
Median [ms]	44.33
Minimum [ms]	16.49

The cell level DL BE Queue Latency Average at 5 MHz channels for cells A and B is presented in Figure G.3; these are the daily average values for each cell.

The trends presented by both cells do not show clear increase or decrease tendencies.

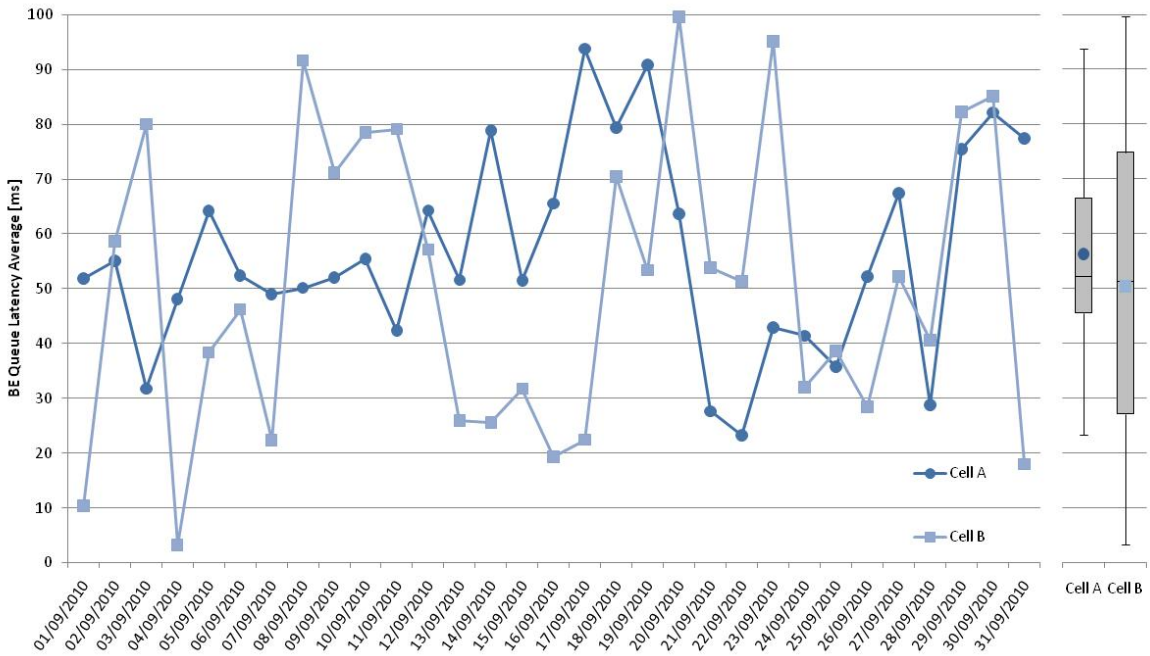

Figure G.3. DL BE Queue Latency Average at 5 MHz channel for cells A and B.

The main statistical elements related to Figure G.3 are presented in Table G.3.

Table G.3. Statistic values for DL BE Queue Latency Average at 5 MHz channel for cells A and B.

Statistics	BE Queue Latency Average 5 MHz channel	
	Cell A	**Cell B**
Count	31	31
Average (μ) [ms]	56.33	50.40
Standard Deviation (σ) [ms]	18.32	27.08
Minimum [ms]	23.29	3.22
Q1 [ms]	45.52	27.16
Median (=Q2) [ms]	52.16	51.30
Q3 [ms]	66.50	74.82
Maximum [ms]	93.78	99.56

From the statistics values one verifies that both cells show very similar averages and medians as well as maximum values, although cell B has a wider spread in values, as shown by an higher standard deviation, this still shows a similar behavior in terms of latency for both cells at 5 MHz.

Comparing to the network values, both cells show higher averages of 43% for cell A and 28% for cell B and higher median of 54% for cell A and 52% for cell B, but 50% lower maximum values for cell A and 47% for cell B, thus not being among the ones with the highest latency level and confirming as 5 MHz channel representatives for this thesis, since from a user traffic perspective the results would not be influenced by high latency.

The cell level DL BE Queue Latency Average at 10 MHz channels for cells A and B is presented in Figure G.4; as well as for 5 MHz these are the daily average values for each cell.

Again, the trends presented by both cells do not show clear increase or decrease tendencies.

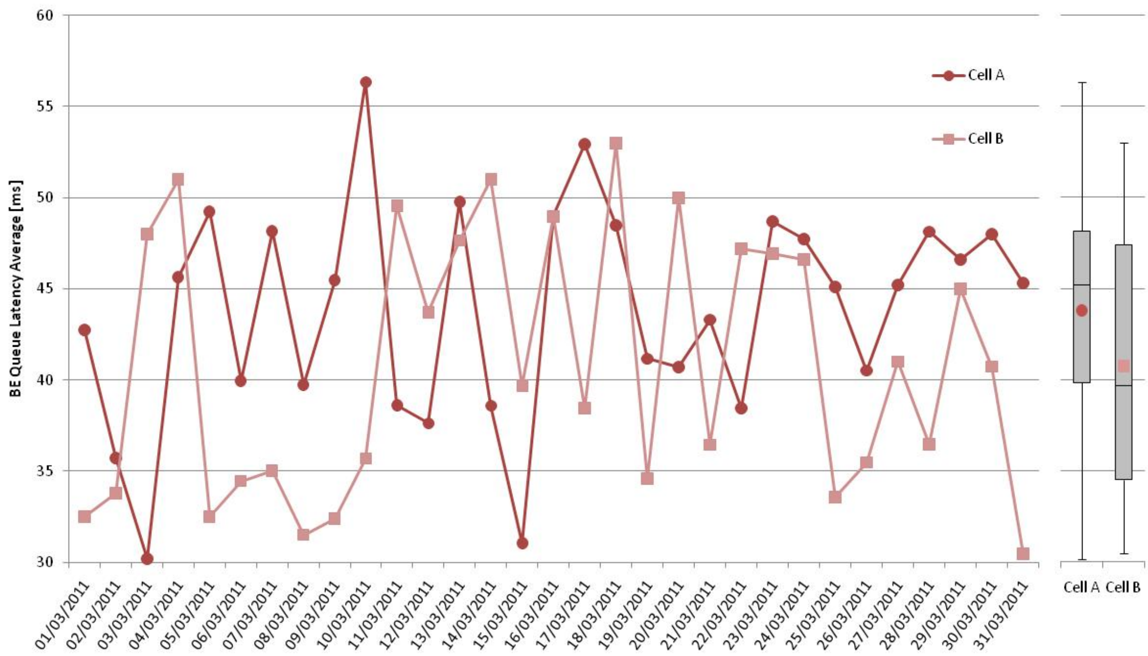

Figure G.4 DL BE Queue Latency Average at 10 MHz channel for cells A and B.

The main statistical elements related to Figure G.4 are presented in Table G.4.

Table G.4. Statistic values for DL BE Queue Latency Average at 10 MHz channel for cells A and B.

Statistics	BE Queue Latency Average 10 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ) [ms]	43.81	40.75
Standard Deviation (σ) [ms]	5.96	7.15
Minimum [ms]	30.18	30.46
Q1 [Mbps]	39.85	34.52
Median (=Q2) [mps]	45.20	39.68
Q3 [ms]	48.15	47.41
Maximum [ms]	56.35	53.00

From the statistics values one verifies that both cells show very similar averages and medians as well as maximum values. This shows a similar behavior in terms of latency for both cells as well as at 10 MHz.

Comparing to the network values both cells show lower averages of 11% for cell A and 17% for cell B and similar median of 2% more for cell A and 10% less for cell B, in opposition to what is presented at 5MHz; the maximum values are 74% lower for cell A and 76% lower for cell B, thus confirming as not being among the ones with the highest latency level, and substantiating as 10 MHz channel representatives for this thesis, since from a user traffic perspective the results would not be influenced by high latency. This is opposite to the difference between network level statistics where, 10 MHz tend to present worst latency values than 5 MHz.

A deeper analysis of the network behavior of the latency is out of the scope of this thesis, but to present one possibility would be that these cells have been optimised in the time elapsed between the upgrade from 5 to 10 MHz channels.

The database network level DL Average Dropped Packet Rate for 5 MHz is presented first, followed by the 10 MHz one, both are directly related to Bearer Traffic Percentage of Packet loss (PL_{BT}) KPI for BE QoS Class. The values retrieved from the database, for the network level analysis, are the averages of the daily average values of each cell sampled over one month period and are ordered let to right on a descendent way.

The network level DL Average Dropped Packet Rate for 5 MHz channels is presented in Figure G.5.

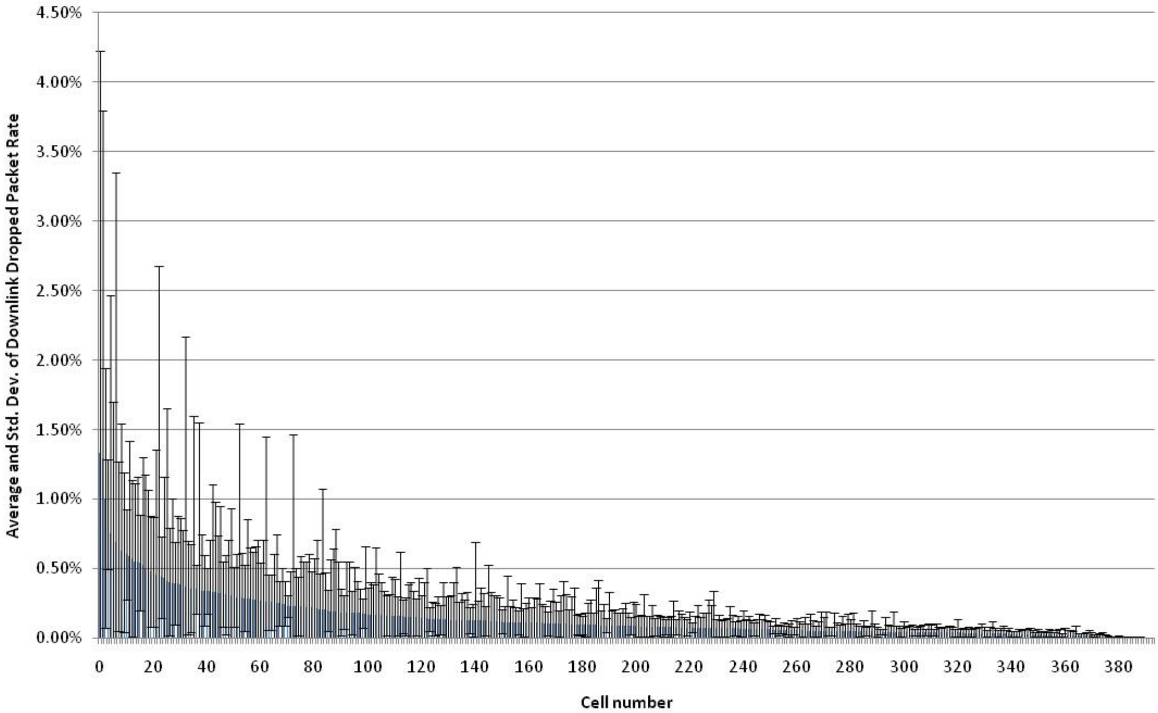

Figure G.5. Average and Std. Dev. for Network DL Dropped Packet Rate at 5 MHz channel.

Only a reduced number of cells (3 in total) present values over 1%, and it is also visible that less then 20 cells have values over 0.5%, evidencing a low DL dropped packet rate at 5 MHz. over the entire network.

The main statistical elements related to Figure G.5 are presented in Table G.5.

The statistics confirm that a much reduced DL packet drop is experience by the network at 5 MHz as for what was visible in Figure G.5, from these one assesses that half the cells are under 0.1% packet drop.

Table G.5. Network statistic values for Average of DL Dropped Packet Rate at 5 MHz channel.

Statistics	**Average of Downlink Dropped Packet Rate 5 MHz Channel**
Count	394
Average (μ)	0.15%
Standard Deviation (σ)	0.17%
Average Standard Deviation ($\bar{\sigma}$)	0.22%
Maximum	1.33%
Median	0.09%
Minimum	0.00%

The network level DL Average Dropped Packet Rate for 10 MHz channels is presented in Figure G.6.

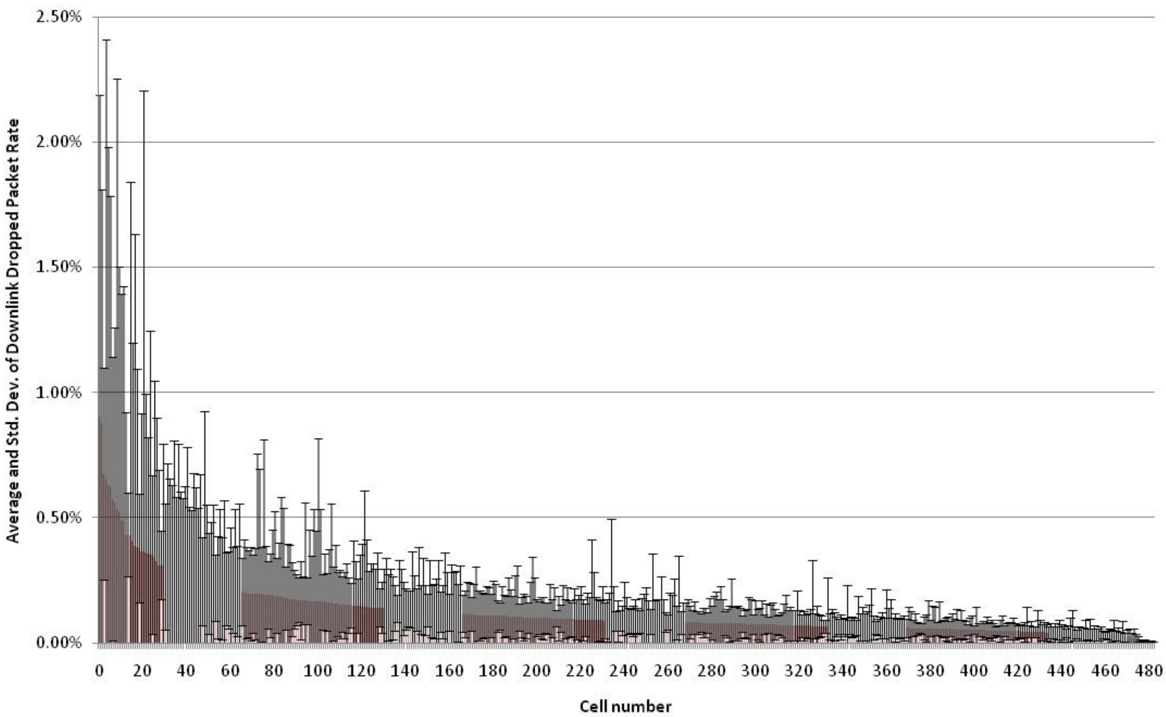

Figure G.6. Average and Std. Dev. for Network DL Dropped Packet Rate at 10 MHz channel.

At 10 MHz no cell shows values over 1%, and it is also visible that less then 10 cells have values over 0.5%, evidencing a low DL dropped packet rate at 10 MHz. over the entire network and a relative better performance for this in relation to 5 MHz.

The main statistical elements related to Figure G.6 are presented in Table G.6.

The statistics confirm that a much reduced DL packet drop is experience by the network at 10 MHz as for what was visible in Figure G.6, from these one assesses that half the cells are under 0.1% packet drop.

The statistical for 10 MHz shown in Table G.6, present equal or better values when compared to 5 MHz. A deeper analysis of the network behavior of the packet drop is out of the scope of this thesis, but to present one possibility would be that these cells have been optimised in the time elapsed between the upgrade from 5 to 10 MHz channels.

Table G.6. Network statistic values for Average of DL Dropped Packet Rate at 10 MHz channel.

Statistics	Average of Downlink Dropped Packet Rate 10 MHz Channel
Count	483
Average (μ)	0.12%
Standard Deviation (σ)	0.11%
Average Standard Deviation ($\bar{\sigma}$)	0.16%
Maximum	0.90%
Median	0.09%
Minimum	0.00%

The cell level DL Dropped Packet Rate Average at 5 MHz channels for cells A and B is presented in Figure G.7; these are the daily average values for each cell.

The trends presented by both cells do not show clear increase or decrease tendencies, and in general cell B presents slightly worst values than A.

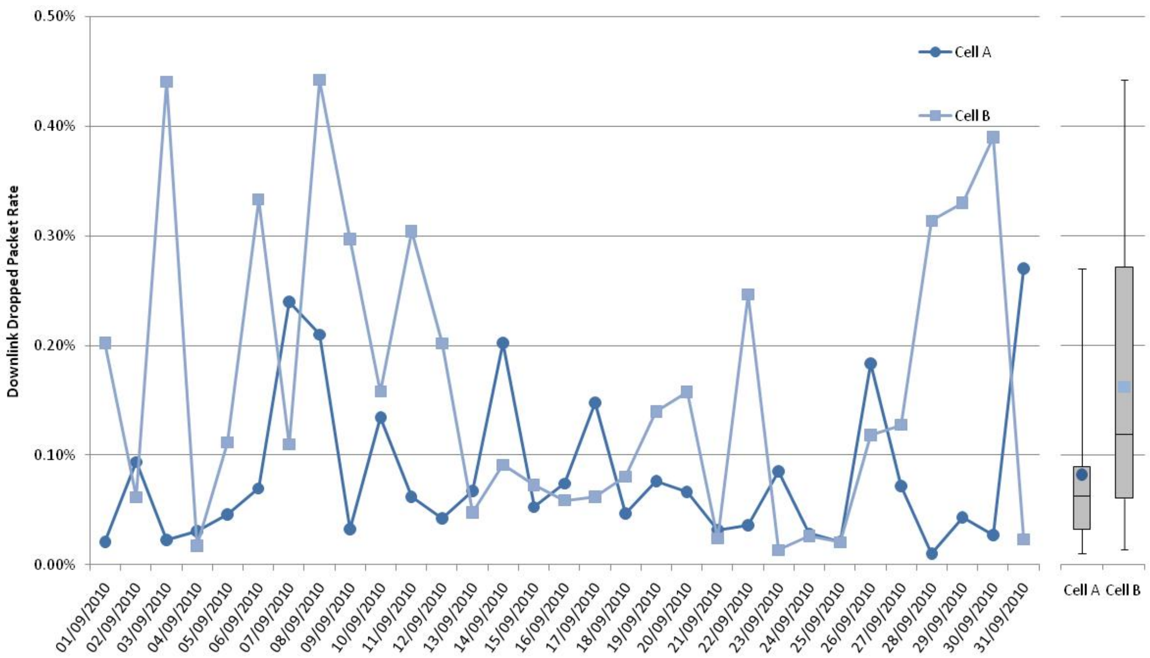

Figure G.7 DL Dropped Packet Rate at 5 MHz channel for cells A and B.

The main statistical elements related to Figure G.7 are presented in Table G.7.

From the statistics it is clear that cell A has a better performance when compared to B at 5 MHz.

Comparing with the network at 5 MHz one assesses that cell A presents better performance on all statistical vales, while cell B shows a very similar average but a higher median, placing it on the top worst half.

Table G.7. Statistic values for DL Dropped Packet Rate at 5 MHz channel for cells A and B.

Statistics	Downlink Dropped Packet Rate 5 MHz channel	
	Cell A	Cell B
Count	31	31
Average (μ)	0.08%	0.16%
Standard Deviation (σ)	0.07%	0.13%
Minimum	0.01%	0.01%
Q1	0.03%	0.06%
Median (=Q2)	0.06%	0.12%
Q3	0.09%	0.27%
Maximum	0.27%	0.44%

Given the above values one verifies that both cells are not among the ones with the highest DL Drop Packet Rate level and confirming as 5 MHz channel representatives for this thesis, since from a user traffic perspective the results would not be influenced by high DL Drop Packet Rate.

The cell level DL Dropped Packet Rate Average at 10 MHz channels for cells A and B is presented in Figure G.8; these are the daily average values for each cell.

The trends presented by both cells do not show clear increase or decrease tendencies, but in general cell B presents slightly worst values than A, similar to 5 MHz.

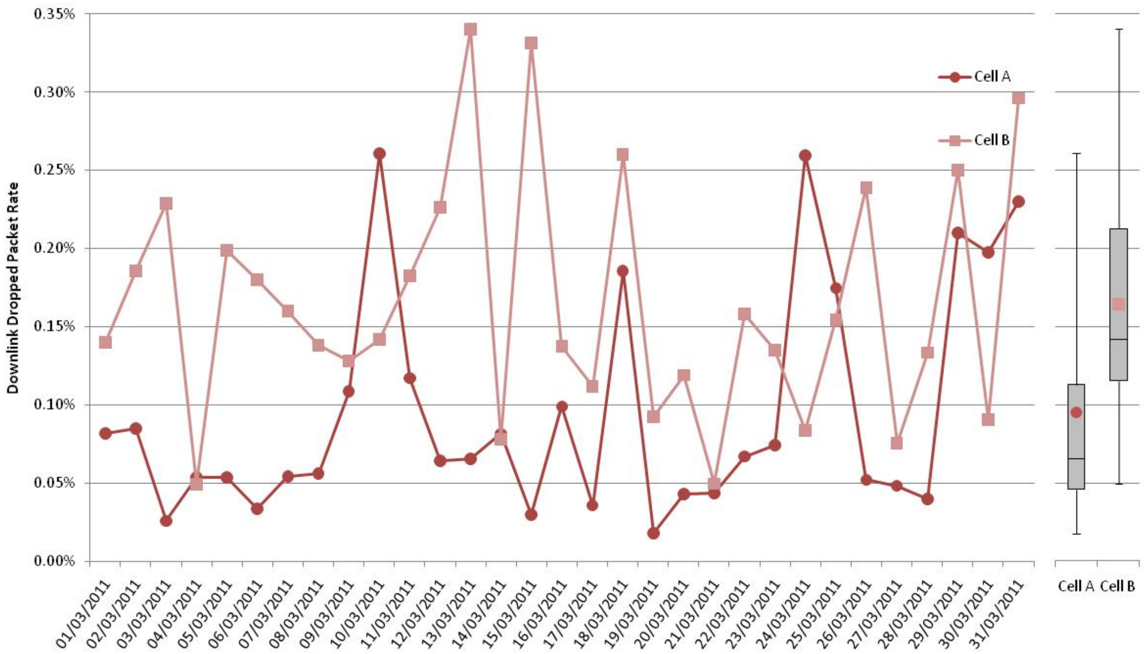

Figure G.8 DL Dropped Packet Rate at 10 MHz channel for cells A and B.

The main statistical elements related to Figure G.8 are presented in Table G.8.

From the statistics it is clear that cell A has a better performance when compared to B at 10 MHz similar to 5 MHz.

Comparing with the network at 10 MHz one assesses that cell A presents better performance on all statistical vales, while cell B shows both higher average and median, placing it on the top worst half.

Table G.8. Statistic values for DL Dropped Packet Rate at 10 MHz channel for cells A and B.

Statistics	**Downlink Dropped Packet Rate 10 MHz channel**	
	Cell A	**Cell B**
Count	31	31
Average (μ)	0.10%	0.16%
Standard Deviation (σ)	0.07%	0.08%
Minimum	0.02%	0.05%
Q1	0.05%	0.12%
Median (=Q2)	0.07%	0.14%
Q3	0.11%	0.21%
Maximum	0.26%	0.34%

Given the above values one verifies that both cells are not among the ones with the highest DL Drop Packet Rate level and confirming as 10 MHz channel representatives for this thesis, since from a user traffic perspective the results would not be influenced by high DL Drop Packet Rate.

Comparing with 5 MHz the statistical values are very similar maintaining the consistency of cell A showing better values than cell B. A deeper analysis of the network behavior of the DL Drop Packet Rate is out of the scope of this thesis.

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