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Performance Gains Evaluation from UMTS/HSPA+ to LTE at the Radio Network Level

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To the Ones I love

“Computers are useless. They only can give you answers.” *Pablo Picasso*

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Abstract

Wireless radio technologies are continuously in progress, catching up to the rise of new challenging applications. Recent releases of UMTS/HSPA+ and LTE, two dissimilar systems, are evaluated in terms of performance in a dual scenario regarding the number of users. A single user model is developed aiming at the cell radius calculation, concerning a certain requested throughput and employing all available system resources. Additionally, the multiple users' model presents a further realistic approach with shared resources in a random fading channel. Given the differences between the two technologies, the impact of some system metrics was taken into account throughout the two models. In the single user case, it is shown that more robust modulations lead to a higher radius, while in indoors, coverage constraints were detected especially in UL, with cell radii below 100 m. When the number of users increases, as far as performance is concerned, LTE unveils higher average network throughput of 13.5 Mbps and an average ratio of served users of 72% compared to 9.8 Mbps and 66% in UMTS/HSPA+, however, the latter covers 26% more users. In addition, LTE presented superior results over almost all analysed situations.

Keywords

LTE, UMTS/HSPA+, Capacity, Throughput, Coverage, QoS

Resumo

As tecnologias sem fios estão em constante evolução, acompanhando o emergir de aplicações e serviços cada vez mais exigentes. Desenvolvimentos como UMTS/HSPA+ e LTE, dois sistemas dissemelhantes foram analisados numa dualidade de cenários, tendo em consideração o número de utilizadores. Para este efeito, um modelo de utilizador único foi desenvolvido, com o objectivo de calcular o limite da célula, utilizando todos os recursos rádio disponíveis, tendo em conta o débito a transmitir. Adicionalmente, o modelo de múltiplos utilizadores traduz uma abordagem mais realista, partilhando recursos através de um canal rádio aleatório. Dadas as diferenças entre UMTS/HSPA+ e LTE, o impacto de várias métricas foi avaliado. Do modelo de utilizador único conclui-se que com o uso de modulações mais robustas resultam células maiores, ao passo que em ambiente interior, problemas de cobertura foram detectados, especialmente em UL onde os raios obtidos são menores que 100 m. Com o aumento do número de utilizadores, LTE revela um débito binário médio por célula de 13.5 Mbps e rácio médio de utilizadores servidos de 72% comparativamente a 9.7 Mbps e 66% obtidos em UMTS/HSPA+, todavia, este último consegue cobrir mais 26% de utilizadores. Adicionalmente, constatou-se que LTE apresentou resultados superiores em praticamente todas as análises realizadas.

Palavras-chave

LTE, UMTS/HSPA+, Capacidade, Débito Binário, Cobertura, QoS

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List of Acronyms

2G	2 nd Generation Systems
3G	3 rd Generation Systems
4G	4 th Generation Systems
3GPP	Third Generation Partnership Project
ACK	ACKnowledgement
A-DCH	Associated DCH
AM	Adaptive Modulation
AMC	Adaptive Modulation and Coding
AMR	Adaptive Multirate
APP	Application
ARQ	Automatic Repeat ReQuest
BCH	Broadcast Channel
BER	Bit Error Ratio
BLER	Block Error Ratio
BLEP	Block Error Probability
BPSK	Binary Phase Shift Keying
BS	Base Station
BW	BandWidth
CDF	Cumulative Distributed Function
CDMA	Code Division Multiple Access
C++	C Plus Plus
CH	Channel
CN	Core Network
COST231-W-I	COoperation européenne dans le domaine de la recherche Scientifique et Technique 231-Walfisch-Ikegami
CP	Cyclic Prefix
CPC	Continues Packet Connectivity
CPCH	Common Packet Channel
CQI	Channel Quality Indicator
CS	Circuit Switch
CTO	Chief Technology Officer
DCH	Dedicated Channel
DL	DownLink
DOB	Downlink-Optimised Broadcast

DP	Default Profile
DRX	Discontinuous Reception
DS-CDMA	Direct Sequence CDMA
DSCH	Downlink Shared Channel
DSL	Digital Subscriber Line
DTX	Discontinuous Transmission
DVB	Digital Video Broadcasting
E-AGCH	E-DCH Absolute Grant Channel
E-DCH	Enhanced DCH
E-DPCCH	E-DCH Dedicated Physical Control Channel
E-DPDCH	E-DCH Dedicated Physical Data Channel
E-HICH	E-DCH HARQ acknowledgement Indicator Channel
E-RGCH	E-DCH Relative Grant Channel
E-UTRAN	Evolved-UTRAN
EIR	Equipment Identity Register
EIRP	Equivalent Isotropic Radiated Power
eNB	evolved Node B
EPA	Extended Pedestrian A
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
ETU	Extended Typical Urban
EVA	Extended Vehicular A
F-DCH	Fractional-DCH
FACH	Forward Access Channel
FDD	Frequency Division Duplex
FDS	Frequency Domain Scheduling
FFT	Fast Fourier Transform
FRC	Fixed Reference Channel
FST	Frame Structure Type
FTP	File Transfer Protocol
GBSB	Geometrically Based Single Bounce
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPRS	General Radio Packet System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HARQ	Hybrid ARQ
HDTV	High-Definition Television
HLR	Home Location Register
HOM	Higher Order of Modulation

HS-DPCCH	High-Speed Dedicated Physical Control Channel
HS-DSCH	High-Speed Downlink Shared Channel
HS-PDSCH	High-Speed Physical Downlink Shared Channel
HS-SCCH	High-Speed Shared Control Channel
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSPA+	High-Speed Packet Access Evolution
HSS	Home Subscriber Server
HSUPA	High-Speed Uplink Packet Access
I/O	Input / Output
ICI	Inter-Chip Interference
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunications
IMS	IP Multimedia Sub-system
IP	Internet Protocol
IR	Incremental Redundancy
ISDN	Integrated Services Digital Network
ISI	Inter-Symbol Interference
ITU	International Telecommunications Union
L1	Layer-1
L2	Layer-2
LBS	Location-Based Services
LoS	Line of Sight
LTE	Long Term Evolution
M-GW	Media GateWay
MAC	Medium Access Control
MBMS	Multimedia Broadcast Multicast Service
MCS	Modulation Coding Schemes
MID	Mobile Internet Device
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MMS	Multimedia Messaging Service
MSC	Mobile Switching Centre
MT	Mobile Terminal
MU	Multiple Users
NACK	Negative ACKnowledgement
NB	Node B
NLoS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

OSI	Open Systems Interconnection
OVSF	Orthogonal Variable Spreading Factor
P2P	Peer-To-Peer
P-CPICH	Primary Common Pilot Channel
P-GW	PDN GateWay
P-SCH	Primary-Synchronisation Channel
PAR	Peak Average Ratio
PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PCRF	Policy and Charging Rules Function
PDA	Personal Digital Assistant
PDCCH	Physical Downlink Control Channel
PDCCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDR	Peak Data Rate
PDU	Protocol Data Unit
PDSCH	Physical Downlink Shared Channel
PHY	Physical
PMI	Pre-coding Matrix Indicator
PP	Professional Profile
PRACH	Physical Random Access Channel
PS	Packet Switch
PSTN	Public Switched Telephone Network
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RACH	Random Access Channel
RAN	Radio Access Network
RB	Resource Block
RF	Radio Frequency
RLC	Radio Link Control
RMG	Relative MIMO Gain
RNC	Radio Network Controller
RP	Recreational Profile
RRC	Radio Resource Control
RRM	Radio Resource Management
RS	Reference Signal

RTT	Round Trip Time
S-GW	Serving GateWay
S-SCH	Secondary-Synchronisation Channel
SAE	System Architecture Evolution
SC	Single Carrier
SCH	Synchronisation Channel
SC-FDMA	Single Carrier – Frequency Division Multiple Access
SDU	Service Data Unit
SF	Spreading Factor
SGSN	Serving GPRS Support Node
SHO	Soft handover
SIM	Simulator (Generator Engine)
SIMO	Single Input Multiple Output
SIP	Session Initiation Protocol
SIR	Signal-to-Interference Ratio
SISO	Single Input Single Output
SINR	Signal-to-Interference-plus-Noise Ratio
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SU	Single Users
TBS	Transport Block Size
TD-SCDMA	Time Division-Synchronous Code Division Multiple Access
TDD	Time Division Duplex
TDS	Time Domain Scheduling
TTI	Time Transmission Interval
UE	User Equipment
UHF	Ultra High Frequency
UL	UpLink
UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunications System
USIM	UMTS Subscriber Identity Module
UTRAN	UMTS Terrestrial RAN
VHF	Very High Frequency
VLR	Visitor Location Register
VoIP	Voice over IP
WCDMA	Wideband CDMA
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

List of Symbols

α	DL orthogonality factor
δ	Sigmoid function
Δf	Sub-carriers Bandwidth
η	Load Factor
η_{BLER}	Block Error Ratio
$\eta^{APP/PHY}$	Total overhead ratio plus BLER
μ	Average value
μ_d	Mean value of the correspondent statistical distribution
μ_{RMG}	Average RMG
v_j	Activity factor
ρ_N	Signal to Noise Ratio
ρ_{IN}	Signal-to-Interference-plus-Noise Ratio
ρ_{pilot}	P-CPICH E_c/N_0 when HSDPA is active
σ	Standard deviation
σ^2	Variance
σ_{RMG}^2	RMG distribution variance depending on the cell-type, N_T and N_R
τ	Cyclic Prefix duration
φ	Street orientation angle
Φ	Maximum interference margin considered
Ω	Channel Quality Indicator
B	Passband Bandwidth
B_C	Coherence Band
B_N	Subchannel Bandwidth
C_{MIMO}	Capacity gain of a MIMO system
C_{SISO}	Capacity gain of a SISO system
d	Distance between BS and MT
e	Relative Error
E_b	Energy per bit
E_c	Energy per stream chip
f	Frequency
F	Equipment Noise Figure
g	Geometry factor
G_{div}	Diversity gain

G_{MHA}	Masthead amplifier gain
$G_{M/S}$	Relative MIMO Gain
G_p	Processing gain
G_r	Receiving antenna gain
G_t	Transmitting antenna gain
h_b	BS height
h_m	MT height
H_B	Building height
H_{roof}	Roof height
i	Ratio of inter- to intra-cell interferences
I_0	Interference
$I_{inter\ n}$	Normalised inter-cell interference
k_a	Dependence of the path loss for BS antennas below rooftops of the adjacent buildings
k_d	Dependence of the multiscreen diffraction loss versus distance
k_f	Dependence of the multiscreen diffraction loss versus frequency
L_0	Free space loss
L_{bsh}	Losses due the antennas position
L_c	Cable losses between transmitter and antenna
$L_{COST231}$	COST231-W-I propagation losses
L_{int}	Indoor penetration losses
L_{ori}	Street orientation loss
L_p	Path loss
$L_{p\ outd}$	Outdoor path loss
$L_{p\ ind}$	Indoor path loss
L_{rm}	Approximation for the multi-screen diffraction loss
L_{rt}	Rooftop-to-street diffraction loss
L_u	User losses
M	Total margin
M_{FF}	Fast fading margin
M_I	Interference margin
M_{SF}	Slow fading margin
N	Total noise power
N_0	Noise spectral density
N_b	Number of bits
N_{bs}	Number of bits per symbol carried within a modulation scheme
N_{BS}	Number of active BS in the network
N_R	Number of Rx antennas
N_S	Number of sub-carriers
N_{sect}	Number of sectors in the BS

N_{serv}	Number of data services considered
N_{SF}	Number of symbols per sub-frame
N_T	Number of T_x antennas
N_u	Number of users
N_{uBS}	Number of served users in a BS
N_{uhBS}	Number of users per hour in the BS
N_{uhnet}	Total number of served users per hour in the network
N_{uhserv}	Number of users per hour performing a certain service
N_{U_j}	Number of users in the BS j
$N_{U_{max}}^{BS}$	Number of users of the most populated Node B
N_{uTOT}	Total number of covered users
N_z	Number of samples
P_{HSDPA}	HSDPA transmit power
$P_{HS-DSCH}$	Received power of the HS-DSCH summing over all active HS-PDSCH codes
P_{inter}	Received inter-cell interference
P_{intra}	Received intra-cell interference
P_{noise}	Received noise power at the RF band
P_{pilot}	P-CPICH transmit power
P_r	Power available at the receiving antenna
P_{Rx}	Received power at receiver input
P_{RXmin}	Receiver sensitivity
$P_{S\&C}$	Signalling and Control Power
P_t	Power fed to the transmitting antenna
P_{total}	Total transmit power
P_{Tx}	Total BS transmission power
P_{Tx}^{BS}	Power allocated to the dedicated channels
$\overline{r_{net}}$	Average network radius
R	Cell radius
R_b	Data rate or throughput
R_{bBS}	Instantaneous served throughput per BS
R_{bj}	Instantaneous throughput of the user j .
R_{bmax}	Maximum BS allowed throughput
$R_{b\ mod}$	Total throughput for one specific modulation scheme
$\overline{R_{bnet}}$	Average network throughput
R_{bNORM}	Normalised throughput
$R_{b\ RB}$	RB instantaneous throughput
R_{breq}	Requested throughput
R_{bser}	Served throughput

R_b^{APP}	Data rate over the application layer
R_b^{PHY}	Data rate over the physical layer
R_c	WCDMA chip rate
R_x	Receiver component
RB_j	Number of RB attributed to the user
RB_{BS}	Total number of RBs
s	Slope of the Sigmoid function
SF_{16}	HS-PDSCH Spreading Factor of 16
S_G	Satisfaction grade
$\overline{S_{Gnet}}$	Average network satisfaction grade
$\overline{S_U}$	Average ratio of served users
T_{BS}	Total BS traffic transferred in an hour
T_{net}	Total network traffic in an hour
T_{SF}	Sub-frame period
T_x	Transmitter component
u	Random value with a Uniform distribution
V_u	Data volume per user
w_B	Distance between middle points of adjacent street buildings
w_s	Street width
z	Set of samples
z_i	Sample i
z_r	Reference Value

List of Software

Borland C++ Builder v.6.0

MapBasic v.6.5

MapInfo Professional v.7.5

Microsoft Excel 2007

Microsoft Word 2007

Microsoft PowerPoint 2007

Microsoft Visio 2007

ANSI C++ Integrated Development Environment

Programming software and language, sharing functionalities and interoperating with MapInfo Professional

Geographical Information System (GIS) software

Calculation and graphical chart tool

Text editor software

Presentation software

Design tool (e.g. diagrams, flowcharts, etc)

Chapter 1

Introduction

This chapter introduces the theme of this dissertation, in particular over a contextual and motivation perspective, and additionally provides an overview of the assumptions and objectives established for the work development, as well as a detailed synopsis of its structure and original contributions.

1.1 Overview

Mobile communications systems revolutionised the way people communicate, joining together communications and mobility everywhere, anytime. The basic need for communication between people is the dominant driver for the telecoms business, [Eric04].

The first mobile systems were analogue and provided only voice. The specification of the Second Generation (2G) known as Global System for Mobile Communications (GSM) was published in 1990 by the European Telecommunications Standards Institute (ETSI). Third Generation (3G) systems, e.g., the Universal Mobile Telecommunications System (UMTS), were designed for multimedia communications: person-to-person communication can be enhanced with high-quality multimedia files, access to information and services through public and private networks is improved by the higher data rates and new flexible communication capabilities. Its specification has been created by 3rd Generation Partnership Project (3GPP), which is also responsible for important evolution steps, e.g., High Speed Packet Access (HSPA).

UMTS/HSPA and HSPA+ are commonly known as 3G and LTE as 4G. Due to the nature of changes that LTE introduces in the mobile communications paradigm, commonly LTE is referred as a 4thG technology erroneously. Still, LTE beyond every release specified is a 3.9G technology, while the requirements made by ITU-R, specifically identified as International Mobile Telecommunications – Advanced (IMT-Adv), concern capabilities that go further the ones implicit in IMT-2000 for 3G/3.5G technologies, Figure 1.1. These requirements are in order to be accomplished by 3GPP LTE-Advanced or another emerging technology, the next evolution step of LTE.

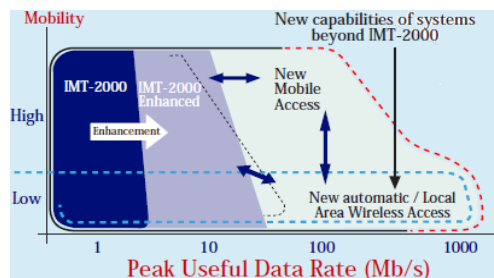


Figure 1.1 ITU-R requirements since the standardisation of UMTS (extracted from [PTIN06]).

In order to accomplish present and future demands of mobile broadband, the 3GPP specified the Long Term Evolution (LTE), a complete new wireless technology, offering a number of enhancements, providing major improvements to end-user performance and network efficiency. The constant performance increase requirements are met by a flexible and spectrally efficient radio link protocol design with low overhead, which meets the challenging targets, [LLMP09]. In addition to reducing the cost per bit by improving spectrum efficiency, LTE can achieve low delays and faster speeds enabling the provision of services with strict delay requirements and the transmission of large files.

LTE is also one strong migration path toward IMT-Advanced requirements, which at the moment are far from being accomplished by LTE or another radio technology, pointing towards 1 Gbps connections in a short range/low mobility connection, combination of MIMO with beamforming or higher bandwidths than the ones specified for LTE, until 100 MHz.

A compilation on Figure 1.2 summarises some performance key features of all UMTS and LTE 3GPP technology releases and associated moment of commercial availability or expected one. One can show that in the 10 years the peak data rates increased 450 times, from 384 kbps to an expectable 173 Mbps in Release 8.

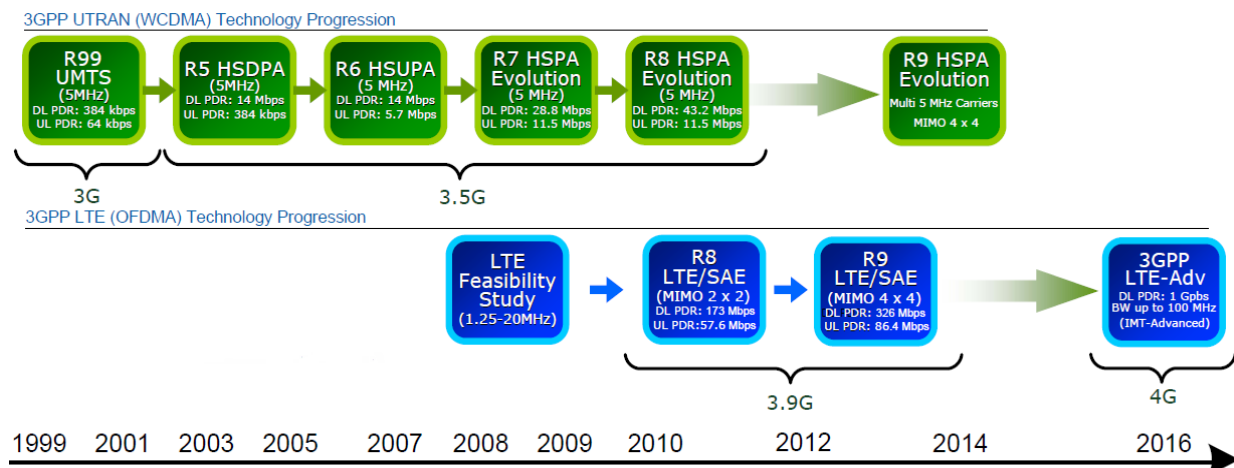


Figure 1.2 Evolution of 3GPP family standards and future timeline projections (note that PDR stands for Peak Data Rate).

The growing demand for mobile Internet and wireless multimedia applications has motivated the development of broadband wireless access in recent years. With an even-closer approximation between wireline and wireless technologies in terms of performance, the old traditional differences between them are getting increasingly similar. In a near future, the telecommunications area can expect a trade-off between wireless and wireline systems, standing for enhancements of wireless radio spectral efficiency achievements and consequent offered performance for such mobility, especially on low density areas or even on developing countries.

The requirements from ITU-R for 4G systems, express that wireless capabilities are able to compete with today's best wireline performance. However, initial deployments of LTE will be best suited for urban hot spots, whereas HSPA+ will cover the existing vast HSPA footprint, [Qual09b]. Even so, HSPA+ is ready to perform today as noticed in [TEK09], running nowadays in Portugal and performing the key features of Release 7, Figure 1.2. LTE trials are running all over the world since the beginning of 2008, which characterizes HSPA+ a mature technology compared with LTE. First LTE commercial projections point to Q4 2010 in two pilot deployments over Stockholm and Oslo, while in Portugal trials will start to follow in 2010.

Anyway, as it happened with UMTS/HSPA+, radio technologies follow a rigorous process of developing enhancements and trial testing through the use of prototypes before the first commercial releases. LTE had already given good results as the ones achieved by [NSNe09] closer to the ones claimed to be the maximum theoretically possible, with an operating frequency band of 2.6 GHz reveal 173 Mbps with MIMO 2x2 and 326 Mbps with 4x4 configurations and 20 MHz channel bandwidth, operated by [Veri09]. Also, LTE will probably make use of released spectrum from the digital dividend procedures.

Pursuing innovations over the network level, specifically over the core networks and radio access, Mobile Terminals (MTs) have also been part of a revolution over the handheld devices, Figure 1.3. The trends and challenges of these manufactures and hardware players are not in the scope of this thesis, but again the innovation must always be present over the MTs in order to go along through the enhancements done over the telecommunications networks. Recent smartphones are the big driver of mobile data use. Concerning LTE initial deployments, MTs will be released with multimode operability with the previous systems, in order to smooth the penetration progress of the new upcoming technology.



Figure 1.3 First commercial MT from 1stG (Analog) and LTE prototypes (adapted from [GSMA09]).

Keep in mind that the whole architecture scheme of a telecommunications network is not in the scope of this thesis. The core network, and the whole system's backhaul characterised by microwave, copper lines (DSL) or optic fibre, and its respective hubs/servers, are elements not analysed throughout this work, which is focused on a radio access performance level evaluation only.

Advances in MT processors and further integration of enabling technologies, like higher mega-pixel cameras, videos, etc., will only exacerbate the challenge of requiring more bandwidth, consuming applications at longer ranges, and a more efficient utilisation of the limited spectrum available to network operators. This trend has already been supported with the new Web 2.0 trends, such as social networking, blogging, or media sharing. Several studies proclaim that the number of smartphones sold is greater than computer retails, which the latter is also projected to be deployed with embedded HSPA data cards henceforth, [Eric08]. By 2009, it is expected 211 million smartphone units sold, driven by innovative new devices and operator subsidies designed to promote mobile data consumption, so that by 2013 almost four in every ten handsets sold worldwide will be a smartphone, [3GAM09b].

Following this, data service requirements also increase, being one excellent revenue opportunity since voice services and the respective profit are stagnant in the last few years. Dick Lynch, Verizon CTO, [Lynch09], shows that data revenues only start to make sense in the last three years and emphasises the evolution between data and broadband. The global increase of data services is notorious, and the expectations go towards a greater growing compared with the one that is noticeable today.

The perspectives are optimistic towards an exponential increase of data traffic within wireless networks, Figure 1.4, supported by the performance of certain applications, in the past classified as "killer-applications", which are now starting to be feasible, like video-on-demand, HD video conferences and TV, robust gaming, other person-to-person services or even 3DTV. At the same time, Portuguese communications regulator entity, Anacom, shows over Figure 1.5 the respective country case, underlining the actual superior number of mobile broadband subscriptions facing other

broadband alternatives. Notice the projection given by [3GAM09a] expecting a worldwide penetration rate of 100% in mobile subscriptions in 2014. In Portugal, at the moment, it is assumed a mobile phone penetration rate of 130% and still growing.

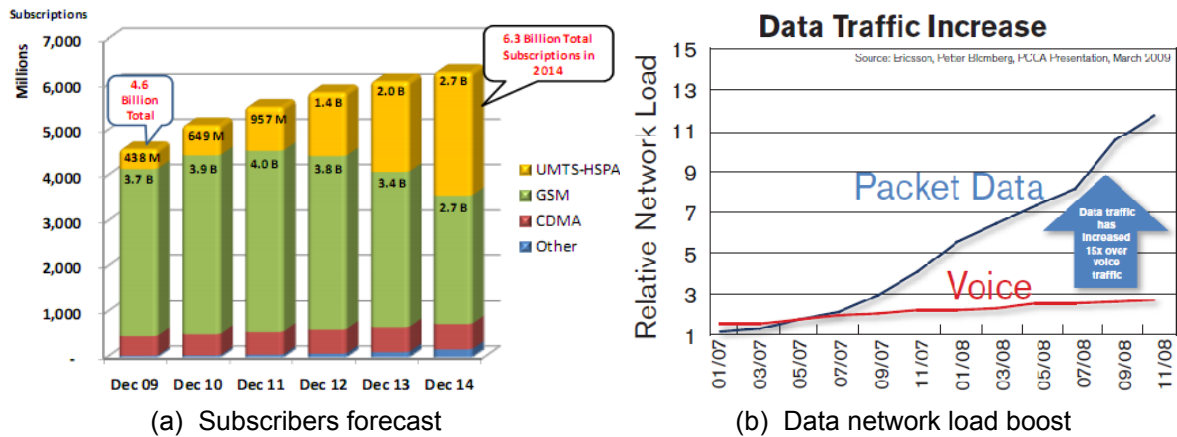


Figure 1.4. Mobile Broadband trends and expectations (extracted from [3GAM09a] and [3GAM09b]).

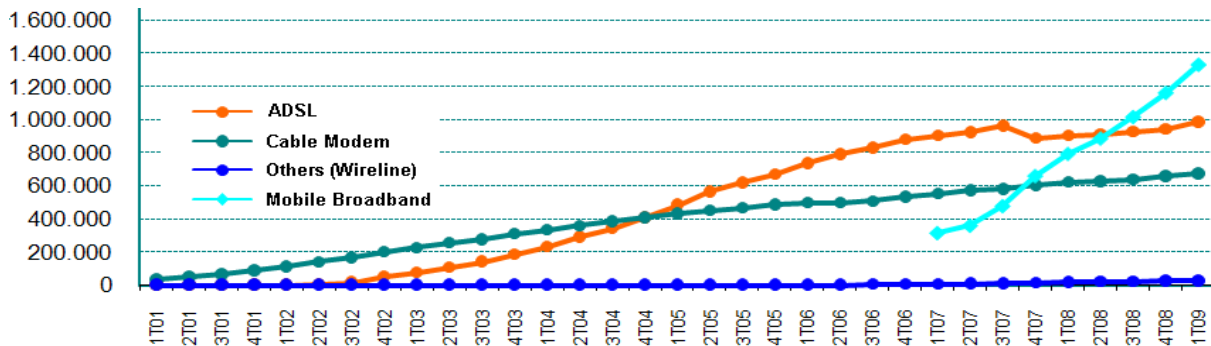


Figure 1.5. Portugal broadband subscriptions scenario (adapted from [Anac09]).

1.2 Motivation, Assumptions and Contents

The main purpose of this thesis is to study UMTS/HSPA+ and LTE in a radio network perspective level, divided into single and multiple users performance, classified alongside different environment scenarios and offered services, and in particular, addressing coverage and capacity aspects. As described in the previous section, the proposed topic is of great importance, concerning the two top technologies on wireless telecommunications for the next 10 years, thus, the outcomes and conclusions are adequate to the future telecommunications days.

In order to accomplish the desired results, two different models for two different network perspectives were developed and implemented. For the creation of these models, information from literature was gathered and compiled, mapped into models, also based and adapted from existing ones.

Parameters like coverage (expressed in cell radius), capacity (data rate), users satisfaction grade, network transported traffic, frequency band, among others, are compared in a unique scenario of data services, whereas speech services like voice or video-telephony are intended to be served by an older system, e.g., UMTS Release 99, not taken in the evaluation performed.

A comparison between UMTS/HSPA+ and LTE is performed, employing the superior performance of HSPA+ assigned by the latest UMTS 3GPP releases, in order to face the LTE specifications.

This thesis was made in collaboration protocol with a Portuguese mobile telecommunications operator VODAFONE – Comunicações Pessoais, S.A., Several technical details, as well as reviews, were discussed with the mobile operator, giving the opportunity of collecting many valuable critics and suggestions used throughout the development of this thesis.

The main contributions of this dissertation are the analysis and assessment of UMTS/HSPA+ and LTE in both single and multiple users within a non uniform-traffic service distributions, over different scenarios. A model to calculate user throughput as a function of distance for a single user scenario was implemented. These models were adapted to a multiple users viewpoint, and implemented in a simulator, allowing the analysis of UMTS/HSPA+ and LTE performance in a real network, calculating several metrics, as averages network radius and throughput, offered traffic and relation of covered users along the metropolitan centre of Lisbon taken as scenario. The developed simulator evaluates the influence of several system parameters variation and the associated repercussion on the network.

The present thesis is composed by 5 chapters, including the present one. Chapter 2 presents an introduction to UMTS/HSPA, and HSPA+. UMTS basic concepts are explained, and the respective key features of the releases under studied emphasised. The radio interface in particular performance grades, are presented in a coverage and capacity outlook. Equal attention is devoted to the same subjects for LTE in a subsequent section. At the end, a full comparison and evaluation is presented contrasting strengths and weaknesses of each technology,

Chapter 3 introduces the developed models, single user radius model, the simulator developed for multiple users and services, based on previous developed routines, and main modifications being pointed out. UMTS/HSPA+ and LTE modules developed for both DL and UL are described in detail. In addition, the I/O files are highlighted, and the simulator assessment is presented.

In Chapter 4, achieved results are analysed and submitted into a discussion, where the influence of several system parameters being taken into account. The outcomes of both developed models, single and multiple users are presented for UMTS/HSPA+ and LTE and for the two links, DL and UL. Moreover, all the scenarios are defined, including a default scenario analysed for both systems.

The present dissertation concludes with Chapter 5, where a critical analysis is also taken followed by the main work conclusions. Furthermore, suggestions for future evolution possibilities of the mobile communications area, as well as mid-term future academic work proposals, are presented. Finally, a set of annexes closes the present document with supplementary information, when there is a need to the global comprehension of the described problem.

Chapter 2

Fundamental Concepts

This chapter provides a synopsis of UMTS and its evolution, namely HSPA in Section 2.1 and HSPA+ in Section 2.2, focusing on radio link performance, coverage and capacity topics. The same approach is done for LTE in Section 2.3, which finalises with a comparison of these two technologies.

2.1 UMTS/HSPA

UMTS Release 99 basic concepts are presented in this section, based on [Lope08] and [HoTo06], namely network architecture, radio interface, capacity and coverage aspects. Yet, a description of High Speed Packet Access (HSPA) principles such as new technologies, improvements and key enhancements, is also performed.

2.1.1 Network Architecture

UMTS Network Architecture is composed of several logical nodes with a specific function, grouped in three main functional elements, Figure 2.1:

- User Equipment (UE)
- UMTS Terrestrial Radio Access Network (UTRAN)
- Core Network (CN)

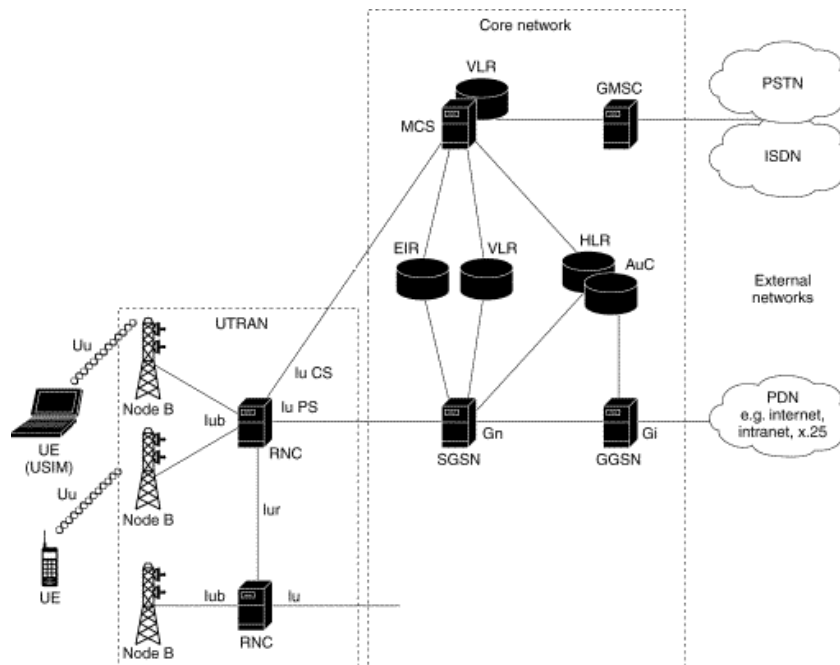


Figure 2.1. UMTS System Architecture (adapted from [CiSy08]).

The interfaces at the above architecture are differentiated namely over the radio access, core network connections and external networks connections. UE and UTRAN handle radio aspects based on Wideband Code Division Multiple Access (WCDMA), the UMTS radio interface. The UE is the combination of the subscriber's Mobile Terminal (MT) and the UMTS Subscriber Identity Module (USIM), which contains the subscriber profile performing authentication routines and security functions; nevertheless, from now on, UE will be referenced as MT.

UTRAN has two distinct elements, Node Bs (NBs), also known as Base Stations (BSs), dealing with radio channels including the multiplexing/demultiplexing of user voice, data information, and Radio Network Controllers (RNCs) which are responsible for controlling and managing BSs sites in its covering area, including the Radio Resource Control (RRC). RNCs also perform user data processing

with higher-level protocols to manage the usage of radio network services. Other functions assigned to RNC are broadcast signaling, power settings and handover control.

UMTS CN is based on the GSM/GPRS network topology. It provides the switching, routing, transport, and database functions for user traffic. The CN contains Circuit-Switched (CS) elements such as:

- Mobile Switching Centre (MSC), is a switch that serves the UE in its current location, switching voice and data connections.
- Gateway MSC (GMSC) performs connection to the external CS networks, both the MSC and GMSC handle control functionalities, but user data goes through the Media Gateway (M-GW), which performs the actual switching for user data and network inter-working processing.

as well as Packet-Switched ones:

- Serving GPRS Support Node (SGSN) is responsible, for the delivery of data packets from and to the BSs within its geographical service area. Its tasks include packet routing and transfer, mobility management and charging functions.
- Gateway GPRS Support Node (GGSN) connects the CN to other external packet data networks, such as the Internet.

The following elements are both CS and PS data based:

- Visitor Location Register (VLR) is a distributed database that saves temporarily information about the MTs that are active in the geographic area allocated to it. A VLR is associated with each MSC in the network. When a new subscriber roams into a Location Area, the VLR is responsible for copying subscriber information from the HLR to its local database.
- Home Location Register (HLR) is the central database for all users registered in the network. It stores static and dynamic information about subscribers and their associated services.
- Equipment Identity Register (EIR) is a database that stores the International Mobile Equipment Identities (IMEIs) in the network. This register also provides security features, such as blocking calls from MTs that have been lost/stolen.
- Authentication Centre contains the algorithms for authenticating subscribers and the necessary keys for encryption to safeguard the user input, being associated to the HLR.

External networks can be CS or PS. Integrated Services Digital Network (ISDN) and Public Switched Telephone Network (PSTN) are CS networks, although the Internet is a well-known PS network.

2.1.2 Radio Interface

UMTS radio interface WCDMA is based on Direct-Sequence Code Division Multiple Access (DS-CDMA), initially specified in Release 99 by the 3rd Generation Partnership Project (3GPP), [3GPP07a]. The access method leads to a very high bandwidth, providing highly variable user data rates. Enhanced capabilities are low delay, great mobility between different data type, possibility of service differentiation, and acquiring network QoS. The user data rate is kept constant during each 10 ms frame; however, the data capacity among users can change from frame to frame.

Besides the differences with GSM systems, UMTS supports different handovers between, and

currently operates in the Frequency Division Duplex (FDD) mode, making use of 4.4 MHz channels bandwidth, separated by 5 MHz carriers both for Downlink (DL) and Uplink (UL). The frequency bands for Portugal, as well for all the rest Europe and Japan are [1920, 1980] MHz for UL and [2110, 2170] MHz for DL, [3GPP07b].

Spreading is used to separate the physical data and control channels in UL, and to distinguish the connections to different users within one cell in DL, defining two operations: channelisation and scrambling, [Corr08]. The former originates a wideband signal by multiplying the user's data by a sequence of chips, being specified the chip rate of 3.84 Mcps, associating to a spreading factor, the use of the Orthogonal Variable Spreading Factor (OVSF). This technique obtains the code enabling to maintain different spreading codes orthogonal to each other, and also to change the spreading factor among them. The latter is used over spreading, whereas in DL, it differentiates the sectors of the cell, and in UL, it separates MTs from each other without changing signal bandwidth.

Power management, Soft and Softer handovers are key features in UMTS radio interface. There are two types of power control: open loop, to avoid the use of excessive power, thus, keeping minimum interference levels, and outer loop, to adjust the Signal-to-Interference-Ratio (SIR) of each individual link, instead of defining a SIR target for the worse case, resulting on a waste of capacity. Soft handover occurs when a MT is associated to two sectors from different BSs, while Softer handover happens when the MT is overlapping the cell coverage of two adjacent sectors from the same BS. The combined information is matched in the RNC for the former, and at the BS for the latter.

UMTS has four types of channels: radio, logical, physical and transport, [3GPP02b]. Radio channels are related to the frequency of the carrier. Logical channels are responsible for transferring specific information. The transport channels carry the user's information from the higher layers of the network being divided into two groups: common channels, shared by all users in the cell, and dedicated channels, for a single user, where there is only one Dedicated transport Channel (DCH), [3GPP02b]. Since an extended acquaintance about UMTS detailed channels are out of this thesis scope, please check [CoLa06] and [Lope08] for a deeper study.

High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA) are Release 99's evolutions, being part of High Speed Packet Access (HSPA), and patented by 3GPP, [3GPP07c] as Release 5 and Release 6, respectively. While in Release 99 the scheduling control is based on the RNC, and the BS only has power control functionality, in HSDPA capacity and spectral efficiency are improved. Scheduling and fast link adaptation based on physical layer retransmissions was moved to the BS, minimising latency and providing a whole change in Radio Resource Management (RRM). Notice that with this function, the average cell throughput increases about 6 to 9%, [HoTo06]. From the network perspective, the use of HSDPA or HSUPA causes great changes on the physical and on the Radio Link Control (RLC) layers.

The transmission method is different, with a frame length of 2 ms obtaining less latency and fast scheduling among users. The duration of the transmission also known as Transmission Time Interval (TTI), is variable between 10 ms and 80 ms, in Release 99.

HSDPA does not support soft handover or power control. Higher data rates are accomplished through the use of higher order modulations, such as 16 Quadrature Amplitude Modulation (QAM) with 4 bits per symbol, which can only be used under good radio channel conditions. Quaternary Phase Shift Keying (QPSK) is mainly used to maximise coverage and robustness.

The BS has a fast physical layer transmission using Hybrid Automatic Repeat ReQuest (HARQ) with 2 transmission types. Only a fixed SF_{16} is used, in the High-Speed Physical Downlink Shared Channel (HS-PDSCH) with a maximum of 15 Walsh-Hadamard channelization codes per MT, as the last one is reserved for High-Speed Shared Control Channel (HS-SCCH), allowing a system's theoretical peak bit rate of 14.4 Mbps within perfect conditions. The HS-SCCH carries critical information for de-spreading of the correct codes, and HARQ information providing the user's Modulation and Coding Scheme (MCS) based on received transmissions, [BBSS04].

Release 6, introduces mainly changes for enhancing UL capabilities as HSDPA improves DL features and basically is an extension of Release 99 known as HSUPA. The interaction between MT and BS and the introduction of QPSK are some of the improved differences. Table 2.1 points a briefly comparison between some key features of HSPA with the initial UMTS Release 99. The power control feature is maintained, as well as the most of Release 99 specifications.

HSUPA has some of the features of HSDPA with its new transport channel (E-DCH), namely fast BS based scheduling, fast physical layer HARQ and, optionally, a shorter TTI of 2 ms. The main difference between HARQ used in HSDPA and HSUPA is the fact that, for the latter, it is fully synchronous, avoiding the need for sequence numbering, and it can operate in soft handover, while in the DL the UE stores data from previous transmissions to enable joint decoding of retransmissions. The allowance of lower required E_b/N_0 at the BS, when comparing similar throughputs with Release 99, increases UL spectral efficiency. Capacity improvements regarding the use of fast HARQ are about 15 to 20%, [Lope08].

Table 2.1 Comparison between UMTS stages.

Feature / Stage	Release 99	Release 5 (HSDPA)	Release 6 (HSUPA)
Variable Spreading Factor	Yes	No (SF16)	Yes
Adaptive Modulation	No (QPSK in DL; BPSK in UL)	Yes	No (QPSK)
Soft Handover	Yes	No	Yes
Fast Power Control	Yes (0.667 ms)	No	Yes
Scheduling	RNC	BS	BS
Fast Layer-1 (L1) HARQ	No	Yes	Yes
TTI length [ms]	80, 40, 20, 10	2	10, 2
Maximum data rate [Mbps]	0.384 (urban outdoor), 2 (hotspots)	14.4 (TTI = 2ms)	5.7 (TTI variable)

As related previously for HSDPA, HSUPA also introduces new channels for scheduling and retransmission control, as well as for data transmission; nevertheless a meticulous channel analysis is not done. Notice only that DCH channels from Release 99 were left unchanged.

In HSDPA, one of the criteria for admission of new users is the available transmission power, however in HSUPA; the use of fast BS scheduling allows fast adaptation to interference variations, and also a better resource sharing among users. The tighter UL noise factor control with the BS scheduling helps to avoid network overload, and in those situations it reduces the necessary time to return to a stable state.

2.1.3 Coverage and Capacity

In this thesis, the main performance parameters under focus are coverage and capacity, however interference is a primordial factor to take into account in a communications system.

There are 3 main parameters limiting capacity, [HoTo04]: the number of available codes in DL, the system load (both UL and DL and directly related with interference issues), and the shared DL transmission power. The number of available channelisation codes limits the number of simultaneous active users within the cell sector, because these codes are given by the SF. As data rate increases, SF must decrease to allow higher data rates, leading to a decrease of the allowed users in the network. The use of different scrambling codes in the same sector is not recommended, since it would decrease the orthogonality of the DL channels, hence, increase interference. The maximum value for the SF is limited to ensure a minimum QoS, whereas high SF values would increase interference.

It is essential to differentiate UL from DL, since traffic flow is asymmetric between them and different transmission powers characterise each transmitter. As the load increases in UL, a larger interference margin is needed, leading to a decrease of the cell coverage area. The network load is defined by the UL and DL load factors, given by (2.1) and (2.4) respectively. The UL load factor and the Signal-to-Noise Ratio (SNR) can be defined as:

$$\eta_{UL} = (1+i) \sum_{j=1}^{N_u} \frac{1}{1 + \frac{G_{P_j}}{\rho_{N_j} \cdot v_j}} \quad (2.1)$$

$$\rho_N \equiv E_b / N_0 \quad (2.2)$$

where:

- i : ratio of inter- to intra-cell interferences (typically [40, 60] %);
- N_u : number of users per cell;
- v_j : activity factor of user j (typically 50% for voice and 100% for data);
- ρ_{N_j} : SNR of user j , equivalent to energy per bit over noise power spectral density ratio, required to meet a predefined QoS;
- E_b : energy per bit;
- N_0 : noise power spectral density;
- G_{P_j} : processing gain of user j , given by:

$$G_{P_j} = \frac{R_c}{R_b} \quad (2.3)$$

- R_b : data bit rate;

- R_c : chip rate (= 3.84 Mcps);

and the DL load factor:

$$\eta_{DL} = \sum_{j=1}^{N_u} v_j \frac{(\rho_N)_j}{G_{P_j}} [(1-\alpha_j) + i_j] \quad (2.4)$$

where:

- α_j : DL channel orthogonality of user j (between 0.4 and 0.9 in multipath propagation);
- i_j : ratio of inter- to intra-cell interferences for user j .

The main difference between UL and DL load factors is that in the latter the maximum transmission power does not vary with the number of active users, being shared by all users, while in UL, each MT has its own transmitter power.

Coverage in rural areas is more dependent on the UL load factor and on the limited MT transmission power. For urban micro- or pico-cells, intended for high data rates, capacity is limited by the DL load factor. In general, one can say that load factors affect the cell coverage whatever the scenario. A raise of the load factor leads to a reduction in coverage, via the increase of the associated interference.

The interference margin, M_i , is defined by (2.5) and qualifies the interference caused by all system users' interference. To calculate cell capacity, one should use the load equations (2.1) and (2.4) considering that the noise in M_i includes the intra- and inter-cell interferences. When η_{UL} or η_{DL} approaches unity value, the system reaches its pole capacity and the noise rises up to infinity. Typical values for the interference margin in the case of coverage limitation are 1 to 3 dB, corresponding to 20-50% of load according to [RuHa05].

$$M_{i[dB]}^{UL/DL} = -10 \cdot \log(1 - \eta_{UL/DL}) \quad (2.5)$$

In DL, cell coverage is more load dependent than in UL, since the BS has a maximum transmission power to deliver. Consequently, it is fundamental to calculate the total transmission power of the BS expressed by:

$$P_{Tx[W]} = \frac{N_0 \cdot R_c \cdot \sum_{j=1}^{N_u} v_j \cdot \frac{(E_b/N_0)_j}{G_{P_j}} \cdot L_{p_j}}{1 - \overline{\eta_{DL}}} \quad (2.6)$$

where:

- $\overline{\eta_{DL}}$: average DL load factor value across the cell;
- L_{pj} : path loss between BS and user j ;
- N_0 : noise power spectral density at the MT;

Increasing the BS transmitter power, in order to increase cell capacity, is not an efficient method at all due, to the reciprocal interference raise. The transmission power of the BS for macro-cells is usually around 30 W (44.7 dBm), or some suppliers these days can offer around 40 W (46 dBm). The latter is being commonly used by antenna manufactures and second-handed by the telecommunications operators. The BS transmission power, is shared among all MTs in the cell, while MTs have a

transmission power according to the performed service, i.e., typically 21 dBm for voice, and 24 dBm for data.

Common control channels take some of the total power available at the transmitter for signalling and control issues over the network, while the remaining power goes to the dedicated channels. Regarding the Release, the total BS transmission power can be separated into two components:

$$P_{Tx} = P_C^{BS} + P_{Tx}^{BS} \quad (2.7)$$

where:

- P_C^{BS} : Power allocated to the common channels (Signalling and Control)
- P_{Tx}^{BS} : Power allocated to the dedicated channels (User Data)

The power allocated to each channel group is variable according to the operating Release. In Release 99, the transmission power is shared with a ratio of 75% for data channels, and 25% for signalling and control. In HSPA and HSPA+, the enhancements done over the network signalling result in a greater portion of power to execute these tasks properly, therefore, 40% of transmission power is delivered to the common channels, being the sum of all common channels from Release 99 and on top of those the addition of the specific ones from HSPA. The remaining 60% is taken for the dedicated user's channels in the DL.

2.1.4 Performance Analysis

In Release 99, a well-known metric to evaluate system performance is the SNR, approximated by the normalised measure E_b/N_0 . Depending on the service, and on the bit rate, the associated SNR values are different, e.g. in voice (12.2 kbps) the SNR should be within [4.8, 8.8] dB, while for data (384 kbps) it should be [0.4, 3.2] dB, [Corr08]. Additionally, Annex J presents the service classes and type of differentiation that is done over the service layer.

On the other hand, in HSDPA, the bit rate can change every TTI with different modulations and coding schemes, thus, the metric used in this case has to be different from the one used in Release 99. The method to evaluate HSDPA performance is the average High-Speed Downlink Shared Channel (HS-DSCH) Signal-to-Interference-plus-Noise Ratio (SINR), ρ_{IN} , after despreading the HS-PDSCH, [HoTo06]:

$$\rho_{IN} = SF_{16} \frac{P_{HS-DSCH}}{(1-\alpha) \cdot P_{intra} + P_{inter} + P_{noise}} \quad (2.8)$$

where:

- SF_{16} : HS-PDSCH spreading factor of 16;
- $P_{HS-DSCH}$: received power of the HS-DSCH summing over all active HS-PDSCH codes;
- α : DL orthogonality factor;
- P_{intra} : received intra-cell interference;
- P_{inter} : received inter-cell interference;

- P_{noise} : received power noise at the RF band;

HS-DSCH SINR is a critical measure for network dimensioning and link budget planning, since it is independent of the number of HS-PDSCH codes used, modulation scheme or antenna configuration. This measure is also used to accomplish a specific MCS and a Block Error Ratio (BLER) target for a given number of HS-PDSCH codes per TTI. In Release 99, there is a requirement of SNR to achieve the bit rate for several services, while in HSDPA, due the use of Adaptive Modulation Coding (AMC), the bit rate is a continuous function of the HS-DSCH SINR.

[Pede05] plots continuous functions of HS-DSCH user throughput as a function of the respective SINR, including link adaptation effects and HARQ for 5, 10 and 15 HS-PDSCH HSPA codes; it is perceived that for a certain SNR, the increase of HS-PDSCH allocated codes results in higher throughputs achieved. The limit of minimum error codes transmitted within a certain bandwidth is close to Shannon's Limit, which is approached with the use of 15 HS-PDSCH codes, e.g., a higher spectral efficiency, taking noise and interference into account, [Draj07], Figure 2.2.

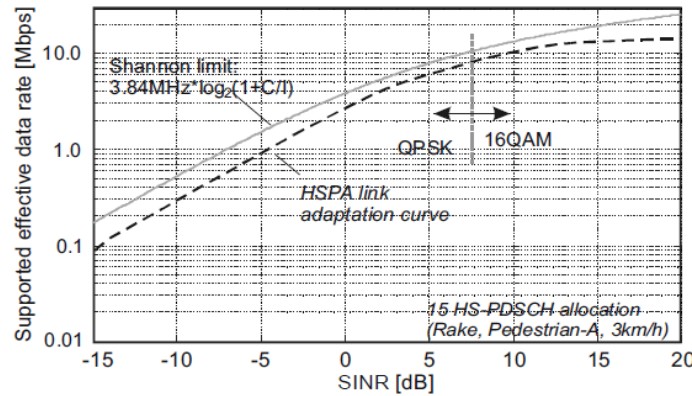


Figure 2.2. Throughput compared with Shannon's Limit as a function of the SINR (adapted from [HoTo07]).

Moreover, for performance circumstances it is assumed along the thesis that the comparison performed is over maximum capacity configurations, with the allocation of 15 HS-PDSCH for HSPA, as well as HSPA+, referred later and shown in Figure 2.3, with the use of feature software upgrades.

Due the use of link adaptation, a MCS is suitable selected for the transmission, allowing for the scheme to change on a burst-by-burst basis per link, concerning the radio channel quality. Using the Channel Quality Indicator (CQI), the MT can provide to the BS, feedback on the DL channel quality, [CEGH02]. For UL, the BS can estimate the channel quality, based on the received SINR. Subsequently the SINR is settled with the purpose of extracting the higher throughput and the lowest delay possible. For lower SINR values QPSK is used, while for higher ones 16QAM is the common modulation used. Note that network capacity depends on the type of user and the respective scenario, and on type of service provided.

The pilot energy per chip to interference, based on the P-CPICH feedback is used frequently to network dimensioning consisting on channel estimation. This estimation is exploited over the UE level, and is monitor reference for other DL channels. Measurements for handover and cell selection/reselection are performed on P-CPICH. The average SINR is expressed by:

$$\rho_{IN} = SF_{16} \frac{P_{HSDPA}}{\frac{P_{pilot}}{E_c/I_0} - \alpha P_{total}} \quad (2.9)$$

where:

- P_{HSDPA} : HSDPA transmission power,
- P_{pilot} : P-CPICH transmission power,
- P_{total} : total BS transmission power,
- E_c : Energy per chip stream,
- I_0 : Interference.

It is possible to express the BS HS-DSCH transmit power as a function of SINR, rearranging (2.8);

$$P_{HS-DSCH} \geq \frac{P_{total}}{SF_{16}} \left[\frac{1}{g} + 1 - \alpha \right] \rho_{IN} \quad (2.10)$$

where,

- $P_{HS-DSCH}$: BS HS-DSCH transmission power,
- g is the so-called geometry factor,

$$g = \frac{P_{intra}}{P_{inter} + P_{noise}} \quad (2.11)$$

returning a wideband ratio between the total power received by the MT from the serving cell and the other cell interference plus noise, [KePP03]. This association is made because the intra-cell interference is the total transmitter power of the serving cell multiplied by the average power attenuation. Thus, and due that, the g factor reflects the distance of an MT to the associated BS, which decreases when distance increases and the required transmission power has to be increased to balance the worse SINR obtained. To assure minimum HS-DSCH throughput at the cell edge, (2.10) can be used to calculate the minimum required HS-DSCH transmission power to guarantee a certain service, assuming that the geometry factor at the cell edge is known. The ρ_{IN} values are taken from Figure 2.3 depending on the service requested throughput.

HSUPA performance as in HSDPA depends on multiple factors such as MT transmitter capabilities, network algorithms, BS performance and capabilities, type of services, and scenario environment. Since there is no differentiation in the number of HS-PDSCH codes and AMC, the performance metric is similar to Release 99, i.e., E_c/N_0 . High E_c/N_0 at the BS is required in order to achieve higher data rates, although it leads to an increase of UL noise and subsequently, cell coverage decreases. For this reason, a maximum level for the UL noise may be defined for macro-cells, to guarantee the coverage area, however, limiting data throughput.

HSUPA gets higher average data rates, less delay, greater scanning mainly due to fast L1 HARQ retransmissions, and allows SNR decreasing at the BS, when comparing with similar data rates over the Release 99. Additionally, increasing the Block Error Probability (BLEP), the UL spectral efficiency raises and again consequently a lower SNR is obtained.

Considering the fast BS scheduling, it gives to the system two main advantages; faster reallocation of radio resources through users and better control of total UL power received. A faster reallocation of radio resources manages the available resources dynamically, i.e., defines a set of users profiles, analysing through which of the resources are not being used, and allocates those into the most demanding users. The use of L1 HARQ, BS scheduling and a 2 ms shorter TTI improves capacity gain by 50 to 70% relatively to Release 99, [MZDW04]. Conversely, [HEEE05] goes even beyond, regarding relative gains within 70-100%, depending on the service and scenario, comparing with Release 5.

2.2 UMTS/HSPA Evolution

High Speed Packet Access Evolution (HSPA+) evolves from the previous Releases to enable progress in terms of capacity, coverage, and latency times resulting in higher user data rates and greater spectral efficiency. Important to mention that, HSPA+ analogously to HSPA, is built on existing Release 99 features and capabilities. The foreseen large increase in data traffic leads to a request in increasing system performance in order to transmit mainly packet data. To support this enhanced capabilities, HSPA+ introduces new features over the Releases 7 and 8:

- Higher-Order Modulation (HOM) in both DL and UL;
- Multiple Input Multiple Output (MIMO);
- Advanced G-rake Receivers;
- Superior Interference techniques cancellation;
- Continuous Packet Connectivity (CPC);
- Layer-2 (L2) protocol enhancements;
- Multimedia Broadcast Multicast Service (MBMS) single-frequency network;
- Enhanced Cell Forward Access Channel (CELL_FACH);
- Support optimization for Voice over IP (VoIP);

Despite all these developments, Release 8 states that theoretically peak data rates will be 42 Mbps for DL, and 11 Mbps in UL (per 5 MHz carrier), [BEGG08]. Additionally for further Releases, 3GPP is considering DL-Optimised Broadcast (DOB), multi-5MHz-carrier transmission that will offer a wider bandwidth, higher data rate pipe to the user and increases the overall cell capacity, [BGG09] and standardised support for femtocells, [3GPP09a].

Data rates can be increased through the use of MIMO, i.e., transmitting multiple transport blocks in parallel using multiple antennas to a single user, taking advantage of spatial multiplexing. Using the channel properties exploits multipath, providing higher data throughput and simultaneously link reliability and higher spectral efficiency, all without consuming extra radio frequency. Within separate streams, these are encoded, modulated and transmitted with different transmit weights, estimated in the BS/MT, spatially spread, and by different antenna ports. MIMO uses advanced receivers', allowing a superior interference cancellation and expected boost of performance. In order to update the

network with these features, 3GPP updates several physical channels, like HS-SCCH, HS-DPCCH, E-AGCH and E-DPCCH to incorporate and update signalling information, like ACK/NACK, MIMO information (pre-coding weigh, number of streams, modulation), to allow larger Transport Block Sizes (TBS) and a larger range for the CQI between 1-30.

This CQI metric is obtained via models developed by [3GPP02c], being studied by several researchers with quite a lot of alternative models making comparisons among them, [BBSS04], nevertheless the same background is perceived, where the sum of all HS-PDSCH codes used in a transmission link is the user's MT SNR. Also, knowing the channel's BLER, which can be variable but mostly is assured to be 10 % maximum, a CQI mapping is performed in order to maximize the throughput in each MT's TBS, since each MT Category has a maximum TBS, and is variable according with the acquired CQI, where for a higher CQI, larger TBS are taken, see Annex A. The respective maximum TBS divided by the system's TTI results in the maximum physical throughput that the MT can get. Expressions are presented, in each of the references above as a function of SNR and BLER for CQI estimation, e.g., [BBSS04]:

$$\rho_{IN[dB]} = \frac{\sqrt{3} - \log(\Omega)}{2} \cdot \log(\eta_{BLER}^{-0.7} - 1) + 1.03 \cdot \Omega - 5.26 \quad (2.12)$$

where:

- η_{BLER} : target BLER efficiency
- Ω : CQI value

So, when UE reports a particular CQI, is reporting that for the current radio conditions the MT is able to receive data, with a TBS corresponding to the reported CQI, or lower, at a fix BLER value (typically 10%) given the total power level at the HS-PDSCH given by the P-CPICH measurement.

HOM brings the opportunity of even higher throughputs, incorporating new digital modulations, 16 QAM for UL and 64 QAM on the DL. Additionally, with the usage of MIMO configurations, the theoretical peak data rates grows linearly with the number of data transmitted data streams [HoTo07], likely 14.4 to around 28 Mbps in a 2x2 MIMO configuration. Also in Release 8, HSPA+ will reach in DL around 42 Mbps with 2x2 MIMO configuration and 64 QAM, [BEGG08] while in UL doubles from 5.7 Mbps to 11 Mbps with 16 QAM per 5 MHz carrier. In Figure 2.3 for DL and Figure 2.4 (a) for UL, is possible to overview some data rates achieved with detailed configuration information. Note down, the slightly differences in the DL with the use of multiple receiver branches SIMO, which extend the benefits of HOM in lower SNRs and the better power efficiency resulting in a better performance of QPSK when the data rate target is under 4 Mbps in the UL instead of use of the 16 QAM. QPSK as noticed in Table 2.1 is power limited compared with other modulations and ensue a maximum throughput of 5.7 Mbps

3GPP defined a set of UL E-DCH channel configurations, namely Fixed Reference Channel (FRC). FRC5 represent the first HSUPA and HSPA+ UL phase with a 10 ms TTI, while FRC2 and FRC6 represents the incoming MTs releases with advanced capabilities, like higher coding rate and support for 2 ms TTI. [Carv09] shows the expected data rate over a indoor channel characterized by a single window attenuation, as a function of the available E-DCH E_c/N_0 , pointing out that with a lower TTI

higher data rates are achieved, being achieved only with high demanding E_c/N_0 values. Among the use of lower order modulations, which leads to simpler receivers, Table A.1, and the two optional TTI values, network can lead with the coverage and capacity issues. The optional 2 ms TTI is used under greater radio channel conditions and potentiates higher data rates, while the 10 ms TTI is proposed for a higher number of covered users and when, due to path loss increase, there is a high number of retransmissions.

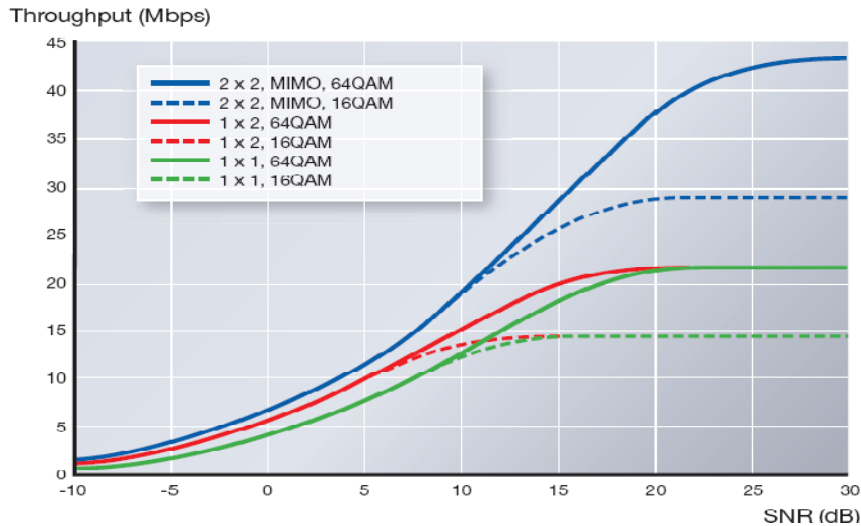


Figure 2.3. The 90th percentile throughput in DL Pedestrian A channel for HOM (extracted from [BEGG08]).

End-user throughputs depend on the user scenario/cell type. Annex B contains HSPA+ models of the data rates achieved as a function of SNR and vice-versa based on collected measurements.

At the present in Portugal, operators are deploying HSPA+ with a MIMO configuration on 16 QAM, providing a theoretical DL peak data rate in the physical layer of 28.8 Mbps. On Figure 2.4 (b) it is exposed a collection of measurements with the aim of register the achievable DL average throughput varying the cell traffic volume. Also is perceived the 30% increase of average throughput using MIMO configurations combined with 16 QAM.

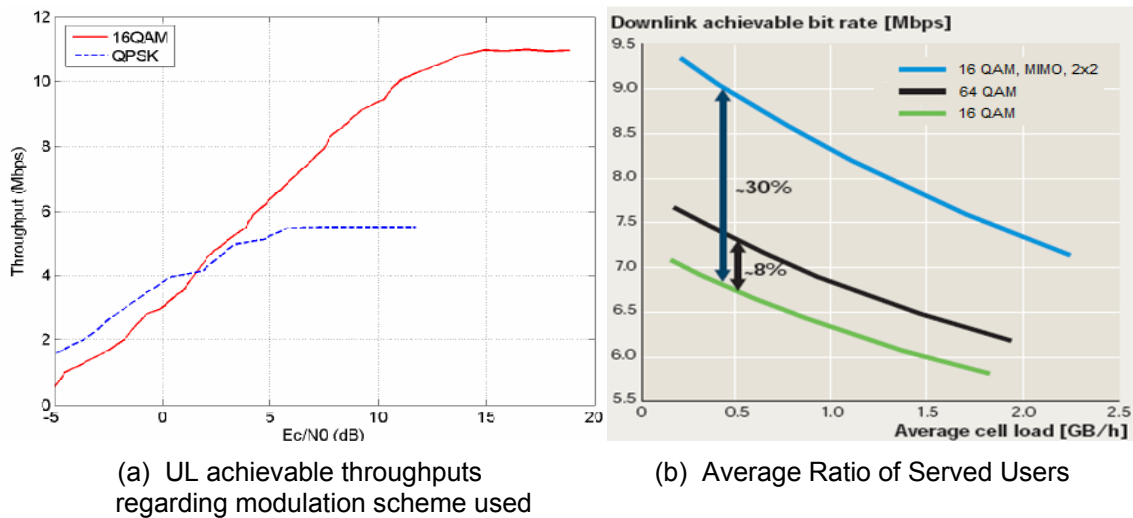


Figure 2.4. Throughput as a function of E_c/N_0 in UL Pedestrian A channel (extracted from [PWST07]) and Average DL achievable throughput measured in a real scenario (extracted from [BGG09]).

Detached from theoretical models, it is not feasible that a certain network can fix a single modulation and operates around that scheme. MCS tables determine the best combination of modulation and coding scheme for a given SNR. With existing MCS tables, high symbol SNRs maximises the choice of MCS, returning the highest order modulation with the least amount of coding. As a result, these high SNR systems become peak rate limited.

HSDPA as previously, and recently HSPA+, make use of Adaptive Modulation and Coding (AMC), or link adaptation, which adjusts the modulation and coding scheme according to the radio channel instantaneous conditions, returning the best modulation with the possible higher user data rate. The fundamental parameters to be settled in are, modulation scheme, coding levels, among several others e.g., power levels, spreading factors, signalling bandwidth and so on. The transmission power is kept constant but the data rate varies, with the transmission radio channel conditions. On the other hand the Release 99 DCH is designed to maintain constant the data rate by varying the power level, through a power control loop. The HSPA method is more efficient than power control for services that can tolerate short term variations per TTI in the data rate, [Wang04].

The AMC link, incorporated over the BS scheduler, is based on the feedback strength received from the MT, i.e., CQI instantaneous reports, stood on the P-CPICH signal. CQI and P-CPICH analysis was not implemented; neither is under the scope of this thesis; however in [Carv09] a more detailed study under this thematic is performed. This feature evolves the system in a better RRM strategy and significantly increases the overall system capacity, as it allows real-time trade-off between throughput and robustness on each link.

Represented in the Figure 2.5, are illustrations of the dynamically assignation of the available resources, hence, the radius increases a greater robust modulation is used, accordingly with the Figure 2.5 (b) which green plots the perfect adaptation on that channel, always returning the best spectral efficiency without SNR 'saturation'. Each modulation requires different sensitivities resulting in different coverage areas.

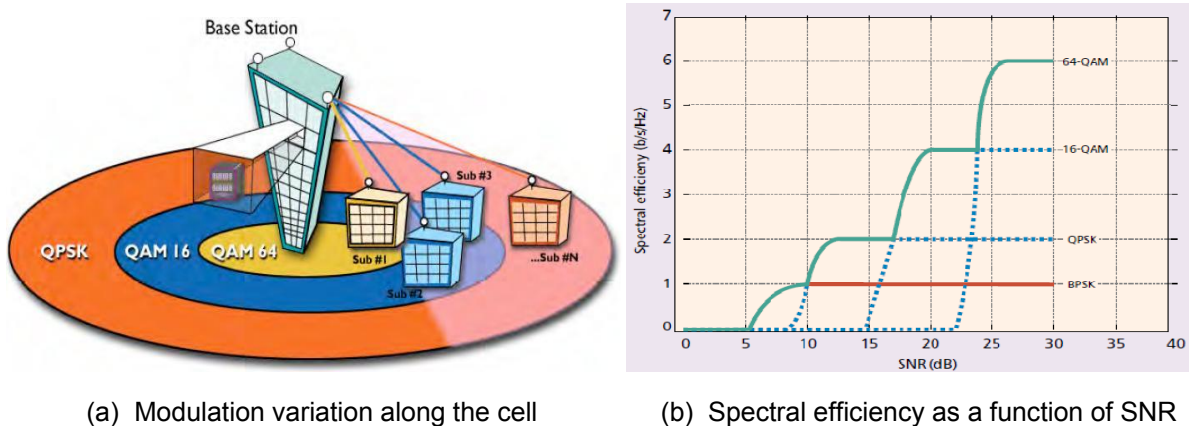


Figure 2.5. Adaptive Modulation across cell radius (extracted from [Mark03]), and the spectral efficiency variation according to each modulation behaviour (extracted from [CEGH02]).

Unfortunately when dealing with data applications, end-users can experience states of higher latency or long waiting times. In order to avoid these delays associated with state transitions, 3GPP has

worked in Release 7 to make a dedicated connection state more efficient and is commonly named as CPC, which has two main features called UE Discontinuous Transmission and Reception (UE DTX/DRX), and HS-SCCH-less operation. With these features, the MT is now allowed to switch off continuous transmission when there is no packet on DL or UL, and deals only with signalling and control powers, resulting in reduced battery consumption and in a reduction of interference or increase in capacity. In some situations of dense traffic transmission the control channel HS-SCCH can carry a significant code overhead that is reduced according to a new channel format requiring less transmitting power known as the “less operation” referred above. In fact this operation reduces code usage as well as interference from control signalling, consequently increases capacity.

The MT equipments and BSs requirements are constantly being improved to raise system performance, while the evolution of features is rolling over these several 3GPP Releases. Releases 6 and 7 introduced the use of receive diversity antennas (G-rake receiver type 1), linear equalisers (type 2), and the combination of linear equalisers with receive diversity antenna (type 3). Release 8 shows up an advanced receiver, with inter-cell interference cancellation support. Simulations in [HGMT05] exhibit, that the introduction of CPC in Release 7 increases VoIP capacity by 40% in UL and 10% in DL.

The DL peak data rate is limited by the size of Radio Link Control (RLC) window, RLC Protocol Data Unit (PDU) and by the RLC Round-Trip Time (RTT). On the other hand, to support the 64QAM modulation a larger RLC PDU is needed, also Release 7 specifies flexible RLC sizes, Media Access Control (MAC) segmentation and MAC multiplexing for DL transmission. L2 protocol overhead can be reduced due the ability of the transmitter to select RLC PDU sizes, which means that minor PDU sizes can be better, processed by the MT. As well at the BS level, a new protocol was created, the MAC-ehs that carry on the possibility of RLC PDUs segmentation. These enhancements improve system coverage and reduce processing tasks at L2.

Due to the greater use of HSPA, for Internet connections, some changes had to be made in the network in order to keep up the data traffic level that has been carrying out. In Release 7 CELL_FACH has been activated in DL, whereas in Release 8, 3GPP improved the transport channel E-DCH in CELL_FACH, enabling continuous data transmissions free from any interruption even when channel switching occurs. It is also important to note that in Release 7, DL optimisation in broadcasting services like mobile TV broadcast, with enhancements towards the elimination of inter-cell interference. Power efficiency is improved beyond new levels, while the limiting factor are codes rather than power, resulting in a larger ability of WCDMA technology concerning radio transmissions.

The deployment of existing HSPA from the service providers' point of view should be simple, due the minor system changes, namely software features, comparing to other available technologies that are not WCDMA based.

2.3 Long Term Evolution

The LTE is the proposed along Release 8 and Release 9 by 3GPP to evaluate a new whole system for Mobile Communications. Network architecture is presented in the Subsection 2.3.1 followed by a description of the radio interface in Subsection 2.3.2. Parameters like capacity and coverage are addressed in a performance analysis done in Subsection 2.3.3, and finally a comparison is carried out in Subsection 0. This section is based on [3GPP08a] and [Duar08].

2.3.1 Network Architecture

This new architecture reflects the uptake of IP-based services in mobile communications, likewise the full optimisation of network performance and improve cost-efficiency. LTE network architecture has several main differences from the UMTS one, being a flat architecture that reduces the involved nodes in the connections, besides a hierarchical one. Figure 2.6 gives the idea of the logical modules (red ones) over the LTE network.

One of the most important features that has been changed was giving “intelligence” to the BS, being designated now as evolved Node B (eNB). All radio tasks and functionalities are done at the BS, such as RRM, Radio Link Control (RLC), Radio Resource Control (RRC) and Packet Data Convergence Protocol (PDCP). Radio bearer control, radio admission control, connection mobility control, dynamic resource allocation and measuring/reporting configurations are also performed at the BS level.

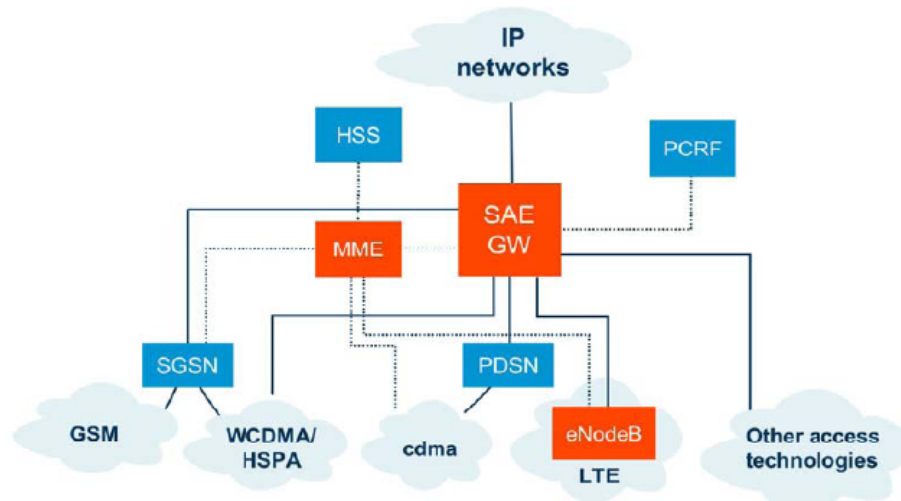


Figure 2.6. LTE Network architecture interoperating with existing systems (extracted from [Eric09]).

The Evolved-UTRAN (E-UTRAN) consists in one single element, the BS. The BSs are interconnected with each other by means of the X2 interface. It is assumed that there is always an X2 interface between BSs to communicate between, e.g., for radio or handover purposes, Figure 2.7 (a), eliminating large data flow through the RNCs. Connected to the BSs, by means of an S1 interface or Radio Access Network (RAN) interface, is the Evolved Packet Core (EPC). The EPC is composed of the Mobility Management Entity (MME), the Serving Gateway (S-GW) or (SAE_GW) and the PDN Gateway (P-GW). The functionalities allocated to E-UTRAN and EPC are summarised in Figure 2.7

(b). The UMTS RNC functions are now divided between BS and S-GW, which has also the functionalities of SGSN.

MME is the equivalent of HLR and VLR in UMTS. MME deals with signalling and control, mobility management and idle-mode handling the distribution of paging messages to the BSs. This facilitates optimized network deployments and enables fully flexible capacity scaling. The Home Subscriber Server (HSS) cover functionalities like the HLR, i.e., user-specific information. Furthermore the S-GW and P-GW control tasks related to mobility management, such as encryption of user data streams, termination of user-plane packets for paging reason and IP header compression. Both also handle the interoperability through other 3GPP radio systems. Note also the Policy and Charging Rules Function (PCRF) which is related to QoS and charging user policies.

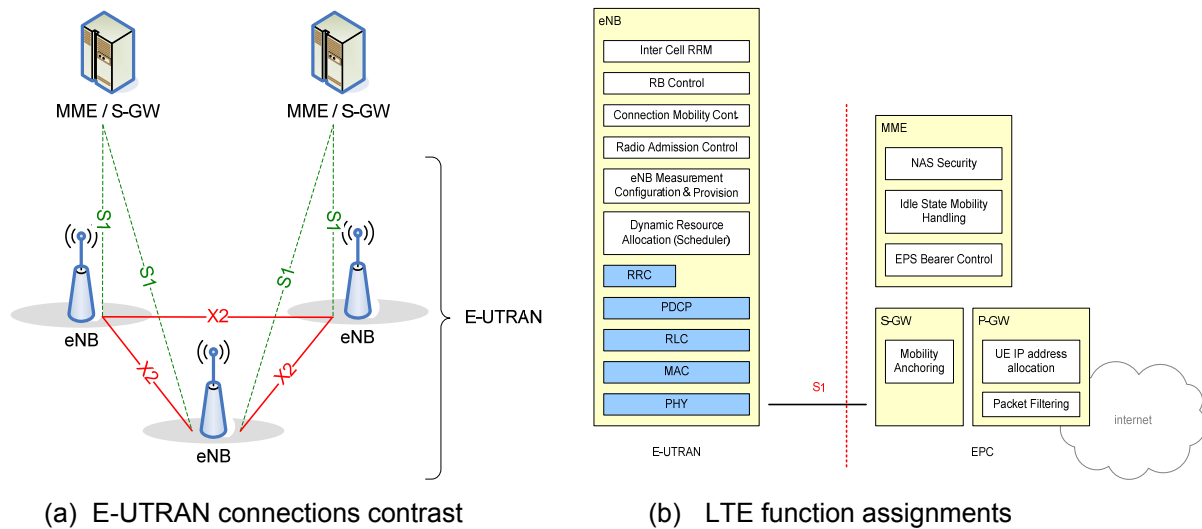


Figure 2.7. LTE new logical elements and functional split associated (extracted from [3GPP08a]).

2.3.2 Radio Interface

3GPP is developing LTE radio interface, through the interoperability with the previous communications systems technologies. The production of multimode remote radio heads in a simple way to interoperate in GSM/WCDMA/LTE especially for handover purposes, and regard greater mobility capacity. So regarding 3GPP specifications LTE can be deployed among different frequency bands along the globe, highly dependent on local variables. According to the specifications, [3GPP09c], there are 17 frequency FDD bands and 8 TDD bands of LTE spectrum allocated. For instance, in the U.S., trials are pointing towards the 700 MHz frequency band as a replacement of analogue TV signal; however in Europe, operators and vendors are in common agreements with 2.5 - 2.6 GHz frequency bands, due to the scarce spectrum problem, as well the refarming policy of LTE in GSM 900 and 1800 MHz bands [Moto08], following a recently approved norm by European Commission aiming the usage of GSM bands for another mobile communications technologies. Remember that, the greater efficiency of GSM frequency bands is pleasant for all mobile radio technologies, [HoTo09]. Higher frequencies are already being studied, due to larger bands of spectrum available, but propagation issues for mobile communications are a barrier for these advances.

The LTE's air interface is likewise the WCDMA interface, is composed of channels and protocols distributed along Open Systems Interconnection (OSI) Reference Model. Transport channels and logical channels keep the data flow between layers and were redefined from HSPA+ over the LTE's radio interface. Notice that there are no dedicated channels in LTE, which is a characteristic of packet-only systems. There are two radio frame structures types in each link (DL/UL) which differ in the duplex mode. Frame Structure Type 1 (FST1) uses FDD/TDD and the type 2 frame structure (FST2) uses only TDD; however FST1 drawn on Figure 2.8 is optimised to co-exist with 3.84 Mcps WCDMA systems, [3GPP08c]. This thesis addresses only the FDD mode since the majority of European networks are done under this specification, but LTE for instance, is also ready to interoperate with Time Division-Synchronous Code Division Multiple Access (TD-SCDMA) TDD systems.

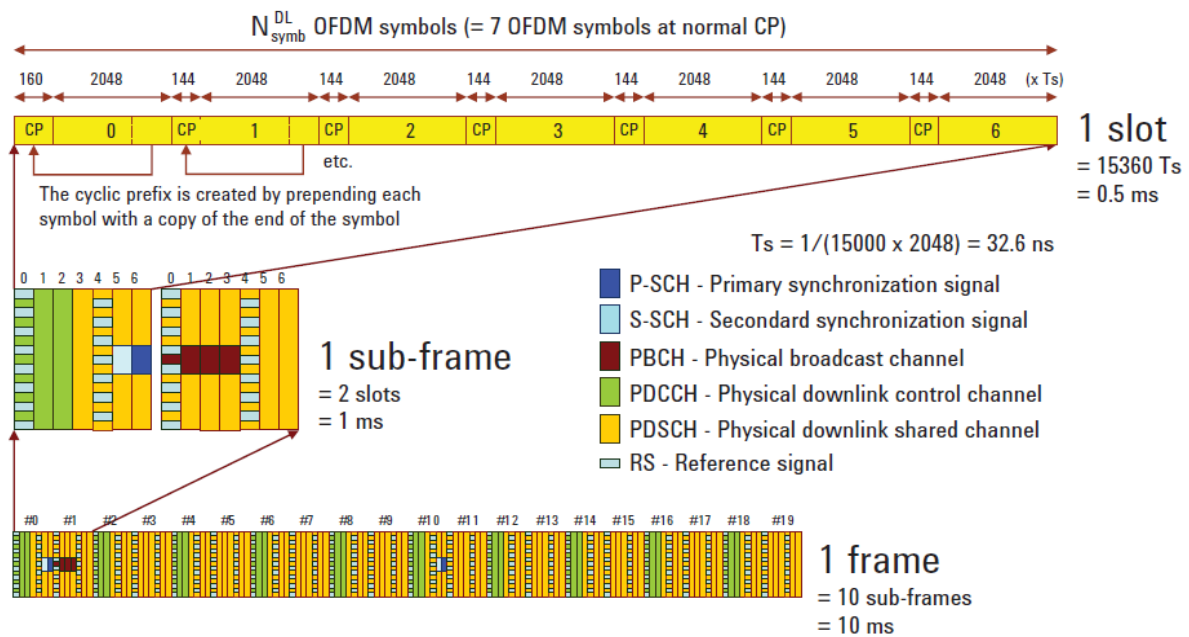


Figure 2.8. DL Frame Structure Type 1 (extracted from [Agil07]).

The physical mapping of the main DL physical signals, for FST1 is:

- Reference Signal (RS) is used for channel estimation, which is over the entire bandwidth in the DL but in UL does not go beyond the MT allocation, commonly known as pilots;
- Primary-Synchronisation Channel (P-SCH) and Secondary-Synchronisation channel (S-SCH) both used for cell search and synchronisation the MT to the network;
- Physical Downlink Control CH (PDCCH) with functions of scheduling, ACK/NACK;
- Physical Control Format Indicator CH (PCFICH) which defines the number of OFDMA symbols per subframe;
- Physical Broadcast CH (PBCH) and Physical Downlink Shared CH (PDSCH) have similar functions as the respective ones in WCDMA systems.

The UL FST1, has got the same sizes for frame, sub-frame and slots as DL FST1, although the allocation of the channels is quite different. In UL a new so called Physical Random Access CH (PRACH) hold call setup purpose, while Physical Uplink Control CH (PUCCH) and Physical Uplink Shared CH (PUSCH) have analogous functions as in DL.

The multiple access methods are different for the DL and UL, OFDMA is used in the DL, Figure E.1, whereas in the UL Single Carrier - Frequency Division Multiple Access (SC-FDMA) with Cyclic Prefix (CP) is the one specified.

CP cancels the ISI in a very effective way and returns low complexity equaliser receivers. By the receiver side there is a need to combat the multipath interference due to the short symbol duration with an equaliser. Still, the difference between both access techniques is due to the single carrier characteristics of better efficiency power, low peak average ratio (PAR) and low complexity that SC-FDMA gives to the MT. Also, SC transmission is solid to carrier frequency offsets widely affected by a multipath channel causing ISI and does not have the same robustness as multi-carrier signalling with the usage of Fast Fourier Transform (FFT) against this factor. For a detailed explanation of the access techniques used in LTE, observe Annex E for central definitions in OFDM and OFDMA.

LTE employs the usage of variable bandwidths from 1.4 MHz up to 20 MHz, defined according to the FFT lengths, sampling rates and multiples of 180 kHz. As a result the system bandwidth is scalable, and it can be selected according to the volume to transmit or a QoS priority level to accomplish. Table 2.2 shows the scalable bandwidths allocated for LTE and several parameters associated such as sampling rates derived from WCDMA chip rate (3.84 Mcps). Bear in mind that LTE is designed for maximum efficiency of packet-data-based transmission.

It is noticeable that the DL radio frame has a duration of 10 ms. Every one of these frames is composed of 20 slots with a duration of 0.5 ms each, and a group of 2 slots called a sub-frame or TTI with a duration of 1 ms. This sub-frame size is reduced in 1 ms by the frame size in HSPA systems allowing shorter access times.

Table 2.2. Key Parameters (extracted from [HoTo07]).

Bandwidth [MHz]	1.4	3.0	5	10	15	20
Sub-frame (TTI) [ms]	1					
Sub-carrier spacing [kHz]	15					
Sampling [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
FFT	128	256	512	1024	1536	2048
Sub-carriers	72+1	180+1	300+1	600+1	900+1	1200+1
Symbols per frame	4 with short CP and 6 with long CP					
Cyclic prefix	4.69 μ s with short CP and 16.67 μ s with long CP					

DL in addition contains the control information on the UL resources to be used in a way to optimise scheduling, [3GPP08c]. The smallest time-frequency unit for DL is called a resource element, defined by one symbol on one sub-carrier. A group of 12 contiguous sub-carriers in frequency and one slot in time form a Resource Block (RB), where data is allocated in units of RB over each MT. This discrete allocation of resources in a way limits the load signalling overhead. Variations on number of symbols, N_s as a function of CP configuration are summarised on Table 2.3. The CP, normal or extended, is chosen to be slightly longer than the longest delay spread in the radio channel, in order to mitigate ISI and ICI, Figure E.2 demonstrates a relative comparison is taken from the duration of cyclic prefix versus OFDMA symbol and HSPA chip durations.

Table 2.3. Physical Resource Blocks parameters (extracted from [3GPP08c]).

Configuration		N_{sc}^{RB}	$N_s^{DL/UL}$
Normal CP	$\Delta f = 15$ kHz	12	7
Extended CP	$\Delta f = 15$ kHz	12	6

For the FST1, using normal CP, a RB concentrate 12 consecutive sub-carriers and 7 consecutive OFDMA symbols in a slot. For extended CP, a RB has the same sub-carriers as the previous situation and 6 OFDMA symbols per slot. A CP is appended to each symbol as a guard interval. Consequently, a RB has (12 sub-carriers \times 7 symbols) resulting 84 resource elements corresponding to one slot (0.5 ms) in the time domain, and 180 kHz (12 sub-carriers \times 15 kHz spacing) in the frequency domain.

The size of an RB is independent of bandwidth, but the number of available physical RBs depends on it. In the frequency domain, the number of available RBs can range from 6, when transmission bandwidth is 1.4 MHz, to 100, when transmission bandwidth is 20 MHz, Table 2.4. Otherwise, in UL the number of symbols in a slot depends on the CP type, if it is a normal one, 7 SC-FDMA symbols are within a slot, while if it is an extended CP, 6 SC-FDMA symbols per slot are used.

Three OFDMA sub-carriers are specified: data, pilot and null; for data transmission, channel and synchronisation estimation and guard band, the first two types being grouped into subchannels. The subcarriers forming a subchannel can be either distributed or adjacent in the frequency domain.

Figure 2.9 represents for both links, the resource grids detailed with fundamental components, built over different radio access techniques.

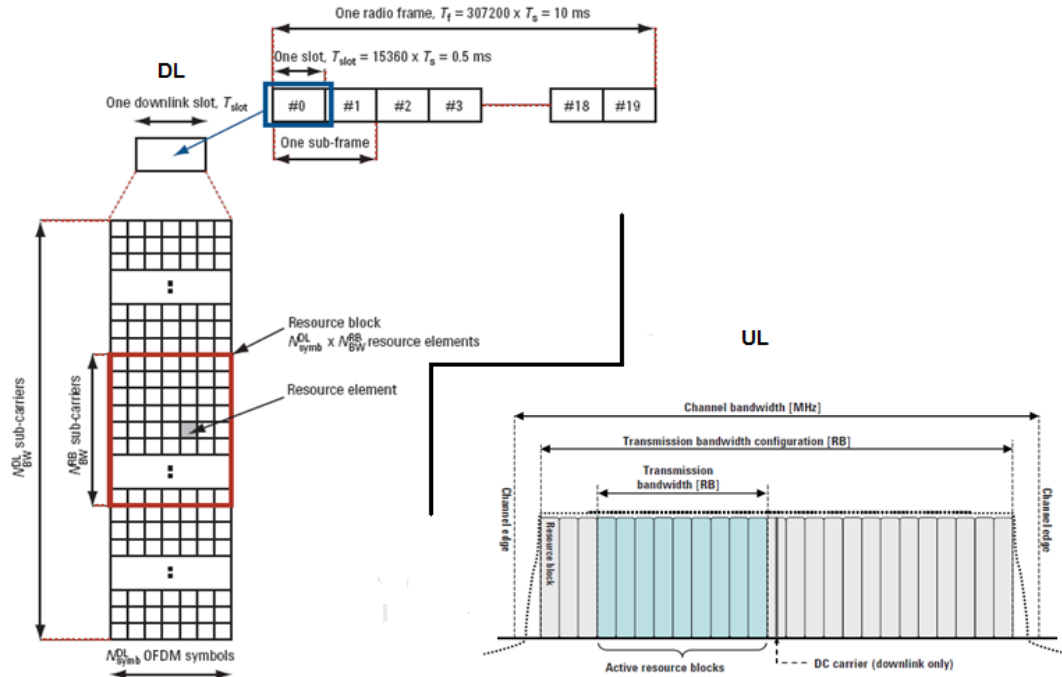


Figure 2.9. DL and UL Resource Grids respectively (adapted from [Agi07]).

2.3.3 Coverage and Capacity

The DL peak bit data rates can be obtained by;

$$R_b \text{ [Mbps]} = \frac{N_{bs}}{\text{Hz}} \cdot N_s \cdot \frac{N_{SF}}{T_{SF}} \quad (2.13)$$

where:

- N_{bs} is the number of bits per symbol carried within a modulation scheme
- N_s is the number of subcarriers;
- N_{SF} is the number of symbols per sub-frame (assumed 13 symbols);
- T_{SF} is the sub-frame period, 1ms.

End-user throughput depends on several parameters, like modulation, channel coding rate, antenna configurations, overhead amount, including whether long or short cyclic prefix is used and the number of resource blocks allocated per bandwidth. The respective system model is described in Annex B where functions of data rate and SNR are shown. Taking into account that the size of an RB is the same for all bandwidths, the number of RB per bandwidth used throughout this thesis is the one presented in Table 2.4 and the achievable DL peak data rates are shown in Table 2.5. Remain present that these values are achievable in ideal radio conditions.

Table 2.4. Number of RBs per bandwidth.

Bandwidth [MHz]	1.4	3	5	10	15	20
Number of RBs	6	15	25	50	75	100

QPSK modulation carries 2 bits per symbol, 16QAM 4bits per symbol and 64QAM 6 bits. Yet, 2×2 MIMO configuration doubles the peak bit rate. Therefore, QPSK ½ rate coding carries 1 bps/Hz, and 64QAM without any coding and with 2×2 MIMO carries 12 bps/Hz, while each possible bandwidth correspond to a number of sub-carriers. For UL the achievable peak data rates are shown in Table 2.6. The peak data rates are lower in UL than in DL, given MT limitations. Notice that UL MIMO is not yet specified by 3GPP however the literature considers these antenna configurations. Specifications are still careful on MIMO over one MT or Multiple Users (MU) MIMO, taking advantage on different antennas from different devices. For more details over MIMO types, see Annex I and for further considerations please check [Agil08].

Table 2.5. DL peak data rates and number of sub-carriers per bandwidth (extracted from [HoTo07]).

Modulation / Coding Rate	Antenna Configuration	Number of subcarriers/bandwidth combination [MHz]				
		72/1.4	180/3.0	300/5.0	600/10	1200/20
QPSK ½	SISO	0.9	2.2	3.6	7.2	14.4
16QAM ½	SISO	1.7	4.3	7.2	14.4	28.8
16QAM ¾	SISO	2.6	6.5	10.8	21.6	43.2
64QAM ¾	SISO	3.9	9.7	16.2	32.4	64.8
64QAM 4/4	SISO	5.2	13.0	21.6	43.2	86.4
64QAM ¾	2×2 MIMO	7.8	19.4	32.4	64.8	129.6
64QAM 4/4	2×2 MIMO	10.4	25.9	43.2	86.4	172.8
64QAM 4/4	4×4 MIMO	16.6	47.7	80.3	161.9	326.4

Table 2.6. UL peak data rates and number of sub-carriers per bandwidth (extracted from [HoTo07]).

Modulation / Coding Rate	Antenna Configuration	Peak bit rate per sub-carrier/bandwidth combination [MHz]				
		72/1.4	180/3.0	300/5.0	600/10	1200/20
QPSK $\frac{1}{2}$	SISO	0.9	2.2	3.6	7.2	14.4
16QAM $\frac{1}{2}$	SISO	1.7	4.3	7.2	14.4	28.8
16QAM $\frac{3}{4}$	SISO	2.6	6.5	10.8	21.6	43.2
16QAM $\frac{4}{4}$	SISO	3.5	8.6	14.4	28.8	57.6
64QAM $\frac{3}{4}$	SISO	3.9	9.0	16.2	32.4	64.8
64QAM $\frac{4}{4}$	SISO	5.2	13.0	21.6	43.2	86.4

From Table 2.5 and Table 2.6 it is well noticed that, with the increase of channel bandwidth, the system performance also increases, mainly due the increase of spectral and overhead efficiency as long as a wider channel bandwidth is applied.

2.3.4 Comparison between HSPA, HSPA+ and LTE

Nowadays, the latest technologies for mobile communications are the UMTS/HSPA+ and LTE, regarding the latest releases from 3GPP family technologies. Both target packet data services as primary objective, regarding the new rising content trends. One of the main differences between the systems is the use of different radio interfaces, while HSPA+ employ WCDMA as an heritage from HSDPA and HSUPA, in LTE the OFDMA/SC-FDMA new interface is applied, with greater immunity to multipath interference.

LTE's system architecture is much simpler than the UMTS one developed since the Release 99. This new one is an IP-based flat architecture with fewer components, Figure 2.6, than the legacy of the hierarchical architecture used in HSPA+, Figure 2.1. However to implement HSPA+ features, there is no need at all to modified the current UMTS network architecture, unless if MIMO configurations been used, hence new port antennas have to be installed.

LTE's architecture is based on the UMTS one, but there are several new interfaces, and functional upgrades that are more costly to implement, e.g., the new E-UTRAN OFDM radios, Figure 2.7 (a). All radio-related functionalities, mobility management, header compression and packet retransmissions are located in the BS, including all those algorithms that were located in RNC on 3GPP Release 6 and previous. Notice that, in the user plane it is possible with LTE the direct connection between them and the EPC, especially with one of the elements, the S-GW, in order to improve performance, although, in UMTS all user's actions are firstly scheduled in the RNC, Figure 2.10 (a).

One of the demands for Release 8 was to improve performance and reducing latency by reducing the number of network elements, Figure 2.10 (b). The evolution in terms of data rate and performance, already done in Table 2.7, that is additionally present on Figure 1.2.

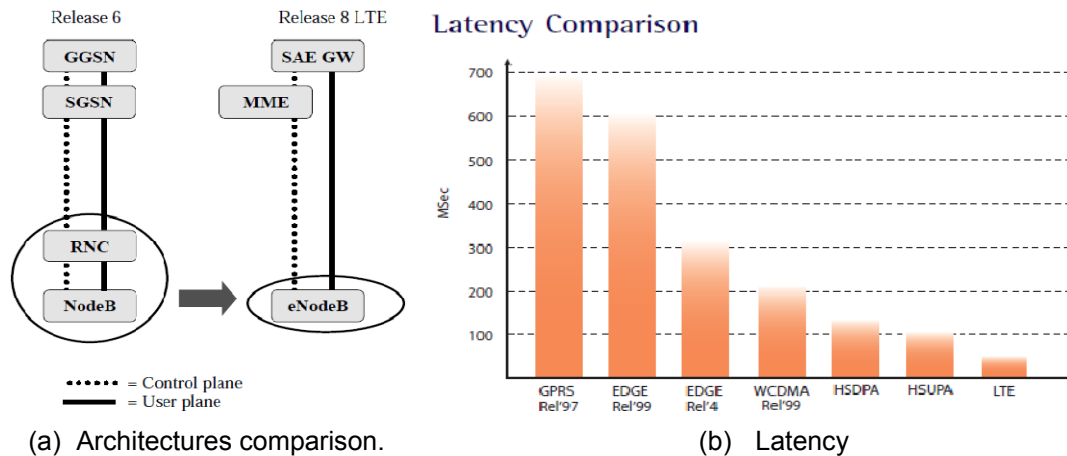


Figure 2.10. Architecture evolution between HSPA and LTE (extracted from [HoTo09]) and Latency evolution along different technologies (extracted from [UMTS09b]).

Table 2.7. Highlight features comparison of UMTS/HSPA, UMTS/HSPA+ and LTE.

Feature/ Release	HSPA	HSPA+	LTE
Duplex Mode	FDD (under analysis, however all operate in TDD as well)		
Multiple Access	WCDMA		OFDMA (DL) / SC-FDMA (UL)
Frequency [MHz]	[1920, 1980] for UL; [2110, 2170] for DL (Europe case)		900, 1800, 2100, 2600
Channel Bandwidth [MHz]	5		1.4, 3, 5, 10, 15, 20 (Scalable)
Switching map	Circuit and Packet Switch (few IP protocols)		All Packet Switch IP-based
Scheduling	TDS		TDS & FDS
Frame size [ms]	10, 2	2	1
Modulation	16 QAM (DL), QPSK (DL/UL), BPSK (UL)	QPSK (UL), 16 QAM (DL/UL), 64 QAM (DL/UL)	
Coding	Convolutional Turbo Codes		
Multi-antenna support	No	Yes	Yes
DL theoretical Peak Data Rate [Mbps]	14.4 (16 QAM)	42 (MIMO 2×2, 64QAM)	172.8 (20 MHz, MIMO 2×2, 64QAM) 326.4 (20 MHz, MIMO 4×4, 64QAM)
UL theoretical Peak Data Rate [Mbps]	5.7 (QPSK)	11.5 (SISO, 16QAM)	86.4 (20MHz, SISO, 64 QAM) 57.6 (20MHz, SISO, 16 QAM)

The European Telecommunications Standards Institute (ETSI) looked already for OFDM in the late of 1980s for GSM; however the processing power to perform the many required FFT operations was an expensive investment over that time, being the same reason referenced in 1998 for the UMTS

specifications beginning. Nowadays the digital signal processing cost has been greatly reduced, and OFDM is now commercially viable.

Regarding the use of OFDM/OFDMA, the flexible channel bandwidth usage is possible, thus, the increase of achievable data rates, being feasible different rollouts for different areas depending on the needs of the worldwide markets. LTE with the use of IFFT, takes advantage to place the transmission in the correct position of the transmit spectrum, i.e., transmission scheduled by RBs. This feature is not possible in UMTS with the use of a fixed chip rate and 5 MHz bandwidth where the signal is spread over the whole transmission bandwidth.

The spectral efficiency improvements in LTE over HSPA are mainly due to the orthogonality of OFDM and frequency domain packet scheduling, using the best propagation sub-carrier (not faded ones) to transmit and interference cancelation easier to apply in multi-carrier systems, due the use of CP, Annex E. The bandwidth efficiency is greater with OFDMA when compared with other multiple access schemes and managed channels/users with less power consumption. Also it increases when larger is the channel bandwidth. Such scheduling is based on CQI reporting, pointing the best RBs to transmit, [HoTo07], and being more efficient with the increase of the channel bandwidth. Even so, the CQI has the same purpose in both systems, returning the best MCS in the instantaneous moment of the report; nevertheless, LTE has a more complex reporting structure comparing with HSPA+, [Agil07]. Making use of Pre-coding Matrix Indicator (PMI), a second indicator, used in conjunction with MIMO which indicates the BS the available pre-coding MIMO matrices to accomplish the best performance.

Users' separation is differently performed between systems; while in UMTS they are separated by orthogonal spreading codes, in LTE the distinction is made in frequency and time, Figure E.5.

Smart antenna technologies are also easier to support with OFDM, since pre-coding weights can be optimised per sub-carrier on the frequency domain, [Moto07]. Furthermore, due the OFDM characteristics, channel equalisers are much simpler to implement in LTE rather than in UMTS. Low latencies and shorter TTI are also achieved, since in HSPA+ has a greater delay in signalling. Additionally, LTE returns between 2-4 times best spectral efficiency than HSPA.

Considering that HSPA+ is ready and deployed before LTE, this can be taken into account, since HSPA+ is an evolution of HSPA, which is already being deployed in several countries. Otherwise, LTE will allow interoperability to all previous cellular systems such as GSM and UMTS, resulting in a great benefit to customers, this way introducing a business model in order to accommodate LTE since the kickoff, which is not the case for WiMAX, which is not retro compatible with the previous mobile communications systems.

Chapter 3

Models and Simulator Description

This chapter provides a functional description of the UMTS/HSPA+ and LTE Simulator and the associated models. First developed approaches are presented, the Single User one, providing an overview of network planning, regarding cell radius when a unique user is at the cell edge requiring a certain service. Then the Multiple Users' one, with the objective of analysing a more realistic scenario, with users randomly spread within the coverage area, performing multiple services along the metropolitan Lisbon area. Implementation details are presented, as well as the I/O of the simulator. The chapter concludes with the respective assessment and validation of the developed simulator.

3.1 Single User Radius Model

The purpose of this section is to evaluate the performance of HSPA+ and LTE in a single user model, following the same method that has been used in [Lope08]. The evaluation is done with a single user in a cell requiring a certain service; hence, requesting a throughput and the maximum cell radius calculation is done within a set of parameters. It is considered that all resources are available to the unique cell user and the propagation conditions are perfect.

The maximum distance stands for the cell radius, which is the distance between the BS and the MT, Figure 3.1. Several parameters can be modified, such as:

- Environment: Pedestrian, Vehicular and Indoors;
- Modulation scheme;
- Antenna MIMO configuration;
- Total BS transmission power;
- Frequency;
- Bandwidth;
- BS and MT antenna gains;
- Fading margins.



Figure 3.1. Single User Radius Model.

The default values used along the simulations are stated in Table 4.2 and Table 4.3 for HSPA+ and LTE, respectively. Other parameters like, additional losses as cable losses or user losses, noise figures, diversity gain and traffic power percentages can also be modified. In the HSPA+ case, with the use of a SF_{16} , it is assumed that 15 HS-PDSCH spreading codes are available at the MT, however only 14 are used for data, while the last is allocated to HS-SCCH and Associated-DCH (A-DCH) for the use of network signalling and control operations.

To obtain the maximum range of a cell for a certain service, it has to be considered that the radio channel is totally known, thus, it is assumed a codification rate of 100%.

Furthermore, the real throughput achieved by the end-user is not the one measured at the BS, due to the multipath and the use of signal overheads along the OSI Model, [Zimm80]. The application throughput R_b^{APP} is calculated, in DL, taken into account the following overheads – application (5%), MAC (3.125%), RLC (2.5%) and BLER (10%). According to [3GPP07d], the MAC/RLC overhead depends on the MAC/RLC header size (fixed at 16 bits) plus the MAC/RLC Packet Data Unit (PDU)

size, being 640 Service Data Unit (SDU) bits + 16 header bits = 656 bits for RLC and 792 bits for MAC, [Voda09]. The overall overhead decreases with the increase of PDU sizes. As a result, the application layer throughput is given by:

$$R_b^{APP} = \eta^{APP/PHY} \cdot R_b^{PHY} \quad (3.1)$$

where:

- $\eta^{APP/PHY}$, sum of all overhead ratio for all layers plus BLER
- R_b^{PHY} , throughput at the physical layer

Otherwise, for UL, all the overhead ratios are maintained except for RLC layer which remains 0.625%.

For LTE, the single user model radio parameters are the ones used for HSPA+. Limiting factors are the bandwidth available, modulation scheme chosen and also antenna MIMO configuration. These three restrain the maximum throughput. The LTE receiver sensitivity, as well as the path loss, is calculated using the link budget shown in Annex D.

It is important to notice that being a single user model, the interference margin is not considered and all resources are given to the user, therefore, a low SNR is needed than if a limited resources was given. The maximum transmission antenna gain was used in order to have the maximum radius, and also the lowest frequency in the frequency bands was considered. Assumptions like perfect radio channel conditions, absence of interference due to both internal and external factors were taken, noise raise was also not considered, and uncorrelated sub-channels in MIMO were considered in order to extrapolate the 3GPP measures. This model is based on a snapshot analysis, not taking variations during the time frame into account. Moreover, it is designed to work under the best radio link conditions, but fixed slow and fast fading margins, shown in Table 4.1, were considered in the three environments, with the purpose of achieving a good cell radius estimation for a certain throughput. This request is mapped onto SNR and E_c/N_0 , using model expressions taken of the interpolations and extrapolations performed and figure in Annex B. This way, it is possible to perform the calculation of the receiver's sensitivity, i.e., the minimum received power that allows the user to be served with the requested throughput.

In LTE, Extended Pedestrian A (EPA) is a pedestrian channel, assigned to indoor users due to the static (or almost) characteristics. On the other hand due to a lack of information of performed simulations, Extended Typical Urban (ETU) is applied to vehicular users. Also, this model only performs with MIMO antenna schemes of 2x2 and 4x4, following the available information at 3GPP.

Path loss is calculated using the link budget detailed in Annex D. From the COST231-Walfish-Ikegami propagation model, one has [DaCo99]:

$$L_{p[dB]} = EIRP_{[dBm]} - P_{r[dBm]} + G_{r[dBm]} - M_{[dB]} = L_{o[dB]} + L_{rt[dB]} + L_{rm[dB]} \quad (3.2)$$

where:

- L_o is the free space loss;
- L_{rt} is the rooftop-to-street diffraction and scatter loss;
- L_{rm} is the approximation for the multi-screen diffraction loss;

- $EIRP$ is the Equivalent Isotropic Radiated Power;
- M is the total margins considered.

Through the manipulation of (3.2) and the L_{rt} and L_0 expressions from the COST231-Walfisch-Ikegami model, Annex C, the cell radius R , can be calculated by:

$$R_{[km]} = 10^{\frac{EIRP_{[dBm]} - P_{t_{[dBm]}} + G_{r_{[dBi]}} - M_{[dB]} - L_{COST231_{[dB]}}}{20 + k_d}} \quad (3.3)$$

$L_{COST231}$ takes into account for all losses over the propagation model being:

$$L_{COST231_{[dB]}} = L'_{0_{[dB]}} + L_{rm_{[dB]}} + L'_{rt_{[dB]}}$$

where;

- $L'_{rt} = L_{rt} - k_d \cdot \log_{10}(d_{[km]})$;
- $L'_0 = L_0 - 20 \cdot \log_{10}(d_{[km]})$;
- k_d is the dependence of the multiscreen diffraction loss versus distance.
- d is the distance between the user and the BS.

When using the single user scenario, all existent multipath are considered completely uncorrelated with the objective to apply MIMO gains.

3.2 UMTS/HSPA+ and LTE Simulator

The developed HSPA+ and LTE program routines and algorithms are introduced in this section. First, in Subsection 3.2.1, the simulator file structure is presented, with the simulator's implementation being described in Subsection 3.2.2. In Subsection 3.2.3, the simulator's input and output files are presented and in the last section a global simulator evaluation is performed.

3.2.1 Simulator Overview

The simulator developed in this thesis is an evolution of the ones developed on [SeCa04], [CoLa06] and lately in [Duar08] and [Perg08]. The global simulator's structure is presented in Figure 3.2. The main simulator core was left unchanged however new routines and analysis were added, with the purpose of a better models adaptation in order to extract maximum system performance conditions for new service types. Also, was implemented Adaptive Modulation (AM) algorithms given the available channel information for HSPA+ and LTE both for DL and UL. The primary objective of the simulator is to evaluate the performance on the multiple users' perspective of HSPA+ and LTE, being composed of 3 main modules:

- Users Generation,
- Network deployment without load,
- HSPA+ and LTE analysis sub-divided in DL and UL.

The user's generation module was implemented in C++, being described in [CoLa06]. Multiple users

are distributed along Lisbon's map, taken as scenario, according to the population density areas. The user's request services follows a given service penetration percentage. Figure 3.3 draws an example of the users' position in a single network cell. The users' placement is taken on the network deployment module, [CoLa06]. Unlike the single user radius model, in this simulator there is a large number of users performing different services at a time, trying to reproduce a realistic situation in a radio network.

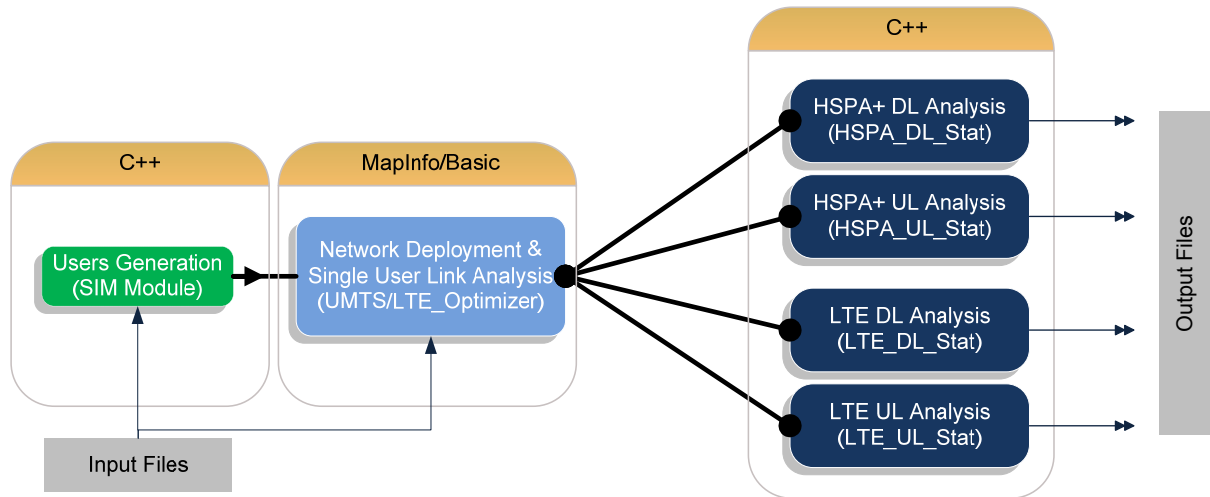


Figure 3.2. UMTS/HSPA+ and LTE Simulator architecture.

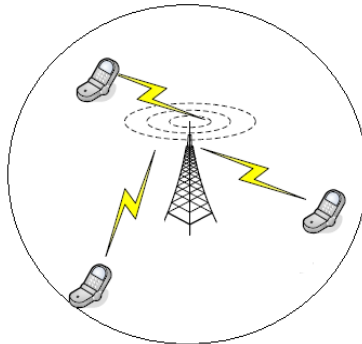


Figure 3.3. One cell at the multiple users' model.

The network deployment module, implemented in MapBasic programming language, is responsible for placing users, from the output file from the SIM Module, in the network distributing according the most populated areas. After the user's placement, the network is deployed using given coordinates of all BSs considering that LTE and UMTS/HSPA+ employ co-located BSs, however not sharing resources between the two systems. Then, a first analysis is performed, where the cell radius is calculated for each service and for the reference throughput. These calculations are done using the link budget present in Annex D, and verifying the users within the coverage area of all BSs.

3.2.2 HSPA+ and LTE Implementation Issues

The four modules developed in C++ have the purposes to do the main overall calculations which lead to final output results, i.e., the analysis of coverage and capacity for both systems, through an instantaneous snapshot approach, for a time frame as it was considered for the single user's model.

Average radius, number of users per BS, data volume traffic, services, covered users, are examples of data collected at the BS level, being performed in all network BSs. The evaluation of the network is also supported by an extrapolation of the average results for traffic and number of users per hour.

The parameters taken into account for HSPA+ and LTE, both for DL and UL, are the following ones, also possible to be adjust on the user interface covered on the Simulator's Manual, Section G.2:

- | | |
|--|---------------------------------------|
| ▪ BS DL transmission power, | ▪ Noise Figure, |
| ▪ MT UL transmission power, | ▪ Reduction strategy, |
| ▪ Signalling & Control power percentage, | ▪ Reference service, |
| ▪ Frequency, | ▪ Interference margin, |
| ▪ Bandwidth, | ▪ Environment, |
| ▪ MT antenna gain, | ▪ Rayleigh percentage, |
| ▪ Diversity Gain, | ▪ Service's Profile, |
| ▪ User and cable losses, | ▪ QoS priority, |
| ▪ Modulation, | ▪ Traffic model, volume size for each |
| ▪ Antenna configuration, | service. |

DL or UL transmission power is not shared and it is unchanged for both systems. To perform a fair comparison, it was adjusted same power according to hardware manufacturers. Even so, within a snapshot analysis only one system is available at a time, otherwise a more complex study had to be done in order to compare both systems available and sharing the same resources. It is important to note that each user only request one service at the time, and all BSs are characterised by the same parameters chosen. Comparison

Bandwidth, (LTE variable specific), antenna configuration and modulation scheme are performance key parameters, since all of these factores are limitative in the maximum achievable throughput per user, therefore, per BS. The bandwidth is responsible for the allocation of different RBs depending on the channel bandwidth used, Table 2.4, whereas a wider bandwidth has more RBs available, i.e., more available capacity. So, antenna configuration and modulation used defines the maximum physical throughput in a HSPA+ BS, whereas additionally, bandwidth in LTE leads to the same values. Regarding these key parameters, one should be present that the system's capacity not only involves the BS maximum capacity, but also the MT capacity in order to communicate with the BS on the same range of values. MT categories limit the maximum throughput, and are shown in Annex A, however this differentiation is not taken into account, considering that MT support all available throughputs.

Antenna configuration takes a huge role defining coverage and capacity of a radio telecommunications system. Three configurations were adopted; SISO, SIMO (UL) and MIMO. The use of diversity is used to minimise the effects of fast fading consisting of the use of redundancy in signal reception and it is associated to the use of signal combining, [Corr08]. Replicas of the signal with some uncorrelation associated from each antenna are combined in order to get an improved signal, compared to the one in absence of combined techniques. The use of SIMO, Figure I.1, reflects the use of spatial diversity, at the BS and with an associated gain. On the other hand MIMO configurations, consist of two or more antennas sending and receiving different information by means of encoded streams in parallel, Figure

I.1, exploiting the time and spatial diversity of the channel, boosting performance in terms of capacity. Annex I one presents more details concerning antenna topologies.

In order to extrapolate the data collected, considering that LTE DL data available from 3GPP is only measured in SISO configurations, it has to be taken into account the corresponding throughput for SISO configurations using diversity gain, parameter which can be controlled. Afterwards, applying the RMG model, [KuCo08], detailed in Annex I, one is able to calculate the user throughput for a certain MIMO configuration with the given RMG mean values. Bear in mind that the model developed in [KuCo08], was not proposed for this particular situation, however it provides a good approximation. Nonetheless, in LTE UL, there is only reference to MIMO configurations, so these are the options taken on the LTE model developed for UL and DL.

Margins for fading are taken for slow and fast fading, described by Log-Normal, (D.16), and Rayleigh, (D.15), distributions respectively, both in DL and UL, being a good approach to describe these vanishing types. See Annex D for more details on signal fading. Additionally penetration margins were considered for two different environments, presented in Section 4.1.

Concerning the dedicated channels of both systems, a certain power has to be reserved from the total transmission power with the purpose of signalling and control operations. Note that HSPA+ is the latest release of UMTS and is deployed on top of Release 99; therefore, all previous releases require different power amounts. In LTE, the resources are allocated via RB, so by default in DL 1 OFDMA symbol per RB is reserved, whereas in UL 1 SC-FDMA per RB is taken.

Divergent from the single user model, is the radius calculation of each sector from the tri-sectorized BSs, calculated for the reference throughput defined, being the limits of each cell perfectly distinguished over the spatial information in MapInfo, as it can be seen on Annex G. Then, it is possible to evaluate which users are covered by the network, depending on the type of service requested. The models in Annex B, calculate the correspondent SINR to the reference throughput. Later on, the maximum link distance calculation for that SINR is performed corresponding to the cell radius, taken into account the different inherent approaches from the different systems, as shown in Annex D. Nevertheless, if a user is not covered by the network is not considered in the analysis.

Since the simulator leads with multiple users and BSs, interference has to be considered and regard the complexity of analysing the interference per user; a margin for this purpose is established, considering (3.4). The interference margin is based on the total number of users of the BS coverage area. It is assigned a maximum interference margin different for each system, Table 4.2 for HSPA+, Table 4.3 for LTE, and for the other BSs the interference margin is relative to the maximum value given by:

$$M_{I_j \text{ [dB]}} = \frac{N_{u_j}}{N_{U_{max}}^{BS}} \Phi_{\text{[dB]}} \quad (3.4)$$

where:

- N_{u_j} is the number of users in the BS j ;
- $N_{U_{max}}^{BS}$ is the number of users of the most populated BS;

- Φ is the maximum interference value considered.

So, the effects of interference are visible in terms of cell radius, leading to a decrease in total path loss, affecting the SNR and the user's throughput.

The radius calculation is done for all the services required, taken the respective throughputs into account, Table 4.5, where minimum values are adopted to guarantee reasonable services. However, service throughputs can be re-set (minimum and maximum values) for DL and UL. Considering the differences between both systems, the maximum achievable throughput per BS is distinct and differs between an array of parameters. In HSPA+, modulation and antenna configuration determines the range of throughput that may be offered to the end-user, whereas in LTE, all of these have to be considered plus the specified radio channel bandwidth. Once that both systems optionally benefit from AMC techniques for each user SINR, the throughput for the modulations available is calculated, and is assigned to the user the one which maximizes the throughput. Since there are models available only for one combination set modulation/coding rate, see Annex B, AM stands only for the modulation, as it is the only parameter exploit, while the coding due to the complexity involved or to the lack of information associated are not further referenced.

This technique is algorithmically implicit over the manufactures radio hardware and is widely diverse in what calculations and approaches concerns, besides the technical similar characteristics.

When running the UMTS_LTE Optimizer, the number of users inside the coverage area of all the BSs, is calculated followed by the generation of files used in the “*_Stat” C++ modules, Figure 3.2:

- “definitions.dat”, containing the data parameters used, the minimum and maximum throughput for each service, the QoS class priority, the penetration and fading margins considered and another relevant information to the analysis.
- “data.dat”, has the coordinates of all users and BSs, the corresponding BS that the user is connected to, the distance between them, the environment and the service requested.

The simulator connects users to the closest BS when those are on the coverage area of several BSs, however the user should be connected to the BS with more available resources. Usually, in a typical urban scenario, due to the proximity of all BSs, most of the users are covered by more than one BS, although, simulation process does not perform any optimization of the BS resources in terms of capacity, connecting the user to the closest BS possible. Using the link budget in Annex D and mapping the SNR onto the respective system models, (D.8) for LTE and (D.10) for HSPA+, the user is associated to the path loss that returns higher throughput. Consequently, three situations occur:

- The user is served with the requested throughput, when the throughput given by the distance, is higher than the requested throughput;
- The user is served with the throughput given by the distance if the latter is higher than the minimum and lower than the maximum service throughput;
- Otherwise, the user is delayed (not served).

The procedure to calculate the user throughput is extracted from [Perg08] and [Duar08]. This calculation involves a generation of a random number between 0 and 1, multiplied by the throughput

written over the file “definitions.dat” in order to have a reasonable reality approach, when the throughput is limited by network congestions and not caused by the RAN.

After the throughput calculation algorithm, following it is analysed the system capacity, at the BS level. In the capacity context, there are three possible cases:

- all users are served without reduction, if the sum of the RB/instantaneous throughput of all served users is lower than the maximum allowed for the BS considered;
- If not, in LTE, an optimisation algorithm for all RBs with a lower use than 50% is applied, hence, discarded and the user throughput reduced. This process is explained in [Duar08].
- otherwise, one of the reduction strategies are applied.

Reduction strategies considered are the same for DL and UL, since Soft HandOver (SHO) is not considered in the UL. These are graphically drawn in Annex H. Notice that the reductions applied are made relatively to the user throughput in HSPA+, or in OFDMA/SC-FDMA (DL/UL) symbols, since the throughput reduction in LTE is not continuous due to the multiple access technique used and user's sub-channel allocation.

Concerning capacity features, it is important to highlight that both systems have different RRM algorithms regarding the scheduling of the offered services, Figure 3.4. While LTE has the available bandwidth mixed for all types of services, in UMTS, the services are divided into two carriers, voice and video-telephony being dedicated to the Release 99 carrier, and the data services to the latest Release, hence, solely contributing to the capacity of HSPA+ and LTE.

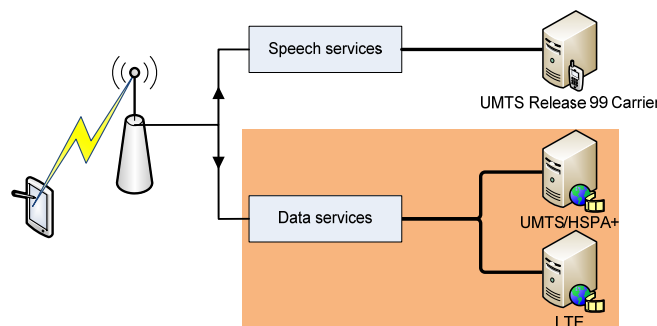


Figure 3.4. Distribution of services in UMTS and LTE.

3.2.3 Input and Output Parameters Index

The simulations require the inclusion of the following files in UMTS/LTE_Optimizer as inputs:

- “Ant65deg.TAB”, containing the BS’s antenna gain for all directions;
- “DADOS_Lisboa.TAB”, with information of Lisbon city and all its districts;
- “ZONAS_Lisboa.TAB”, with the area characterisation such as streets, gardens, among others;
- “*users*.txt”, with the distribution of the users in the network, being an output from the SIM Module;
- “Vodafone_Bstations.TAB”, with the coordinates of the co-located BSs over the city of Lisbon.

The UMTS/LTE_Optimizer module creates 2 intermediary files used by HSPA+ and LTE modules in order to realise the simulations and then those C++ module files return to UMTS/LTE_Optimizer another 2 files to present the simulation results:

- “stats.out”, includes all results for the instantaneous network analysis and statistics by service;
- “stats_per_hour.out”, containing the busy hour results.

The next step of the development computes several network parameters for each BS, given by:

- The instantaneous served throughput, R_{bBS} :

$$R_{bBS}[\text{Mbps}] = \sum_{j=1}^{N_{uBS}} R_{bj}[\text{Mbps}] \quad (3.5)$$

where:

- N_{uBS} : number of users served in a BS,
- R_{bj} : instantaneous throughput of the user j ,
- $R_{bj}[\text{Mbps}] = RB_j \times R_{bRB}[\text{Mbps}]$ (3.6)

where in LTE case:

- RB_j : number of RB attributed to the user,
- R_{bRB} : RB instantaneous throughput.

- The total number of RBs, RB_{BS} :

$$RB_{BS} = \sum_{j=0}^{N_{uBS}} RB_j \quad (3.7)$$

- The normalised throughput, R_{bNORM} :

$$R_{bNORM} = \frac{\sum_{j=1}^{N_{uBS}} R_{bj}[\text{Mbps}]}{R_{bmax}[\text{Mbps}]} \quad (3.8)$$

where:

- R_{bmax} : maximum BS allowed throughput,

- The cell radius of the BS, r :

$$r_{[\text{km}]} = \frac{\sum_{j=1}^{N_{sect}} d_{BSj}[\text{km}]}{N_{sect}} \quad (3.9)$$

where:

- N_{sect} : number of sectors of a BS (= 3),
- d_{BSj} : distance between the user placed further away and the BS.

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

$$\overline{R_{b,j}[\text{Mbps}]} = \frac{R_{bBS}[\text{Mbps}]}{N_{uBS}} \quad (3.10)$$

- The satisfaction grade, S_G :

$$S_G = \frac{\sum_{j=1}^{N_{uBS}} R_{bserj}[\text{Mbps}]}{\sum_{j=1}^{N_{uBS}} R_{breqj}[\text{Mbps}]} \quad (3.11)$$

where:

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

- R_{brej} : requested throughput of user j .

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

$$T_{BS[GB/h]} = \sum_{j=1}^{N_{services}} N_{uhservj} \times V_{uj[GB/h]} \quad (3.12)$$

where:

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

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

$$\overline{V_{u[MB]}} = \frac{T_{BS[MB]}}{N_{uhBS}} \quad (3.13)$$

where:

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

$$N_{uhBS} = \sum_{j=1}^{N_{services}} N_{uhj} \quad (3.14)$$

Additionally, the following parameters are also calculated:

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

These parameters allow an analysis of the influence of each service in the global results. The analysis is done for the entire network, i.e., for all deployed BSs, with the calculation of parameters averages for the number of users performing each service. From the network analysis viewpoint, the most important parameters to be analysed are:

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

$$\overline{S_u} = \frac{\sum_{j=1}^{N_{BS}} N_{uBSj}}{N_{uTOT}} \quad (3.15)$$

where:

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

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

$$\overline{S_{Gnet}} = \frac{\sum_{j=1}^{N_{BS}} S_{Gj}}{N_{BS}} \quad (3.16)$$

- The total throughput for one specific modulation, R_{bmod} :

$$R_{bmod} = \sum_{j=1}^{N_{uBS}} R_{bmodj[Mbps]} \quad (3.17)$$

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

$$\overline{r_{net}} = \frac{\sum_{j=1}^{N_{BS}} r_j}{N_{BS}} \quad (3.18)$$

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

$$\overline{R_{bnet}[\text{Mbps}]} = \frac{\sum_{j=1}^{N_{BS}} R_{bBS}[\text{Mbps}]}{N_{BS}} \quad (3.19)$$

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

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

$$T_{net}[\text{GB/h}] = \sum_{j=1}^{N_{BS}} T_{BS}[\text{GB/h}] \quad (3.20)$$

- The total number of served users per hour in the network, N_{uhnet} is given by:

$$N_{uhnet} = \sum_{j=1}^{N_{BS}} N_{uhBS} \quad (3.21)$$

The last analysis requires the determination of user's session duration, average number of sessions per hour, Table 4.6, the number of users in the busy hour, and the total traffic for each service.

The Graphical User Interfaces (GUIs) are presented in Annex G, compiled in a brief instruction manual.

3.3 Simulator Assessment and Models Evaluation

Before performing simulations and its results analysis, the simulator must be assessed, namely the validity of the output and the necessary number of simulations that ensure statistical relevance. Consequently, several tools and approaches such as averages, relative mean errors and standard deviations were inspected. The propagation model and link budget were confirmed through inspections done in Microsoft Excel, which allows ensuring the correction and agreement with the theoretical model. The assessment of functions used for the calculation of slow and fast fading and reduction strategies was done in [Duar08] and [Lope08].

The output results, were tested for each BS and, in a global perspective, by the whole network using (3.22), (3.23) and (3.24), the average μ , the relative error \bar{e} , and the standard deviation σ , respectively.

$$\mu = \frac{\sum_{i=1}^n z_i}{N_z} \quad (3.22)$$

where:

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

$$\bar{e} = \left| \frac{z_i - z_r}{z_r} \right| \quad (3.23)$$

where:

- z_r : reference value.

$$\sigma = \sqrt{\frac{1}{N_s} \sum_{i=1}^{N_s} (z_i - \bar{z})^2} \quad (3.24)$$

Since user's geographical positions and their requested throughput have a strong randomness associated, several simulations must be taken to ensure result validation. With this value, 30 simulations were performed, in an Intel Pentium D 925 3.00 GHz, 960 MB RAM, with an average duration of 30 min/simulation.

UMTS/HSPA+ DL was considered in the assessment. There is no specific need to evaluate in UL, since the links have different features but are complementary with each other, nevertheless it was performed several debug sessions and point observation code to accurate the results.

The number of simulations is estimated based on Figure 3.5, Figure 3.6 and Figure 3.7, considering several parameters for a variable number of simulations. The evolution of the average network radius and the effective average number of users that the network considers are illustrated in Figure 3.5, the evolution of the average ratio of served users, Figure 3.6 (a) and the average network throughput is respectively presented in Figure 3.6 (b). Notice that, both average values and standard deviations have negligible variations with the increase on the number of simulations.

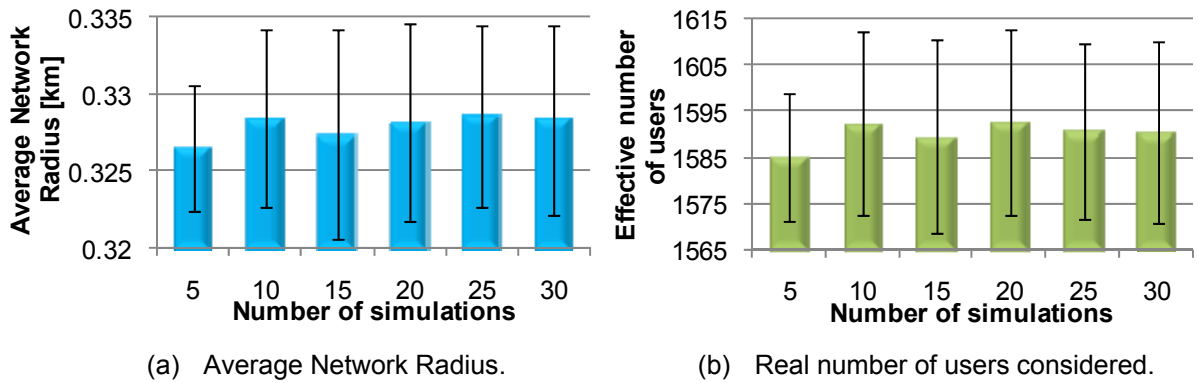


Figure 3.5. Average network radius and effective number of users throughout performed simulations.

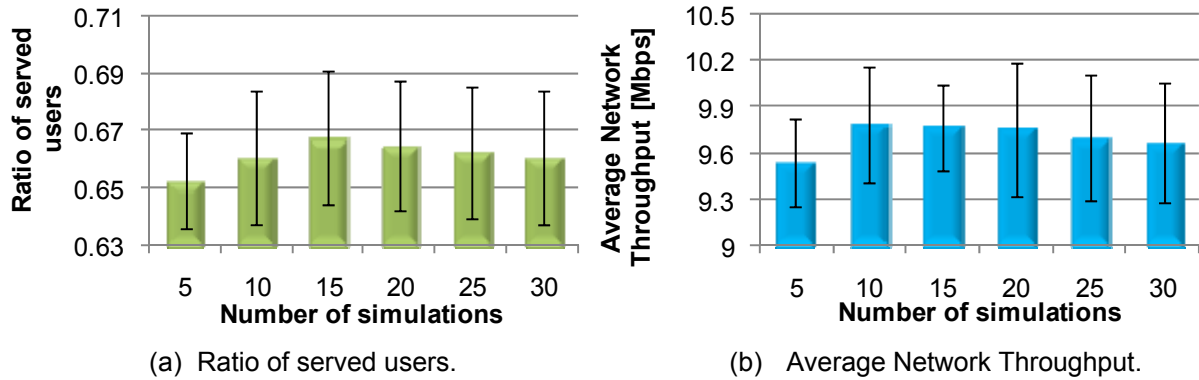


Figure 3.6. Ratio of served users and average network throughput throughout performed simulations.

It is also important to emphasise the different system's capacity according with the configurations chosen, and the users' randomness leading to a different service penetrations, hence, different

network results obtained.

In Figure 3.7, it is possible to see the ratio of the standard deviation over the average value. One can verify that there are no relevant variations of this ratio with the increase of the number of simulations. Notice that all values result in a low ratio, therefore, a hypothetical increase in the number of simulations would not cause any impact on the results. This fact leads to choose 10 simulations as reasonable. In addition, considering not only the precision of the results obtained, but also each simulation running time, one can conclude that 10 simulations are satisfactory.

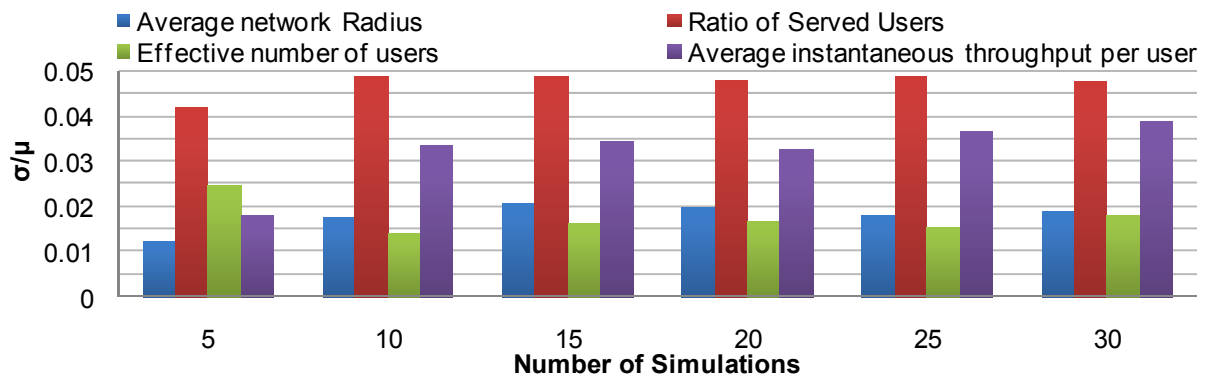


Figure 3.7 Parameters discrepancy analysis along crescent number of simulations.

Concerning the assessment of the simulator, the definition of the number of users introduced in the simulator has to be defined. Although, not all the users introduced are placed in the map of Lisbon, since the module UMTS/LTE_Optimizer places randomly some users out of the region under analysis. So, 10 simulations with 1000, 1500, 2000 and 2500 users were performed, corresponding approximately to 800, 1200, 1600 and 2000 users respectively, inspected over the same parameters, Table 3.1.

Table 3.1. Evaluation of number of users considering simulation parameters.

Parameters	Number of Users							
	1000		1500		2000		2500	
	μ	σ	μ	σ	μ	σ	μ	σ
Average Network Radius [km]	0.31	0.01	0.32	0.01	0.33	0.01	0.33	0.01
Average Ratio of Served Users	0.78	0.03	0.71	0.02	0.66	0.02	0.62	0.01
Average Network Throughput [Mbps]	6.90	0.16	8.52	0.37	9.78	0.39	10.93	0.24
Effective Number of Users	793	13	1189	10	1586	12	1988	19

As expected, the average ratio of served users decreases with the increase of the number of users. The number of covered users increases as well with the increase of the number of users. Regarding the effective number of users placed, the default number of effective users as 1600 in the network area is taken, being a good approximation for the analysis that is required and supported by [Lope08] and [Perg08] for the same type of study.

Chapter 4

Result Analysis

Along this chapter the key results gathered for both models developed are evaluated. Following the same sequence as the preceding chapter, firstly an analysis is carried out for Single User performance divided into UMTS/HSPA+ and LTE; afterwards, Multiple Users performance is also analysed for both systems always underlining the comparison viewpoint. Quite a few parameters' variations, such as frequency, channel bandwidth, service profile, modulations, allow a full analysis and the respective influence on the each system, DL/UL being assessed separately.

4.1 Scenarios description

Three types of environments were considered. The pedestrian environment stands for a static (or almost, 3 km/h as usually in ITU Pedestrian A channel) user at the street level with low attenuation margins; the vehicular for users moving at high-speed, normally considered 50 km/h; and the indoor environment characterises users performing services inside buildings. All these environments were taken in urban cells, and associated fading margins were considered as can be seen in Table 4.1. Default and recommend values of COST231-W-I are described in Annex C, were applied, as well as a typical urban situation.

The global distribution of users among the different environments considered is as follows:

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

The large number of users in indoor environments can be explained by being the most suitable location to perform services through smartphones, PDA's or laptops. However, one does not consider the height of the user inside the building, i.e., the building floor which varies the penetration margin values presented afterwards.

Due to random nature of multipath and terrain configuration the associated signal fading and degradation, were account by fast and slow fading margins respectively set. For the Single User (SU) situation, the margins are shown in Table 4.1, where indoor losses account for the structure effects such as walls and windows, were extracted from several studies over the same frequency or similar such as GSM900, or extrapolated from most used spectrum bands, i.e., the case of 2.6 GHz. Spatial diversity essentially minimise fast fading effects improving the received signal energy, but besides that, power control employment can be responsible, as well, for the mitigation of fast fading specially at low user's speed.

On behalf of MU scenarios due the different approach to describe the fading processes, probabilistic distributions are used, expressed by (D.15) and (D.16). Annex D also contains support parameters for this modelling.

Table 4.1 Fade margins accounted in Link Budget (extracted from [Voda09]).

Environment	Fading and Indoor Penetration margins				
	M_{SF} [dB]	M_{FF} [dB]	L_{int} (f=900 MHz) [dB]	L_{int} (f=1800; 2100 MHz) [dB]	L_{int} (f=2600 MHz) [dB]
Pedestrian	7.6	2.0	0.0		
Vehicular	5.0	0.0	3.5	8.0	9.0
Indoor	7.6	2.0	11.0	20.0	21.0

The default parameters used for simulations and link budget estimation are presented in Table 4.2 for HSPA+ and for LTE in Table 4.3. Remember, that in the SU Model, there is no interference margin neither reduction strategies applied, however in the MU one, there is significant interference among users, dependent on number of users, the distance between the connected BS, service required and

activity factors. A margin of interference is taken into account to limit the maximum noise level, depending on network load factors and interfering with the BS coverage, decreasing with the increase of M_f .

Table 4.2. Default values used in HSPA+ link budget (based on [Voda09], [Perg08] and [HoTo07]).

Parameter	DL	UL
BS DL Transmission Power (maximum) [dBm]	46	---
MT Transmission Power (maximum) [dBm]	---	24
Frequency band [MHz]	2110	1920
Modulations	QPSK, 16 QAM , 64 QAM	
Bandwidth [MHz]	5	
Antenna Configurations	SISO, SIMO (UL), MIMO	
MT Antenna Gain [dBi]	1	
BS Antenna Gain [dBi]	18	
User Losses [dB]	1	
Cable losses between emitter and antenna [dB]	2	
Noise Figure [dB]	9	5
Diversity Gain [dB]	---	2
Interference Margin [dB]	6	
Power reserved for signalling and control issues (Release 99 + HSPA) [%]	40	15

Table 4.3. Default values used in LTE link budget (based on [Voda09], [Duar08] and [Kath09]).

Parameter	DL	UL
BS DL Transmission Power (maximum) [dBm]	46	---
MT UL Transmission Power (maximum) [dBm]	---	24
Frequency Band [MHz]	900, 1800 (MU), 2100, 2600	
Modulations	QPSK, 16 QAM, 64 QAM	
Bandwidth [MHz]	5, 10, 15, 20	
Antenna Configurations	SISO, SIMO (UL), MIMO	
MT Antenna Gain [dBi]	1	
BS Antenna Gain [dBi]	15 (900 MHz); 18	
User Losses [dB]	1	
Cable losses between emitter and antenna [dB]	2	
Noise Figure [dB]	7	5
Diversity Gain [dB]	2	
Interference Margin [dB]	3	2
Power reserved for signalling and control issues [%]	28.5	10

The maximum BS antenna gain for both systems is 18 dBi, with a 65° half power beam width radiation pattern, [Sant04]; still the antenna gain is variable for the user path loss calculation, according to the azimuth between the user and the BS. However, due to antenna's production restrictions it is not

simple to get higher gains for lower frequency bands, so 15 dBi are set for LTE 900 MHz band, [Kath06].

On the other hand, since the MT only performs data services, the antenna gain is set do 1 dBi, assuming that the equipment is not used next to the ear. Both equipment gains are manufacturer dependent and may vary according to the type of hardware. Identical transmission powers were set in order to a fair system's comparison. Actually some HSPA+ sites are already being supplied by 40W, [Voda09], however HSPA BSs general values are below this target, 43 or 44.7 dBm for macro-cells. Micro-cells or even indoor ones have lower power in the order of 20-30 dBm. Otherwise, for LTE, [Kath09] produces already BSs with 46 dBm maximum transmission power.

The human body absorbs energy, which reduces the antenna efficiency, so a body loss margin is established as 1 dB. Moreover, losses generated by feeders, connectors and all external equipment between the antenna and the BS receiver are considered, and vary depending on type of equipment used, so all loss values are extrapolate for all cells taken into account. In order to perform a fair comparison between both systems, the LTE channel bandwidths analysed start from 5 MHz, the same used in UMTS/HSPA+, or higher.

Furthermore, the UL estimation in terms of exclusive power for control channels is tricky and variable due to the technical specifications of the MT and the type service, [Voda09]. Additionally, the maximum transmission power on MT is divided per all channels in use; taking into account some factors for signaling and control, commonly known as constant set beta ratios defined on Annex A, Table A.3. However the precise power contribution is complex to determine, therefore a fraction from the maximum transmission power was set. Also the noise figure, is conditioned by hardware topics, reflecting the device's performance, when the lower is the better.

Along this thesis, the default user profile distribution adopted is the one shown in Figure 4.1. One should remember the case that all requested services data ones, where speech services are sub intended to be conceded in another carrier, Release 99 one, Figure 3.4. Table 4.5 lists the throughput ranges of each service and its QoS priority level associated, whereas Table 4.4 additionally presents default simulation assumptions, such as the selected reference throughput.

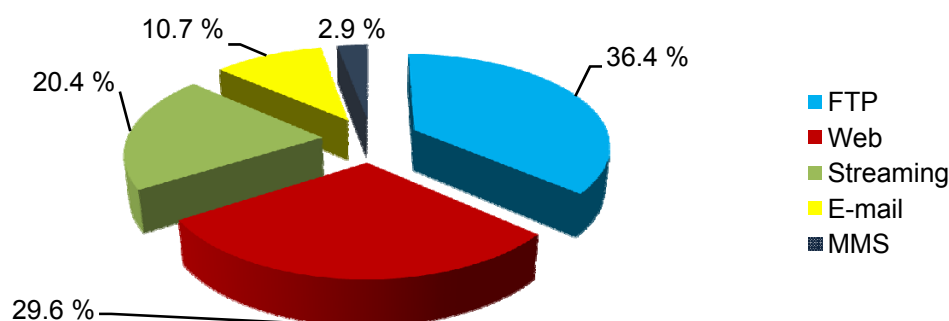


Figure 4.1 Default service profile.

Table 4.4 Further Link Budget standard considerations.

Environment	Pedestrian A	
Reference Throughput [Mbps]	14.4 (DL)	5.7 (UL)
Reduction Strategy	QoS Class Reduction	
Service Profile	Default considered, Figure 4.1	

Table 4.5 Data rate assumptions between data services (based on [Voda09]).

Service	Throughput behaviour [Mbps]		QoS Priority
	Constant	Variable	
Web		$[1.024, R_{b\ max}]$	1
Streaming	$[0.032, 10]$		2
E-mail		$[0.384, R_{b\ max}]$	3
MMS		$[0.128, 0.512]$	4
FTP		$[0.512, R_{b\ max}]$	5

Non-real time applications typically present an asymmetrical nature, as they mostly request information executed by users to remote machines, [Sant04]. Web, FTP and E-mail are non-real time application examples, illustrated in Figure J.1. On the other hand, MMS is a data transfer classified as a background service, see Annex J for additional service and applications definitions.

The higher throughputs reflect the strong trend of requesting, by users for more demanding applications in terms of networks capacity. Given that, it is important to emphasise that the services throughput is limited by the type of system used, $R_{b\ max}$, bearing in mind the differences among them. Additionally, the type of receiver used limits the connection throughput, depending on the hardware category, since each one has different capacity characteristics, Table A.1, Table A.2, Table A.4, however this differentiation is not taken into account.

Streaming has a continuous throughput request that does not vary through the session time but different types of streaming have to be contemplated, like audio, video or even high-definition video, therefore diverse throughput values are taken into account in order to face all possibilities. Although, streaming is intend to be a continuous transmitted file, one has a 3 MB file size for UL in Table 4.6, in order to traduce the rising of new web standards, also known as Web 2.0, introducing greater user interaction on the production and content delivery through the network. Above and beyond, the rising of new types of services is a nowadays reality; real time gaming, interactive software or even the Digital Video Broadcasting (DVB) are examples of new arriving technologies. DVB – Handheld (DVB-H) or – Satellite services to Handhelds (DVB-SH) are mobile broadcast standards maintained by DVB Project. Annex J refers to further considerations about the service layer considered by 3GPP.

The lowest value in the QoS queue on Table 4.5 reveals the highest service priority, so services with a higher value of QoS priority level are the first ones to be reduced if reduction strategies are applied.

Table 4.6 Traffic models for each service type.

Services	Parameter	DL	UL
FTP	Average file size [MB]	20	10
	Average number of files per session	2	1
Web	Average page size [kB]	300	20
	Average reading time [s]	45	
	Average number of pages per session	12	
Streaming	Average video size [MB]	10	3
	Average video duration [s]	180	
	Average number of videos per session	3	
E-mail	Average file size [kB]	200	
	Average number of e-mails per session	2	
MMS	Average file size [kB]	200	
	Average number of messages per session	2	

4.2 Single User Radius Model Analysis

Within this section, first HSPA+ in Subsection 4.2.1 then LTE in Subsection 4.2.2 results are presented, considering the single user analysis, assuming that the user is requesting only one service. In both subsections, DL and UL analysis is performed without a particular distinction.

4.2.1 UMTS/HSPA+

Concerning Figure 4.2, the cell radius is presented for different antenna configurations over the three types of environments considered. The throughputs were fixed, for DL at 15 Mbps in 64QAM, while in UL at 7 Mbps in 16 QAM. In DL one considered only SISO and MIMO configurations due to the use of diversity only at the BS level; due to the real concerns of producing two port antennas at the MT. One can see that in both cases pedestrian users can achieve a higher cell radius because there are no penetration margins, so the signal propagation gets less attenuated.

Analysing antenna configurations, it is noticed that SIMO increases the cell radius making use of the diversity gain, 2 dB, resulting in an increase around 13% comparing to SISO for all environments. However, the higher radii are reached with MIMO, increasing cell radius compared with SISO, of 45 and 49%, in DL and UL, for pedestrians. The reason for this improvement on coverage is due to the fact that MIMO requires a lower SNR for the throughputs considered as one can verify in Figure 2.3 for DL. For instance, one can verify that for any SNR value, the use of MIMO provides a higher throughput compared to SIMO and SISO.

For UL, the relative increase of using MIMO is higher than DL, because there are no available model expressions for this topology; therefore, one considers that, the use of MIMO reduces to half the value

of the associated SNR, i.e., the theoretical capacity gain of MIMO is considered.

Also, the cell radius obtained for the fixed throughputs enunciated in an indoor situation are very low, when one considers macro-cell coverage. It is expectable that coverage problems exist in UL whatever the configuration chosen for throughputs equal or higher than 7 Mbps.

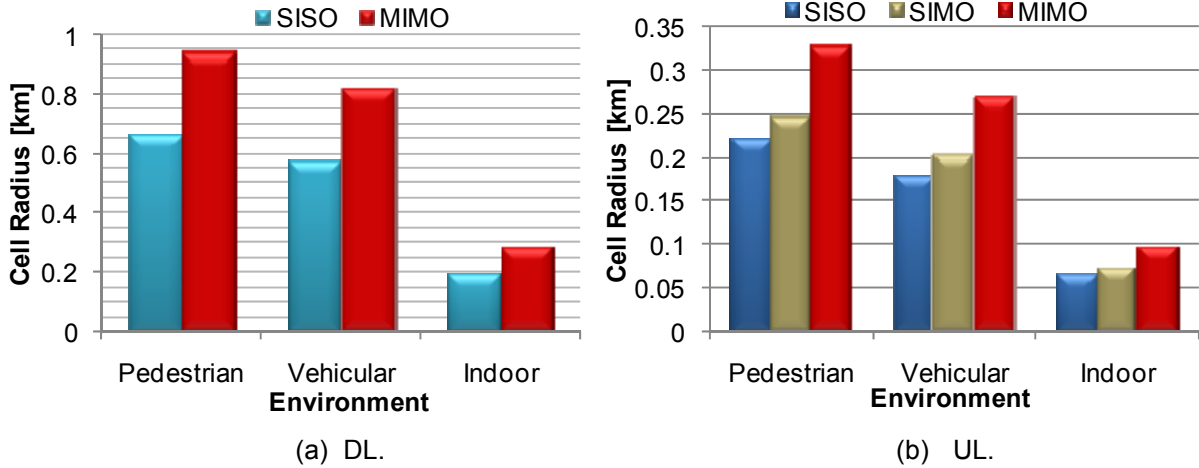


Figure 4.2. HSPA+ cell radius variation for different environments and antenna configurations.

In Figure 4.3, one shows the variation of cell radius with the instantaneous achievable throughput over a DL indoor situation. SISO configurations present a lower range of achievable throughputs as expected, being also the ones that have a lower cell distance, considering the minimum throughput per configuration. These minimum throughputs are set by the system; exploiting the valid lower bound throughput for a certain configuration, as it varies as long the chosen configuration. Through the models available, and knowing that Release 99 maximum performance is 2 Mbps, on hotspots, this was the lower limit considered. Also, as expected, SISO configurations provide lower throughputs when compared to MIMO, using the same modulation, with the latter offering more system capacity.

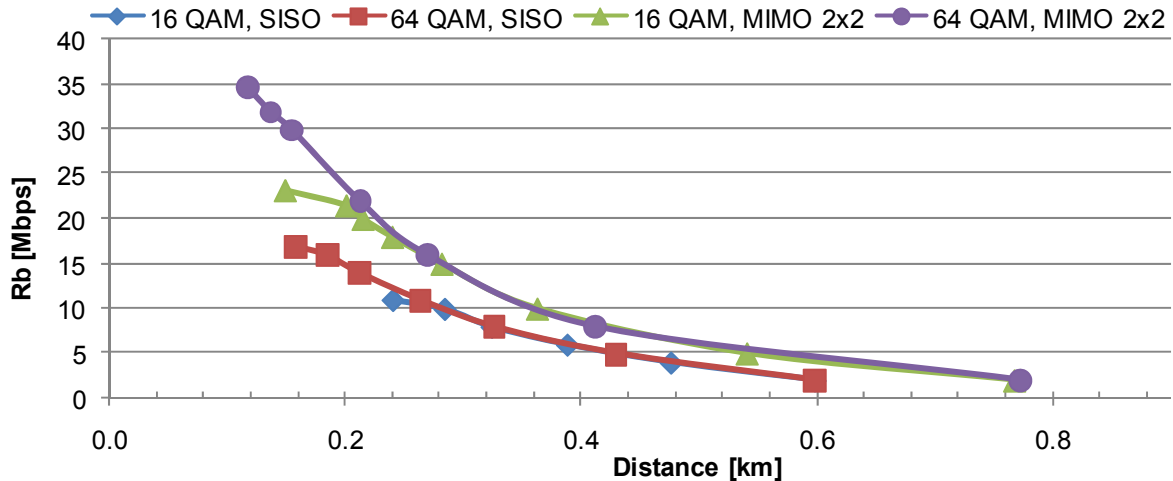


Figure 4.3. HSPA+ DL achievable throughput variation, in indoor environment for different configurations as a function of distance.

As a result, the cell radius decreases with the increase of the throughput, mainly due the fact that higher throughputs require high SNR values, and consequently the path loss, decreases leading to a lower cell radius, i.e., the distance between the MT and the BS. With the SISO at 2 Mbps, the cell can

go almost to 600 m, however, with the use of multi stream configurations the coverage is much similar regarding the modulation, observing an increase of 29% in cell radius distance, comparing to SISO. In contrast, it is remarkable that in all modulations and configurations the maximum throughput is achieved over a distance greater than 100 m, which designs good cell coverage. Also the maximum throughput values vary in order the parameters shown, from 11 Mbps to 35 Mbps approximately.

Comparing the indoor situation with Figure F.1 and Figure F.2, one can see that in the 64QAM SISO configuration, the vehicular environment can have cell radius 2.9 times and pedestrian environment 3.3 times more comparing with the indoor scenario. In the pedestrian and vehicular environments, the former has a greater cell radius due to favourable fading margins, Table 4.1.

For UL, the same scenarios are shown in Annex F, Figure F.3, Figure F.4 and Figure F.5. The distances that the cell can define are different compared with the correspondent ones in DL. In pedestrian, there is a maximum distance for all configurations around 500 m, while in indoor this value is much lower distances being 70% lower comparing with the pedestrian ones. The limitations over the MT in UL are well known when a direct comparison between DL and UL is carried out, such as power, losses, and hardware performance. Consequently, it is expected that the cell distance in UL is quite shorter, but still the maximum throughputs are accomplished beyond 100 m for pedestrian and vehicular user, and 40 m for indoors. Point out that, the behaviour of QPSK and 16 QAM has some variations in UL, where typically for higher throughputs 16 QAM has a larger achievable distance, however when gradually throughput decreases, this tendency is inverted QPSK being the modulation with higher distances for the same throughput, supported by the fact that QPSK is a most robust scheme compared with 16 QAM. This conduct is also shown in Figure F.3, Figure F.4 and Figure F.5.

In Figure 4.4, one shows the cell radius disparity among the different possible modulations and environments in UL and DL. The specified modulations alongside the two paths are different as it was pointed out in Section 2.2. All distances were calculated for the highest throughput possible in SISO configurations, hence, for DL 11.5 (16 QAM) and 17.5 (64 QAM) Mbps were set while for UL 4.5 (QPSK) and 9 (16 QAM) Mbps approximately. Generically, the DL cell radius is higher than the UL one, as explained previously, but additionally one has the differences between a less robust modulation like 16 QAM with QPSK, where more symbols are used leading to higher throughputs.

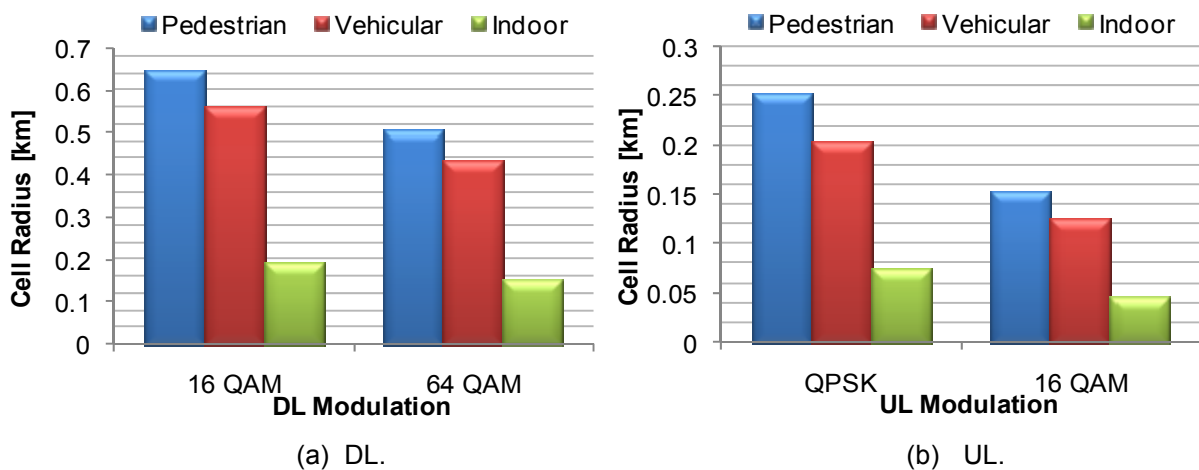


Figure 4.4. HSPA+ cell radius variation, between different modulations.

For a pedestrian user in DL, the radius decreases 22% from 16 QAM to 64 QAM, even so, the difference of cell radius is 71% less for an indoor DL user compared with pedestrian for 16 QAM. In UL, the differences between QPSK and 16 QAM are barely the same, like a decrease of 39% in a vehicular user radius from QPSK to 16 QAM. These differences come from the fact that less robust modulations have higher correspondent throughputs leading to lower cells, visible fact in Figure 2.3 and Figure 2.4. In all situations, for maximum throughputs available, the cell radii are acceptable for urban coverage, exception made for indoor environments, due the high signal attenuation.

Despite the study on the maximum cell radius achievable amid certain system configuration, another perspective is added to this analysis, respectively the behaviour of the used models and the associated analysis. Figure 4.5 shows several functions for some variations in modulation and antenna configuration on a pedestrian environment, for different SNR as a function of throughput. As it can be seen, SISO curves have similar behaviour regarding the modulation, as well as for different antenna formations. With the increase of the SNR, differences become clear, with an increase of throughput is registered, which highest is accomplished by higher spectral efficient modulations. Given that, all curves have a different behaviour over high SNRs and tend to be limitative in some way for higher SNRs, due to the link budget restrictions, i.e. a constant increase of SNR does not reflect a relative throughput increase.

Figure 4.5 shows curves up to the point where beyond an increase of SNR does not result in a linear increase of throughput, i.e., the position where AMC BS scheduler will jump over the next modulation in order to deliver the greatest throughput to the allocated user, Figure 2.5. Subsequently for SISO simulations, approximately at 9.42 dB and 19.23 dB, for 16 QAM and 64 QAM respectively, are the SNR positions before configurations start to reveal a limitative behaviour. Similarly for MIMO 2x2 16 QAM and 64 QAM, 15.14 dB and 21.61 dB resulting in throughputs of 21 Mbps and 32 Mbps respectively were also identified.

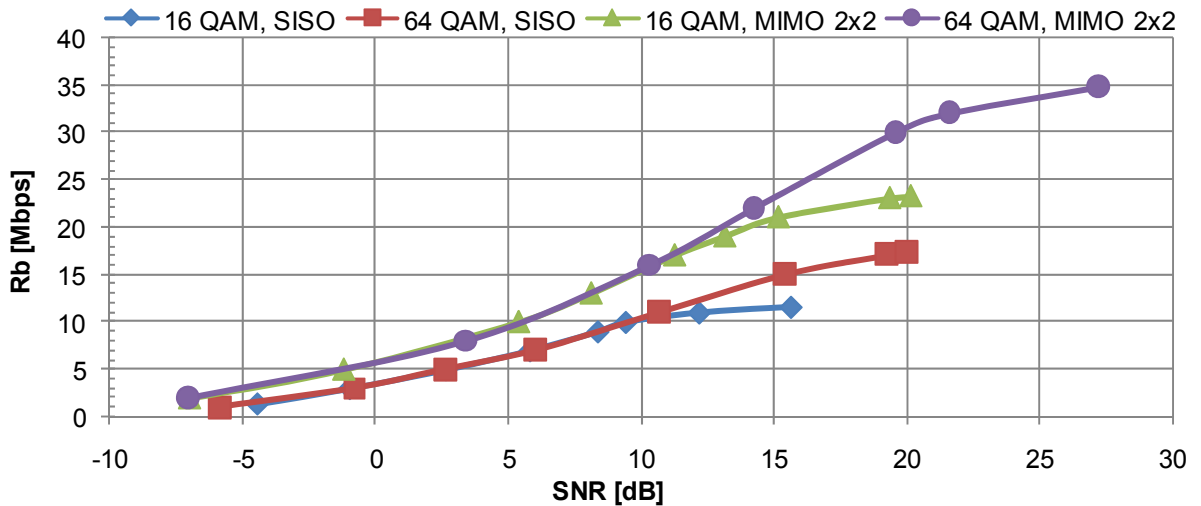


Figure 4.5. Throughput as a function of SINR in DL Pedestrian channel.

Analogous analysis was conducted for vehicular and indoor environments, and results are presented in Figure F.6, Figure F.7 and Figure F.8. For the UL case, the robust modulation scheme performs better throughputs on a lower E_o/N_o range (near 3 dB), being overtaken when the signal strength

increases, that way making possible to 16 QAM to enhance the connection path. Observe that, not always the related $\text{SNR}(R_b)$ curves have the limitative tendency, since the derived expressions have an error associated, or in addition do not get enough simulated points to be valuable for the whole system performance.

4.2.2 LTE

The same preceding analysis was also performed for LTE, plotting different variations of throughput for the possible MIMO configurations, varying the modulation between. QPSK is referred within 3GPP specifications, however for a fair comparison it was not directly considered, being an option of the Single User Radius Model Interface, Annex G. Since the LTE projections are open, towards the frequency band usage; there were considered the same spectrum bands as in Table 4.3.

Observing Figure 4.6, one can see the similar behaviour obtained for UMTS/HSPA+; nevertheless, in LTE, only MIMO configurations were applied supported by the available trials performed by 3GPP. Notice that 64QAM is only used for a SNR higher than 4 dB, according to the 3GPP models, Annex B, making use of a superior modulation over better channel conditions. On the other hand, 16 QAM modulation is only used until the user has a SNR lower than 10 dB, otherwise for enhanced signal only 64 QAM is available, delivering higher throughputs.

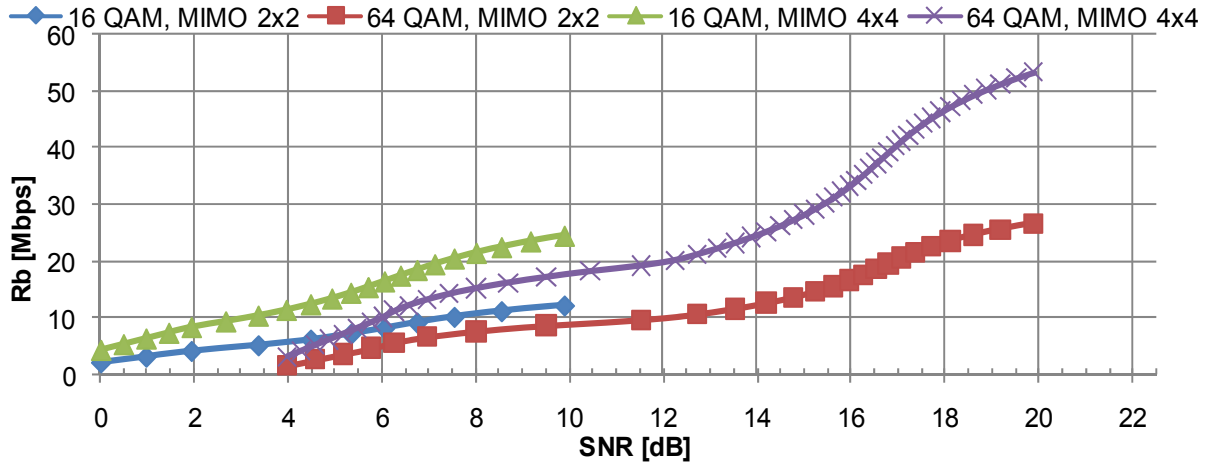


Figure 4.6. SINR as a function of throughput in 2100 MHz for DL pedestrian channel and channel bandwidth of 5 MHz.

In DL, the throughput in MIMO 2×2 is half of the one achievable with the use of MIMO 4×4, assuming an uncorrelated channel. Parallel results were obtained for different frequency bands and channel bandwidths, Figure F.9 for 900 MHz frequency band and 10 MHz channel bandwidth. Results are similar, with the same procedures, where maximum throughputs reveal similar behaviourism as the one over the Figure 4.6, since the same model was employed. The throughputs accomplished are 2 times greater than the ones returned when used a 5 MHz channel bandwidth, the linear proportion being valid for all channel bandwidths available.

On the other hand, regarding all the factors in consideration, if the spectrum band is compared for the same configuration, the same throughputs are achieved for the same SNR, but then for different

distances, since different frequencies have different propagation conducts. The gap between the three bands is considerable, the 900 MHz band being the one who returns better coverage regarding the 2100 and 2600 MHz bands, whose difference is minimal. Remember that this evaluation was done only with one user in a cell, using the same propagation model COST231-W-I in DL/UL, and perfect simulation conditions were taken in order to realize the maximum system's performance.

For a minimum throughput of approximately 12.5 Mbps one has for 2600 MHz a maximum cell range of 0.42 km. With the use of 2100 MHz there is an increase of 39 % of cell radius, whereas with 900 MHz 3.5 times more cell radius is obtained for the same throughput, Figure 4.7, where one sees the frequency band variation for a pedestrian environment in DL, with the use of 64 QAM, with 20 MHz channel bandwidth and MIMO 4×4. Since the penetration margins change with frequency, Table 4.1, in other environments the difference between 900 MHz frequency band and the other spectrum bands is higher. Keep in mind that a larger range of throughputs is supported due to the use of maximum channel bandwidth, 20 MHz, and a complex antenna configuration since it is the best performance combination that LTE delivers. Even so, a similar behaviour is observed as previously, in terms of coverage along all throughputs. Additionally, in Figure F.10, the same type of results was compiled for the respective channel bandwidth, modulation and MIMO type of 5 MHz, 16 QAM, and MIMO 2×2.

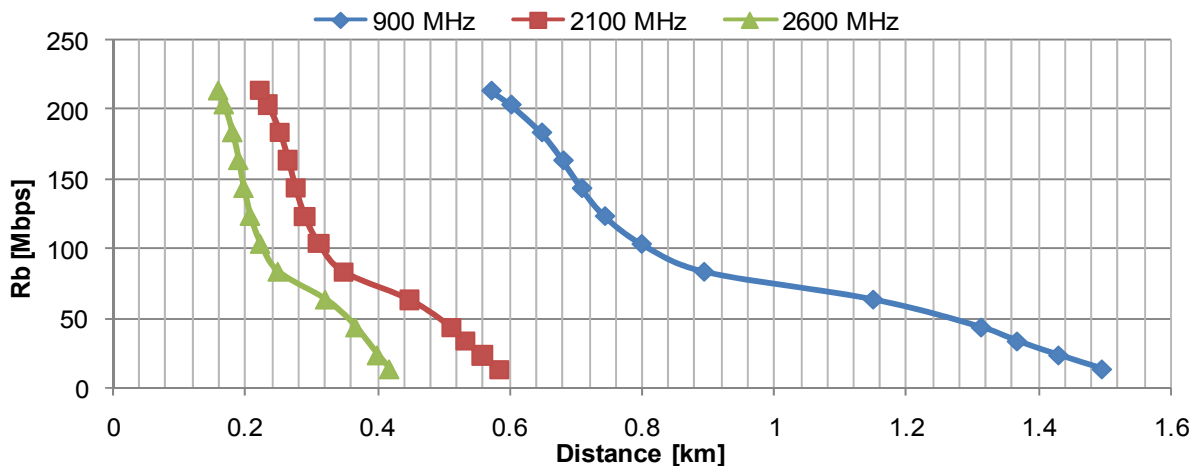


Figure 4.7. Throughput as a function of cell radius for different frequency bands.

Concerning UL, the same results were obtained as it can be seen on Figure F.11 where the variation between 5 and 10 MHz channel bandwidth is illustrated. Despite the differences in MIMO and bandwidth, the system performs in similar way as in the DL, regarding the expected differences in achievable throughputs due to the bandwidth used; anyway comparing the same frequency band, the possible coverage varies around 15-20% less when used 10 MHz channel bandwidth comparing with 5 MHz. This distinction is expected, since the higher the throughput the higher SINR is required, then lower cell radius is obtained. Nonetheless, channel bandwidth variations also reflect in cell radius, where with the increase of the bandwidth, the BS capacity also increases, resulting in higher throughputs available, although with a lower cell radius, which sometimes are not viable to cover typical urban macro-cells. Comparing the radius obtained in UL with the ones in DL, in the former cell radius are 1.89 km, 0.7 km and 0.52 km lower for a channel bandwidth of 5 MHz. Therefore, one can state that UL restricts the system on coverage matters, since both links are simultaneously deployed.

An additional perspective is displayed in Figure 4.8 provides the influence of the environment on the possible maximum cell radius. Over the 2600 MHz frequency band, with 20 MHz channel bandwidth, 64 QAM and MIMO 2×2, it is notable that the pedestrian scenario reaches a higher cell distance allowing an average increase of 47% and 3.5 times more comparing to vehicular and indoor scenarios. The margins accounted in (D.14) characterise these differences which result in distinct cell radius through (D.17) and (3.3). However, regarding the distribution of users considered in Section 4.1, the pedestrian users' percentage is minimal, 10%, compared with the indoor ones, 80%, which is the most suitable situation to perform data services. Figure F.13 presents the variations for the 2100 MHz frequency band.

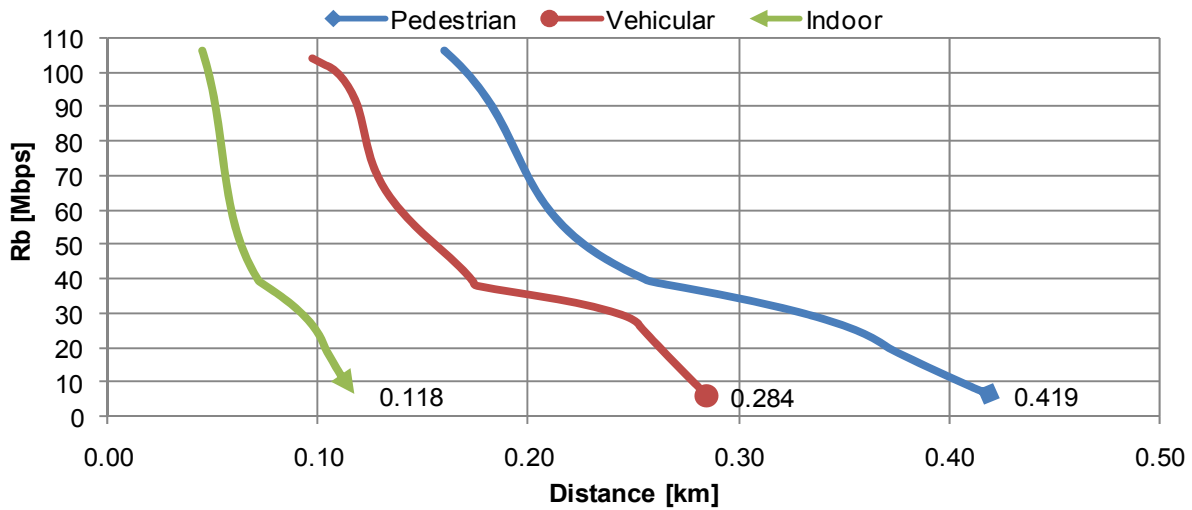


Figure 4.8. Throughput as a function of cell radius for different environments.

4.3 DL Multiple Users Scenarios Comparison

Throughout the present section, UMTS/HSPA+ and LTE results for multiple users scenarios are analysed, comparing capacity and coverage aspects for DL. First the results of the default scenario are presented; then, particular system's parameters are studied.

4.3.1 Default Scenario

The results, were obtained in order to detailed specify the two systems performance in DL with the default values and considerations taken in Table 4.2 and Table 4.3. The reference service throughput is equivalent for both systems and is defined for the cell radius calculation purpose. This calculation is kept constant for whole network within each simulation, due to the snapshot analysis considered. The reference throughput was defined to be the limit of the previous UMTS/HSPA+ release on the maximum performance, i.e., 14.4 Mbps. In addition, the chosen environment was the Pedestrian A one, since it is the one which reveals greater performance, meaning, larger coverage areas in the SU analysis and less attenuation factors. Still, the environment only takes part to define the sector radius

for all network BSs, being the users' distribution the one exposed in Section 4.1. Bear in mind that, all the results take only into account the network covered users, regardless those who are out of sector radius.

Considering Figure 4.9 (a) one can notice that, in HSPA+ the average network radius is higher compared to LTE, returning a decrease of 28% between. The different radius are explained by the different channel bandwidth in both systems, being 5 MHz higher in LTE, leading to lower radius, as well as the higher carrier frequency used (the European expected LTE spectrum band 2.6 GHz against 2.1 GHz in UMTS). On the other hand, these results reflect directly on the coverage area, Figure 4.9 (b), where HSPA+ has a superior percentage of covered users, for the same total number of users placed. HSPA+ radii are very reasonable, the network covering almost all the users in the metropolitan area of Lisbon, against 26% less in LTE. Nevertheless, remember that these covered users do not mean that all are performing services; most of them get delayed due to system limitations, i.e., BSs capacity.

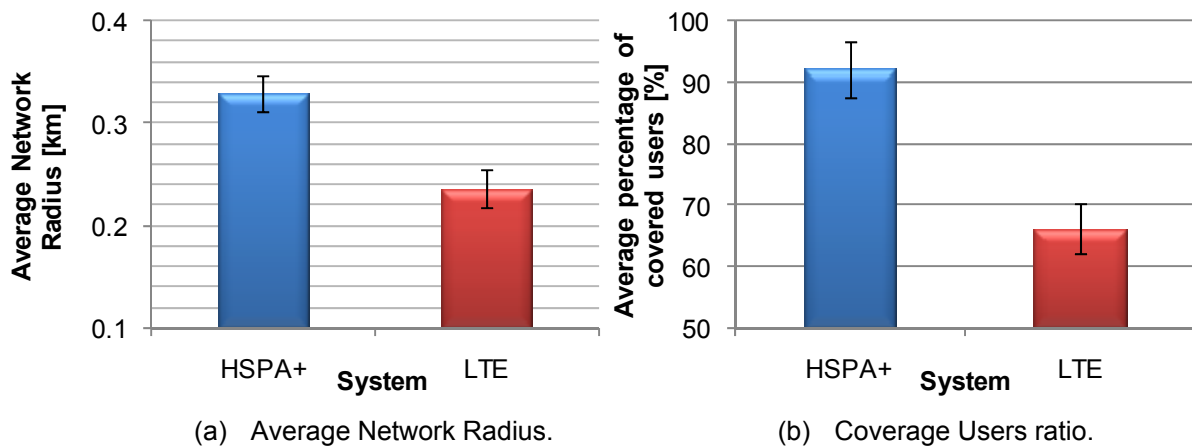


Figure 4.9. DL Average Network Radius and Average percentage of Covered Users.

The ratio of served users Figure 4.10 (a), shows which of them are performing services with the network. Despite the greater radius from HSPA+, LTE serves more users due to the higher BS capacity; however neither of the systems serves more than 75% of the covered users, due to BSs capacity achieved or to low SINRs and channel conditions. LTE's higher channel bandwidths, as well as a greater operating frequency are conditions for a higher system capacity, but less coverage comparing with HSPA+, with 5 MHz channel bandwidth and 2.1 GHz band. In regions with higher user density, since HSPA+ presents a larger coverage, the corresponding BSs have more users connected, the capacity of some BSs can be reached, hence users have to be reduced or delayed, resulting in less served users.

On the other hand, common to both systems, is the generic radio link sensitivity problem, i.e., due to signal fading and especially over the urban scenario, the receiver sensitivity can be below a certain threshold for the minimum throughput for a given service, resulting in a lower SINR. With the increase of the user's distance to the BS, and with the increase of the number of served users, being more users connected into the BS, interference increases which requires more power to accomplish the connection with the desired service; this causes situations of delayed users due to the fact that the

corresponding SINR is below the bound for the minimum service required throughput.

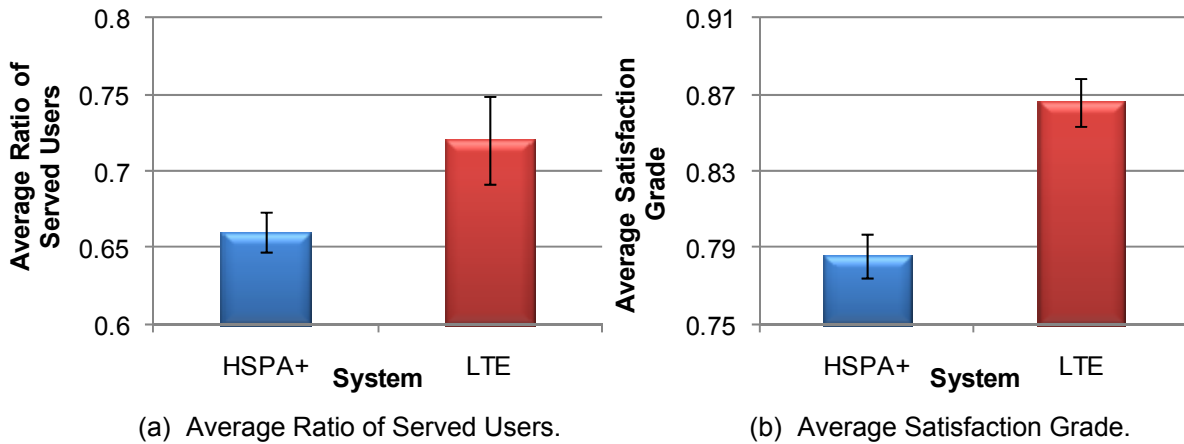


Figure 4.10. DL Network average ratio of Served Users and Satisfaction Grade.

Users' satisfaction grade is shown in Figure 4.10 (b), for LTE being approximately 10% more than in HSPA+. It is well stated that this quality measure is not unitary since, the requested throughput cannot always be served, given the attenuation problems, penetration and fading margins and interference associated to users. In general, LTE serves more of its covered users, with a higher satisfaction compared to HSPA+. With the normal increase of user's distance to the BS, the throughput naturally decreases, thus, users placed farther away from the BS have more probabilities of not being served. Therefore, two situations may happen; depending on the reduction strategy applied, the user gets reduced in terms of throughput or RB and still gets served with a throughput lower than the requested one, or the user is delayed, i.e., the associated throughput is below the minimum service throughput and then the user does not perform the desired service.

The average throughput per service is visible in Figure 4.11. Globally LTE has higher delivered average throughputs than the ones obtained for HSPA+, due to the superior capacity revealed by LTE in order to serve more users with higher data rates. The same LTE average service throughput superiority is found in the average service satisfaction grade, Figure 4.12. Some differences on throughputs per service are depicted, since Web and FTP are the most demanding services, requesting the higher maximum throughputs, they are also the ones that achieve higher average throughputs. Email is also affected by the same behaviour, although with lower requested throughputs. In order to differentiate these types of services, which from the user's viewpoint are not throughput upper limited, i.e., they consume as much resources as possible to assign, the nature of the protocols renders the fact that more throughput leads to a better connection, hence, a better service.

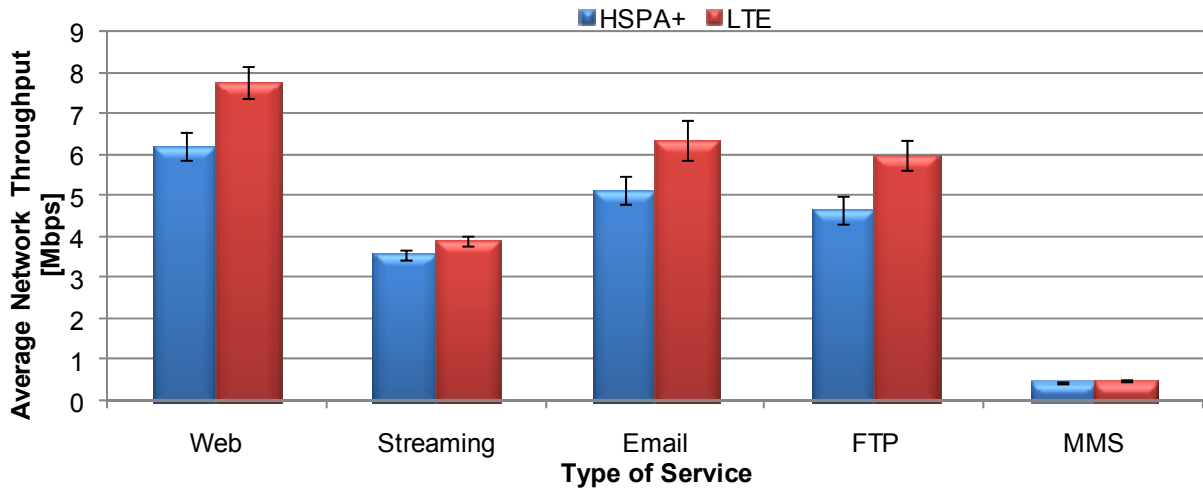


Figure 4.11. DL Average Network Throughputs per service.

Even in these types of services, whenever the throughput increases, the connection time decreases and normally the satisfaction grade also raises, since users always want more quicker and demanding data transfers. In Streaming and somehow MMS, no matter how much higher the delivered throughput is, the quality of the delivered service will not raise at the same scale, as mentioned in Section 4.1. The most critical situation is for voice services, since this type of service does not profit with the progressive demanding of mobile broadband, because there is no need in increasing the service throughput, to return improved quality over voice services.

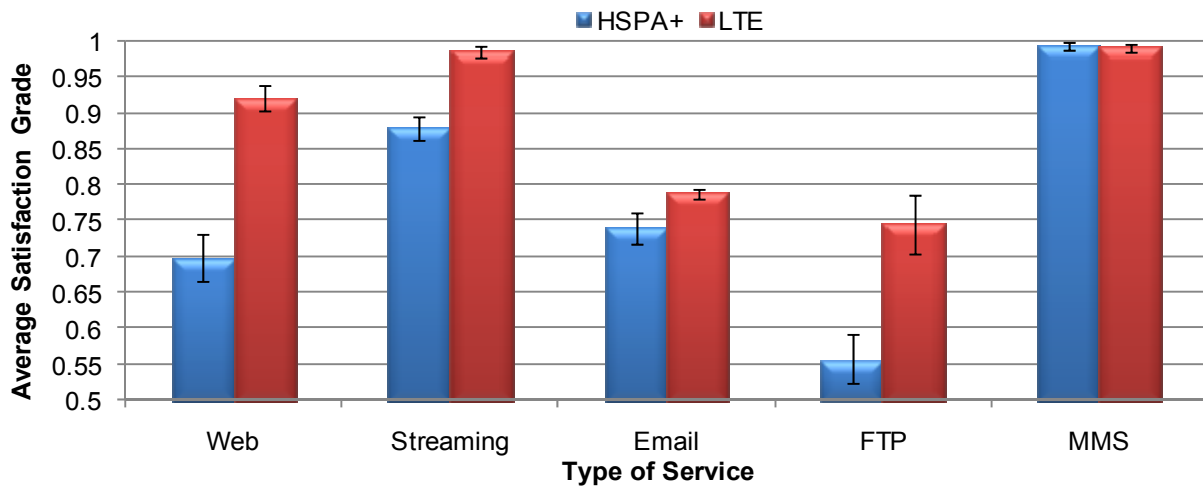


Figure 4.12. DL Average Satisfaction Grade per service.

Meanwhile, it is noticeable in Figure 4.12 that MMS users have the highest average satisfaction grade, even though having a low average network throughput, meaning that this service has a low requested throughput. On the other hand, FTP is one of the most demanding services and also the one with least priority in the QoS queue, being the first class of users reduced in case of maximum BS capacity achieved. Take into account that Web, FTP and Email have both high requested throughputs; the standard deviation presents slightly higher values comparing with Streaming and MMS ones.

On an overall perspective, users are further satisfied with LTE, this being the system where users get less reduced/delayed, supported by the network trend in Figure 4.10 (b).

Despite the fact that the analysis done in this thesis is from a snapshot perspective, an extrapolation can still be performed in order to estimate the network behaviour in an hour. This analysis is commonly named 'Busy Hour', and examines essentially the number of served users and the total traffic consumed in an hour. Figure 4.13 show the results of that extrapolation. The total network traffic depends essentially, on the number of users performing in an hour.

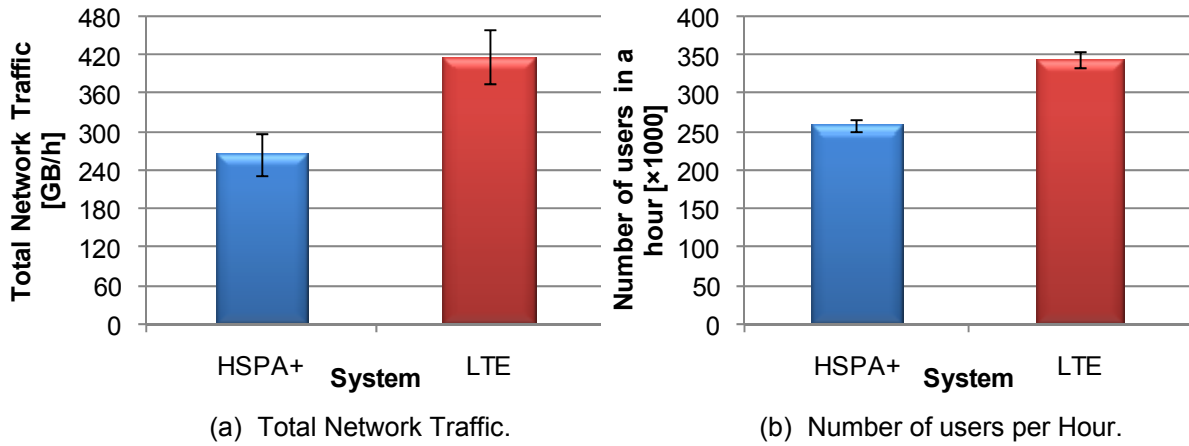


Figure 4.13. DL busy hour metrics.

The global network traffic flow is divided into the network services, concerning the relative penetration among the users, Figure 4.1. Nevertheless, the served quantity of each service can be different from the original one offered to the network; Table 4.7 shows the served traffic for both systems, according to the final number of users served by the network. A good network performance is characterised by not differentiating the services requests; though, the differences to the default service profile are caused to the network inability of serving all users, which is noticed on the lowest priority service, FTP, where the served users are most decreased. Despite the fact of being a less demanding service, MMS collects a higher percentage of traffic due to the increase of delayed users from the most exigent services. Take into account all the margins associated to the scenario, the achievable throughputs are limited and depend on users' SINR, resulting in a higher probability for most demanding users being delayed.

Generally, LTE achieves better performance metrics than UMTS/HSPA+, however, despite this the same relation of superiority is not perceived on the achieved global trends. Regarding the major difference on the access technique, OFDMA provides a higher granularity and flexibility in resources allocation, as well as more degrees of freedom in user's scheduling and QoS profiles.

Table 4.7. DL Served traffic detailed for each service.

System / Service	Web	Streaming	Email	FTP	MMS
HSPA+ [%]	29.3	19.5	10.6	29.8	10.8
LTE [%]	30.8	20.1	10.7	34.1	4.3

4.3.2 Bandwidth

This subsection presents the performance analysis of both systems with the allocation of the same channel bandwidth. As it is already known, HSPA+ has a channel bandwidth of 5 MHz, specified in the

early years of Release 99, with a fixed chip rate of 3.84 Mcps, spreading the signal all over the bandwidth. Although, LTE has the possibility of scalable that channel bandwidth according with the network requirements and the planning purposes. The spectrum bands allocated were the same as the ones selected on the default scenario.

One performed simulations with LTE at 5 MHz bandwidth, resulting in similar trends as Subsection 4.3.1. In Figure 4.14 (a), it is possible to inspect that the LTE average network radius rise with the decrease of bandwidth, contrasting with the results obtained in Figure 4.9 (a). This tendency is accomplished by the decrease of the bandwidth, while the number of RBs also decreases; hence, fewer sub-carriers are available for transmission, leading a reduction of the total noise power, (D.9) since the interference margins are kept constant on both scenarios, as well as hardware noise figures. LTE average network radius increases 21% from the 10 MHz bandwidth allocated for the default scenario, but still it does not goes beyond the HSPA+ radius, within a 30 m difference between. One must have in mind, the similar fading margins for each 2100 MHz and 2600 MHz, Table 4.1, nonetheless originating some differences on results.

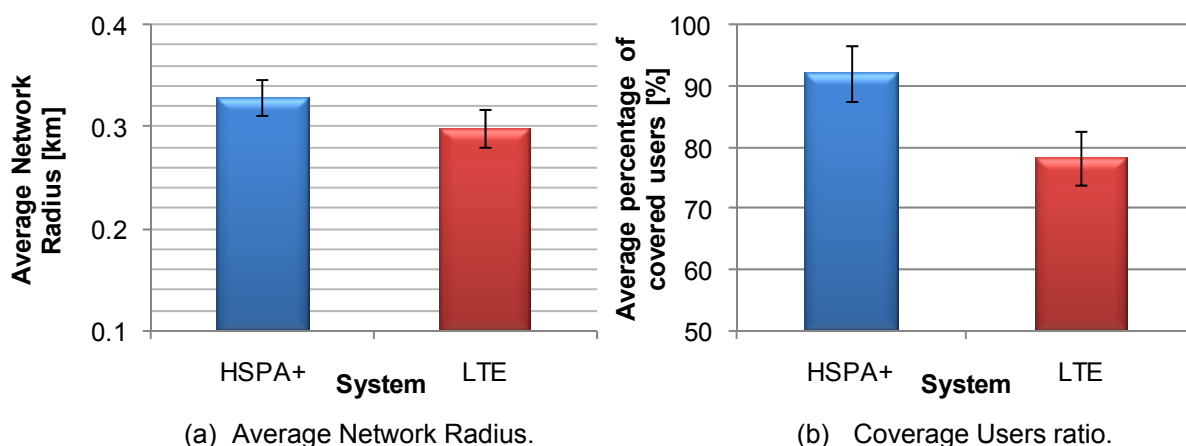


Figure 4.14. DL Average Network Radius and Average percentage of Covered Users with LTE 5 MHz.

Figure 4.14 (b) illustrates the differences on the covered users ratio, a direct consequence of the increase of the radius, since more users will be incorporated into the BSs radius area, hence, a raise of 12% of covered users compared with the default scenario for LTE. Still, HSPA+ is able to cover more users due the minimal discrepancy but larger radius.

Despite the fact that HSPA+ covers more users, LTE is capable of serving more users than HSPA+, the differences being negligible. Additionally, there are no differences to point out due to the closest average ratios collected; however LTE served users decreases from the default scenario around 7.5%, indicating that with the bandwidth decrease, the capacity of the network also decreases. As expected, with the decrease of the channel bandwidth, less RBs are available; therefore, fewer users can be served. As shown in Figure 4.15 (b), those served users obtain on average an increase of 3.8% on the satisfaction grade, comparing between LTE with HSPA+. LTE users are served with throughputs nearer to the requested ones, facing HSPA+ with a lower average satisfaction grade obtained; however the ratio of delayed users' increases with the use of 5 MHz bandwidth as reflected on the average satisfaction grade decreasing 6% from the one achieved in the default scenario.

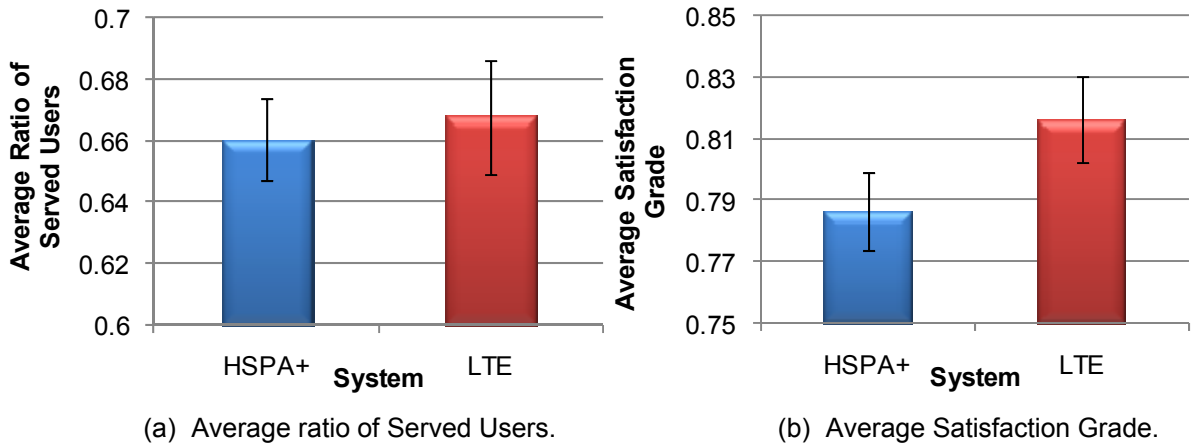


Figure 4.15. DL averages network ratio of Served Users and Satisfaction Grade with LTE 5 MHz.

The average network throughput, regarding all users and associated services performed, the results are shown in Figure 4.16. The identical performance between both systems is perceptible, except the higher standard deviation returned for LTE. The performance of both systems provides globally the expected trend with the usage of identical bandwidth, in comparisons carry out on the most literature, e.g., [Qual09a]. Moreover, as shown in Table 2.5, LTE maximum throughputs over the physical layer with 5 MHz bandwidth are quite similar to the ones achieved by HSPA+ and described along Section 2.2, both systems being different on the overhead charge, higher around 6% for HSPA+, [SSOA07].

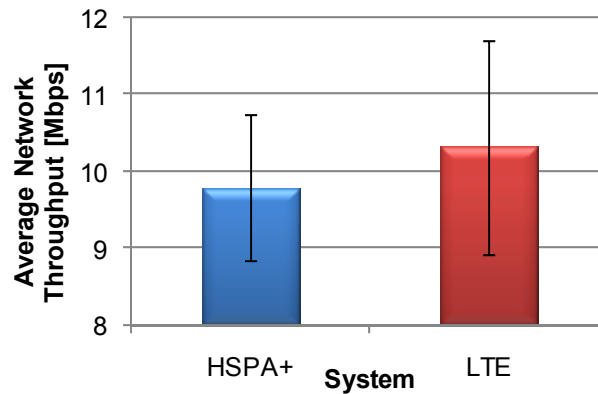


Figure 4.16. DL Average Network Throughput with LTE 5 MHz.

At the same time, as the channel bandwidth increases, the number of RBs increases as well as shown in Table 2.4, and overhead signal load drops, giving an increase of efficiency when greater the channel bandwidth is; however the overhead was set independently of the bandwidth chosen. Even so, overheads along a scalable channel bandwidth are also varying between the selected transmit spectrum, [Qual09c]. In addition, [Qual09c], projections present with the usage of same channel bandwidth, leads to similar spectral efficiency when also applicable same number of antennas.

4.3.3 Frequency Band

The frequency band is obviously a crucial factor for a radio communications system planning stage. Besides the UMTS spectrum band being licence since the later 90s, LTE expectations are still open on which band or bands it will operate, simultaneously or not. Despite the economical background,

LTE is foreseen for the frequency bands in Table 4.3, depending in country spectrum availability. This subsection evaluates the influence of the frequency band chosen regarding several other system parameters in LTE and compares it against 2.1 GHz HSPA+ deployed frequency. Subsequently, in Figure 4.17 one shows the average network throughput and the coverage users' ratio over the 900, 1800, 2100 MHz on both system and 2600 MHz.

LTE average network throughput for 1.8 and 2.1 GHz is quite similar, since the gap between the two is not enough to reproduce higher differences on the metrics analysed. When the frequency band raises to 2600 MHz the average network radius decreases as expected, mostly due to the propagation model and fading margins. The not so distinct results over the proximity 1.8 and 2.1 GHz bands are also supported by equal penetration margins established over Table 4.1.

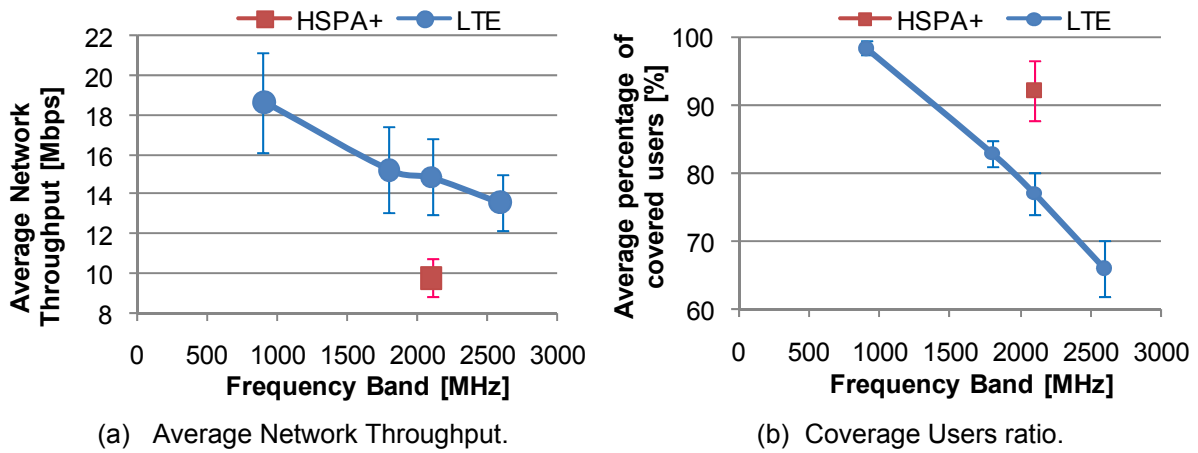


Figure 4.17. DL Averages Network Throughput and percentage of Covered Users for different frequencies.

At the 2.6 GHz the same throughput as the default scenario is achieved, otherwise for 900 MHz, the difference is notorious (18.68 Mbps is the average network throughput), 20% higher than the average results for 2.1 GHz and 27% for 2.6 GHz. Once again the frequency discrepancy has a major influence on the path loss calculation, reflecting a global trend on the results taken in this subsection, i.e., the superiority of lower bands on what concerns coverage and capacity, consequently the higher coverage ability of 900 MHz, increases the number of users covered, hence, the number of served ones as well. Particularly, with such a coverage area increase shown in Figure 4.17 (b), where 98.4% of the users are covered at 900 MHz, against 82%, 77% and 66% at 1800, 2100 and 2600 MHz respectively, more users will be served with 900 MHz, hence expected averages throughput will increase, as confirmed previously. The uncovered area increases with the frequency band raise and consequently decreases the covered ones.

The reduction of the frequency band to the 900 MHz band leads to an increase of the average network radius, presented on Figure 4.18 (a). This increase is due to the propagation model used, COST231-W-I, with frequency dependence on free space path loss, multiple screen diffraction loss, rooftop-to-street diffraction and scatter losses, (C.3), (C.9) and (C.4) respectively. In addition, the indoor penetration margins established are distinct regarding the frequency band, leading to different results as different experienced signal attenuations. As a result, indoor users and vehicular ones, which

correspond to 90% of the total distribution considered on Section 4.1, have significant penetration margins, contrasting with the pedestrian users.

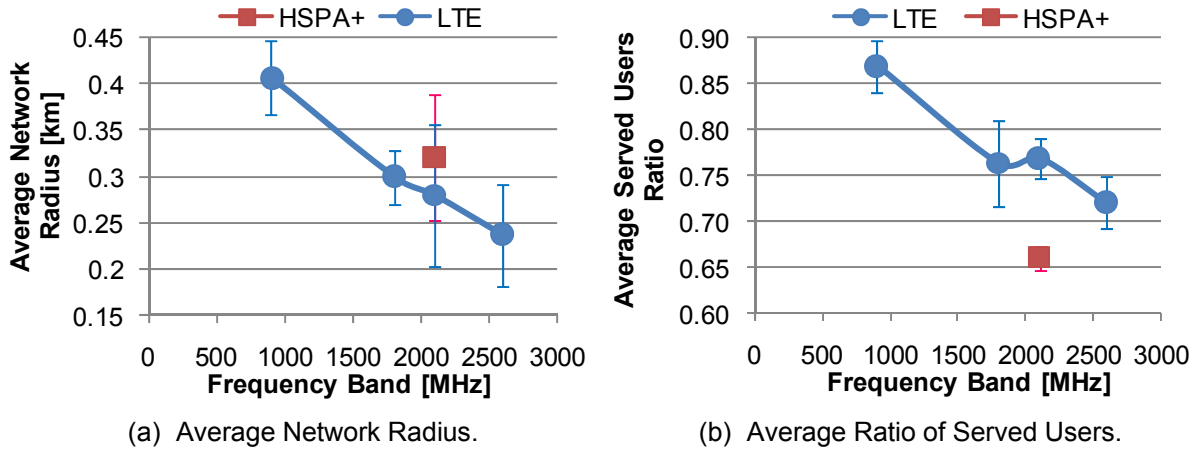


Figure 4.18. DL Averages Network Radius and Served Users ratio for different frequencies.

The 2.1 GHz operational DL frequency band defined in [3GPP07b] for HSPA+ reveals an average network throughput below 10 Mbps, since is the same result from the default scenario. The superior LTE capacity is visible among all frequency bands, as the comparison already done for the 2.6 GHz. Regarding coverage issues; HSPA+ presents greater coverage in the order of 15% comparing with the same frequency for LTE, which is supported by the higher average network radius delivered by UMTS BSs, Figure 4.18 (a) of 320 m. From the same figure, one can observe that in the 900 MHz band the radius has an increase of 32% over LTE 2100 MHz and respectively 19% for HSPA+. Comparing with related data gathered in [HoTo07], the same behaviour is observed in the results, still with different simulation assumptions and environments' range. The difference between the most opposite frequencies, 900 and 2600 MHz is 114%.

As already expected, the served users' ratio decreases with the increase of frequency, hence the 900 MHz band covers more users, apart which serves relatively more than the other bands. Therefore, 2.6 GHz serves 19% less users than 900 MHz, whereas 1800 MHz serves less than the adjacent band 2100 MHz, but besides the minimal difference, around 1%, the standard deviation is greater for 1800 MHz. Also register that, the served users' difference is about 11% comparing 900 MHz with LTE 2100 MHz, and 24% with HSPA+, unveiling the superior capacity of LTE, also over the same spectrum of UMTS with 14% more served users.

Given the re-farming possibility of the GSM spectrum jointly with LTE, especially as seen with 900 MHz band, the metrics involved in this analysis present improvements over other frequency options, and as well for HSPA+. One should, bear in mind that using a lower frequency and maintaining the same number of BSs in the network, makes larger radius possible, hence, larger cells, bringing the possibility of existing some cell overlap between them. Accordingly, the signal will be improved as seen before, but the user's interference will also rise in this case, respectively. However, due the use of a maximum interference limit, i.e., interference margin, the associated effects are limited by this implementation and do not reflect on the results presented.

4.3.4 Alternative Service Profiles

Alternative service profiles were created to evaluate the results from the default profile, Figure 4.1. Different penetration percentages were considered among a Recreational Profile (RP), Figure 4.19 (b), aim at a youth or leisure usage profile and a Professional Profile (PP), as a business or enterprise utilisation, Figure 4.19 (a).

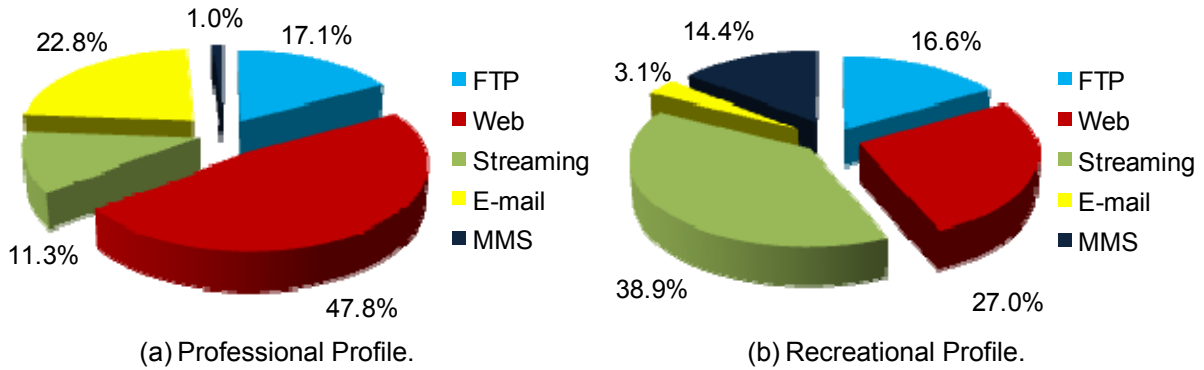


Figure 4.19. Alternative Service Profiles.

There is a substantial increase of Web services on PP, while in the RP, MMS and Streaming penetration percentages rise due to the behaviour of such entertainment services. Streaming does not involve as normally the dependence of Web, i.e., normally a streaming content is Web access available, but the profile intends to be streaming services only, like mobile TV, video streaming or audio streaming. Also it is important to emphasise that the service time sessions are invariant regardless of the profile chosen.

HSPA+, over the Default Profile (DP), delays more users on the most demanding services than LTE, with the offered traffic of most challenging services lower than the LTE one.

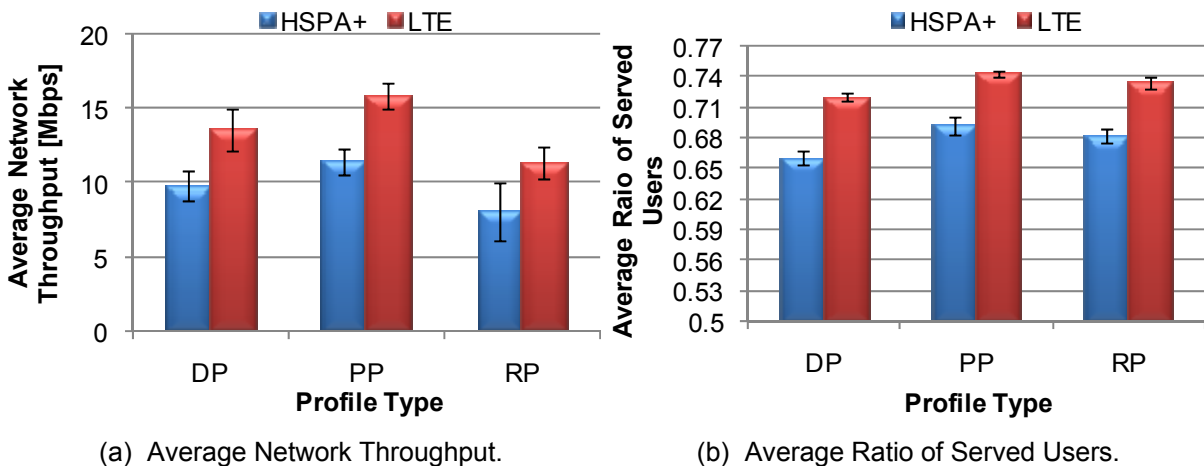


Figure 4.20. DL alternative profiles averages Network Throughput and Served Users ratio.

The same DP tendency is found on both PP and RP. LTE has higher averages network throughput than HSPA+, regardless of the profile considered, in the order of 38%. PP has a considerable penetration of Web, and since, Web is one of the most demanding services with highest requested throughputs, average network throughputs for this profile type are higher compared with the other profiles. RP in

relative terms considers more users performing streaming, being slightly less demanding than Web. Since that the global average network throughput is lower compared with PP, and the DP highly FTP requested. Even so, Email is also demanding from the network viewpoint when matched up with MMS.

In average ratio of served users, LTE can serve more users than HSPA+, and different service profiles or penetration percentages do not change this trend. Perceive the higher ratio of served users in PP, fact supported by being Web the service with highest QoS priority, and correspondent PP Web suffrage is almost 50%. RP, can lead to more users compared to DP, 3% more for HSPA+ and an increase of around 2% with LTE. This profile delays fewer users than DP, since the higher FTP penetration on DP associated to higher requested throughputs deals with more reductions in relative terms than RP. RP in fact has a less demanding profile than DP, with fewer users using FTP and Web, the most demanding services offered. Still, the discrepancy obtained between the three profiles is negligible (in the order of 10^{-2}).

The total network traffic consumed in an hour and the associated number of users is illustrated in Figure 4.21. As expected, LTE can serve more users than HSPA+, since over a snapshot frame, LTE is able to serve more users, therefore, when extrapolated to an hour analysis, more users can be served for the respective profile considered. Observe that the number of users per hour decrease on both systems when PP is considered, 13% in HSPA+ and 10% in LTE, respectively, compared with DP. Take into account the Web service into PP, and based on the traffic model used presented on Table 4.6, is characterised by an average time of page reading in the browser, i.e., idle times conceded by the user since Web is not always requesting data from the network. To visualize a Web traffic session please confer detailed in Figure J.1 with packets arrival and user session timings. Despite the fact of PP serves more users instantaneously, if the time period increases, the same conclusion is not valid due to the reading times of Web. RP shows a high number of users per hour, due the less demanding services, being the profile who secondly serves them the most, slightly less users than PP, but with higher standard deviation.

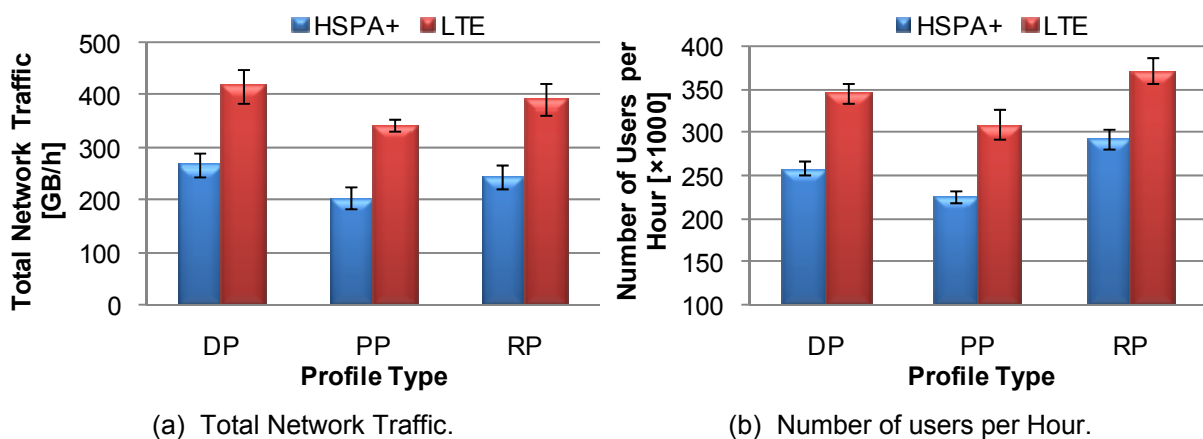


Figure 4.21. DL busy hour metrics.

The total network traffic provided for each profile in an hour is dependent on the previous analysis taken, leading to lowest traffic for PP whereas DP reveals a superior traffic compared with the others explained by a higher users' penetration of greatest demanding services. Still, the differences between

DP and RP are not accentuate, LTE RP users perform less 26 GB/h than those in DP while in HSPA+ the difference is 23 GB, explained by the large files transferred in the DP contrasting with the lower file volume of RP.

4.3.5 Adaptive Modulation

With the purpose of a fair comparison and based on the models available for 16 QAM and for 64 QAM, these are analysed on DL in spite of the QPSK, with the same assumptions of the default scenario, namely different frequency bands. Nonetheless it is presented in Figure 4.23 the average network throughput plus the average satisfaction grade for the two modulations taken into comparison, being well patented the higher throughputs of LTE and the best performance delivered by 16 QAM. These reflect the average number served users for each modulation, i.e., more users leading to higher averages throughputs. The inner differences for LTE are approximately 33% less throughput on 64 QAM comparing with 16 QAM with a variation between around 2.5 Mbps, while HSPA+ the difference is pointed to 40% with less 2.09 Mbps for 64 QAM.

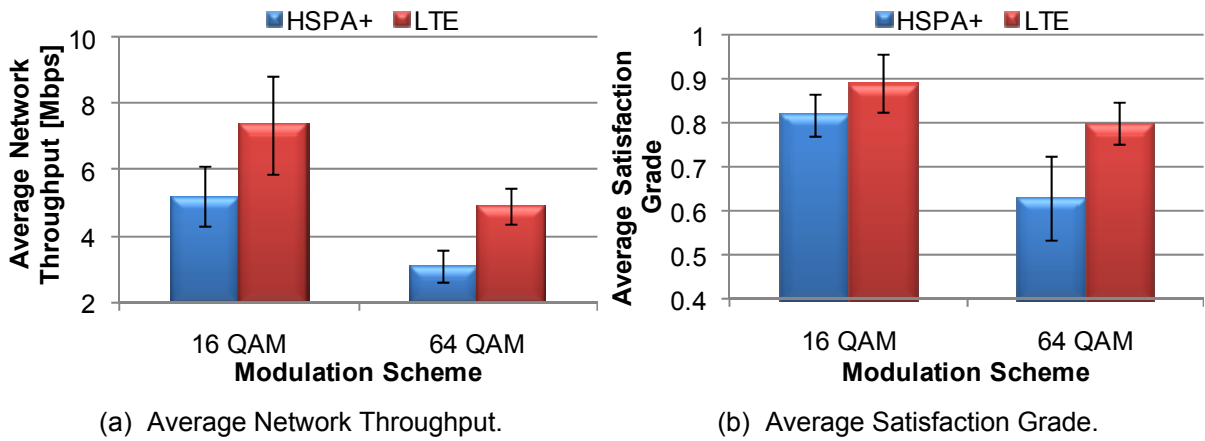


Figure 4.22. DL modulation scheme allocation.

16 QAM scheme is able to serve more users per BS compared to 64 QAM, justified by the fact that the former has a larger range of SINR with a higher or equal performance to 64 QAM which shows up for higher SINR values, returning also greater instantaneous throughputs carrying more symbols per bit compared with other modulations. Given the challenging conditions to transmit over a less robust scheme, a reduced amount of users are served. Remember that a small bunch of users are also served with QPSK, but then again, those results were not taken into account for this analysis, for the reasons pointed out earlier, and due to the small percentage of served users, with that modulation due to the high demanding service throughputs are not feasible to be served with QPSK. The more robust modulation requires lower SINRs, leading to greater cell radius, therefore, the expected trade-off of lower instantaneous throughputs per user is observed.

For extreme lower SINR values, users are served with QPSK, while for a great range of SINR values users make the best use of 16 QAM associated also to longer distances to the BS, while 64 QAM being a less robust modulation, allocates users with better SINR, closest to the BS, with higher instantaneous throughput per user.

4.4 UL Multiple Users Scenarios Comparison

A comparison of UMTS/HSPA+ and LTE is performed in this section with the purpose of analysing UL enhancements, as done on the prior section for DL. First the default scenario is shown and then different network parameters' variations are considered.

Additionally, all results are analysed in order to focus on coverage and capacity issues, with the associated needed references to DL results. Since the same network parameters were studied for UL as for DL, globally the same arguments remain valid for UL as well.

4.4.1 Default Scenario

As in Section 4.3.1, the Default Scenario is based on the same DL assumptions exposed along the Section 4.1, with the purpose of evaluating the impact of using one system or another.

Despite the differences in DL, UL default parameters taken are shown in Table 4.3, Table 4.4 and Table 4.5. The reference throughput reflects the performance limitation of HSUPA, i.e., 5.7 Mbps was taken as reference, and the asymmetry is observed from the respective DL reference, frequently common in the Internet services available today, despite being wireless or wireline. The radius and coverage area achieved are reduced compared to DL. Figure 4.23 (a) shows that both systems sector radii are reduced around 58.5% and 50% for HSPA+ and LTE on DL, respectively.

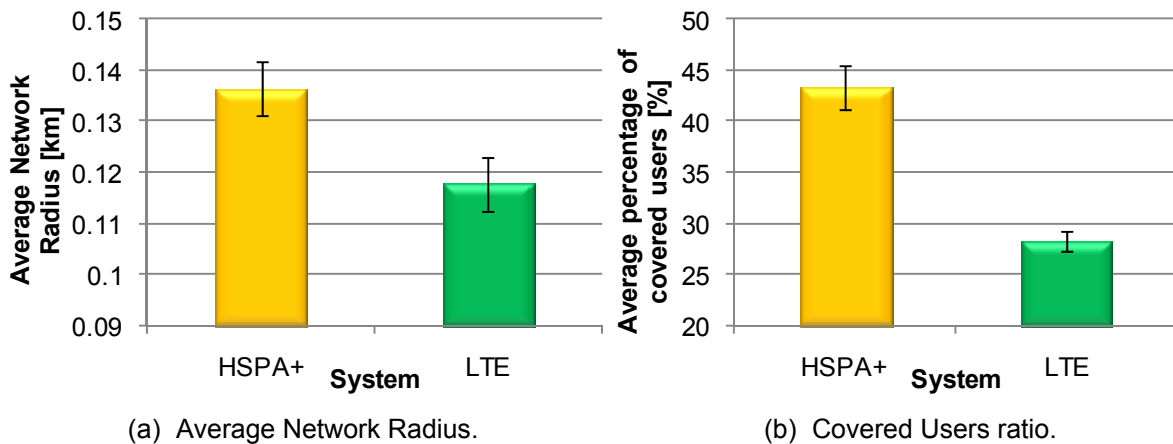


Figure 4.23. UL Average Network Radius and Average percentage of Covered Users.

The reduced coverage area is contrasting with the DL achieved area, closely related with the covered users' ratio, Figure 4.23 (b), since the coverage area decreases with the decrease of the BSs radius. These differences come mainly from MT limitations, namely noise figure (lower on MTs), and power issues. HSPA+ leads to a larger area, so a greater number of users will be within the BSs' range, while in LTE the number of covered users decreases approximately 16%, being covered by LTE 28% of the total number of users spread on the Lisbon metropolitan area. Since BSs' are co-located, within different time frames, the different coverage areas are explained by the different SINR requirements for a certain throughput.

With a fixed interference margin and MT transmitting power, interference effects are limited, related to

the number of users. Typically, when more users are connected, the global interference increases, thus, more power is needed to transmit. Given the dependence of users with network load factors, summing all users' contributions by means of link load factors, and the associated complexity, these factors are invariable throughout the simulations performed and limit the randomness of the metrics.

In Figure 4.24 (a), one can see that LTE, as observed in DL, can serve more users than HSPA+. The increase of served users for LTE is around 17% comparing with HSPA+, given the larger capacity of the former. Remember that users whose are not served have been delayed, even if they are inside the BS coverage area. The satisfaction grade shown in Figure 4.24 (b) is larger in LTE, since those users have average throughputs closer of the requested ones, contrary to HSPA+, where users are more reduced, globally getting lower average throughputs. Hence, in UL there are some constrains to deliver the requested user performance, i.e., the attendance of high throughputs, as it can be seen in Figure 4.25. Therefore, LTE acquire a satisfaction grade of 0.84, approximately 11% higher than HSPA+.

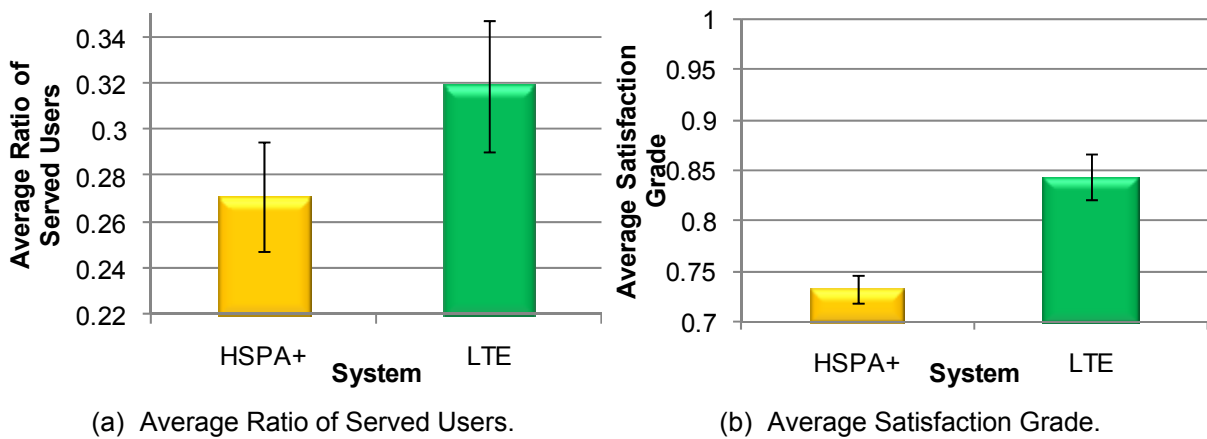


Figure 4.24. UL Network average Ratio of Served users and average Satisfaction Grade.

A service analysis focused on average network throughput is presented on the Figure 4.25. Following the trend that has been shown, LTE has a better performance in terms of data rate along compared to HSPA+. Similar performance between systems is only achieved in the less demanding service and with lowest penetration, MMS. The lowest requested throughputs allow the respective users to be served with throughputs near the maximum set.

Same behaviour does not happen for the other offered services. Web and FTP are the most demanding services, due the highest reference throughputs associated, leading to a larger standard deviation contrasting with the others. In addition, FTP average throughputs are 46% less than Web in HSPA+, while in LTE the reduction is approximately 33%. On the other hand, Email was set to a maximum achievable throughput of 3.5 Mbps, unlike DL, pointing to a less challenging scenario, where the achievable throughputs are larger than Streaming.

MT power limitations are associated to a lack of resources to cope with fading margins towards a higher path loss, and causing a global reduction in users' satisfaction grade. The estimation of users' satisfaction grade is shown in Figure 4.26, and the explanations given in Section 4.3.1 for DL remain valid.

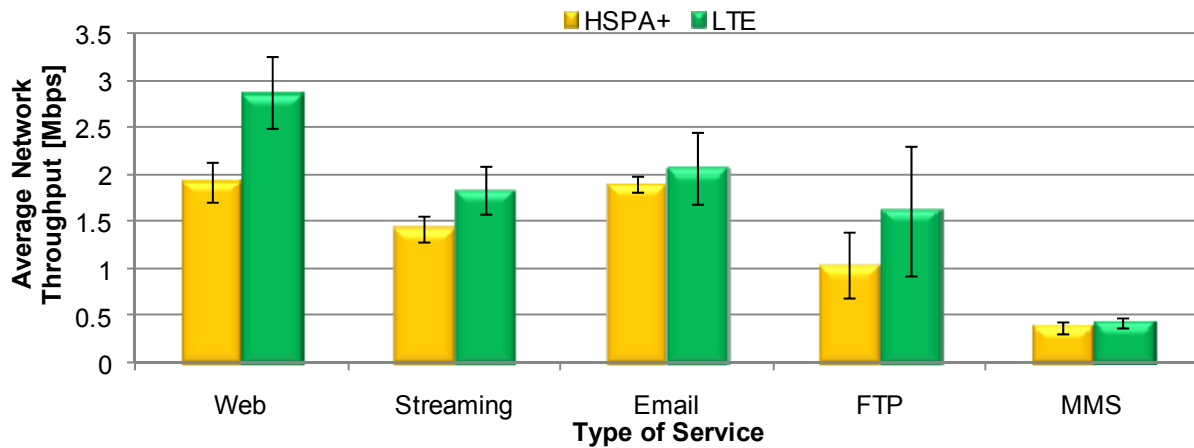


Figure 4.25. UL Average Network Throughputs per service.

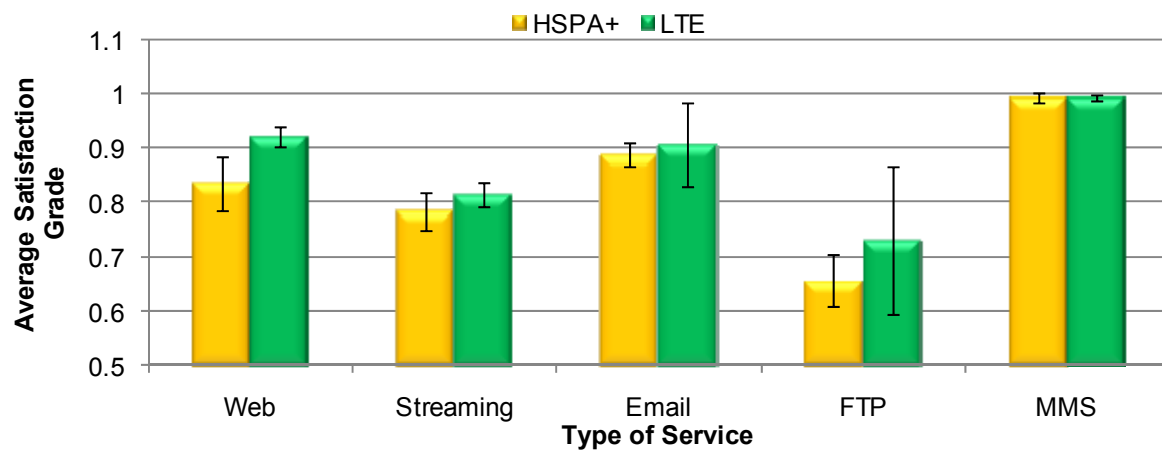


Figure 4.26. UL Average Satisfaction Grade per service.

Note also that none of the systems has averages satisfaction grades above 0.9, exception made for the less demanding service, MMS, contrasting with all the others. The differences between systems are no higher than 11% with the exception of FTP. Email and MMS have a similar grade performance, being in Email just a 2% of increase from HSPA+ to LTE. However the overall satisfaction is higher than in DL for HSPA+ and LTE, taking into account, that only served users are included in this ratio. Bear in mind that a higher number of users are delayed compared to DL, since, SINRs are more demanding for lower requested throughputs.

The busy hour analysis is present in Figure 4.27 for the same metrics as DL. Besides LTE covering a lower number of users, it serves more users than HSPA+, and with higher throughputs. LTE is able to serve around 51 000 users against 35 000 for HSPA+. Keep in mind that none of the simulations was performed with both active systems, so there is no chance of sharing resources between HSPA+ and LTE.

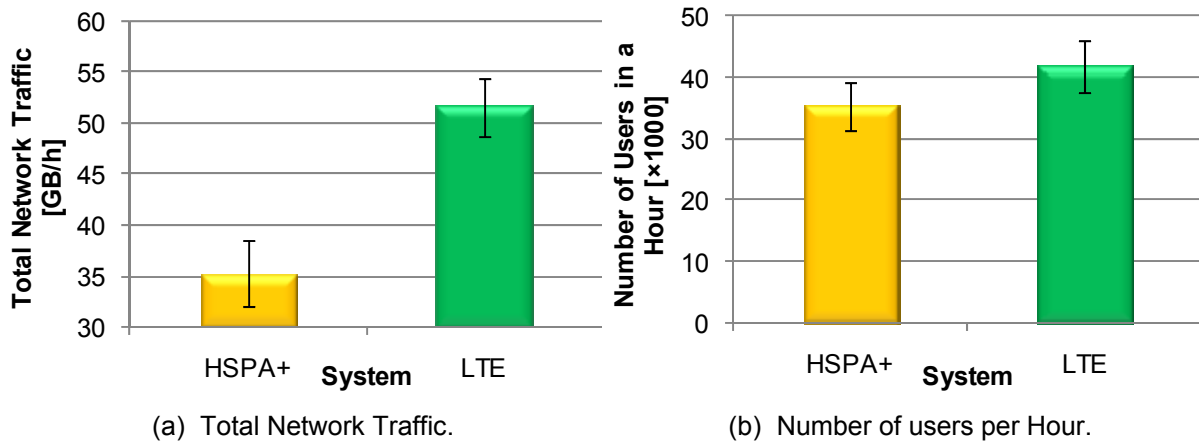


Figure 4.27. UL busy hour metrics.

Regardless of the QoS strategy applied and the radio requirements to perform a certain service, the default service profile, can be modified according to the network and link conditions, as well as with the number of users. One can notice that HSPA+ has larger differences compared with Figure 4.1 than LTE, FTP being the service which reveals higher discrepancy due to the lower QoS priority; on the other hand, MMS has a percentage increase on both systems.

Table 4.8. UL Served traffic specified for each service.

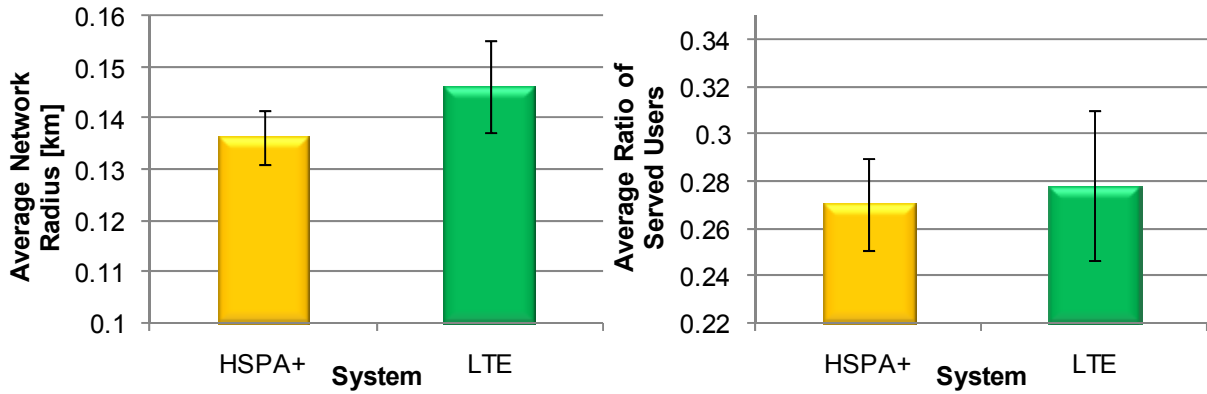
System / Service	Web	Streaming	Email	FTP	MMS
HSPA+ [%]	27	17.6	18.8	25.7	10.9
LTE [%]	30.9	20.2	12.1	28.2	8.6

4.4.2 Bandwidth

As in DL, the same conditions were simulated in UL, regarding the channel bandwidth usage. Figure 2.9 shows how RBs are distributed along the transmission bandwidth for LTE. Unlike UMTS, LTE performance changes with the possibility of adjusting the channel bandwidth, regarding planning purposes and the spectrum available for each operator.

In Figure 4.28 (a), LTE radius increases with the decrease of the bandwidth for 5 MHz, resulting in link budget improvements from less noise resultant for the less applied RBs, hence, higher BS's radius. Also note that multi-carrier systems like LTE improve over noise power compared with SC ones, given CP considerations on channel bandwidth. Over the same bandwidth, LTE defines cell edges 10 m farther than the ones from HSPA+, leading to a slightly increase of 7%.

Still, this minimal difference does not produce major changes in the ratio of covered users, being practically identical on both systems, such as the served users presented in Figure 4.28 (b). With the use of a lower bandwidth system resources are also fewer, compared to the ones available at higher bandwidths, so that LTE ratio of served users decreases 17% from the default scenario considering the same number of users.

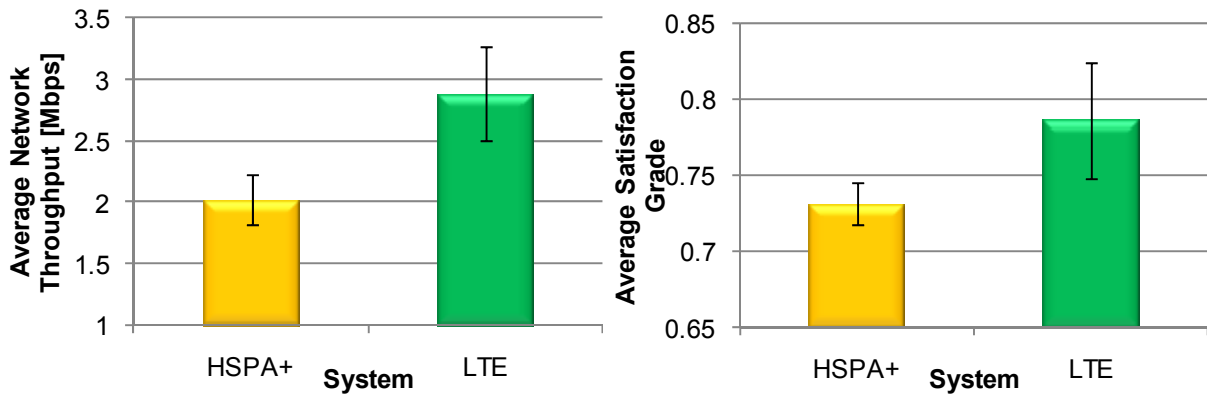


(a) Average Network Radius.

(b) Average ratio of Served Users.

Figure 4.28. UL Averages Network Radius and ratio of Served Users with LTE 5 MHz.

Concerning network throughput, Figure 4.29 (a) shows the average network throughput for both systems, where LTE confirms the tendency of better performance than HSPA+, even if the average throughput obtained is lower than the one with a 10 MHz channel bandwidth, almost 1.2 Mbps, with a difference between of 0.8 Mbps on average, with an increase of 44% for LTE. Globally, LTE's standard deviation is higher to the one achieved for HSPA+. One possible reason for this difference is the used models and the intrinsic interpolation error, being higher for LTE. For several parameters, as modulation, radio channel, antenna configuration and within different technologies, the mean error associated to these models can be obviously unrelated, diverging in some conditions, resulting in some unexpected results. While in HSPA+ the worst relative mean error is around 5%, in LTE the same error increased up to 24.4%. Those differences can also be related to the technology maturity, regretting greater information for UMTS rather than LTE.



(a) Average Network Throughput.

(b) Average Satisfaction Grade.

Figure 4.29. UL Averages Network Throughput and Satisfaction Grade with LTE 5 MHz.

Users satisfaction grade is 8% higher for LTE, for the same reasons pointed out for DL, getting less reduced or delayed, receiving throughputs closer to the ones requested compared to HSPA+.

Overall, the UL metrics analysed do not experience a decrease of the order shown in Subsection 4.3.2 for DL, hence, UL models are relatively more optimistic than the ones applied in DL, bearing in mind that in both cases the differences are negligible, since the comparison is based on similar conditions.

4.4.3 Frequency Band

The frequency band produces a larger path loss impact, given the propagation model used, COST231-W-I. In addition, the same DL rationale is also applied to UL.

Regarding the technical concerns between the two systems, the same analysis performed in Subsection 4.3.3 for DL is taken. The main difference between DL and UL is the growth behaviour of the achieved results. Associated to the already shown differences between the links, UL has a lower performance as expected compared to DL. In Figure 4.30, one presents the averages network throughput and percentage of covered users, the differences being noticeable, with 7.8% more covered users for HSPA+ than LTE over 2.1 GHz, supported by a larger network radius. Even so, among the several LTE frequencies, 900 MHz is able to cover 25.5% and 17.6% more users than 2.1 GHz for LTE and HSPA+ respectively, where the difference between the 1.8 and 2.1 GHz is 3.5% less users for the higher frequency. Comparatively in UL, this distribution diverges faster than the one achieved in DL.

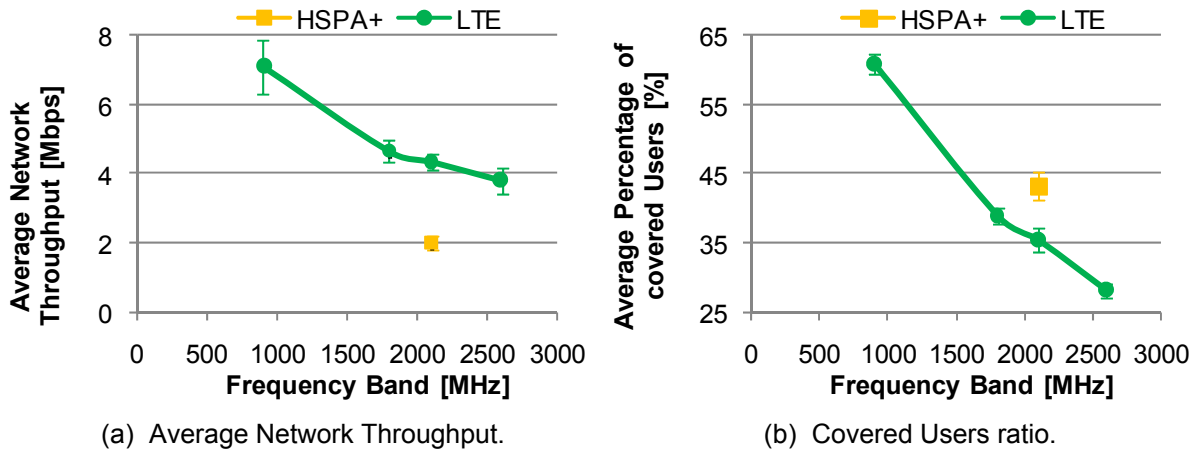


Figure 4.30. UL averages Network Throughput and percentage of Covered Users for different frequencies.

Concerning the average network throughputs, sole the increased performance of LTE at the same frequency of HSPA+, offering more than the double of the throughput, with 2.01 Mbps for the later and 4.34 Mbps for the former. It is also shown that with the decrease of frequency the average network throughput raises significantly, e.g., the difference between the two extreme frequencies analysed is 47%, with a highest average network throughput of 7.19 Mbps, Figure 4.30 (a). The lowest frequencies are able to cover more users; therefore, a greater ratio is also served contrasting with highest frequency bands, Figure 4.31. The 900 MHz has an average network throughput 138% higher than 2100 MHz, and 2600 MHz has 21% less. With the increase of the network radius and covered area at the 900 MHz band, there are users taking advantage of the network capacity, from the raise of the average network throughput delivered.

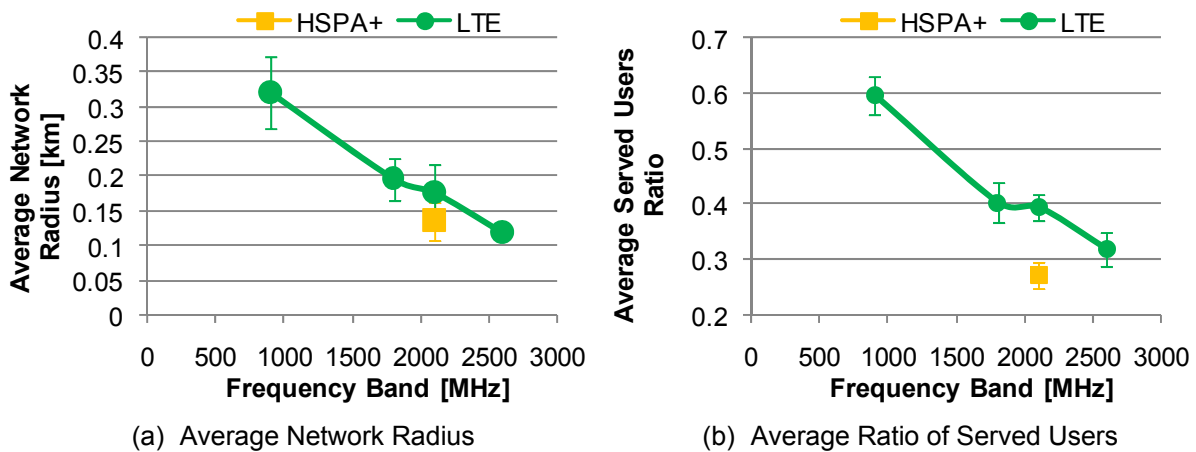


Figure 4.31. UL Averages Network Radius and Served Users ratio for different frequencies.

The uncovered area decreases at 900 MHz; therefore, there is an increase of approximately 173, 82, 64 and 134% of the average network radius, compared to 2.6 GHz, 2.1 GHz, 1.8 GHz and 2.1 GHz HSPA+ bands. The same behaviour is observed for the average served users' ratio, LTE being capable of serving more users given the higher associated capacity. One can say that, more covered users by LTE have SINR values above the threshold for the minimum throughput, compared to HSPA+. Note the identical served users' ratio ranging from 1.8 GHz and 2.1 GHz, characterised by a higher standard deviation at the former frequency band, as it is observed in DL. From HSPA+, the increase of served users is approximately 45% compared with 2.1 GHz LTE, distinguished from the 15% increase in DL.

Since the 2.6 GHz band is the most probably LTE deploying frequency, is also the slice of spectrum with greater coverage problems, the average network throughput is also the lowest, due to the less amount of users requesting services; however with the use of the 900 MHz, major coverage problems are overtaken, due to the considerable radius increase and minimized by the installation of some BSs in the "darker" zones for the higher frequency band.

4.4.4 Alternative Service Profiles

The new service profiles, PP and RP were introduced in Subsection 4.3.4. The study and the basis conduct is the same for UL, as well as the main conclusions. Remember from Figure 4.24 (b) that the covered users' relation is considerably lower in DP, but it affects also the other service profiles, because it has a horizontal impact in every service profile under analysis. The randomness of users' position combined with a low coverage area provides a higher standard deviation on the results.

The average network throughput is shown in Figure 4.32, as well the average ratio of served users. The global average throughput is below the one observed in DL, the difference between HSPA+ and LTE being greater in UL. HSPA+ has a mean decrease of 46% compared to LTE, PP being the one with the highest average throughput, due to the increase of Web penetration and associated requested throughput raise. In Figure 4.32 (b), it is visible that PP serves more users, due the fact that Web is the service with highest priority considered, serving more users than DP or RP. The difference

detected on RP and DP is minimal, explained by the larger FTP users delay in DP compared to RP, which at the same time serves more less demanding streaming users.

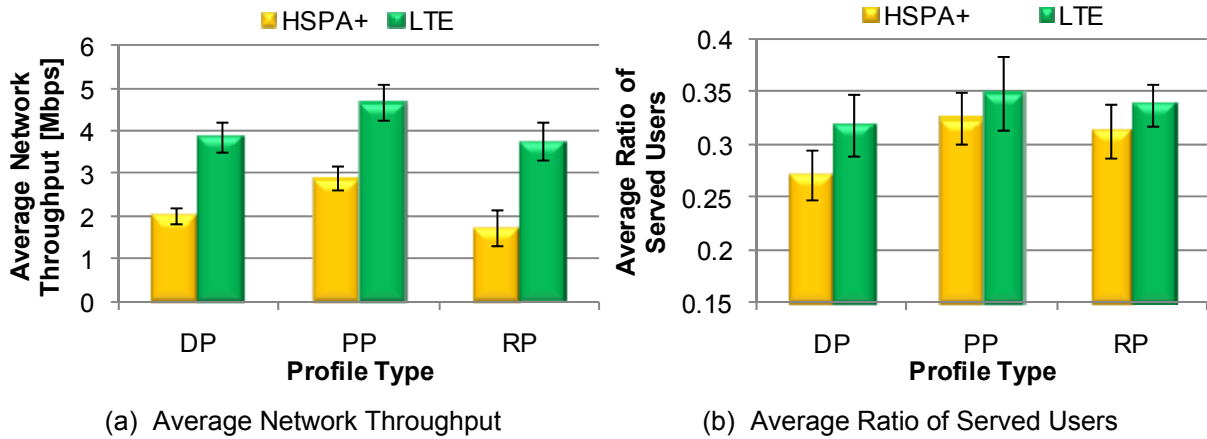


Figure 4.32. UL alternative profiles averages Network Throughput and Served Users ratio.

The total number of users per hour is shown in Figure 4.33 (b), and as expected from DL, LTE serves more users than HSPA+. Nevertheless, the different data profiles considered do not cause a strong impact on the busy hour, leading to lower differences in the number of users considered in an hour and also in the total traffic transferred in the network over the same time. The large differences are visible at PP, where a decrease is registered on the number of users for about 35% in LTE and 30% in HSPA+ compared with the highest values from RP. The same conclusions from DL are applicable for UL, since DP gives a larger traffic, due to the large data files transmitted, provided by a large combination of FTP and Web penetration among users. PP otherwise, typically characterised by Web users, suffers from the long session times from those users type, as represented in Figure J.1, reading times and idle times contributing to longer sessions by Web users.

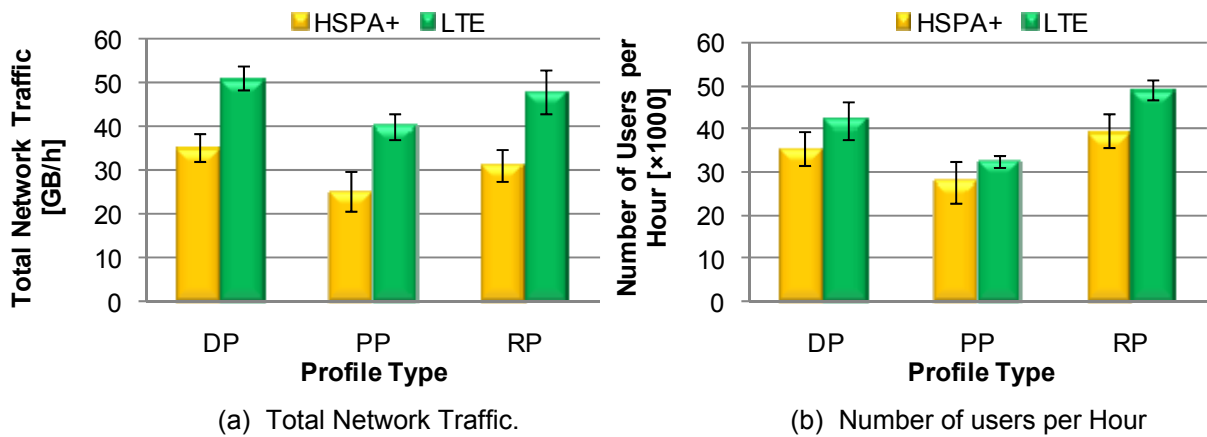


Figure 4.33. UL busy hour metrics.

4.4.5 Adaptive Modulation

While the most used UL modulations are QPSK and 16 QAM, 64 QAM is optionally deployed by 3GPP specifications for LTE, [3GPP08c]. Results were obtained for the most used modulations, accounting the fact that HSPA+ UL does not work in 64 QAM.

Figure 4.34 shows the average network throughput and average satisfaction grade, presenting a DL analogous behaviour. LTE returns better performance for 16 QAM compared with HSPA+. This modulation is able to serve more users, since more users are characterised by a larger range of possible SINRs. On the other hand, QPSK is only suitable for users near cell edges; Figure 2.5 (a), with non favourable conditions, i.e., low SINRs mainly resulting from long distances to the BSs. Figure 2.2 shows the separation between these two modulation schemes with adaptive modulation and a comparison to the spectral efficiency perfection enunciated by Shannon.

Given the differences shown in the average satisfaction grade, it results in a decrease of 12% using QPSK in LTE from HSPA+, and a increase of 3% for 16 QAM with a difference of 0.03; the majority of users are most satisfied with 16 QAM, regarding the high SINR range needed to perform a good connection closest to the requested service throughputs. With the use of QPSK, HSPA+ users have a larger satisfaction grade according to the number of served users of each system. The higher number of served users by HSPA+ with QPSK gives a slightly higher satisfaction for those instead of LTE users, which is caused by systems models differences, mainly SINR limits, where the adjacent modulation, 16 QAM, can serve users with a lower SINR compared to HSPA+ served by QPSK. QPSK, on the other hand, serves users not included in 16 QAM and 64 QAM for LTE, being labelled with worst signal conditions; therefore, the lowest averages network throughputs as presented.

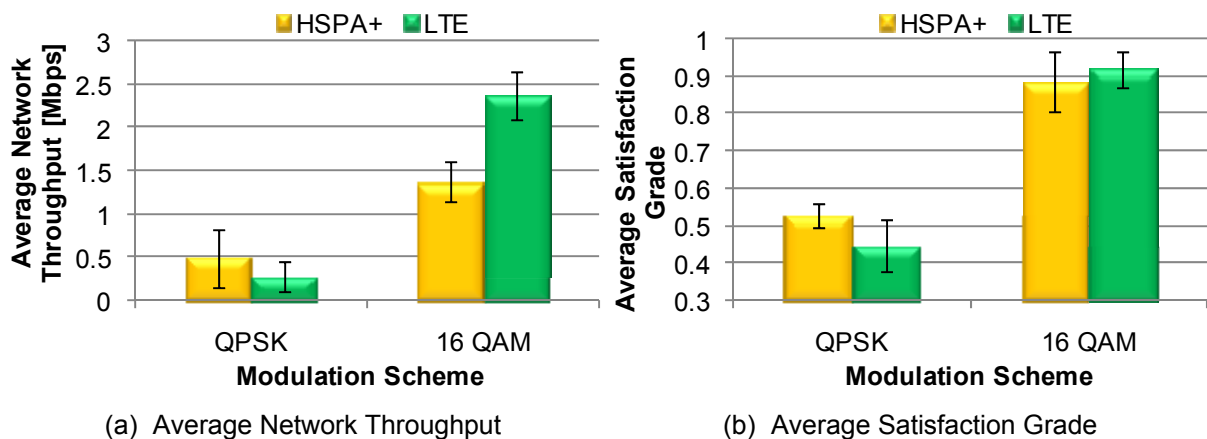


Figure 4.34. UL modulation scheme allocation.

Furthermore, the average network throughputs diverge according the system. While QPSK average network throughput for HSPA+ is dimly higher than in LTE, the difference between both in 16 QAM is approximately 2 Mbps. Large differences are already seen between modulations where 16 QAM provides throughput enhances of 1.8 and 7 times higher compared to the ones obtained with QPSK. The reduced users' quantity served by QPSK leads to low throughputs; however, technically QPSK is not able to exceed much more the presented values.

Globally UL served users' average throughputs are lower than in DL, associated with lower distances to the BS, being the maximum throughputs achieved, related to MT power limitations. From DL, with the use of 16 QAM, on average between both systems have a decrease in average network throughput of 70% and an increase of 5% in average satisfaction grade, explained by the fact that QPSK users are not taken into account on DL analysis.

Chapter 5

Conclusions

This chapter concludes the present dissertation, compiling a discussion and a critical analysis of the results, presenting future evolution possibilities of mobile communications, as well as mid-term future academic work proposals.

The main objective of this M.Sc. Thesis is to evaluate UMTS/HSPA+ and LTE performance, giving special emphasis to capacity and coverage aspects, within two major different scenarios, regarding the number of users. To accomplish this goal, a great amount of information was gathered, in order to develop and implement two models: the single and the multiple users. These models were developed based on literature results, as well as on some previously developed models. The COST231-Walfisch-Ikegami propagation model was used to calculate the cell radius or the distance to the connected BS, based on the associated path loss, being used over the complexity of other propagation models and presenting results with a good accuracy. Bear in mind the fact that both system models were developed and implemented separately, and network simulations were performed taken into account the non-inter-compatibility between technologies, therefore, RRM is not considered.

Only the latest UMTS release specified was taken into account, in order to contrast with a more recent system, LTE. Consequently, the comparison was done for UMTS/HSPA+ with MIMO antenna configurations and HOM schemes compared to 3GPP LTE specifications. The single user model was developed and implemented in the C++ programming language. Concerning different system parameters, as frequency band, bandwidth, MIMO configuration, modulation, fading margins, and others, the maximum cell radius is calculated for a user's requested throughput. Since there is only one user performing in a cell for all available resources, interference is not taken into account in this model.

The aim of the Multiple Users scenario is to assess the system performance with a further realistic approach over real networks, simulating a mixed and randomly users scenario displaced over the metropolitan Lisbon area, in a snapshot approach, requiring multiple services and analysing individually DL or UL performance. A default scenario was established, and evaluations were performed in a comparison perspective, on the sensitivity to variations compared with the default scenario.

The fundamental differences between the two models is that, while for the multiple users scenarios the resources available in each BS are shared among all users, the need to account for the users' interference emerges through the introduction of an interference margin, since a superior number of users are now connected in several cells. Additionally, for a more realistic consideration, statistical distributions describing fading phenomena, as Log-Normal and Rayleigh are considered for slow and fast fading respectively. With the user distance to the BS, the SINR is mapped onto the throughput. If the throughput given by the distance is lower than the minimum throughput of the requested service, the user is delayed. A BS analysis is performed to evaluate if the BS is capable of serving all users placed in its coverage area simultaneously. When the capacity is exceeded, one of the reduction strategies is applied in order to cope with QoS network requirements; normally the class reduction is taken. On the other hand, if the maximum capacity is not reached and the throughput given by distance is higher than the minimum one, lower than the maximum service throughput, and also lower than the requested one, the satisfaction grade is reduced.

Regarding Single User scenarios, for UMTS/HSPA+, the radio parameters considered in the analysis were antenna configuration, environment and modulation scheme, being constant BS and MT antenna

gains, transmission power and traffic power percentage remains constant. For all environments, it is observed that, both for DL and UL, the cell radius decreases with the increase of the application throughput, because higher throughputs require higher SNR values, which leads to a decrease of the path loss and a reduction of cell radius. The UL cell radius is considerable lower, especially in indoor environments, not being appropriate to cover the city of Lisbon with the same number of BSs, differing from DL results, leading to satisfactory radii.

Analysing antenna configurations, using fixed throughputs for DL at 15 Mbps in 64QAM, while in UL at 7 Mbps in 16 QAM, it is noticed that SIMO increases the cell radius making use of the diversity gain, resulting in an increase around 13% comparing to SISO for all environments. However, the higher radii are reached with MIMO, since the user is able to perform the established throughputs for a longer distance to the BS. It was obtained an increase of 45 and 49% in DL and UL, for a pedestrian environment compared to SISO. One can notice that, MIMO SNR requirements are below the ones need to perform with SISO. When one considers an indoor environment, for the same throughputs the maximum cell radius achieved was 98 m with MIMO. On the other hand, for DL with SISO at 2 Mbps (minimum throughput), the cell can go almost to 600 m, nevertheless, with the use of multi stream configurations the coverage is much similar regarding the modulation, observing an increase of 29% in cell radius distance, comparing to SISO.

Concerning the LTE Single User's Model, additional radio parameters have to be taken into account, due to the inherent differences between the two radio access schemes. Different frequency band, lead to a major 4 spectrum slices, and the scalable channel bandwidth. The simulations performed allow to conclude that the cell radius decreases with the increase of channel bandwidth, associated also to less robust modulation, thus, more data sub-carriers and sub-channels are allocated, and the noise level also increases; accordingly, throughputs achieved are also greater. Also, to perform higher throughputs, the SNR required also increases, leading to a lower radius in order to transmit higher throughputs. MIMO antenna configurations in addition, allow higher throughputs, and in theory, duplicate or quadruplicate the achieved SISO configuration throughput, according with number of antennas per configuration, assuming uncorrelated multipath channels with the application purpose of MIMO gains.

LTE system's capacity is only variable regarding the bandwidth and modulation scheme used. One should be present that the system's capacity not only involves the BS maximum capacity, but also the MT capacity in order to communicate with the BS on the same range of values. MT categories limit the maximum throughput, and are shown in Annex A; however this differentiation was not taken into account, considering that MT supports all available throughputs.

It is seen that with the increase of frequency the radius decreases. Setting a 5 MHz channel bandwidth, it is noticed that with the increase of the frequency the cell radius for the maximum possible throughput, i.e., 12 Mbps, decreases 61% and 72% for 2.1 and 2.6 GHz respectively, for a pedestrian user using 16 QAM and MIMO 2×2. With the use of 16 QAM, the maximum cell radius possible does not increase at all, due to the similar minimum possible throughput established on the model; however, with a less robust modulation, system capacity raises, leading to higher throughputs,

decreasing the radii achievement, hence 0.8, 0.32, 0.23 km for 900, 2100 and 2600 MHz were obtained. Cell radii are, as a consequence, lower which constitutes a trade-off between coverage and capacity to be analysed careful.

It should be emphasised the higher probability of a data user be within an indoor environment. Those cells have considerable lower radius compared to the other two environments for the same conditions, due the associated signal attenuation leading in some times to radii lower than 100 m.. With the use of 2600 MHz band, 20 MHz bandwidth, 64 QAM and MIMO 2×2, radii decrease 32% from pedestrian to vehicular and 58.5% for an indoor environment.

In relation to the Multiple Users model, the comparative performance study was done for both systems, initialising a default scenario reference. The RMG model, developed by [KuCo08], was applied to predict capacity improvements using MIMO over SISO. MIMO configuration, from a theoretical view point allows having, for same SNR, the double of throughput. However RMG model introduces a more realistic approach but the benefits of MIMO remain valid. Besides the 2.6 GHz is out of propagation model validation interval used, since the frequency is not much farther from the ones applied in [DaCo99], the same model was applied.

Concerning the default scenario, UMTS/HSPA+ covers a large number of users than LTE, caused by the higher radius of the former, the relative difference being 38%. The average network throughput for UMTS/HSPA+ is 9.78 Mbps and for LTE is 13.53 Mbps. LTE has an average ratio of served users 9% higher than UMTS/HSPA+ and the associated average users satisfaction grade is comparably higher as well. Since the trade-off of covered and served users is more advantageous for LTE, this system can serve 345 000 users in an hour, corresponding to more 87 000 users than the ones served by UMTS/HSPA+. The users served in LTE in an hour perform more 150 GB than the data transported by HSPA+, leading to an increase of 57%. The analysis performed for UL reveals that generically both systems radii suffers a minimum decrease of 50% compared to DL, and the associated percentage of covered users decreases around 30%, whereas no more than 32% are served. In general, one can say that LTE has a better performance serving more users, with superior satisfaction grade, along with served traffic being quite similar to the offered ones.

A set of simulations were realised to analyse the impact of using equal channel bandwidth, namely a 5 MHz bandwidth on LTE and compare it with the results taken for UMTS/HSPA+. Although, future HSPA+ release (9) will introduce dual-carrier bandwidth on UMTS, being able to enhance system capacity.

Average network throughput dependence with the decrease of channel bandwidth is seen, since the linear changes of the bandwidth modify the whole system capacity; for this reason a 10.4 Mbps average network throughput was obtained. In consequence, BSs' radii also increase with a lower bandwidth, enabling large coverage areas, leading to approximately 79% of users be within the cell, albeit, users served by LTE are very similar to the ones in UMTS/HSPA+, approximately 66%. Nevertheless, this ratio is below the one got for 10 MHz, due the decrease of channel capacity. Globally, using a 5 MHz bandwidth from the network viewpoint does not bring relative benefits to LTE, due the similar performance with negligible differences to UMTS/HSPA+ in almost all analyses

performed. One has observed that the usage of 20 MHz bandwidth does not bring relative advantageous, due the number of users placed not being enough to exceed system capacity, especially over the BSs located in the peripheral Lisbon districts, the ones with lowest network traffic.

The real advantage of scalable channel bandwidths to be compliant with the worldwide spectrum requirements; different channel bandwidths are also targeted to different coverage and capacity needs. For instance, an operator can apply narrower bandwidths for rural areas aiming at coverage, while in urban environments wider channel bandwidths are preferable for higher capacity at the cost of reduced coverage.

While UMTS radio access is deployed at the 2.1 GHz, new spectrum opportunities are being discussed for LTE implementation, mostly with differences in the region to operate regarding regulation aspects. However there is the possibility in the course of the years that the operating frequency can change due to economical reasons or even due the digital dividend, releasing the frequency once occupied by analogue TV signal. So, lower frequency (700 MHz band) can also be deployed for LTE, such as the refarming of GSM900, GSM1800 and the European already licensed on Sweden/Norway 2.6 GHz band.

A frequency scan in 900, 1800, 2100 and 2600 MHz was done, showing that lower frequency bands can lead to higher BS radii and cover relative for higher percentage of users. For instance, the increase of radii obtained from 2.6 GHz to 900 MHz is 60%, and the served users' difference is pointed to be more than 10%. The average throughput of those users rises to 18.6 Mbps with MIMO 2x2, 5 Mbps more than the highest frequency band. Generically, with a lowest frequency band coverage problems are overtaken, and with a higher relation of served/covered users. The majority of metrics display better results than the default LTE frequency simulated.

An adaptive system modulation was considerate despite fixing a single modulation scheme for whole network. Throughout the user's SINR it was calculated beyond the possible modulations which scheme delivers greatest throughput, being the one allocated to the user. It is possible to adapt the modulation according with the radio channel condition, and chose for each user the best spectral efficient option. Differences for LTE are approximately 33% less throughput on 64 QAM comparing with 16 QAM with a variation between around 2.5 Mbps, while for HSPA+ the difference is 40% with less 2.09 Mbps for 64 QAM. 16 QAM is able to serve more users per BS compared to 64 QAM, due to the fact that the former has a larger range of SINR with higher or equal performance than 64 QAM. For UL, QPSK and 16 QAM were considered, while UMTS/HSPA+ is not specified with the use of 64 QAM in UL. Differences show for the average satisfaction grades, nearly a decrease of 15% using QPSK in HSPA+ over LTE, and a increase of 3.5% for 16 QAM with a difference of 0.03 explained by the fact that the majority of users are most satisfied with 16 QAM in spite of QPSK.

LTE is flexible enough so that different QoS profiles can almost be set on a per application basis, as long as demonstrates superior user/content/service adjustment compared to UMTS. Traffic shaping policies should also be easier to apply, limiting the user's throughput regarding the type of subscription. The defined scenarios and profiles carry out only one service per user in a snapshot frame, so this optimisation is not observed. Additionally, two more service profiles were tested, the

greatest differences being between the two mainly emerging in DL, supported by the traffic asymmetry tendency. Globally, LTE performs at a higher average network throughput of 5 Mbps, while in an hour extrapolation LTE shows a transport of more than 100 GB compared to UMTS/HSPA+. In contrast, UL does not lead to great differences, explained by the MT constraints and connection limitations in terms of coverage and capacity, as long as deeper developments and enhancements over the terminal devices are not implement.

It is well known that LTE and UMTS/HSPA+ are upcoming wireless radio systems, far from being considered mature technologies. Currently upgrades from HSPA to HSPA+ are being carried out, while LTE brings in a near future a new complement to HSPA+, with optimised OFDMA solutions, maintaining backward compatibility. HSPA+ on the other hand, has simple features upgrade face the actual deployments of HSPA, comparing with the new LTE. Still, an evolution path is designed around both technologies, which will not compete in the long term, but will complement each other. The results from this work show a superior performance of the newest technology, however for some conditions the evaluation does not lead to the greater differences expected from theory.

A lack of information and uncertainty are patent on today's available knowledge, especially in LTE since will take long until is deployed worldwide. Even so, this thesis can be explored in academic fields, in order to analyse further enhancements. From that viewpoint, one proposes the study of further releases of UMTS/HSPA+, namely dual cell operation and inclusion of higher order MIMO configurations. On the other hand LTE, should be explored with MIMO 4×4 configuration, analysing at the BS level RRM, this way optimising user's connection despite the distance dependence.

Recent requirements of IMT-Advanced, point towards 3GPP LTE-Advanced, which should release a good starting point for a new era in mobile communications, hence, new horizons and investigation perspectives. Service and traffic issues, can be prospected, particularly in a statistical approach of which gadgets type provide certain types of traffic and vice-versa, namely laptops, smartphones, PDA, and another Mobile Internet Devices (MID).

Additionally, a new component impact can be studied, i.e., the use of femtocells on the current networks. Femtocells will be a breakthrough over coverage topics in the future networks, as it is design for a low range coverage providing enhanced capacity on complex radio planning areas. Coverage, capacity, and interference can be metrics to analyse within those implementations. On the other hand, hardware suppliers are deviating their product lines for an energy efficiency purpose, globally pursued nowadays. It should be interesting to study new BS alternative energy sources, like solar, and the impact of these with the new transmission and reception powers, especially in recent deployed networks.

Despite the common multiple radio access, OFDMA, in LTE and WiMAX (non-3GPP technology), interesting results are expected from low interference models, not only due the rivalry between both standards but also because they compete for common network purposes, hence, new networks deployed from scratch.

Annex A – HSPA & LTE Categories

Table A.1 presents the MT categories each for FDD HS-DSCH physical layer categories, meaning HSDPA and HSPA+ DL. Each category has its own characteristics like modulation, and maximum theoretical peak data rate which is the maximum number of HS-DSCH transport block bits received within a TTI. Still, performance indicators on the majority time are below the maximum values and are referenced by CQI. Table A.2 shows HSUPA and HSPA+ UL MT categories and Table A.4 the equivalent for DL and UL-SCH but then for LTE terminals.

Table A.1. FDD HS-DSCH physical layer terminal categories (adapted from [3GPP09a]).

MT Category	Maximum number of HS-DSCH codes received	Modulation	Supported Modulations with MIMO	Maximum N_b on a HS-DSCH TBS	Maximum theoretical peak data rate [Mbps]
1	5	QPSK & 16QAM	Not applicable (MIMO configurations not supported)	7298	1.22
2	5	QPSK & 16QAM			1.22
3	5	QPSK & 16QAM			1.82
4	5	QPSK & 16QAM			1.82
5	5	QPSK & 16QAM			3.65
6	5	QPSK & 16QAM			3.65
7	10	QPSK & 16QAM		14411	7.21
8	10	QPSK & 16QAM			7.21
9	15	QPSK & 16QAM		20251	10.20
10	15	QPSK & 16QAM		27952	14.40
11	5	QPSK only		3630	0.91
12	5	QPSK only			1.82
13	15	QPSK, 16QAM & 64QAM		35280	17.64
14	15			42192	21.10
15	15	QPSK & 16QAM	QPSK & 16QAM	23370	23.37
16	15	QPSK & 16QAM		27952	27.95
17	15	QPSK, 16QAM & 64QAM		35280	23.37
18	15			42192	27.95
19	15		QPSK, 16QAM & 64QAM	35280	35.28
20	15			42192	42.20
21	15	-	(Reserved for dual cell operation)	23370	23.37
22	15	-		27952	27.95
23	15	-		35280	35.28
24	15	-		42192	42.20

The common categories that 3GPP standardised for HSDPA goes up to the 12th, the following ones were frozen from Release 7 and 8 accomplishing the associated requirements, with the introduction of MIMO systems and in some cases dual cell operation (21st to 24th MT categories).

Table A.2. HSUPA and HSPA+ UL terminal capability categories (adapted from [3GPP09a]).

MT Category	Maximum number of E-DCH codes transmitted	TTI length [ms]	Supported Modulation	Minimum SF	Maximum N_b on an E-DCH TBS	Maximum theoretical peak data rate [Mbps]
1	1	10	QPSK	SF ₄	7110	0.711
2	2	2, 10		2 x SF ₄	2798, 14484	1.448
3	2	10		2 x SF ₄	14484	1.448
4	2	2, 10		2 x SF ₂	20000, 5772	2.886
5	2	10		2 x SF ₂	20000	2.000
6	4	2, 10		2 x SF ₄ + 2 x SF ₂	20000, 11484	5.740
7	4	2, 10	QPSK & 16QAM	2 x SF ₄ + 2 x SF ₂	20000, 22996	11.500

As it can be noticed, the maximum theoretical peak data rate per link increases while the UE TTI decreases. Given that, the correspondent physical throughput available at the UE depends on the capacity of TBS in bits and by system TTI;

$$R_{b \max [\text{Mbps}]} = \frac{\max(N_b)}{\min(TTI_{[\text{ms}]})} \quad (\text{A.1})$$

In UL, due to the variable TTI within a single MT category, the resulting throughput is calculated for the maximum system performance case. Later, the creation of a 7th category, respects to the introduction of a higher order of modulation in the UL, meaning 16QAM, which belongs to the specifications of Release 7.

An average of beta factors over multipath channels for HSUPA is shown in Table A.3. For each FRC, power ratios are defined in order of DPCCH, however, these ratios are not taken into UL signalling and control reserved power.

Table A.3. Beta Factors defined for the FRC (extracted from [HoTo06]).

UMTS Beta Factors	E-DPDCH / DPCCH [dB]	E-DPCCH / DPCCH [dB]
FRC1	9	2.05
FRC2	10	4.08
FRC3	6	0
FRC4	9	- 1.94
FRC5	9	- 1.94
FRC6	10	- 5.46
FRC7	6 0	0

The radio bandwidth on Table A.4 refers to a maximum not to a nominal value, so all five MT categories can serve for all LTE bandwidths according to the specifications. Moreover, [Agil08] refers

that all LTE MTs will include diversity on the reception due a required specification.

Table A.4. LTE MT categories (extracted from [3GPP09b]).

MT Category	Highest-Order DL Modulation	Highest-Order UL Modulation	MIMO Configuration	Bandwidth [MHz]	Maximum theoretical DL peak data rate [Mbps]	Maximum theoretical UL peak data rate [Mbps]
1	64 QAM	16 QAM	Optional	Up to 20	10	5
2			2×2		51	25
3					102	51
4		150			51	
5		64 QAM	4×4		303	75

Annex B – Systems SINR and Data Rate Models

The present Annex, presents the HSPA+ and LTE models, which accurate the SINR and Throughput of each considered system for several system configurations. Remember that the trial executed measurements conditions for HSPA+ are different from the ones performed for LTE.

These models are referred to the throughput over the physical layer standardized on the OSI Reference Model, [Zimm80]. In addition, the models for the different branches of all functions do not take into consideration all the necessary throughput reductions, such as overheads load and BLER to obtain the throughput at a higher level/layer, or up into the Application level, see (3.1).

B.1 UMTS/HSPA+

For instance, HSPA+ theoretical throughput values are presented in Figure 2.3 and Figure 2.4 for a Pedestrian A channel, although in [Perg08] there are some experimental expressions to precise SINR, ρ_N , as a function of throughput, R_b , and throughput as a function of SINR for several types of antenna configurations and modulations, supported by Ericsson measurements. Note that all throughputs obtained are valid for the physical layer, and the extrapolations do not have relative mean errors, (3.23), greater than 5%, acceptable for this kind of approximations.

Nevertheless, the importance to extend the measurements among different radio channels connoted by different characteristics is significant. Estimations for a Vehicular A channel were not properly done due to the lack of simulations for HSPA+ with the necessary assumptions, however, the HSDPA curve of SINR as a function of physical throughput for a Vehicular A channel in [HoTo04] is extrapolated to HSPA+, shifting down the Pedestrian channel A curve in 1 dB.

Still, as mentioned in Section 3.1, the following models consider 15 HS-PDSCH codes contrary to the real 14 HS-PDSCH available for traffic, since there was no available data for the latter number of codes.

Considering a SISO configuration with 16 QAM, for DL, one has:

$$\rho_{IN[dB]} = \begin{cases} -0.0541 \times R_b^6 + 0.9496 \times R_b^5 - 6.7214 \times R_b^4 \\ + 24.6466 \times R_b^3 - 49.805 \times R_b^2 + 55.0299 \times R_b - \\ 31.1894, & 0.7 \leq R_{b[Mbps]} < 4.5 \\ -0.0319 \times R_b^2 + 1.7534 \times R_b - 6.9882, & 4.5 \leq R_{b[Mbps]} < 9.7 \\ 0.1529 \times R_b^3 - 5.1218 \times R_b^2 + 57.816 \times R_b - 211.471, & 9.7 \leq R_{b[Mbps]} \leq 14.4 \end{cases} \quad (B.1)$$

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

$$\rho_{IN[dB]} = \begin{cases} -0.0541 \times R_b^6 + 0.9496 \times R_b^5 - 6.7214 \times R_b^4 \\ + 24.6466 \times R_b^3 - 49.805 \times R_b^2 + 55.0299 \times R_b \\ - 31.1894, & 0.7 \leq R_{b[Mbps]} < 3.7 \\ 1.3691 \times R_b - 5.8516, & 3.7 \leq R_{b[Mbps]} < 8.7 \\ 0.9565 \times R_b - 2.3371, & 8.7 \leq R_{b[Mbps]} < 20 \\ 0.0396 \times R_b^2 + 0.0799 \times R_b + 1.9286, & 20 \leq R_{b[Mbps]} \leq 21.5 \end{cases} \quad (B.2)$$

In a 1x2 configuration with 16 QAM modulation, for DL, the SINR can be calculated by:

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

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

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

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

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

In a MIMO 2x2 configuration with 64 QAM, for DL, the SINR can be calculated by:

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

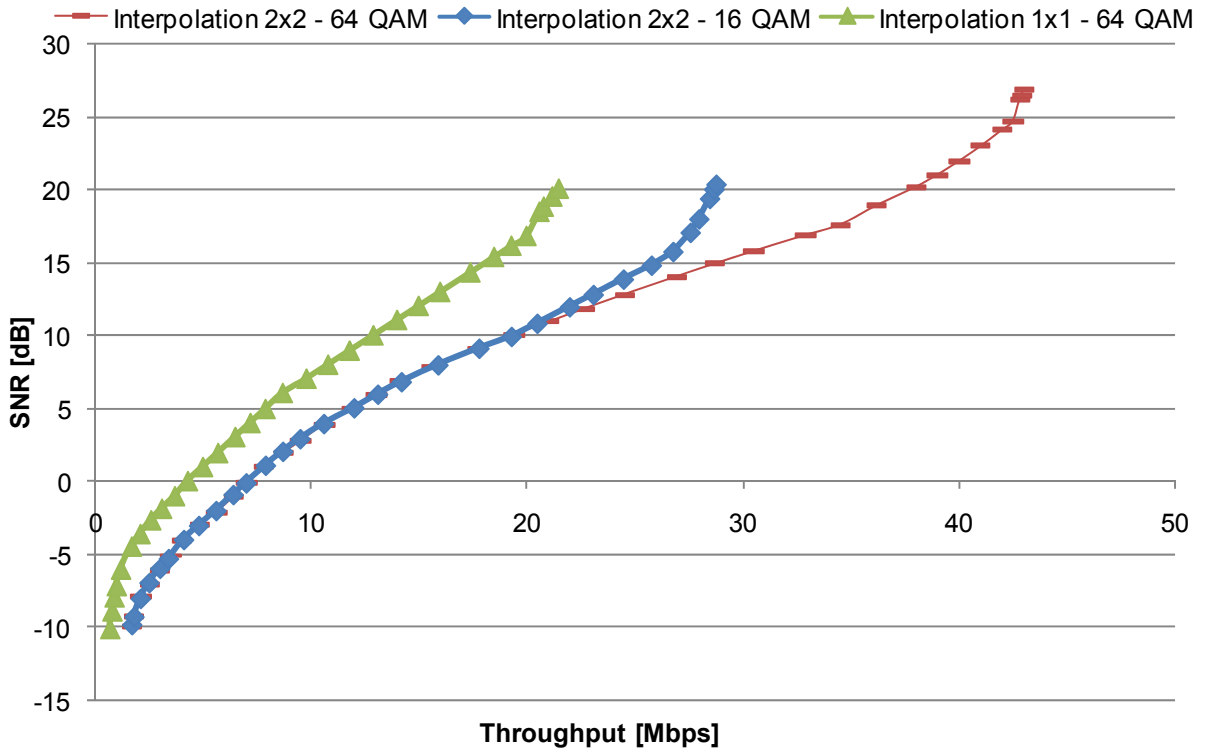


Figure B.1. HSPA+ DL with MIMO configurations – SNR as function of physical Throughput.

Calculations made for the UL direction are the following:

For QPSK, in UL direction, one has:

$$(E_c / N_0)_{\text{[dB]}} = \begin{cases} -3.33 \times R_b - 10.0, & 0 \leq R_{b[\text{Mbps}]} < 1.5 \\ -0.5998 \times R_b^2 + 5.0194 \times R_b - 11.1447, & 1.5 \leq R_{b[\text{Mbps}]} < 3.4 \\ -5.2083 \times R_b^3 + 62.5 \times R_b^2 - 244.7917 \times R_b + 313.5, & 3.4 \leq R_{b[\text{Mbps}]} < 4.2 \\ -4.3821 \times R_b^3 + 65.5602 \times R_b^2 - 321.7734 \times R_b + 521.6365, & 4.2 \leq R_{b[\text{Mbps}]} < 5.5 \end{cases} \quad (\text{B.7})$$

Considering 16 QAM for UL, the respective interpolation given by (B.8) is shown at the Figure B.2.

$$(E_c / N_0)_{\text{[dB]}} = \begin{cases} -1.5432 \times R_b^3 + 6.9444 \times R_b^2 - 6.9444 \times R_b - 3, & 1.8 \leq R_{b[\text{Mbps}]} < 3 \\ 0.6818 \times R_b^2 - 4.6136 \times R_b + 8.7955, & 3 \leq R_{b[\text{Mbps}]} < 4.6 \\ 0.1307 \times R_b^4 - 3.041 \times R_b^3 + 26.0522 \times R_b^2 \\ -95.8265 \times R_b + 129.0191, & 4.6 \leq R_{b[\text{Mbps}]} < 7.7 \\ 0.1386 \times R_b^3 - 3.5025 \times R_b^2 + 30.979 \times R_b \\ -87.2192, & 7.7 \leq R_{b[\text{Mbps}]} \leq 11 \end{cases} \quad (\text{B.8})$$

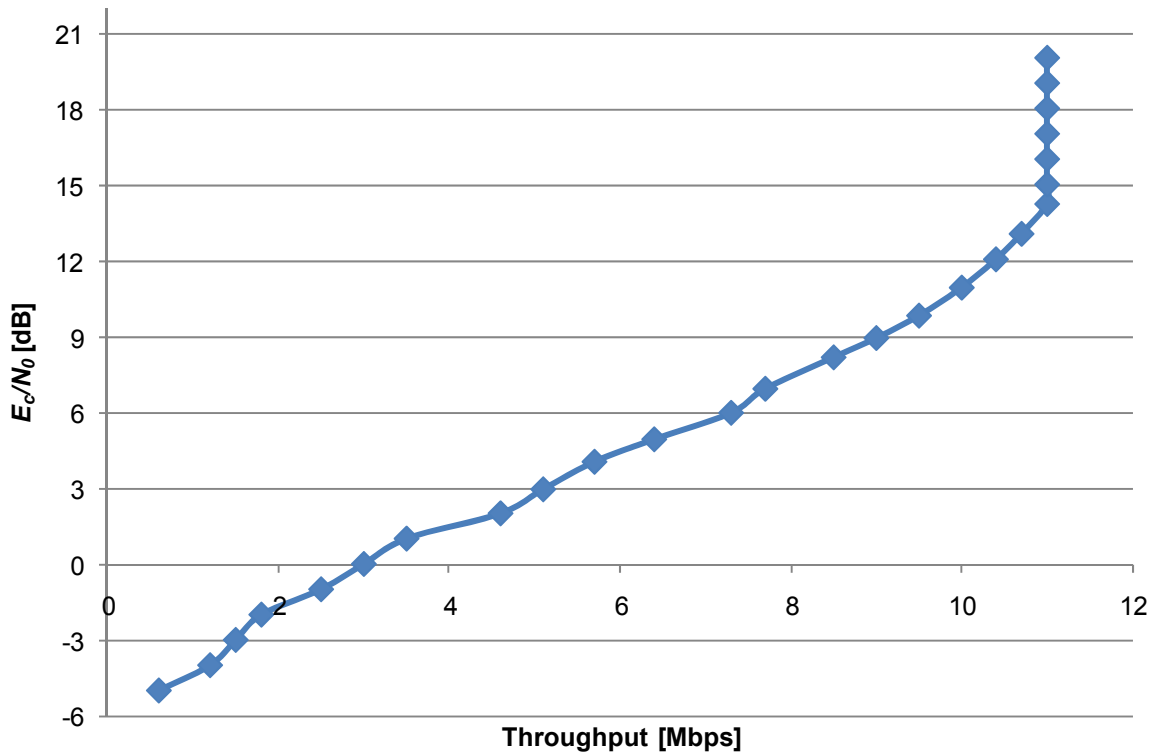


Figure B.2. HSPA+ UL with 16 QAM – E_c/N_0 as a function of Throughput (extracted from [Perg08]).

In virtue of Figure 2.3, the expressions of throughput as a function of SINR were calculated, [Perg08], for HSPA+ DL:

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

$$R_{b[\text{Mbps}]} = \begin{cases} 0.0143 \times \rho_N^2 + 0.3486 \times \rho_N + 2.7657, & -10 \leq \rho_{N[\text{dB}]} < -6 \\ 0.05 \times \rho_N^2 + 0.85 \times \rho_N + 4.5, & -6 \leq \rho_{N[\text{dB}]} < -1 \\ 0.0223 \times \rho_N^2 + 0.631 \times \rho_N + 4.3203, & -1 \leq \rho_{N[\text{dB}]} < 10 \\ -0.05 \times \rho_N^2 + 1.5757 \times \rho_N + 1.9286, & 10 \leq \rho_{N[\text{dB}]} < 18 \\ 14.4, & 18 \leq \rho_{N[\text{dB}]} \leq 30 \end{cases} \quad (\text{B.9})$$

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

$$R_{b[\text{Mbps}]} = \begin{cases} 0.0143 \times \rho_N^2 + 0.3586 \times \rho_N + 2.7657, & -10 \leq \rho_{N[\text{dB}]} < -6 \\ 0.0005 \times \rho_N^3 + 0.0208 \times \rho_N^2 + 0.6167 \times \rho_N + 4.3131, & -6 \leq \rho_{N[\text{dB}]} < 11 \\ -0.0652 \times \rho_N^2 + 2.85 \times \rho_N - 9.7048, & 11 \leq \rho_{N[\text{dB}]} < 20 \\ 21.6, & 20 \leq \rho_{N[\text{dB}]} \leq 30 \end{cases} \quad (\text{B.10})$$

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

$$R_{b[\text{Mbps}]} = \begin{cases} 0.03 \times \rho_N^2 + 0.7823 \times \rho_N + 5.8266, & -10 \leq \rho_{N[\text{dB}]} < 3 \\ -0.0626 \times \rho_N^2 + 1.6205 \times \rho_N + 3.813, & 3 \leq \rho_{N[\text{dB}]} < 13 \\ 14.4, & 13 \leq \rho_{N[\text{dB}]} \leq 30 \end{cases} \quad (\text{B.11})$$

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

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

$$R_{b[\text{Mbps}]} = \begin{cases} 0.0255 \times \rho_N^2 + 0.7265 \times \rho_N + 5.6914, & -10 \leq \rho_{N[\text{dB}]} < -1 \\ 0.0105 \times \rho_N^2 + 0.8517 \times \rho_N + 5.783, & -1 \leq \rho_{N[\text{dB}]} < 13 \\ -0.0542 \times \rho_N^2 + 2.2054 \times \rho_N - 0.9696, & 13 \leq \rho_{N[\text{dB}]} < 19 \\ 21.6, & 18 \leq \rho_{N[\text{dB}]} \leq 30 \end{cases} \quad (\text{B.12})$$

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

$$R_{b[\text{Mbps}]} = \begin{cases} -0.0139 \times \rho_N^3 + -0.2714 \times \rho_N^2 - 1.3004 \times \rho_N + 1.9524, & -10 \leq \rho_{N[\text{dB}]} < -5 \\ 0.0021 \times \rho_N^3 + 0.0209 \times \rho_N^2 + 0.7905 \times \rho_N + 7.0537, & -5 \leq \rho_{N[\text{dB}]} < 10 \\ -0.0722 \times \rho_N^2 + 3.1463 \times \rho_N - 5.2526, & 10 \leq \rho_{N[\text{dB}]} < 20 \\ 28.8, & 20 \leq \rho_{N[\text{dB}]} \leq 30 \end{cases} \quad (\text{B.13})$$

In a MIMO 2x2 configuration with 64 QAM, the physical throughput can be calculated by:

$$R_{b[\text{Mbps}]} = \begin{cases} -0.0083 \times \rho_N^3 - 0.1357 \times \rho_N^2 - 0.2131 \times \rho_N + 4.8057, & -10 \leq \rho_{N[\text{dB}]} < -6 \\ 0.0005 \times \rho_N^4 + 0.0018 \times \rho_N^3 + 0.0089 \times \rho_N^2 + 0.7812 \times \rho_N + 7.0784, & -6 \leq \rho_{N[\text{dB}]} < 1 \\ -0.0001 \times \rho_N^3 + 0.0657 \times \rho_N^2 + 0.5792 \times \rho_N + 7.211, & 1 \leq \rho_{N[\text{dB}]} < 6 \\ -0.0008 \times \rho_N^3 + 0.0593 \times \rho_N^2 + 0.8046 \times \rho_N + 6.0472, & 6 \leq \rho_{N[\text{dB}]} < 17 \\ -0.0757 \times \rho_N^2 + 4.3661 \times \rho_N - 19.392, & 17 \leq \rho_{N[\text{dB}]} < 30 \end{cases} \quad (\text{B.14})$$

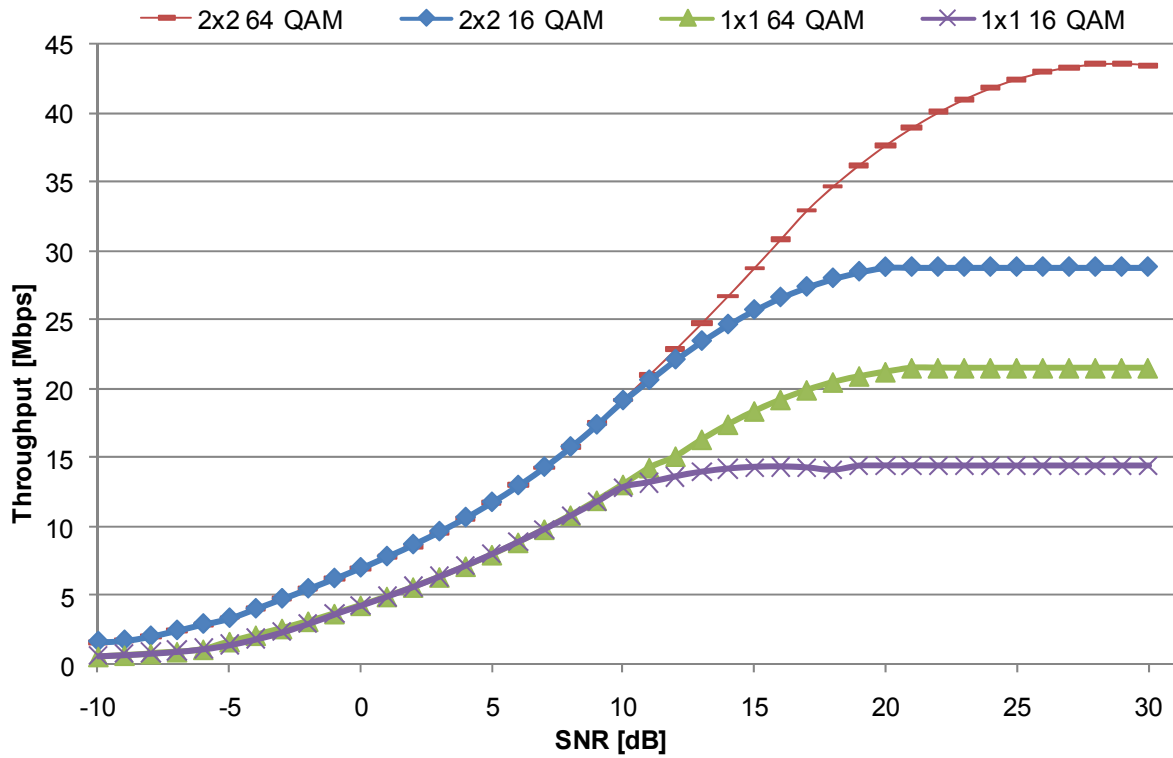


Figure B.3. HSPA+ DL for MIMO 2x2 and SISO configurations – Throughput as function of SNR.

Otherwise for HSPA+ UL, based on Figure 2.4 the values of R_b^{PHY} as a function of E_c/N_0 , are calculated in [Perg08]. For QPSK modulation one can define;

$$R_{b[\text{Mbps}]} = \begin{cases} 0.0643 \times (E_c/N_0)^2 + 0.8557 \times (E_c/N_0) + 4.18, & -5 \leq E_c/N_{0[\text{dB}]} < -1 \\ -0.05 \times (E_c/N_0)^2 + 0.31 \times (E_c/N_0) + 3.77, & -1 \leq E_c/N_{0[\text{dB}]} < 2 \\ 0.0417 \times (E_c/N_0)^3 - 0.5429 \times (E_c/N_0)^2 + 2.5012 \times (E_c/N_0) + 1.04, & 2 \leq E_c/N_{0[\text{dB}]} < 6 \\ 5.5, & 6 \leq E_c/N_{0[\text{dB}]} \leq 11 \end{cases} \quad (\text{B.15})$$

While for 16 QAM modulation:

$$R_{b[\text{Mbps}]} = \begin{cases} -0.0087 \times (E_c/N_0)^4 - 0.0669 \times (E_c/N_0)^3 - 0.0936 \times \\ (E_c/N_0)^2 + 0.6056 \times (E_c/N_0) + 3.0522, -5 \leq E_c/N_{0[\text{dB}]} < -3 \\ \\ 0.0333 \times (E_c/N_0)^4 + 0.1 \times (E_c/N_0)^3 - 0.0333 \times (E_c/N_0)^2 + 0.4 \times \\ (E_c/N_0) + 3, -3 \leq E_c/N_{0[\text{dB}]} < 1 \\ \\ 0.0583 \times (E_c/N_0)^3 - 0.575 \times (E_c/N_0)^2 + 2.3667 \times (E_c/N_0) + \\ 1.66, 1 \leq E_c/N_{0[\text{dB}]} < 5 \\ \\ -0.0003 \times (E_c/N_0)^3 - 0.0195 \times (E_c/N_0)^2 + 0.9558 \times (E_c/N_0) + \\ 2.1899, 5 \leq E_c/N_{0[\text{dB}]} < 15 \\ \\ 11, 15 \leq E_c/N_{0[\text{dB}]} \leq 20 \end{cases} \quad (\text{B.16})$$

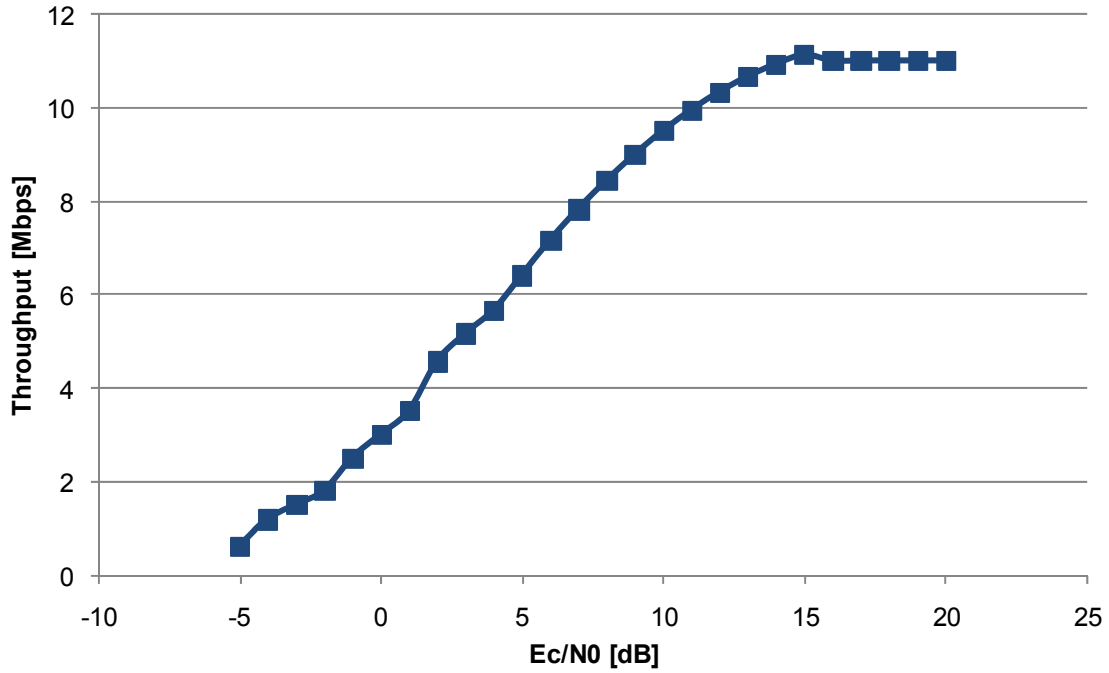


Figure B.4. Interpolation for HSPA+ UL curve for 16QAM modulation – Throughput as function of SNR.

B.2 LTE

Collected trial measurements were fundamental in order to generate these models, since these experimental simulations are accounted for numerous ‘players’ on the Telecommunications Industry such as operators, manufactures and electric hardware suppliers from all over the world and supervised by 3GPP who draws and continuously evaluate the reports taken as a standardisation

body.

Specific LTE case simulations which were not performed by 3GPP over combinations in the parameter set (modulation, channel model) were extrapolated, in order to obtain a good approximation. The expressions achieved are step-wise, mainly because the results returned are heavy computational polynomial interpolations presenting relative mean errors, (3.23), higher in the worst case over the order of 24%.

LTE is initially addressed in [Duar08] for three channels outlined by 3GPP and presented in Table B.1. The main outlined channels for LTE are based on low, medium and high delay spreads, specifically EPA, Extended Vehicular A (EVA) and ETU. Due to the variety of information available in what configurations concern, an approximation was performed in order to have single RB results, bearing in mind that RB is equal regarding the bandwidth. Remember the variations according with the chosen channel bandwidth in Table 2.4.

Table B.1. Overview of channel models (extracted from [Duar08]).

Channel Model	Doppler Frequency [Hz]	Delay Spread [ns]
EPA 5Hz	5	43
EVA 5Hz	5	357
EVA 70Hz	70	357
ETU 70Hz	70	991
ETU 300Hz	300	991

DL interpolations were performed with SIMO configurations and normal CP. For QPSK with the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} 139.1968058 \cdot R_b - 12.9993, & 0.079019806 < R_b [\text{Mbps}] < 0.093387952 \\ 733.4013 \cdot R_b - 68.49085, & 0.093387952 < R_b [\text{Mbps}] < 0.096114972 \end{cases} \quad (\text{B.17})$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 80.48807972 \cdot R_b - 5.95475, & 0.0491346 < R_b [\text{Mbps}] < 0.073983 \\ 133.7077 \cdot R_b - 9.8921, & 0.073983 < R_b [\text{Mbps}] < 0.088941 \\ (1.1798 \cdot R_b - 0.10293) \cdot 10^3, & 0.088941 < R_b [\text{Mbps}] < 0.0906362 \end{cases} \quad (\text{B.18})$$

For 16 QAM the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} 41.37141679 \cdot R_b - 4.138024, & 0.051678764 < R_b [\text{Mbps}] < 0.100021319 \\ (1.5568 \cdot R_b^3 - 0.9155 \cdot R_b^2 + 0.2088 \cdot R_b - 0.0133) \cdot 10^3, & 0.100021319 < R_b [\text{Mbps}] < 0.286368144 \end{cases} \quad (\text{B.19})$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 36.99712399 \cdot R_b - 2.034694, & 0.000937744 < R_b [\text{Mbps}] < 0.054996 \\ \left(\frac{2.1664 \cdot R_b^4 - 1.3996 \cdot R_b^3 +}{+0.3082 \cdot R_b^2 - 0.0221 \cdot R_b + 0.0005} \right) \cdot 10^4, & 0.054996 < R_b [\text{Mbps}] < 0.27349 \end{cases} \quad (\text{B.20})$$

For 64 QAM the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} -291.0892 \cdot R_b^2 + 70.0593 \cdot R_b - 0.21, & 0.003036072 < R_b [\text{Mbps}] < 0.037337248 \\ 25.4196 \cdot R_b + 1.0509, & 0.037337248 < R_b [\text{Mbps}] < 0.116016576 \\ 966.0917 \cdot R_b^3 - 108.0894 \cdot R_b^2 + 1.3053 \cdot R_b + 3.7948, & 0.116016576 < R_b [\text{Mbps}] < 0.2287376 \\ 225.0551 \cdot R_b^3 - 299.6906 \cdot R_b^2 + 144.2672 \cdot R_b - 10.03, & 0.2287376 < R_b [\text{Mbps}] < 0.62271664 \end{cases} \quad (\text{B.21})$$

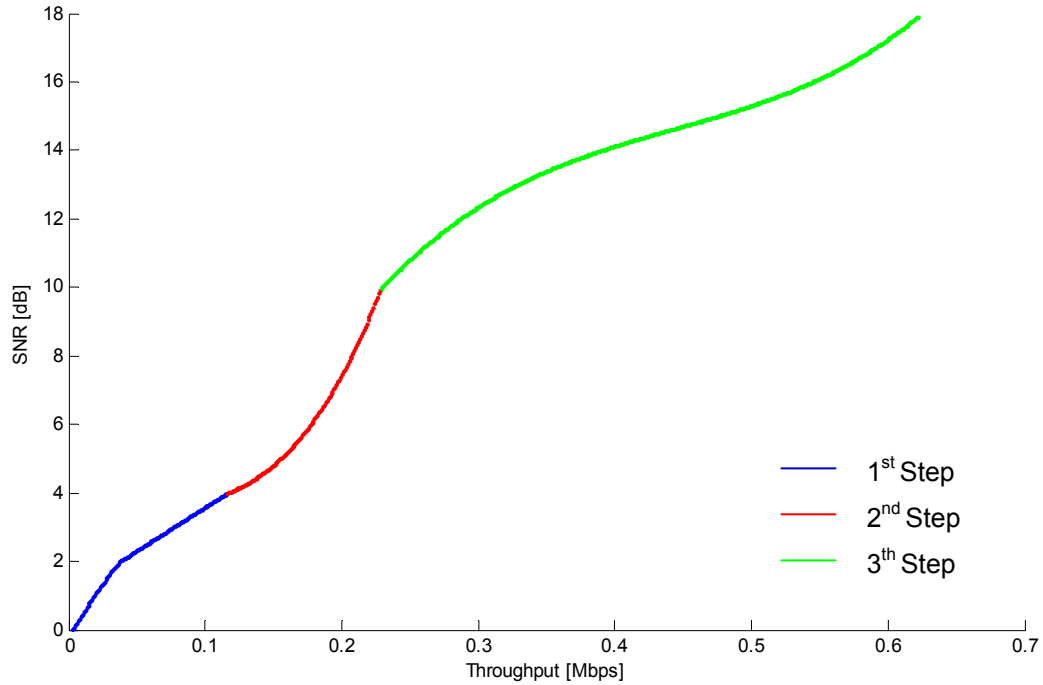


Figure B.5. Step-wise DL RB Throughput interpolation for 64QAM, coding rate $\frac{3}{4}$, on EPA 5Hz over a bandwidth of 10MHz.

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 58.3431 \cdot R_b + 2, & 0 < R_b [\text{Mbps}] < 0.03428 \\ 16.7175 \cdot R_b + 3.4269, & 0.03428 < R_b [\text{Mbps}] < 0.1539152 \\ (1.2031 \cdot R_b^2 - 0.3610 \cdot R_b + 0.03305) \cdot 10^3, & 0.1539152 < R_b [\text{Mbps}] < 0.221184 \\ \left(\frac{2.0618 \cdot R_b^4 - 3.2095 \cdot R_b^3 +}{+1.7699 \cdot R_b^2 - 0.3847 \cdot R_b + 0.0403} \right) \cdot 10^3, & 0.221184 < R_b [\text{Mbps}] < 0.587772 \\ 88.6997 \cdot R_b - 32.1352, & 0.587772 < R_b [\text{Mbps}] < 0.61032 \end{cases} \quad (\text{B.22})$$

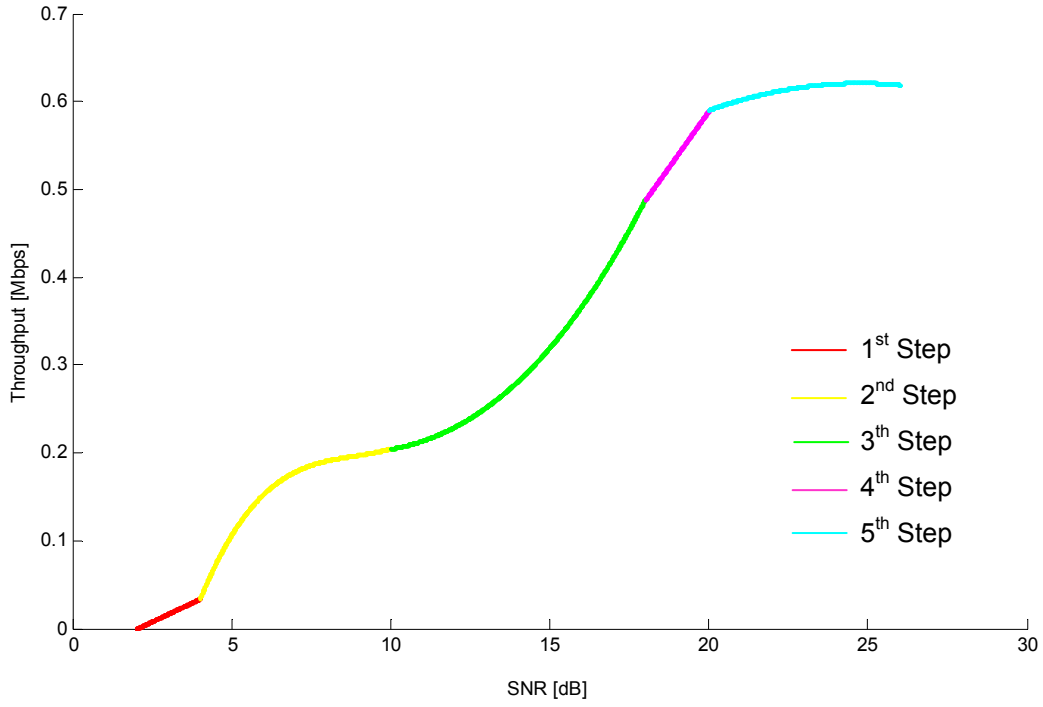


Figure B.6. Step-wise wise DL RB Throughput interpolation for 64QAM, coding rate $\frac{3}{4}$, on ETU 70Hz over a bandwidth of 10MHz.

Then, UL interpolations were carry out for MIMO 2×2 and 4×4 configurations and normal CP. For QPSK and MIMO configuration of 2×2 the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} ((1.1274 \cdot R_b^2 - 0.2015 \cdot R_b + 0.009001) \cdot 10^5, 0.08792454 < R_b [Mbps] < 0.09550812 \\ (5.4466 \cdot R_b - 0.5162) \cdot 10^3, 0.09550812 < R_b [Mbps] < 0.09587532 \\ (1.6041 \cdot R_b - 0.1532) \cdot 10^4, 0.09587532 < R_b [Mbps] < 0.096 \end{cases} \quad (B.23)$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 134.8574927 \cdot R_b - 9.012743359, 0.06683161 < R_b [Mbps] < 0.08166208 \\ 231.8423935 \cdot R_b - 16.93273209, 0.08166208 < R_b [Mbps] < 0.09028863 \\ 459.5736076 \cdot R_b - 37.49427141, 0.09028863 < R_b [Mbps] < 0.09464049 \\ 1644.425808 \cdot R_b - 149.6292642, 0.09464049 < R_b [Mbps] < 0.09585672 \end{cases} \quad (B.24)$$

For 16 QAM and MIMO configuration of 2×2 the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} -675.6188 \cdot R_b^3 + 364.4272 \cdot R_b^2 - 17.8417 \cdot R_b - 0.5122, \\ 0.07884248 < R_b \text{ [Mbps]} < 0.2725038 \\ (1.6370 \cdot R_b^3 - 1.5249 \cdot R_b^2 + 0.5011 \cdot R_b - 0.0484) \cdot 10^3, \\ 0.2725038 < R_b \text{ [Mbps]} < 0.4162308 \end{cases} \quad (B.25)$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} -887.0042 \cdot R_b^3 + 600.5976 \cdot R_b^2 - 79.2833 \cdot R_b + 4.4602, \\ 0.11705298 < R_b \text{ [Mbps]} < 0.3362749 \\ 702.3316 \cdot R_b^2 - 462.6239 \cdot R_b + 88.172, \\ 0.3362749 < R_b \text{ [Mbps]} < 0.4207883 \end{cases} \quad (B.26)$$

For 64 QAM and MIMO configuration of 2×2 the throughput as a function of SINR is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} -644.1481 \cdot R_b^4 + 581.2997 \cdot R_b^3 - 137.502 \cdot R_b^2 + 33.3898 \cdot R_b + 1.1911, \\ 0.11640088 < R_b \text{ [Mbps]} < 0.5095352 \\ 104.2152 \cdot R_b^2 - 95.7213 \cdot R_b + 37.727, & 0.5095352 < R_b \text{ [Mbps]} < 0.7034354 \end{cases} \quad (B.27)$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 218.1556 \cdot R_b^3 - 20.3603 \cdot R_b^2 + 21.9913 \cdot R_b + 1.1564, & 0.1245 < R_b \text{ [Mbps]} < 0.27163 \\ 873.1686 \cdot R_b^2 - 387.3231 \cdot R_b + 50.7834, & 0.27163 < R_b \text{ [Mbps]} < 0.30584 \\ -327.5755 \cdot R_b^3 + 168.9751 \cdot R_b^2 - 28.3087 \cdot R_b, & 0.30584 < R_b \text{ [Mbps]} < 0.3828 \\ 30.8949 \cdot R_b^2 + 20.2801 \cdot R_b + 5.7096, & 0.3828 < R_b \text{ [Mbps]} < 0.46866 \\ 78.2614 \cdot R_b - 14.6782, & 0.46866 < R_b \text{ [Mbps]} < 0.4942 \end{cases} \quad (B.28)$$

For QPSK and MIMO configuration of 4×4 the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = 46360.68614 \cdot R_b - 4448.625869, \quad 0.09595686 < R_b \text{ [Mbps]} < 0.096 \quad (B.29)$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 570.9897 \cdot R_b - 52.4763, & 0.09190412 < R_b \text{ [Mbps]} < 0.09540681 \\ (3.3716 \cdot R_b - 0.3197) \cdot 10^3, & 0.09540681 < R_b \text{ [Mbps]} < 0.096 \end{cases} \quad (B.30)$$

For 16 QAM and MIMO configuration of 4×4 the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} -331.6065 \cdot R_b^2 + 203.4191 \cdot R_b - 26.6376, & 0.18947086 < R_b [Mbps] < 0.2656774 \\ 8.2876 \cdot R_b^2 + 20.9817 \cdot R_b - 2.1593, & 0.2656774 < R_b [Mbps] < 0.4158826 \end{cases} \quad (B.31)$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 425.6356 \cdot R_b^2 - 108.5150 \cdot R_b + 6.7234, & 0.1487703 < R_b [Mbps] < 0.2267275 \\ 849.2806 \cdot R_b^3 - 538.8943 \cdot R_b^2 + 257.31 \cdot R_b - 28.8814, & 0.2267275 < R_b [Mbps] < 0.4094698 \\ 106.0468 \cdot R_b - 33.4230, & 0.4094698 < R_b [Mbps] < 0.4283294 \end{cases} \quad (B.32)$$

For 64 QAM and MIMO configuration of 4×4 the SINR as a function of throughput is given by:

- EPA 5Hz

$$\rho_{IN[dB]} = \begin{cases} 13.0921 \cdot R_b^2 + 15.2877 \cdot R_b - 1.5438, & 0.093498 < R_b < 0.290408 \\ 39.9829 \cdot R_b - 7.6114, & 0.290408 < R_b [Mbps] < 0.3404294 \\ 100.7861 \cdot R_b - 28.3106, & 0.3404294 < R_b [Mbps] < 0.3602734 \\ 47.1514 \cdot R_b - 8.9874, & 0.3602734 < R_b [Mbps] < 0.40269 \\ 23.0273 \cdot R_b^2 - 6.8221 \cdot R_b + 9.0837, & 0.40269 < R_b [Mbps] < 0.7089816 \end{cases} \quad (B.33)$$

- ETU 70Hz

$$\rho_{IN[dB]} = \begin{cases} 68.4795 \cdot R_b^2 + 7.7103 \cdot R_b - 1.2429, & 0.089015107 < R_b [Mbps] < 0.274404959 \\ 96.9622 \cdot R_b - 20.5777, & 0.274404959 < R_b [Mbps] < 0.294730413 \\ 357.6813 \cdot R_b - 97.4196, & 0.294730413 < R_b [Mbps] < 0.300321983 \\ 73.5699 \cdot R_b - 12.0946, & 0.300321983 < R_b [Mbps] < 0.327507025 \\ 740.8213 \cdot R_b^3 - 950.9916 \cdot R_b^2 + 424.8991 \cdot R_b - 51.1773, & 0.327507025 < R_b [Mbps] < 0.54809562 \\ 71.3183 \cdot R_b - 21.0892, & 0.54809562 < R_b [Mbps] < 0.576138926 \end{cases} \quad (B.34)$$

For the DL, interpolations are for simulations for 10MHz of bandwidth, SIMO configurations and normal CP. For QPSK the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_b [bps] = \begin{cases} ((0.0190 \cdot \rho^3 - 0.1455 \cdot \rho^2 + 0.3516 \cdot \rho + 9.3388) \cdot 10^4, & -2 < \rho_{[dB]} < 2 \\ (0.0063 \cdot \rho + 9.6009) \cdot 10^4, & 2 < \rho_{[dB]} < 4 \end{cases} \quad (B.35)$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} (1.2424 \cdot \rho + 7.3983) \cdot 10^4, & -2 < \rho_{\text{[dB]}} < 0 \\ (7.4795 \cdot \rho + 73.983) \cdot 10^3, & 0 < \rho_{\text{[dB]}} < 2 \\ (0.0848 \cdot \rho + 8.7246) \cdot 10^4, & 2 < \rho_{\text{[dB]}} < 4 \\ 90632, & 4 < \rho_{\text{[dB]}} < 6 \end{cases} \quad (\text{B.36})$$

For 16 QAM the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = \begin{cases} (-0.000945 \cdot \rho^4 + 0.0103 \cdot \rho^3 - 0.0141 \cdot \rho^2 + 0.1696 \cdot \rho + 1.0083) \cdot 10^5, & -2 < \rho_{\text{[dB]}} < 6 \\ (0.0048 \cdot \rho^3 - 0.1503 \cdot \rho^2 + 1.5644 \cdot \rho - 2.4858) \cdot 10^5, & 6 < \rho_{\text{[dB]}} < 12 \\ 293820, & 12 < \rho_{\text{[dB]}} < 14 \end{cases} \quad (\text{B.37})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} (2.7029 \cdot \rho + 5.4996) \cdot 10^4, & -2 < \rho_{\text{[dB]}} < 0 \\ (0.0479 \cdot \rho^3 - 0.4804 \cdot \rho^2 + 3.1387 \cdot \rho + 5.4719) \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 8 \\ 14893 \cdot \rho - 124463, & 8 < \rho_{\text{[dB]}} < 10 \\ (0.0116 \cdot \rho + 2.6190) \cdot 10^5, & 10 < \rho_{\text{[dB]}} < 12 \\ 275820, & 12 < \rho_{\text{[dB]}} < 14 \end{cases} \quad (\text{B.38})$$

For 64 QAM the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = \begin{cases} (-0.1292 \cdot \rho^3 + 1.3299 \cdot \rho^2 - 0.4279 \cdot \rho + 0.3036) \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 6 \\ (-0.1018 \cdot \rho^2 + 2.92 \cdot \rho + 3.8494) \cdot 10^4, & 6 < \rho_{\text{[dB]}} < 10 \\ (0.0585 \cdot \rho^2 - 1.0032 \cdot \rho + 6.4581) \cdot 10^5, & 10 < \rho_{\text{[dB]}} < 16 \\ (0.4354 \cdot \rho - 1.6098) \cdot 10^5, & 16 < \rho_{\text{[dB]}} < 18 \\ (-0.0241 \cdot \rho^2 + 1.0214 \cdot \rho - 4.33555) \cdot 10^5, & 18 < \rho_{\text{[dB]}} < 22 \\ 647085, & 22 < \rho_{\text{[dB]}} < 26 \end{cases} \quad (\text{B.39})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} 17140 \cdot \rho + 34280, & 2 < \rho_{\text{[dB]}} < 4 \\ (0.006 \cdot \rho^3 - 0.159 \cdot \rho^2 + 1.4327 \cdot \rho - 3.3994) \cdot 2 \cdot 10^5, & 4 < \rho_{\text{[dB]}} < 10 \\ (0.001 \cdot \rho^3 - 0.00139 \cdot \rho^2 - 0.2088 \cdot \rho + 3.2774) \cdot 10^5, & 10 < \rho_{\text{[dB]}} < 18 \\ (50.916 \cdot \rho - 427.91) \cdot 10^3, & 18 < \rho_{\text{[dB]}} < 20 \\ (-0.0068 \cdot \rho^2 + 0.3366 \cdot \rho - 1.0573) \cdot 2 \cdot 10^5, & 20 < \rho_{\text{[dB]}} < 26 \end{cases} \quad (\text{B.40})$$

Over UL, interpolations are for 10MHz bandwidth, MIMO configurations 2×2 and 4×4 and normal CP. For QPSK and MIMO configuration of 2×2 the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = (0.0021 \cdot \rho^3 - 0.0364 \cdot \rho^2 + 0.2089 \cdot \rho + 4.3976) \cdot 2 \cdot 10^4, \quad 0 < \rho_{\text{[dB]}} < 8 \quad (\text{B.41})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} (-0.0567 \cdot \rho^2 + 0.8052 \cdot \rho + 6.7150) \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 6 \\ 403.36 \cdot \rho + 92629.84, & 6 < \rho_{\text{[dB]}} < 8 \end{cases} \quad (\text{B.42})$$

For 16 QAM and MIMO configuration of 2×2 the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = \begin{cases} (-0.0017 \cdot \rho^4 + 0.0425 \cdot \rho^3 - 0.317 \cdot \rho^2 + 1.905 \cdot \rho + 3.9032) \cdot 2 \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 12 \\ (-0.0801 \cdot \rho^2 + 2.7554 \cdot \rho - 2.1906) \cdot 2 \cdot 10^4, & 12 < \rho_{\text{[dB]}} < 18 \end{cases} \quad (\text{B.43})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} (-0.001415 \cdot \rho^4 + 0.0515 \cdot \rho^3 - 0.6331 \cdot \rho^2 + 5.0866 \cdot \rho + 3.7749) \cdot 10^4, & 2 < \rho_{\text{[dB]}} < 14 \\ (-0.0189 \cdot \rho^2 + 0.7093 \cdot \rho - 2.4465) \cdot 10^5, & 14 < \rho_{\text{[dB]}} < 18 \end{cases} \quad (\text{B.44})$$

For 64 QAM and MIMO configuration of 2×2 the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = \begin{cases} (-0.000245 \cdot \rho^4 + 0.0208 \cdot \rho^3 - 0.4757 \cdot \rho^2 + 5.481 \cdot \rho - 9.8308) \cdot 2 \cdot 10^4, & 4 < \rho_{\text{[dB]}} < 18 \\ (-0.0149 \cdot \rho^2 + 0.7174 \cdot \rho - 5.0529) \cdot 2 \cdot 10^5, & 18 < \rho_{\text{[dB]}} < 24 \end{cases} \quad (\text{B.45})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} ((0.0011719 \cdot \rho^4 - 0.035372 \cdot \rho^3 + 0.204 \cdot \rho^2 + 3.1745 \cdot \rho - 1.554) \cdot 10^4, & 4 < \rho_{\text{[dB]}} < 18 \\ (-0.01165 \cdot \rho^2 + 0.6762 \cdot \rho - 4.566) \cdot 10^5, & 18 < \rho_{\text{[dB]}} < 24 \end{cases} \quad (\text{B.46})$$

For QPSK and MIMO configuration of 4×4 the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = \begin{cases} ((0.0011 \cdot \rho + 4.7978) \cdot 2 \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 2 \\ \frac{4800000}{50}, & 2 < \rho_{\text{[dB]}} < 6 \end{cases} \quad (\text{B.47})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} ((0.1751 \cdot \rho + 9.1904) \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 2 \\ ((0.0297 \cdot \rho + 9.1904) \cdot 10^4, & 2 < \rho_{\text{[dB]}} < 4 \\ 96000, & 4 < \rho_{\text{[dB]}} < 6 \end{cases} \quad (\text{B.48})$$

For 16 QAM and MIMO configuration of 4×4 the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = \begin{cases} ((-0.0045 \cdot \rho^4 + 0.062 \cdot \rho^3 - 0.1263 \cdot \rho^2 + 0.7612 \cdot \rho + 9.4781) \cdot 2 \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 8 \\ ((-0.0078 \cdot \rho^2 + 0.1979 \cdot \rho + 3.0807) \cdot 10^5, & 8 < \rho_{\text{[dB]}} < 14 \\ 432000, & 14 < \rho_{\text{[dB]}} < 18 \end{cases} \quad (\text{B.49})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} ((-0.000703 \cdot \rho^4 + 0.01481 \cdot \rho^3 - 0.0874 \cdot \rho^2 + 0.3562 \cdot \rho + 1.4951) \cdot 10^5, & 0 < \rho_{\text{[dB]}} < 10 \\ ((0.0126 \cdot \rho^3 - 0.5935 \cdot \rho^2 + 9.2854 \cdot \rho - 5.1927) \cdot 10^4, & 10 < \rho_{\text{[dB]}} < 16 \\ 430473, & 16 < \rho_{\text{[dB]}} < 18 \end{cases} \quad (\text{B.50})$$

For 64 QAM and MIMO configuration of 4×4 the throughput as a function of SINR is given by:

- EPA 5Hz

$$R_{b \text{ [bps]}} = \begin{cases} ((-0.0005 \cdot \rho^5 + 0.017975 \cdot \rho^4 - 0.2035 \cdot \rho^3 + 0.7046 \cdot \rho^2 + 1.8927 \cdot \rho + 4.6679) \cdot 2 \cdot 10^4, & 0 < \rho_{\text{[dB]}} < 14 \\ ((-0.0064 \cdot \rho^2 + 0.2227 \cdot \rho - 1.2142) \cdot 10^6, & 14 < \rho_{\text{[dB]}} < 18 \\ 720800, & 18 < \rho_{\text{[dB]}} < 24 \end{cases} \quad (\text{B.51})$$

- ETU 70Hz

$$R_{b \text{ [bps]}} = \begin{cases} ((0.000285 \cdot \rho^4 - 0.005537 \cdot \rho^3 + 0.01017 \cdot \rho^2 + 0.38058 \cdot \rho + 0.9) \cdot 10^5, & 0 < \rho_{\text{[dB]}} < 14 \\ ((0.000269 \cdot \rho^3 - 0.0182 \cdot \rho^2 + 0.4118 \cdot \rho - 2.5431) \cdot 10^6, & 14 < \rho_{\text{[dB]}} < 24 \end{cases} \quad (\text{B.52})$$

Annex C – COST231-Walfisch-Ikegami

COST231-Walfisch-Ikegami (COST231-W-I), is the best known propagation model used in urban and sub-urban scenarios due the lifetime is has after development, and since the scope of this thesis is to analyse data transmissions among these scenarios, conscious of the complexity of another propagation models, and it's validly range, COST231-W-I, [DaCo99], are the base propagation model that is used along this thesis. COST231-W-I is a combination of both Ikegami and Walfisch-Bertoni models. A default situation is considered in Figure C.1.

The path loss for the LoS situation between the BS and MT antennas (when the street orientation angle, $\varphi=0$, Figure C.1 (b)) is:

$$L_{p[\text{dB}]} = 42.6 + 26 \log(d_{[\text{km}]}) + 20 \log(f_{[\text{MHz}]}) , \quad d > 0.02 \text{ km} \quad (\text{C.1})$$

In all other cases, such as NLoS, has

$$L_{p[\text{dB}]} = \begin{cases} L_{0[\text{dB}]} + L_{rt[\text{dB}]} + L_{rm[\text{dB}]} , & L_{rt} + L_{rm} > 0 \\ L_{0[\text{dB}]} , & L_{rt} + L_{rm} \leq 0 \end{cases} \quad (\text{C.2})$$

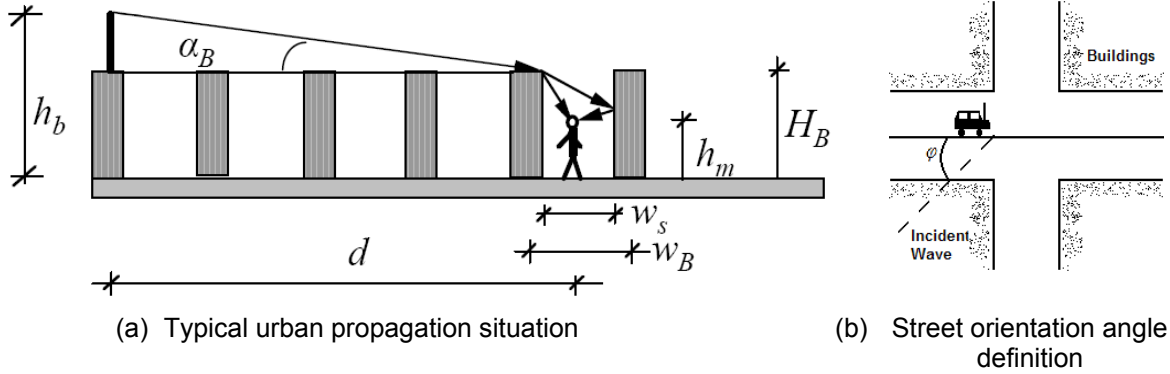


Figure C.1. COST231 W-I predictions and associated definition of the parameters (extracted from [Corr08]).

Decomposing (C.2):

- L_0 : path loss in free space propagation;

$$L_{0[\text{dB}]} = 32.4 + 20 \log(d_{[\text{km}]}) + 20 \log(f_{[\text{MHz}]}) \quad (\text{C.3})$$

- d : distance between the designated BS and the MT
- f : frequency used for the communication

- L_{rt} : rooftop-to-street diffraction loss and scatter loss;

$$L_{rt[dB]} = L_{bsh[dB]} + k_a + k_d \log(d_{[km]}) + k_f \log(f_{[MHz]}) - 9 \log(w_{B[m]}) \quad (C.4)$$

- w_B : distance between middle points of adjacent street buildings

- L_{bsh} : losses due the BS antennas position, meaning if they are above or below the rooftop level:

$$L_{bsh[dB]} = \begin{cases} -18 \log(h_{b[m]} - H_{B[m]} + 1), & h_b > H_B \\ 0, & h_b \leq H_B \end{cases} \quad (C.5)$$

- h_b : BS height
- H_B : building height

- k_a : increase of the path loss for BS antennas below the rooftops of the adjacent buildings:

$$k_a = \begin{cases} 54, & h_b > H_B \\ 54 - 0.8(h_{b[m]} - H_{B[m]}), & d \geq 0.5 \text{ km} \\ 54 - 1.6(h_{b[m]} - H_{B[m]}), & d < 0.5 \text{ km} \end{cases} \Bigg\} h_b \leq H_B \quad (C.6)$$

- k_d : dependence of the multi-screen diffraction loss versus distance;

$$k_d = \begin{cases} 18, & h_b > H_B \\ 18 - 15 \frac{h_{b[m]} - H_{B[m]}}{H_{B[m]}}, & h_b \leq H_B \end{cases} \quad (C.7)$$

- k_f : dependence of the multi-screen diffraction loss versus frequency;

$$k_f = \begin{cases} -4 + 0.7 \left(\frac{f_{[MHz]}}{925} - 1 \right), & \text{urban and suburban} \\ -4 + 1.5 \left(\frac{f_{[MHz]}}{925} - 1 \right), & \text{dense urban} \end{cases} \quad (C.8)$$

- L_{rm} : approximation for multiple screen diffraction loss;

$$L_{rm[dB]} = -16.9 - 10 \log(w_{s[m]}) + 10 \log(f_{[MHz]}) + 20 \log(H_{B[m]} - h_{m[m]}) + L_{ori[dB]} \quad (C.9)$$

- w_s : street width
- h_m : MT height

- L_{ori} : street orientation loss:

$$L_{ori[dB]} = \begin{cases} -10 + 0.654\varphi, & 0^\circ < \varphi_{[^\circ]} < 35^\circ \\ 2.5 + 0.075(\varphi - 35), & 35^\circ \leq \varphi_{[^\circ]} < 55^\circ \\ 4.0 - 0.114(\varphi - 55), & 55^\circ \leq \varphi_{[^\circ]} < 90^\circ \end{cases} \quad (C.10)$$

- φ : street orientation with respect to the direct radio link path

COST231-W-I was developed in 1999, incorporate measurements in several European Cities, and as

a model has own inherent limits. There is below a restricted range of parameters, in [DaCo99] where the measure validation is guaranteed within the intervals underneath;

- $f \in [800, 2000]$ MHz
- $d \in [0.02, 5]$ km
- $h_b \in [4, 50]$ m
- $h_m \in [1, 3]$ m

Considering that the frequency bands for HSPA+ DL, [2110,2170] MHz, are the same used in HSPA, are out of the model validation interval, although the COST231-W-I stills the best model to accurate results in Urban and Suburban NLoS propagation environments. The same issue affect the LTE major frequencies, likely, 2100 MHz and 2600 MHz band.

The model's standard deviation takes values from 4 to 7 dB and the error of the model increases as h_b decreases relatively to H_B .

In the absence of specific values, the following are recommended in [Corr08]:

- $w_B \in [20, 50]$ m
- $w_s = w_B / 2$
- $\varphi = 90^\circ$
- $H_{B[m]} = 3 \times (\# \text{ floors}) + H_{roof[m]}$
- $H_{roof[m]} = \begin{cases} 3, \text{pitched} \\ 0, \text{flat} \end{cases}$

Annex D – Link Budget

The description in Annex C of COST231-W-I was described in the perspective of an outdoor propagation in the radio link path BS-MT or MT-BS. Although in indoor situations there is a need to add an extra attenuation coming for the building/obstacle penetration, $L_{p\ ind}$ standing for the indoor path;

$$L_{P\ total\ [dB]} = L_{P\ outd\ [dB]} + L_{P\ ind\ [dB]} \quad (D.1)$$

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

The path loss, L_P , can be calculated in [Corr08] by:

$$L_{P\ [dB]} = P_{t\ [dBm]} + G_{t\ [dBi]} - P_{r\ [dBm]} + G_{r\ [dBi]} = EIRP_{[dBm]} - P_{r\ [dBm]} + G_{r\ [dBi]} \quad (D.2)$$

where:

- L_P is the path loss;
- P_t is the transmitting power at antenna port;
- G_t is the transmitting antenna gain;
- P_r is the available receiving power at antenna port;
- G_r is the receiving antenna gain.

If diversity is used, G_r in (D.2) is replaced by

$$G_{r\ div\ [dB]} = G_{r\ [dBi]} + G_{div\ [dB]} \quad (D.3)$$

where, G_{div} stands for the diversity gain which depends on diversity type applied, and received correlation signals where therefore depend on propagation environment characterisation. Typical value stands for 2 or 3 dB for 2 antennas and it is essentially considered in UL, since the MT space for spatial diversity is logically reduced, [Sant04].

The Equivalent Isotropic Radiated Power (EIRP) can be calculated for DL by (D.4), and for UL by (D.5).

$$EIRP_{[dBm]} = P_{Tx\ [dBm]} - L_{c\ [dB]} + G_{t\ [dBi]} - P_{S\&C\ [dBm]} \quad (D.4)$$

$$EIRP_{[dBm]} = P_{Tx\ [dBm]} - L_{u\ [dB]} + G_{t\ [dBi]} - G_{MHA\ [dB]} - P_{S\&C\ [dBm]} \quad (D.5)$$

where:

- P_{Tx} is the total BS transmission power at the remote radio head output or at MT;
- L_c is the cable losses between transmitter and antenna;
- L_u is the user losses;
- G_{MHA} is the masthead amplifier gain, being 0 dB in the MU comparison, while in SU is set to 3 dB; The use of near antenna amplifier provides cable loss compensation and consequent

diminish of noise figure.

- $P_{S\&C}$ is the signalling and control power.

The received power can be calculated by (D.6) for DL and (D.7) for UL:

$$P_{RX[dBm]} = P_{T[dBm]} - L_{U[dB]} \quad (D.6)$$

$$P_{RX[dBm]} = P_{T[dBm]} - L_{C[dB]} \quad (D.7)$$

where:

- P_{RX} is the received power at receiver input.

The LTE receiver sensitivity can be approximated defined as:

$$P_{Rx\ min[dBm]} = N_{[dBm]} + \rho_{N[dB]} \quad (D.8)$$

where:

- ρ_N is the Signal to Noise Ratio;
- N is the total noise power given by:

$$N_{[dBm]} = -174 + 10 \log(\Delta f_{[Hz]}) + F_{[dB]} + M_{I[dB]} \quad (D.9)$$

where:

- Δf is the bandwidth of the total RBs allocated, while in UMTS equal to R_c
- F is the receiver's noise figure, Table 4.2 and Table 4.3, whereas in Section 4.2, 2 dB was set to the BS noise figure;
- M_I is the interference margin given by (2.5).

The HSPA+ receiver sensitivity can be approximated by, with the respective processing gain:

$$P_{Rx\ min[dBm]} = N_{[dBm]} - G_{p[dB]} + \rho_{N[dB]} \quad (D.10)$$

where:

- N : total noise power given by (D.12);
- G_p : processing gain, taken values shown on Table D.1;
- ρ_N : SNR, Table D.1;
- R_b : bit rate;
- R_c : WCDMA chip rate;
- E_b : energy per bit;
- N_0 : noise power spectral density.

Table D.1. HSPA+ processing gain and SNR definition.

System	Processing Gain	SNR/SINR
HSPA+ DL	Fixed and equal to 16 (SF ₁₆)	ρ_{IN}
HSPA+ UL	R_c/R_b	E_b/N_0

For HSPA+ UL, the metric used for SNR/SINR is the E_b/N_0 as it was described in Subsection 2.1.4, which depends on the service considered. The E-DPDCH throughput is a continuous function of the E_b/N_0 at the BS.

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

$$\frac{E_b}{N_{0[\text{dB}]}} = \frac{E_c}{N_{0[\text{dB}]}} + G_{p[\text{dB}]} \quad (\text{D.11})$$

In HSPA+ UL, manipulating (D.10) and (D.11), the E_c/N_0 for a certain user's distance is given by:

$$\frac{E_c}{N_{0[\text{dB}]}} = P_{Rx \text{ min}[\text{dBm}]} - N_{[\text{dBm}]} \quad (\text{D.12})$$

For HSPA+ DL, rearranging (D.10), the SINR associated to a certain user distance, is defined as:

$$\rho_{IN[\text{dB}]} = P_{Rx[\text{dBm}]} - N_{[\text{dBm}]} + G_{p[\text{dB}]} \quad (\text{D.13})$$

Despite the losses caused from radio propagation and similar, some margin values must be preset to adjust link calculations, where (D.14) stands for the total fade margin defined:

$$M_{[\text{dB}]} = M_{SF[\text{dB}]} + M_{FF[\text{dB}]} + L_{int[\text{dB}]} \quad (\text{D.14})$$

where:

- M_{SF} is the slow fading margin;
- M_{FF} is the fast fading margin;
- L_{int} is the indoor penetration losses;

Fast and slow fading can be modelled, by Rayleigh and Log-Normal distributions respectively, in order to guarantee more realistic results as well as the randomness associated to the radio channel over MU scenarios. Still, SU Radius Model does not accomplish with these variations and the fixed values of Table 4.1 are set.

Below, the expression (D.15) stands for the CDF of the Rayleigh distribution, while the Log-Normal distribution CDF is given by (D.16) extracted from [Corr08];

$$P(x) = 1 - e^{-x^2/\overline{x^2}} \quad (\text{D.15})$$

where:

- $\overline{x^2}$: mean square error

$$P(x) = \frac{1 + \text{erf}\left(\frac{\ln(x) - \bar{x}_l}{\sqrt{2}\sigma}\right)}{2} \quad (\text{D.16})$$

where:

- \bar{x} , mean;
- σ , standard deviation of the received power;
- $\text{erf}(x)$, error function.

The standard deviations used to describe the fading phenomena are the stated on Table D.2, knowing that those values depend on variables such as path loss, environment, weather conditions, etc.

Table D.2. Distributions and standard deviations used for slow and fast fading margins in MU scenario (extracted from [Voda09]).

Standard Deviation [dB]	Environment		
	Pedestrian	Vehicular	Indoor
$M_{FF}\sigma$	Rayleigh Distribution		
	4	2	4
$M_{SF}\sigma$	Log-Normal Distribution		
	4	7	4

The total path loss can then be calculated using (D.17), whereas $L_{P\text{ máx}}$ means the maximum path loss achieved without any attenuations or losses during the radio propagation being calculated using the COST231-W-I propagation model, Annex C. The $L_{P\text{ total}}$ points the P_{Rx} equal to $P_{Rx\text{ min}}$.

Single User Radius Model accurate the maximum cell range via (3.3), taken into account the maximum path loss as detailed explained in Section 3.1. Moreover, the maximum path loss is used to calculate the receiver sensitivity, (D.18), which allows SINR calculation by means of (D.13) for HSPA+ or LTE without processing gain, in order for it to be mapped on the considered models onto throughput.

$$L_{P\text{ total[dB]}} = L_{P\text{ máx[dB]}} + M_{\text{[dB]}} \quad (\text{D.17})$$

Regarding the calculation necessity of the throughput due to the distance between the user and the associated BS, the first step is to determine the path loss associated to the user distance, using the COST231-W-I, once the path loss calculation, the received power is determined, resulting;

$$P_{Rx\text{[dBm]}} = EIRP_{\text{[dBm]}} - L_{P\text{ máx[dB]}} + G_{r\text{[dBi]}} - L_{c/u\text{[dB]}} \quad (\text{D.18})$$

Annex E – SC-FDMA & Multi-Carrier Systems: OFDM and OFDMA

Multicarrier modulation, like Orthogonal Frequency Division Multiplexing (OFDM,) is used from other mature standards like Digital TV such as Digital Video Broadcasting (DVB)-T/H, IEEE 802.11 a/b/g/n Wireless Local Area Networks (WLAN) or DSL lines. It is based on the principle of transmitting a main bitstream in different sub-streams, whereas these, over different radio channels likely many narrow-band orthogonal frequencies, sub-carriers. In OFDM a very high rate bitstream is divided into multiple parallel low rate bitstreams. Each smaller bitstream is then mapped on to individual data sub-carrier and modulated with a conventional modulation scheme.

Typically the sub-carrier spacing is fixed to 15 kHz and at a sampling instant of a single sub-carrier all other sub-carriers are null, meaning the peak of one sub-carrier coincides with the null of an adjacent sub-carrier, maintaining orthogonality in the frequencies to each other concerning a major advantage; the elimination of inter-channel interference and a higher spectral efficiency compared to another modulation types. This spectral efficiency is obtained as well, since OFDM provides a better multipath delay spread in the radio channel resistance compared to Single Carrier (SC) modulations. With the use of SC

OFDM brings advantage compared to SC modulations revealing an increasing robustness against frequency selective fading and narrowband interference, since a single fade in SC systems can interfere with the entire link, while in multi-carrier configurations only a few sub-carriers are affected.

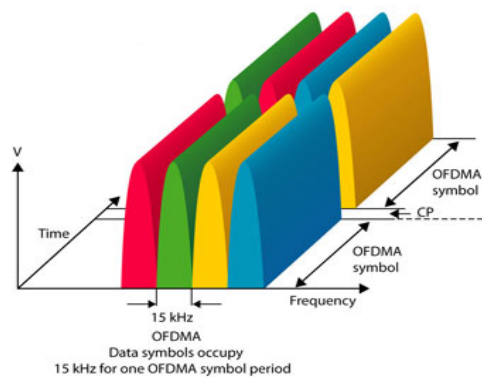


Figure E.1 OFDMA sub-carriers in time and frequency variation (extracted from [Agil08]).

One considers N_s as the number of sub-carriers, R_b the bit rate and B the bandwidth, the objective of a multicarrier modulation is to separate all the bandwidth to all N_s linearly-modulated subsystem in parallel, each with sub-channel bandwidth (B_N), $B_N=B/N_s$. If the N_s is sufficiently large, the sub-channel bandwidth is lower than the Coherence Band (B_C), moreover, the OFDM symbol time is a fixed 66.7 μ s, hence it is much higher compared to the delay spread, Figure E.2. Because of that and with the use of a CP longer than the channel impulse, which is ignored in the receiver, the effect of the

previous symbol is not visible mitigating this way ISI. Just to mention that the duration of a SC-FDMA symbol is not fixed as OFDMA symbol, since it contains M subcarriers of much shorter duration.

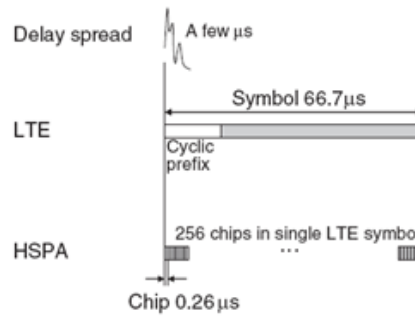


Figure E.2. Comparison between an LTE symbol, HSPA chip and channel delay spread (extracted from [HoTo07]).

An OFDM signal transmits each symbol over one N_s orthogonal frequency guaranteed by the Inverse Fast Fourier Transform (IFFT) transferring the frequency-domain signal into time-domain. The IFFT of N_s symbols compiles an OFDM signal, as it is stated on Figure E.3, after the symbol stream being divided in several sub-streams via a serial-to-parallel converter. It is added to the chain a Cyclic Prefix (CP) to provide the possibility of having a circular convolution which is needed for the IFFT/FFT operations between the analogue signal and impulse response. The CP creates a new kind of samples in the channel output, constituted by τ symbols on a data block with N_s symbols, Figure E.4. For visual clarity, CP is a guard band however the τ symbols are a copy of the end of the next symbol.

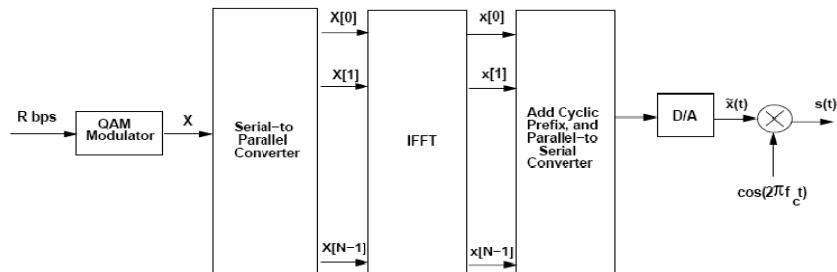


Figure E.3. OFDM signal output with IFFT implementation (extracted from [Gold05]).

CP can eradicate ISI between the data blocks, since CP samples always predict a data block (as guard interval) of the channel output which are affected by ISI. So, the effect of the previous symbol in the receiver is not visible. It is important to notice that these samples can be discarded without any loss relative to the original information sequence, since there is no new or valuable information in the channel chain to preserve. With the use of CP, the maintenance of frequency orthogonality is guarantee, plus ISI sustain. The receiver is able to get efficiently the delay spread due to the multipath. Although the τ/N_s ratio has to respect the multipath level, whereas if the effect is considerably high, a high ratio is needed, and this increases the redundancy, also the CP guard, and will decrease the output data rate since all OFDM symbols are rather smaller. Thus a lower τ/N_s ratio is the right consideration when the multipath effects are lighter.

Despite the proven advantages of this kind of modulation, the closely spaced OFDM subcarriers are sensitive to frequency and phase errors, such as Doppler Shift.

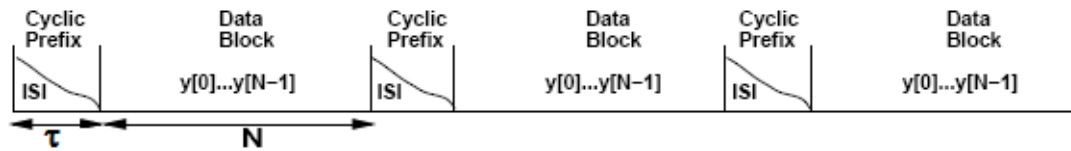


Figure E.4. Channel output separating the CP band guard and data blocks (adapted from [Gold05]).

At the receiver the “tail” of the ISI associated with the end of a given OFDM symbol is added back in to the beginning of the symbol, which recreates the effect of a cyclic prefix due the use of FFT, used in the signal reception.

OFDM provides very narrow UE-specific transmissions which can experience fading and interference, not feasible a single user multiplex across various sub-carriers along a single slot; as a result OFDMA was specified by 3GPP for LTE DL being a more robust access with increased capacity. OFDMA allows the access of multiple users on the available bandwidth assigning dynamically each user to a specific time-frequency resource. This assignment is illustrated in Figure E.5, where it is allocated a sub-channel in time for each downlink or uplink transmissions, differentiating the allocation per user.

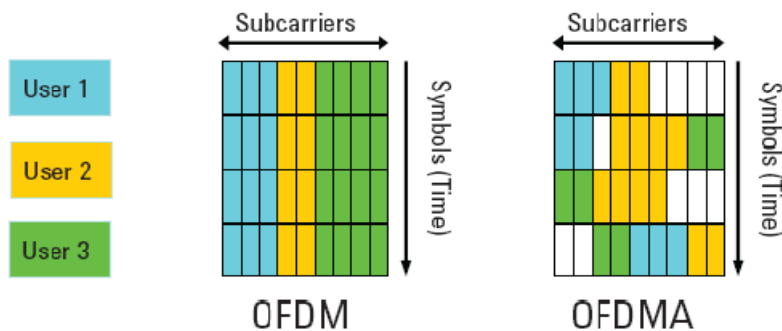


Figure E.5. OFDM and OFDMA multiple access schemes (adapted from [RuYo08]).

According to OFDMA principle, [Nuay07], the OFDMA sub-carriers are grouped into subsets where each subset represents a sub-channel, although the sub-carriers forming one sub-channel may be adjacent or not; Figure E.6. In the uplink, the transmitter may allocate one or more sub-channels, as well as a downlink sub-channel can be connected to different receivers.

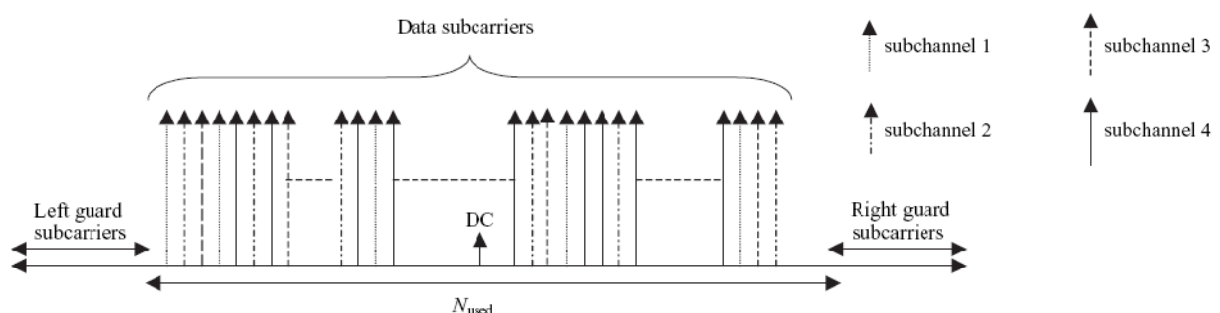


Figure E.6. OFDMA sub-carriers grouped into sub-channels (extracted from [Nuay07]).

Nevertheless, OFDM has some disadvantages comparing with the CDMA systems, specifically leading with inter cell interference, LTE has to make use of frequency re-use to avoid greater inter cell interference on the cell edges, [Agil08]. CDMA, with the use of scrambling codes provide protection from this interference type.

Annex F – Additional Results

Additional and relevant results collected from simulations, for UMTS/HSPA+ and LTE, are presented along this annex.

For the LTE cell radius calculation taken into account the associated configuration throughput range, in [Duar08] is performed similar analysis as the one performed for HSPA+.

Table F.1. HSPA+ DL single user cell radius for the maximum application throughput and several combinations.

Environment	Antenna Configuration	Cell Radius [km]		DL $R_{b \max}$ [Mbps]	
		Modulation		Modulation	
		16 QAM	64 QAM	16 QAM	64 QAM
Pedestrian	SISO	0.646	0.503	11.63	17.36
	MIMO	0.493	0.317	23.26	34.89
Vehicular	SISO	0.558	0.435	11.63	17.36
	MIMO	0.427	0.274	23.26	34.89
Indoor	SISO	0.192	0.150	11.63	17.36
	MIMO	0.147	0.094	23.26	34.89

Table F.2. HSPA+ DL single user cell radius for the minimum application throughput and several combinations.

Environment	Antenna Configuration	Cell Radius [km]		DL $R_{b \min}$ [Mbps]	
		Modulation		Modulation	
		16 QAM	64 QAM	16 QAM	64 QAM
Pedestrian	SISO	2.214	1.847	1.37	2.74
	MIMO	2.192	2.191	3.14	3.14
Vehicular	SISO	1.811	1.597	1.37	2.74
	MIMO	1.796	1.796	3.14	3.14
Indoor	SISO	0.658	0.550	1.37	2.74
	MIMO	0.601	0.601	3.14	3.14

Table F.3. HSPA+ UL single user cell radius for the maximum application throughput and several combinations.

Environment	Antenna Configuration	Cell Radius [km]		UL $R_{b \max}$ [Mbps]	
		Modulation		Modulation	
		QPSK	16 QAM	QPSK	16 QAM
Pedestrian	SISO	0.252	0.153	4.53	9.05
	SIMO	0.284	0.173	4.53	9.05
	MIMO	0.252	0.153	9.06	18.11
Vehicular	SISO	0.205	0.125	4.53	9.05
	SIMO	0.231	0.141	4.53	9.05
	MIMO	0.205	0.125	9.06	18.11
Indoor	SISO	0.075	0.046	4.53	9.05
	SIMO	0.085	0.051	4.53	9.05
	MIMO	0.075	0.046	9.06	18.11

Table F.4. HSPA+ UL single user cell radius for the minimum application throughput and several combinations.

Environment	Antenna Configuration	Cell Radius [km]		UL $R_{b \min}$ [Mbps]	
		Modulation		Modulation	
		QPSK	16 QAM	QPSK	16 QAM
Pedestrian	SISO	0.489	0.361	1.23	2.49
	SIMO	0.552	0.408	1.23	2.49
	MIMO	0.489	0.361	2.47	4.98
Vehicular	SISO	0.398	0.290	1.23	2.49
	SIMO	0.449	0.324	1.23	2.49
	MIMO	0.398	0.290	2.47	4.98
Indoor	SISO	0.145	0.102	1.23	2.49
	SIMO	0.164	0.119	1.23	2.49
	MIMO	0.146	0.102	2.47	4.98

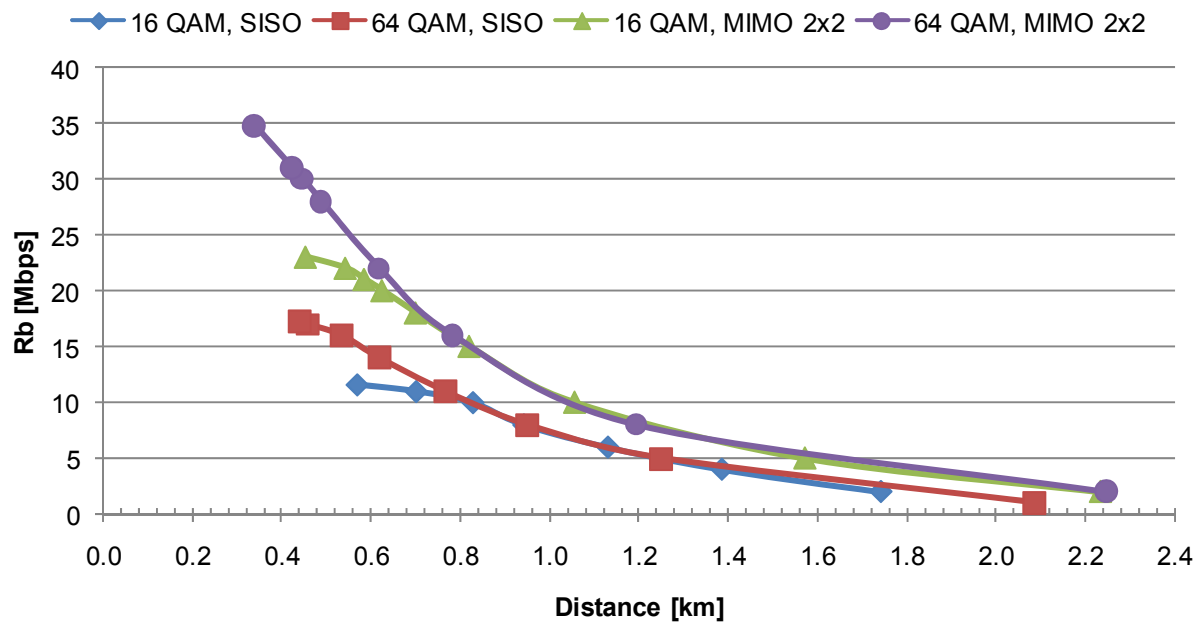


Figure F.1 HSPA+ DL throughput variation, in vehicular environment with different configurations.

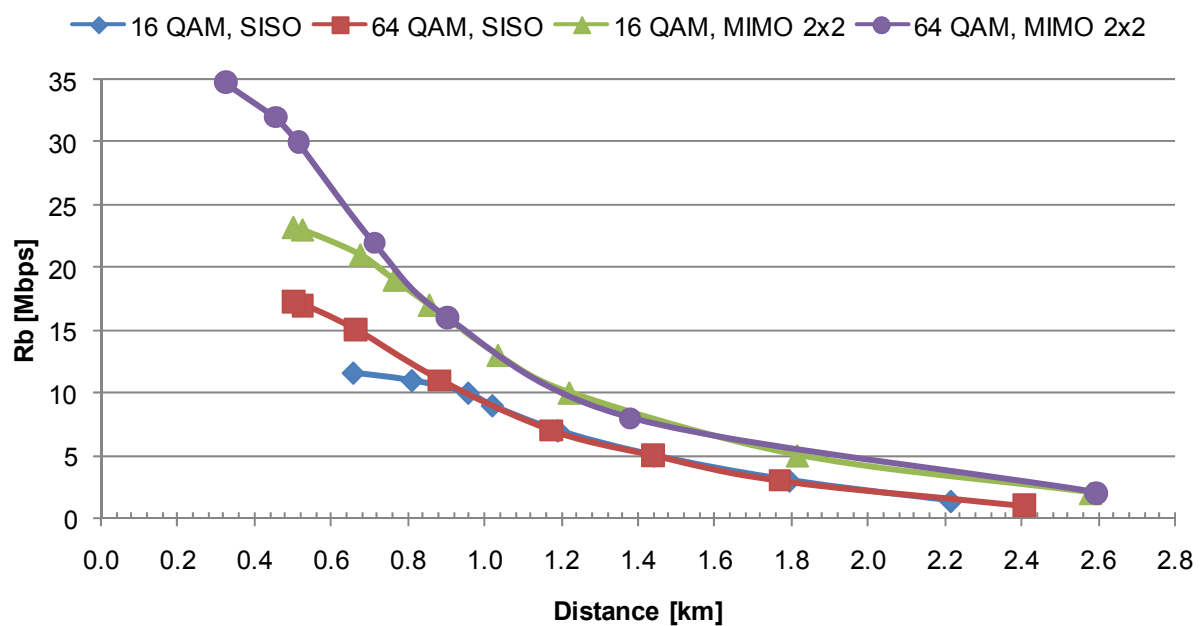


Figure F.2 HSPA+ DL throughput variation, in pedestrian environment with different configurations.

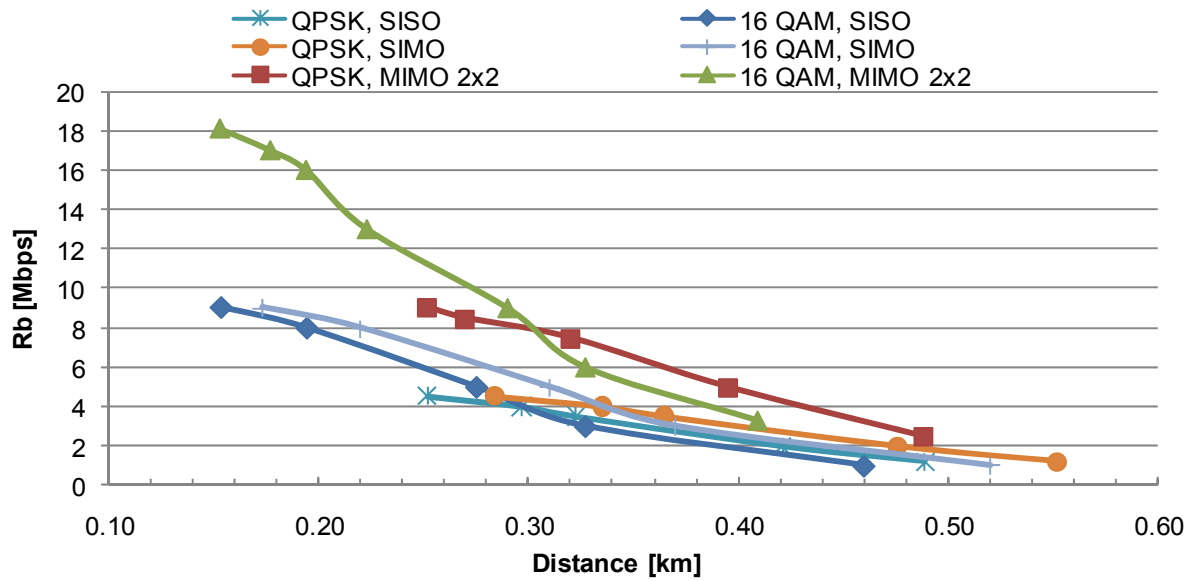


Figure F.3 HSPA+ UL throughput variation, in pedestrian environment with different configurations.

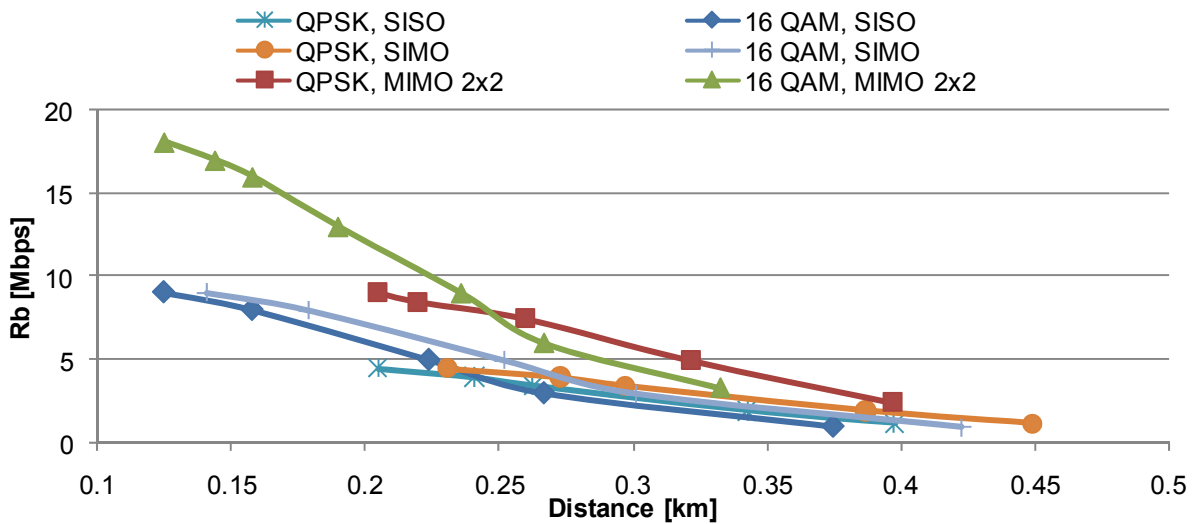


Figure F.4 HSPA+ UL throughput variation, in vehicular environment with different configurations.

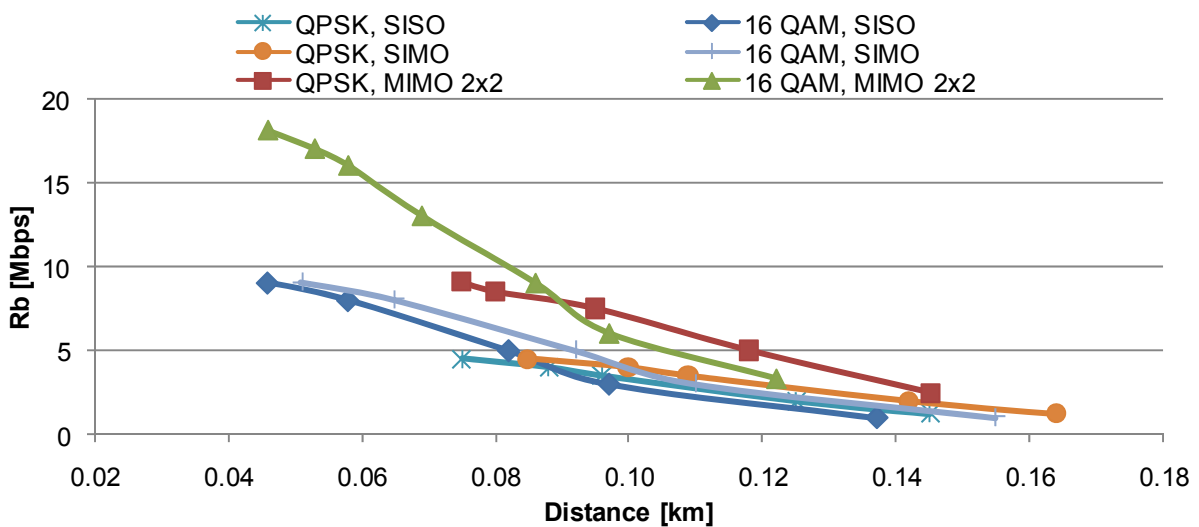


Figure F.5 HSPA+ UL throughput variation, in indoor environment with different configurations.

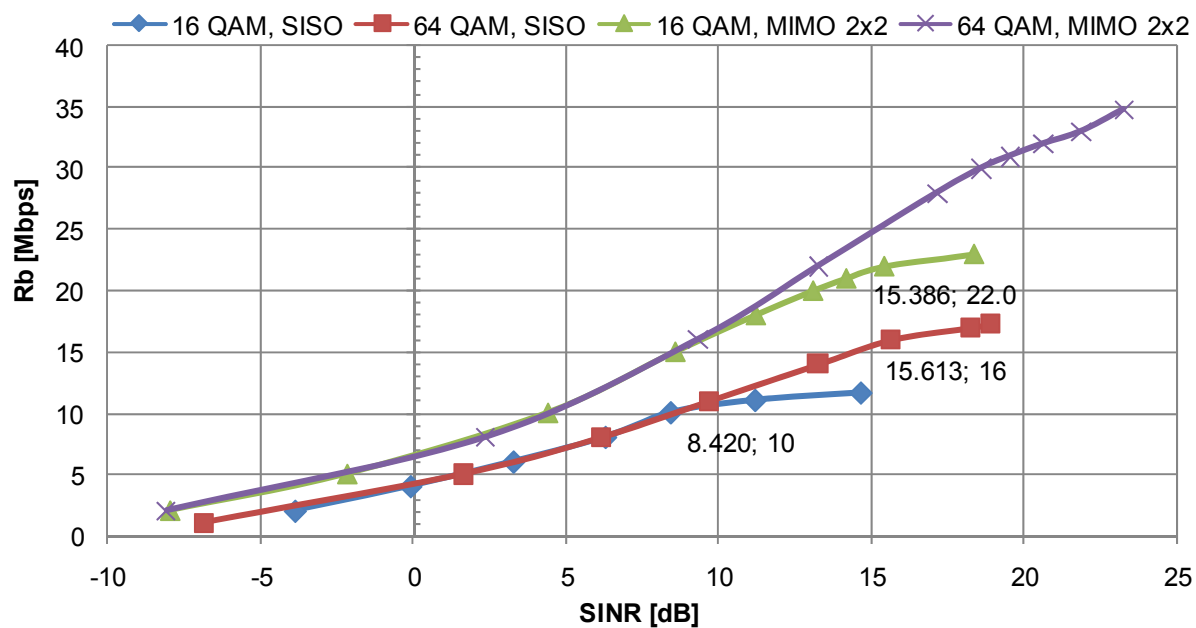


Figure F.6. Throughput as a function of SINR in DL Vehicular channel.

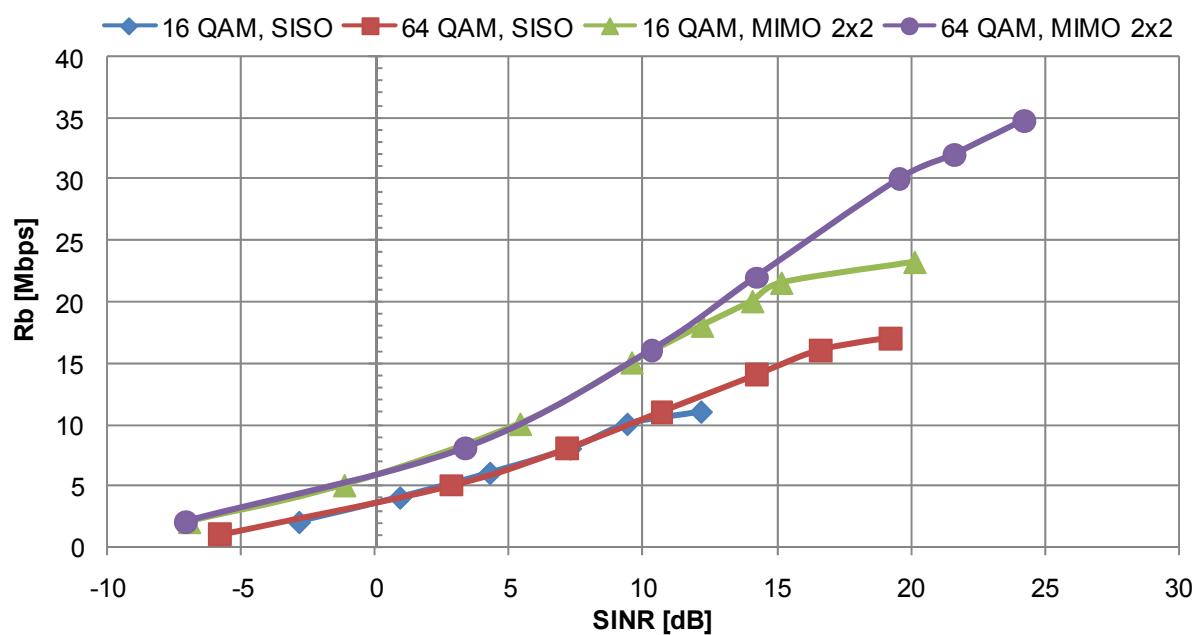


Figure F.7. Throughput as a function of SINR in DL Indoor channel.

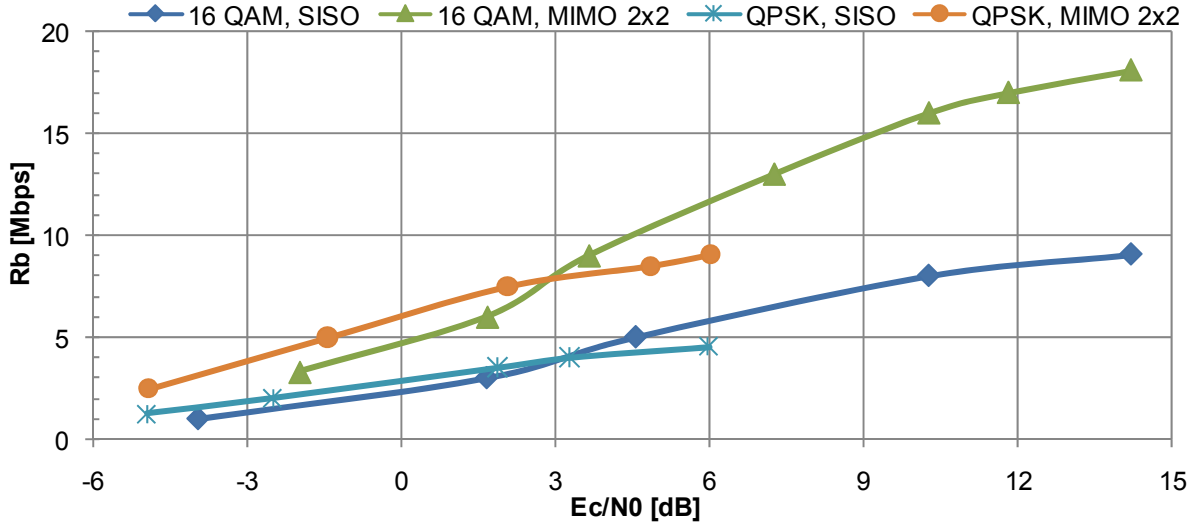


Figure F.8. Throughput as a function of E_c/N_0 in UL Pedestrian channel.

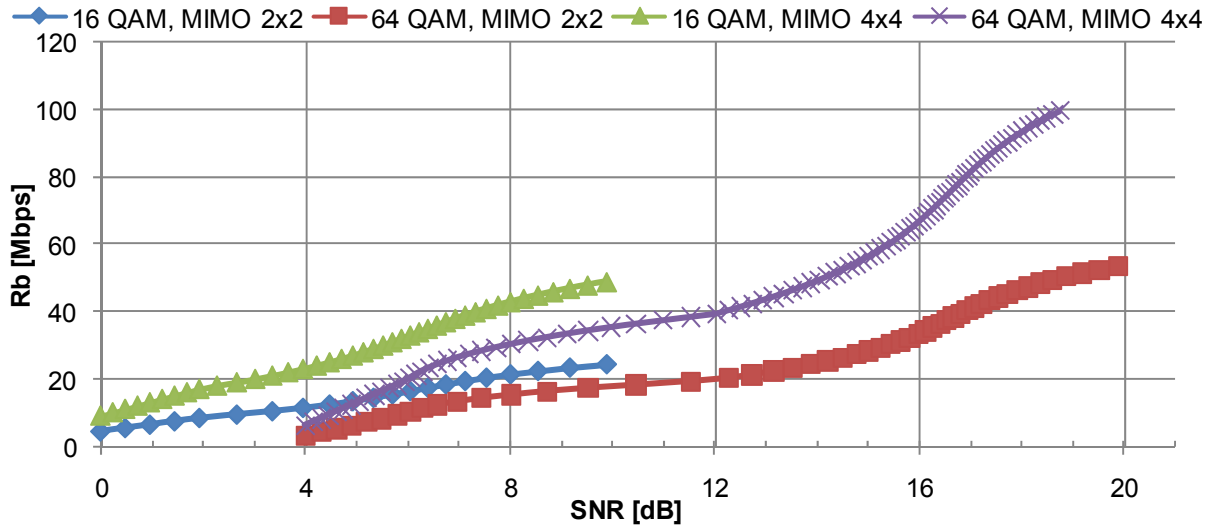


Figure F.9. Throughput as a function of SINR in DL Pedestrian channel, in 900 MHz band and channel bandwidth of 10 MHz.

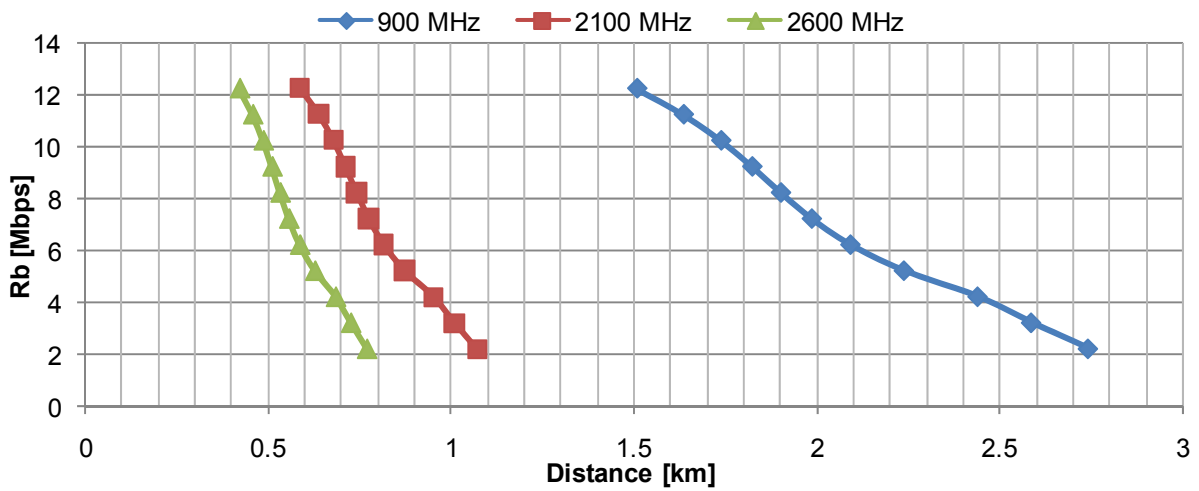


Figure F.10. Throughput as a function of cell distance for different frequency bands in the DL, pedestrian channel and 5 MHz channel bandwidth.

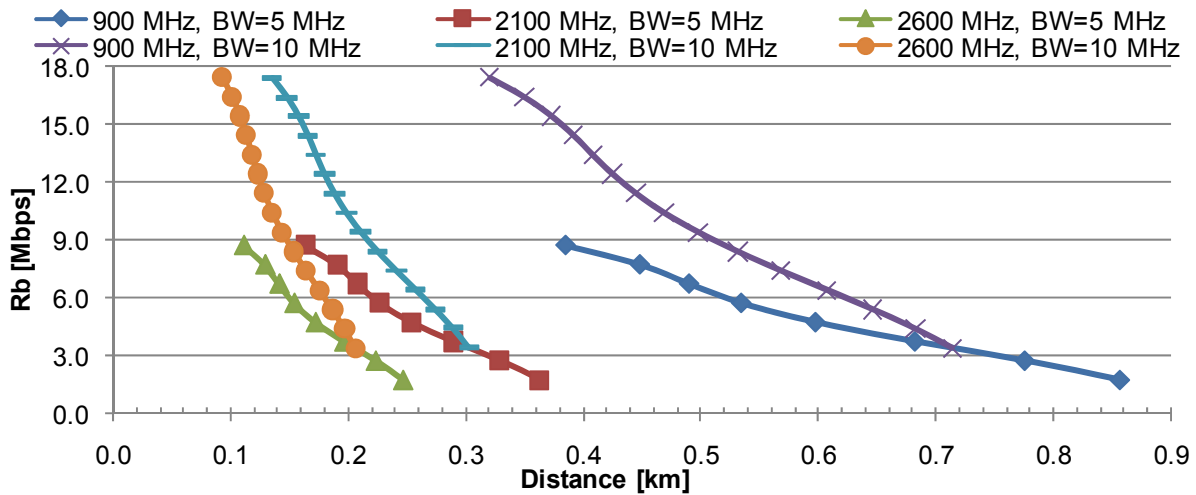


Figure F.11. Throughput as a function of cell distance for different frequency bands in the UL, pedestrian channel, 16 QAM, MIMO 2×2.

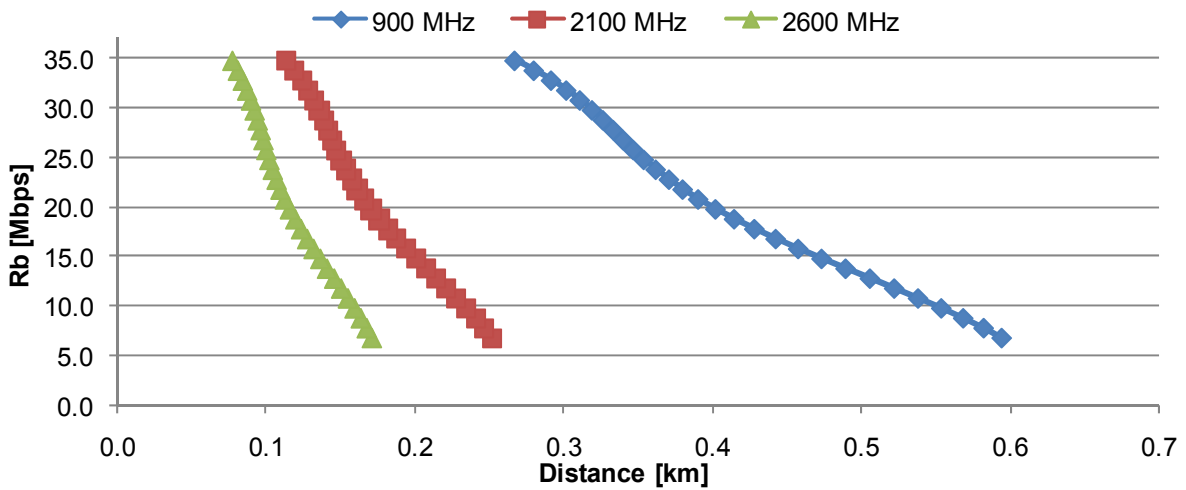


Figure F.12. Throughput as a function of cell distance for different frequency bands in the UL, pedestrian channel, 16 QAM, MIMO 2×2 and channel BW 20 MHz.

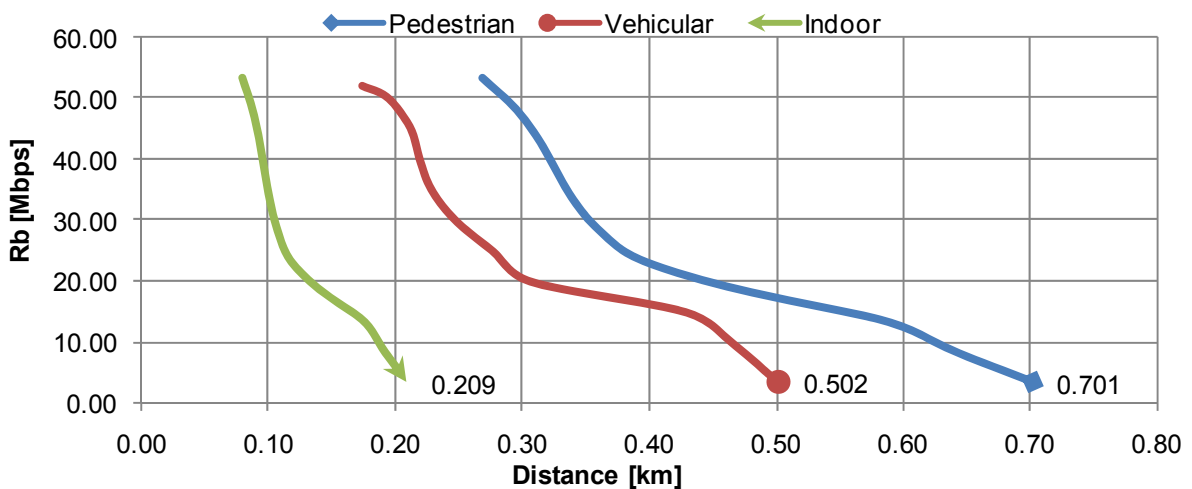


Figure F.13. Throughput as a function of cell distance for DL different environments, 10 MHz channel bandwidth, 2100 frequency band, 64 QAM and MIMO 2×2.

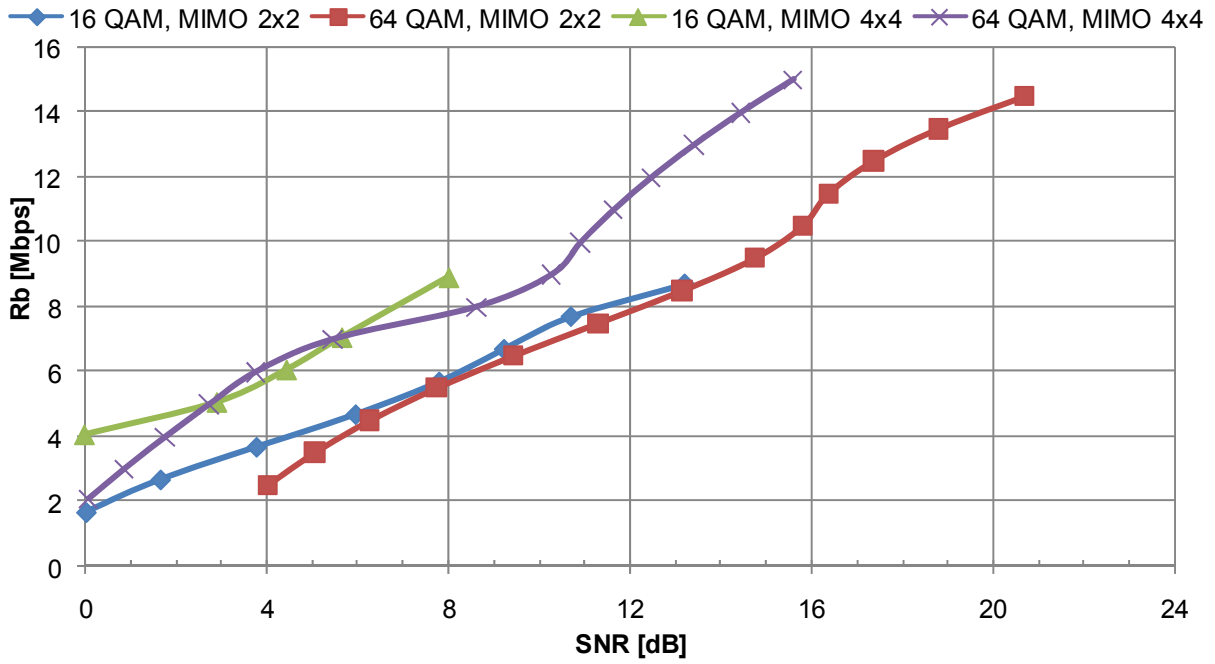


Figure F.14. Throughput as a function of SINR in UL Pedestrian channel, in 2.6 GHz band, channel bandwidth of 5 MHz.

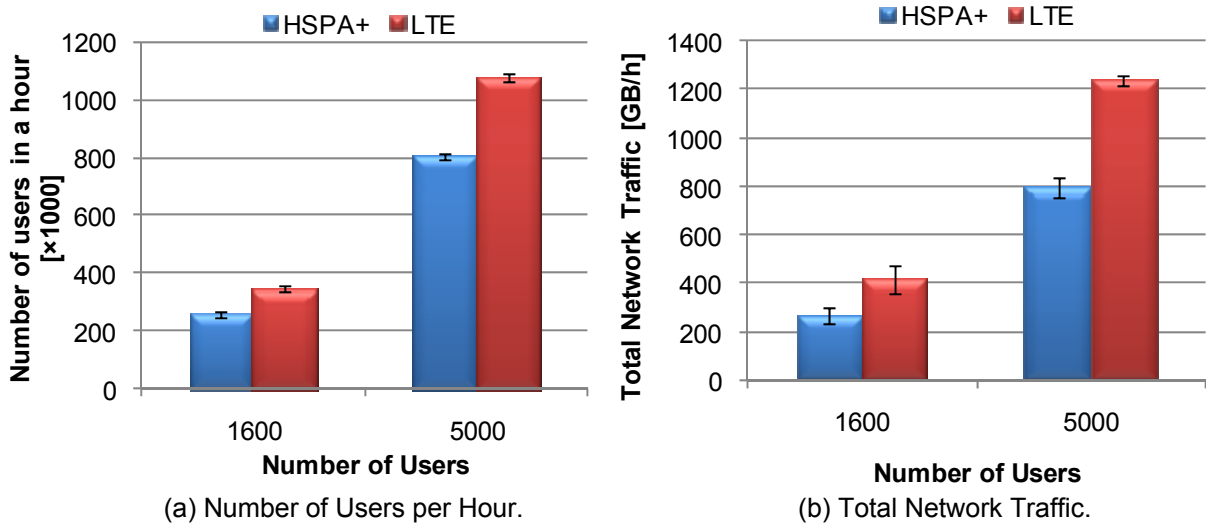


Figure F.15. HSPA+ and LTE DL Number of Users per Hour and Total Network Traffic for different number of users.

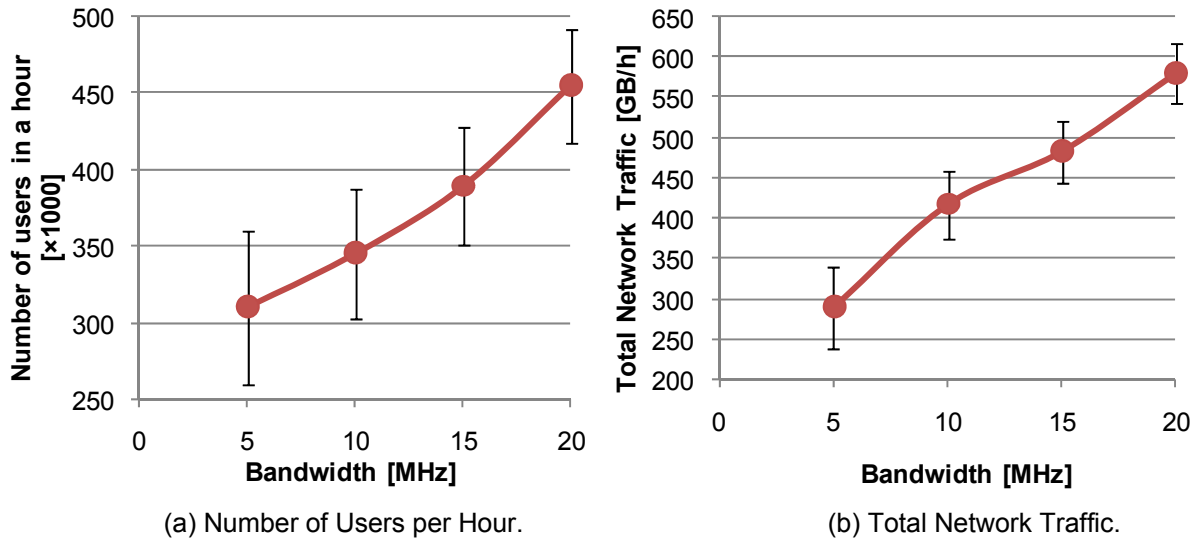


Figure F.16. LTE DL Number of Users per Hour and Total Network Traffic for different channel bandwidths.

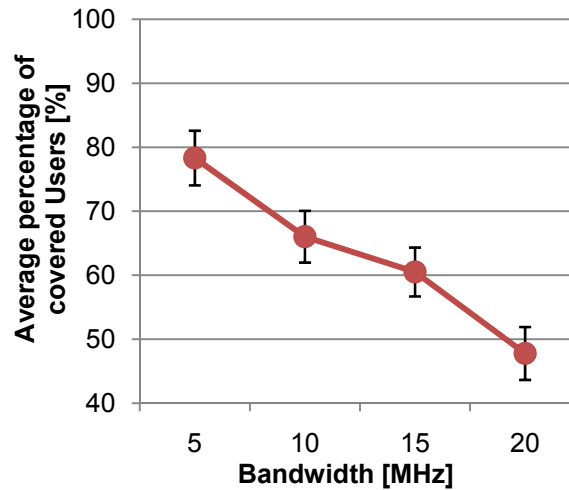


Figure F.17. LTE DL Average percentage of Covered Users for different channel bandwidths.

Despite the service profile chosen, the average network radius obtained is practically unvariable, as it shown on Table F.5.

Table F.5. Average network Radius considering Alternative Service Profiles.

System / Profile	DL			UL		
	DP	PP	RP	DP	PP	RP
HSPA+ [km]	0.328	0.320	0.336	0.136	0.129	0.141
LTE [km]	0.236	0.229	0.241	0.118	0.112	0.123

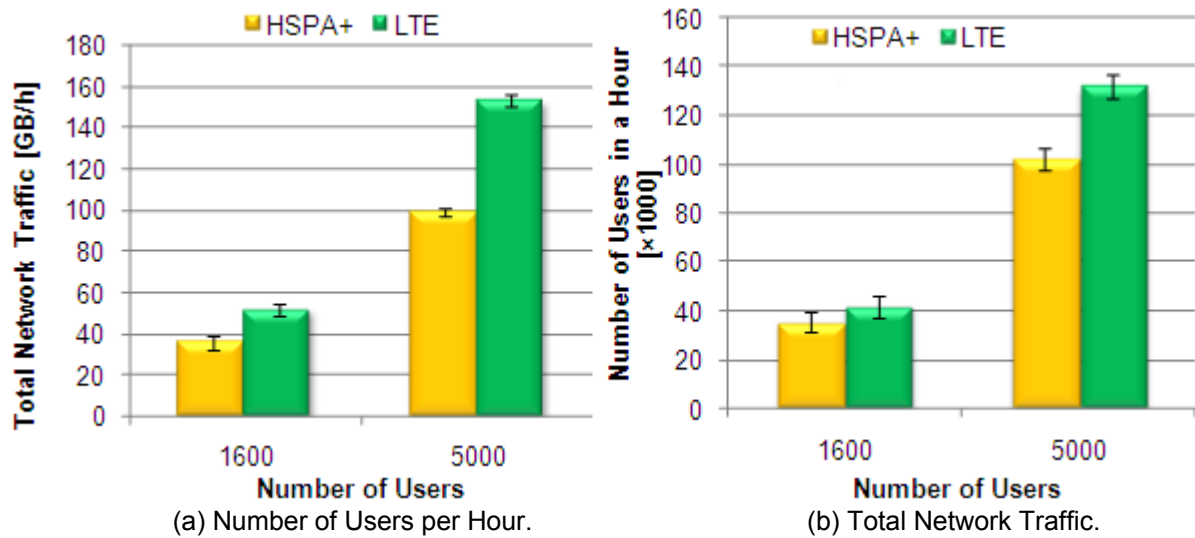


Figure F.18. HSPA+ and LTE UL Number of Users per Hour and Total Network Traffic for different number of users.

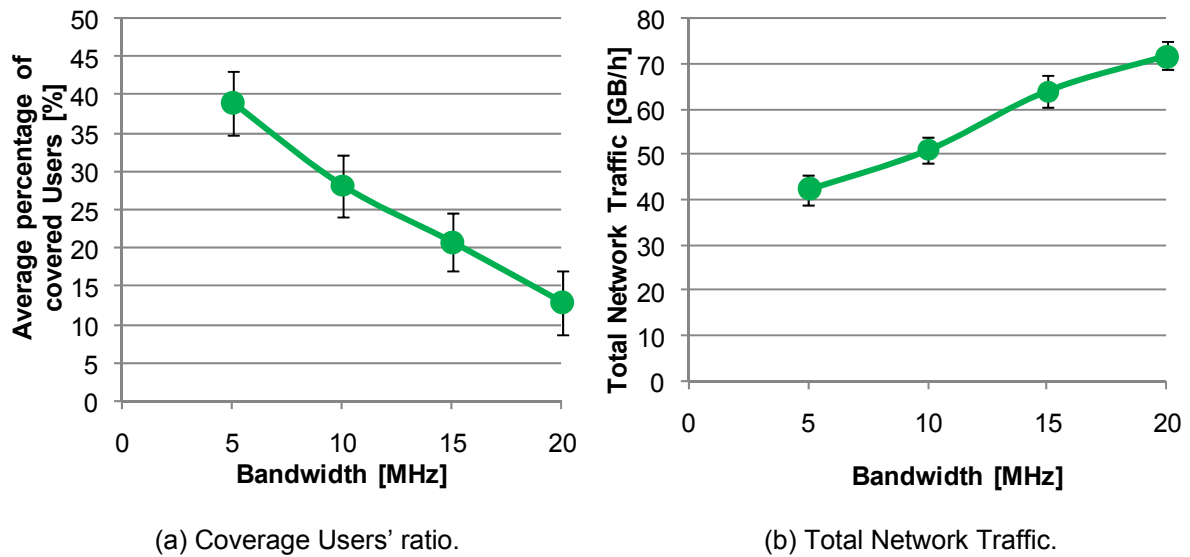


Figure F.19. LTE UL Coverage Users' ratio and Total Network Traffic for different channel bandwidths.

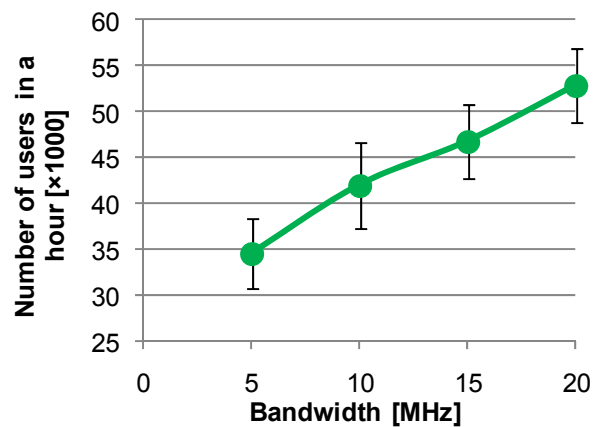


Figure F.20. LTE UL Number of Users per Hour.

Annex G – Models Simulator

Manual and User Interface

This annex includes a reference manual to the Single User Model Interface, UMTS/LTE_Optimizer and SIM Module, enabling a quickly guide with the menus and functional procedures.

G.1 Single User Model Graphical User Interface

Below, it is shown some screenshots of the SU Graphical User Interface (GUI), previously described on the Section 3.1. The figures made part of the SIM Module, where the SU's Model is incorporated, and optionally is chosen the desired radio system, UMTS/HSPA+ or LTE. To run the model there are no other menus to deal than the ones shown, and all the options accounted in the model are on these windows (to remember all the parameters taken into account, consult Section 3.1).

HSPA+ DL

Link Budget Parameters

DL Tx Power: 44.7 [dBm]
DL Frequency: 2112.5 [MHz]
Losses due to user: 1.0 [dB]
Cable losses: 2.0 [dB]
MT gain: 1.0 [dBi]
Node B gain: 18.0 [dBi]
Noise Figure: 9.0 [dB]

Signaling and Control Power

R99: 25.0 [%]
HSPA+ DL: 10.0 [%]

Overheads and Coding Rate

RLC: 2.5 [%]
MAC: 3.125 [%]
BLER: 10.0 [%]
Application: 5.0 [%]
Coding Rate: 100.0 [%]

Modulation

64QAM

Configuration

MIMO 2x2

Environment

☐ Pedestrian
☐ Vehicular
☒ Indoor

Margins

Slow Fading Margin: 7.6 [dB]
Fast Fading Margin: 2.0 [dB]
Indoor Margin: 20.0 [dB]

Throughput

28 [Mbps]

Result:

HSPA+ DL:
The cell radius for 28.000 Mbps is 0.168 km.
The total path loss is 122.298 dB.
The SNR is 18.129 dB.

Default Run Graph Exit New

Figure G.1 Screenshot of HSPA+ Single User Radius Model in DL.

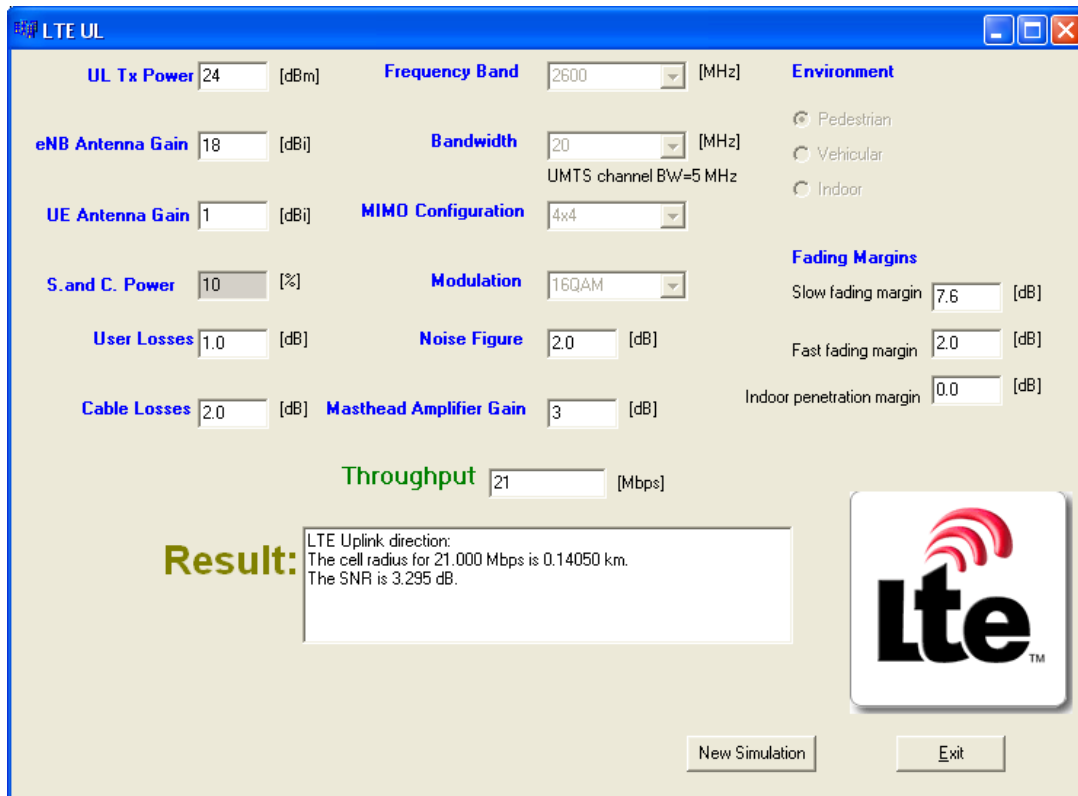


Figure G.2 Screenshot of LTE Single User Radius Model in UL.



Figure G.3 Opening Logo Model.

G.2 UMTS/LTE_Optimizer Graphical User Interface

To start the application, it is necessary to execute the only .MBX file, which represents the MapBasic Application, i.e., UMTS/LTE_Optimizer running on the MapInfo environment. The following is explained for one system only, being HSPA+ or LTE, however the same instructions are valid for both systems. Subsequently the program requests the introduction of the following input files:

- “Ant65deg.TAB”, with the BS antenna gain for all directions;
- “DADOS_Lisboa.TAB”, with information regarding the city of Lisbon and all its districts;
- “ZONAS_Lisboa.TAB”, with the area characterisation, like streets, gardens along with others,

Figure G.4.

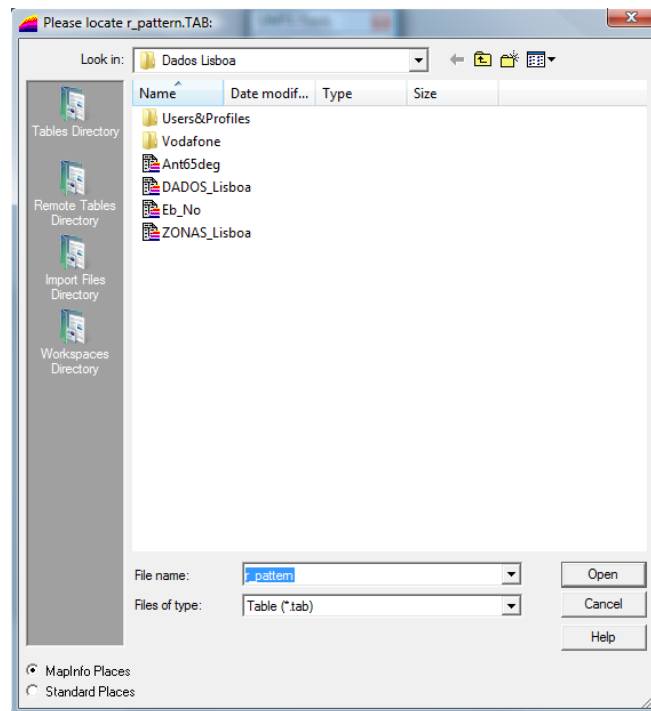


Figure G.4 Window for the introduction of ZONAS_Lisboa.TAB file.

After the introduction of the geographical information, over the MapInfo menu bar, 'System' menu, new options tab allows choosing between DL or UL, Figure G.5, and defining the simulation's characteristics.

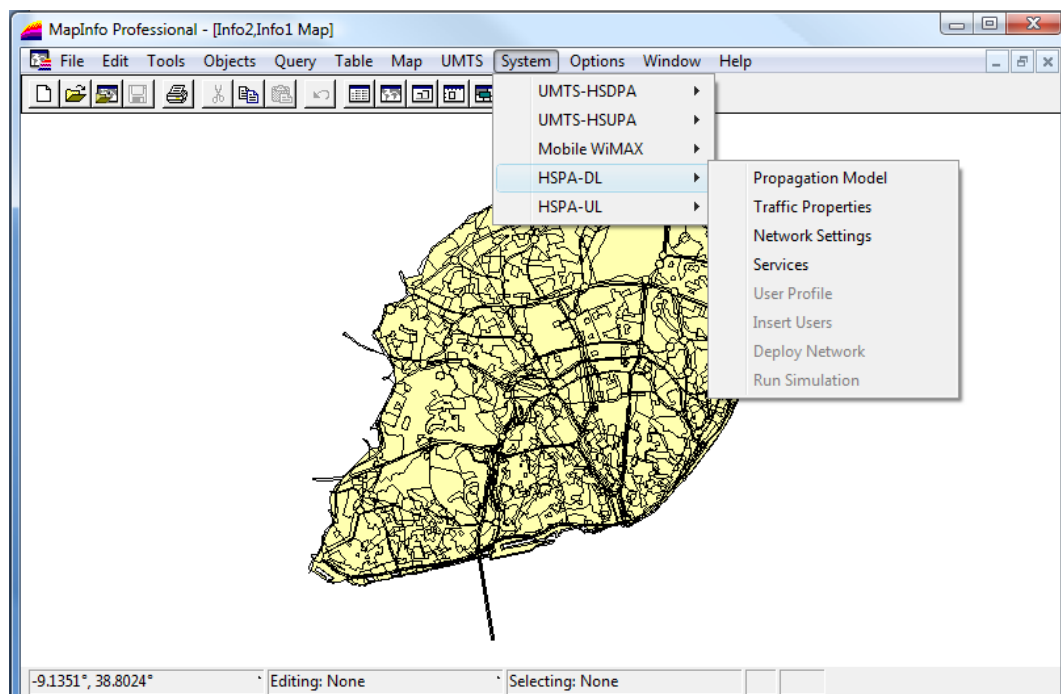
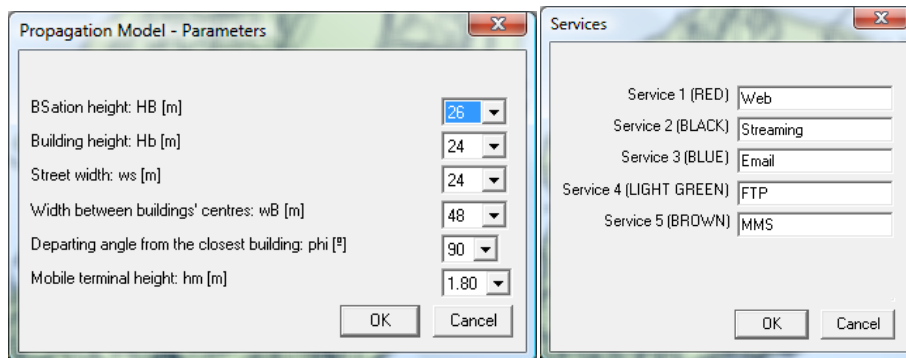


Figure G.5 View of the HSPA+ simulator and respective menu bar.

Among the several options that are available each for DL or UL, the windows for the 'Propagation Model', Figure G.6 (a), with the standard options for the COST231-W-I described on Annex C, 'Traffic Properties' and 'Services' characteristics are common displayed whatever the link chosen, Figure G.6

(b). On the 'Network Settings' window, Figure G.7, it is possible to modify the different radio parameters, along the default scenario, reference throughput and reduction strategy, regarding the inherent differences from DL/UL. After setting the network parameters, the 'User Profile' window is enabled, Figure G.8, being possible to change the maximum and minimum desired throughputs for each service. The values for the minimum throughput are the ones presented in Table 4.5, not being possible to define a minimum service throughput lower than the ones presented. The maximum throughputs are defined by the maximum network performance, i.e., possible to obtain due to bandwidth, MIMO configuration and modulation.



(a) Propagation Model.

(b) Services.

Figure G.6. System menu parameters.

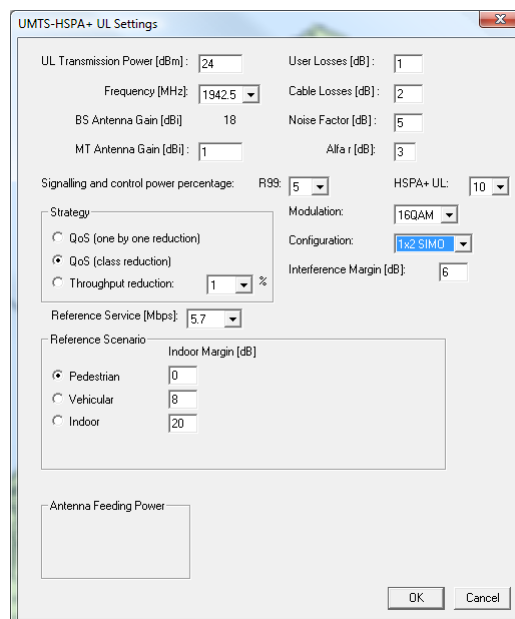


Figure G.7. HSPA+ UL Network Settings.

On the 'Traffic Properties' menu, the user is able to prioritize the QoS level and the volume of each service intended to perform over the network, and 'Services' enables the correspondence Service - colour ID, in order to the simulator graphically distinguish the offered services.

Type of Service	Throughput [Mbps]	Minimum Throughput [Mbps]
Web	5.7	1.024
Streaming	5	0.512
Email	1	0.384
FTP	5.7	1.024
MMS	0.512	0.128

OK Cancel

Figure G.8. HSPA+ UL User Profile.

Type of Service	Priority	Volume
Web - HTTP	1	300 kB
Not Defined	6	0 MB
Streaming	2	10 MB
MMS	4	200 bytes
Email	3	200 kB
FTP	5	20 MB

OK Cancel

Figure G.9. Traffic Properties.

After filling in the previous menu's information, it is displayed in the 'Message' window the results regarding the cell radius for the established service throughputs, Figure G.10.

Since the cell radius results are presented, the 'Insert Users' menu is available over the 'System' tab, with the purpose of introducing the users in the network, by choosing one of the output files from the SIM Module (*.txt).

Remember that one user at a time requests only one service and the input users are not equal to the ones considered over the network. It is shown on Table 3.1 the relation between the number of users effectively considered and the ones that are necessary to consider as input parameter in the SIM Module, as there are some users that are placed outside of the network area, not being considered in the analysis. Nevertheless, the SIM Module placed on Figure 3.2 is the same of the referred on the G.1 section. This is a program compiled only in C++ where are made all the SU simulations and calculations, and has another module which exports the user files (*.txt) as lists of users regarding the associated position over the network and the required service. Parameters, likely service traffic distributions derive from MOMENTUM project, [MOME04], and are adapted in [CoLa06].

The 'Deploy Network' menu is now active, requesting an input file containing the BSs' location (*.tab), so that these can be placed over the Lisbon metropolitan area. After the network is deployed, the 'Run Simulation' is switched on and the various simulations' results are displayed by pressing the 'OK' button.

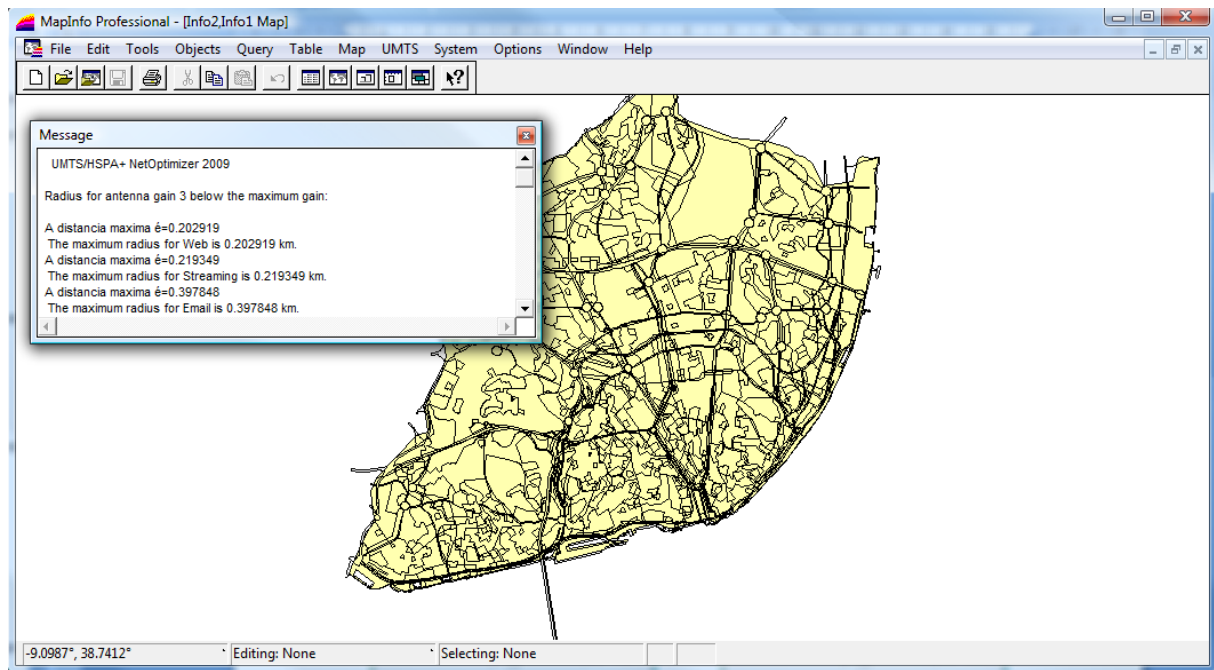


Figure G.10. Visual aspect of the application after running the Network Settings window.

Annex H – Reduction Strategies

Following, are illustrated as examples, the three reduction strategies possibly to apply in the LTE, at the same time they are complementary applied into HSPA+ besides the differences. The reduction strategies, explained in detail in [Duar08] and [Perg08], for both systems are:

- “Throughput reduction”, where all users are reduced for a certain percentage over the end user throughput, HSPA+, or for a certain number of data RBs according to the bandwidth, LTE.
- “QoS class reduction”, where all the users from the same services are reduced according to the services priority list.
- “QoS One by One reduction”, where for a certain service, each user throughput/RB is reduced one by one, according to the QoS priority list.

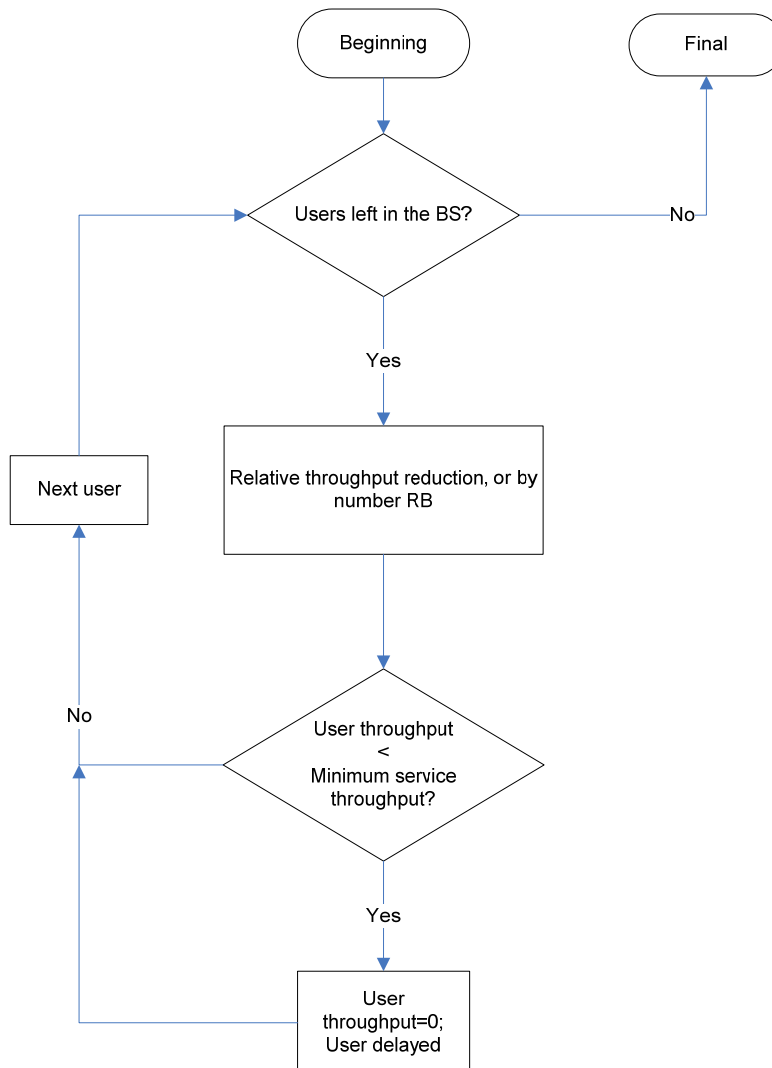


Figure H.1. “Reduction throughput” strategy algorithm.

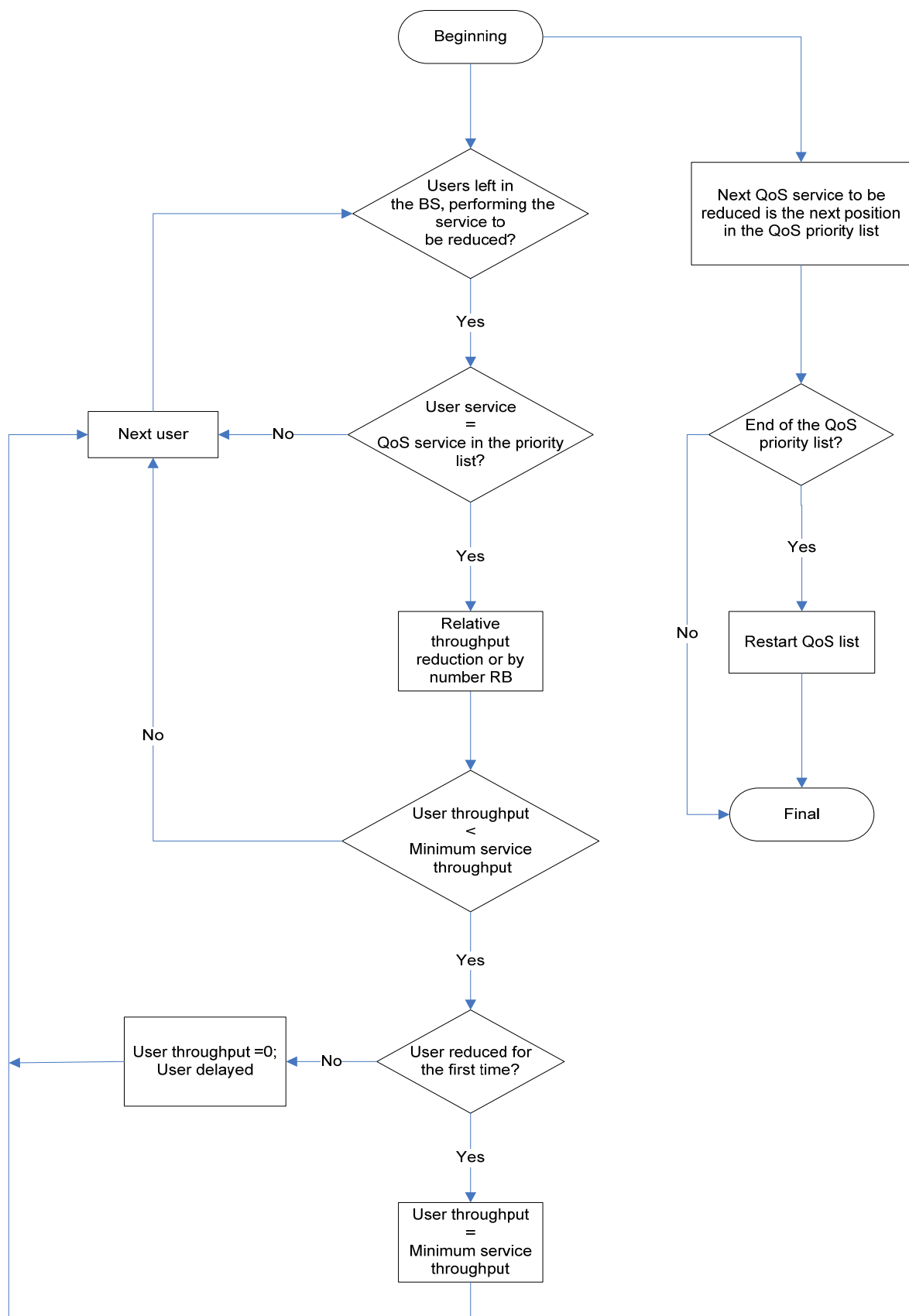


Figure H.2. "QoS class reduction" strategy algorithm.

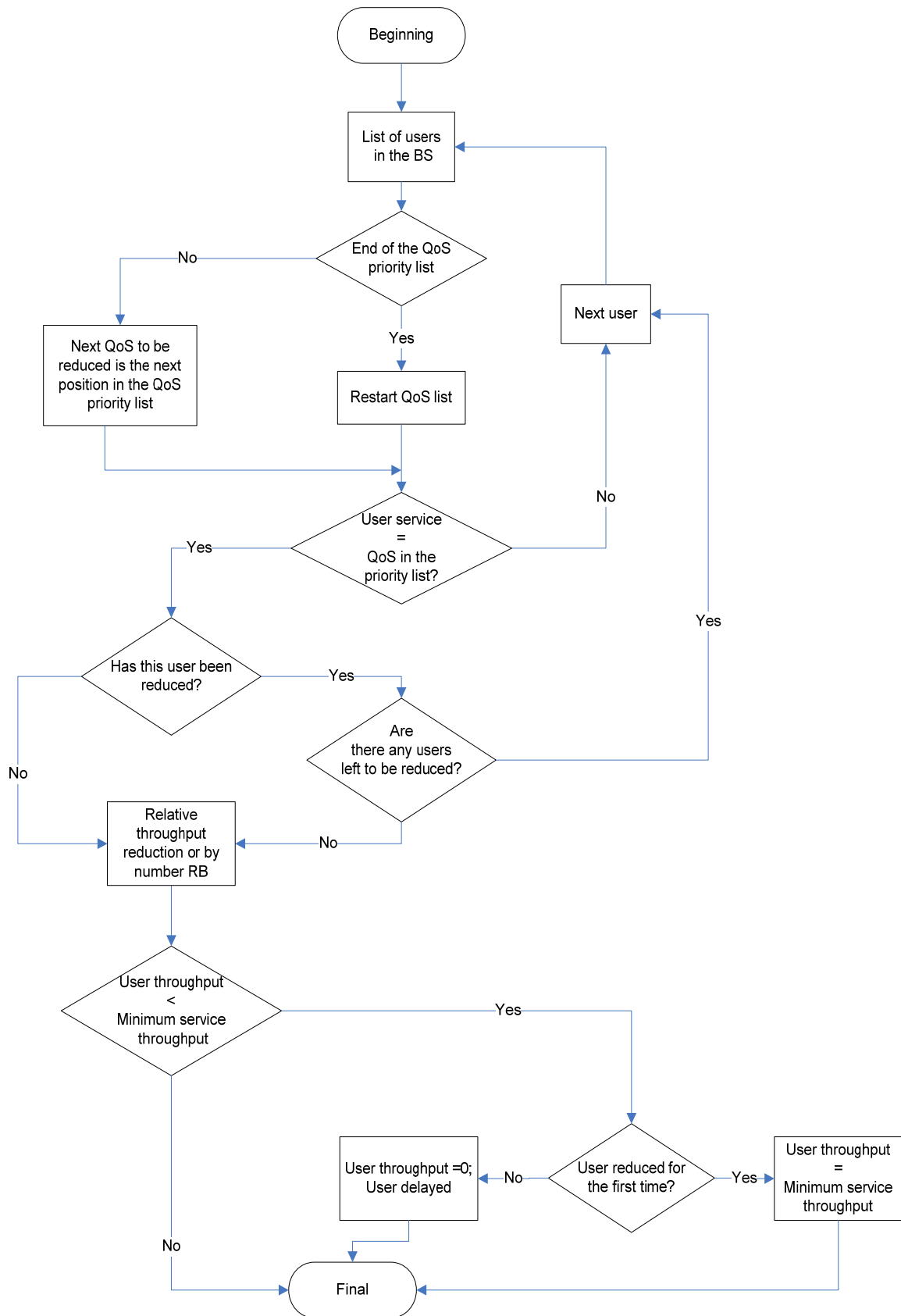


Figure H.3. "QoS one by one reduction" strategy algorithm.

Annex I – Relative MIMO Gain

Model

MIMO schemes are a breaking through into the current most demanding wireless technologies such as 3G, 4G, WiMAX, WLAN and so on. They are the result of parallel deployment of several space-separated antennas between two points, input and output. It not only improves BER performance, but also causes an increase of channel capacity and interference suppression, [Maćk07]. Nevertheless, the capacity in such system strongly depends on the propagation conditions in the radio channel and can vary significantly. Shannon's rule in fact upper limits the capacity of the radio channel, so taken in this case as the reference, the SISO channel capacity.

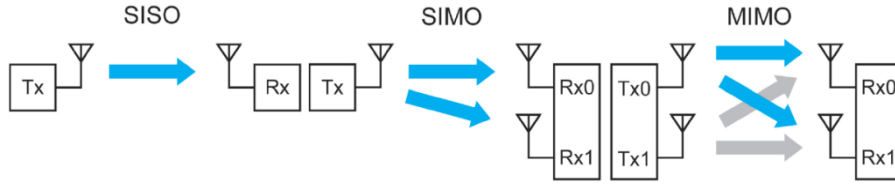


Figure I.1. Different radio transmission accesses (adapted from [Agil09]).

This system takes advantage of the multipath propagation, where the Receiver (R_x) antenna is reached by many copies of the transmitted signal. MIMO systems take advantage of all arriving arrays, [Maćk07] exploiting independently the transmission channels between the Transmitter (T_x) and Receiver (R_x) antennas. Since the correlation of a channel is between 0 and 1, it is possible to derive the upper and lower bounds for capacity. If there is no correlation between parallel paths, i.e., $\xi=0$, and additionally assuming that the signal is propagating without path loss, the maximum capacity is achieved:

$$C_{MIMO} = \min(N_T; N_R) \log_2 \left(1 + \frac{\rho_N}{N_T} \right) \quad (\text{H.1})$$

where:

- C_{MIMO} : capacity gain of a MIMO system;
- ρ_N : SNR;
- N_R : number of receiver antennas;
- N_T : number of transmitter antennas;

Otherwise, when all sub channels are totally correlated, $\xi=1$, the minimum capacity of a MIMO channel occurs:

$$C_{MIMO} = \log_2 \left(1 + \min(N_T; N_R) \frac{\rho_N}{N_T} \right) \quad (\text{H.2})$$

The real complexity of MIMO systems is returned by elaborated computational algorithms and intense processing capacity. In order to predict the improvement in capacity of using MIMO over SISO based on simulation results, the RMG Model developed by [KuCo08], was chosen. The model of the capacity

gains of MIMO described in [KuCo08] is based on simulation results from a MIMO radio channel simulator that takes into account the Geometrically Based Single Bounce (GBSB) channel model. The RMG is defined as the ratio between the MIMO and SISO capacities, C_{SISO} , of a radio link (H.3), with the RMG model being a statistical model developed to approximate the distribution of the RMG, based on simulation results. In order to maintain a low-complexity of the model, the distribution of the RMG is modelled with an inverse sigmoid function, which is completely modelled by its mean and variance.

$$G_{M/S} = \frac{C_{MIMO}}{C_{SISO}} \quad (H.3)$$

The general sigmoid function is given by:

$$\delta(x, \mu, s) = \frac{1}{1 + e^{\frac{x - \mu}{s}}} \quad (H.4)$$

where:

- μ_d , is the mean value of the distribution;
- s , determines the slope which is related to the variance, σ^2 , by: $\sigma^2 = \frac{\pi^2}{3} s^2$ (H.5)

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

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

where:

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

The values for the variance needed for this thesis are presented in Table I.1, and the mean results of the RMG model, μ_{RMG} , are presented in Table I.2, whereas the used ones along the work were the ones with non distance dependence. Simulation conditions and full results of RMG Model for others MIMO configurations can be consult in [KuCo08].

The use of MIMO multiplies, through the RMG model, the throughput obtained in SISO by a constant given by the model, increasing the achieved throughput.

Table I.1 Variance for different number of T_x and R_x antennas (adapted from [KuCo08]).

$\sigma^2_{RMG} (10^{-3})$		[10 – 60] m		[100 – 600] m		[1200 – 2400] m	
N_R		2	4	2	4	2	4
N_T	2	18.5	10.4	24.0	15.9	1.9	1.8
	4	11.8	45.4	15.9	71.4	0.8	1.1

Table I.2. μ_{RMG} for different configurations and distances (adapted from [KuCo08]).

$N_T \times N_R$	Range [m]	μ_{RMG}
2×2	-	1.54
4×4	10-31	$50.32d_{[km]} + 1.77$
	31-57	3.36
4×4	57-686	$-2.00d_{[km]} + 3.47$
4×4	686-2400	2.10

Annex J – Service and Applications Layer

It is been presented an evolution in terms of bit rate and capacity through the Release 99 and followers. These advances made over the network and terminal levels, creates new opportunities for new services and network capabilities; therefore, emerge of new services require high quality, or in other hand, high bandwidth and high bit rates. The introduction of IP Multimedia Sub-system (IMS) along with Session Initiation Protocol (SIP) enables the up rise of new services based on Internet applications [HoTo04].

The following description is made around 3GPP premises and specifications of traffic services description.

In order to manage the access to the different services, 3GPP defined different classes of services, essentially based on their Quality of Service (QoS) requirements. The four classes are: Conversational, Streaming, Interactive and Background and they have some factors distinguish them, such as, delay sensitiveness, the guaranteed bit rate and the different priorities. The following table states and summarizes the main differences between the 3GPP classes:

Table J.1. Services and applications according to 3GPP (based on [3GPP01] and [3GPP02a]).

Service Class	Conversational	Streaming	Interactive	Background
Real time	Yes	Yes	No	No
Symmetric	Yes	No	No	No
Guaranteed bit rate	Yes	Yes	No	No
Delay	Minimum Fixed << 1 s	Minimum Variable ~ 1 s	Moderate Variable < 10 s	High Variable > 10 s
Buffer	No	Yes	Yes	Yes
Bursty (not continuous)	No	No	Yes	Yes
Switching Type	CS	CS	PS	PS
Example	Voice, VoIP	Video Streaming	Web Browsing	SMS, E-mail

The Conversational class is mainly intended for speech services. Real time services require tighter delay requirements to maintain a minimum quality of service. The delay order should not overtake 400ms [HoTo04], e.g. maximum end-to-end delay given by the human perception for audio and video conversation. Examples of services used in this class can be CS or Voice over Internet Protocol (VoIP) which application run over IP, being supposed to work on the PS domain, requiring IP header compression and QoS differentiation to achieve low delays needed for Conversational service. Video telephony has even tighter Bit Error Ratio (BER) requirements than voice due to video compression. It is supposed to work on the PS domain although it can be transmitted on CS. As previous, IP header

compression and QoS differentiation are needed to allow efficiency at VoIP service. This class has priority face to the others classes due that voice is a primary service and the one who is most required.

The Streaming class points toward audio and video streaming. This type of service allows to the end user access data that is stored in several buffers at final terminal while the transmission is being completed. The information is real-time delivered in a continuous stream preserving time relation between packets, however is not delay-sensitive as voice from Conversational class. In this class the traffic is not symmetric thus DL traffic is the most significant.

The Interactive class is one with a lot of asymmetric traffic, being very delay tolerant. This class includes web browsing, online multiplayer games, Location-Based Services (LBS) and push-to-talk applications, services that are based on PS connections. These are characterised by requesting response patterns and preservation of payload contents. Nevertheless there are some delay limits to be respected to provide a good quality service. In web browsing, delay time should be maximum 7 s while in online multiplayer games introduces a new parameter called Round Trip Time (RTT) consisting in end-to-end delay, beyond the fact that gamers share packets between them at low bit rates, they have to be delivered with very short timings, typically below 100 ms [Lope08]. This defines a new challenge for nowadays networks setting high requirements for this new services kind.

Background class include services where transmission delays are not critical (e.g. Short Messaging Service (SMS), Multimedia Messaging Service (MMS), E-mail), on contrary in the interactive class the end-user is not waiting for a response within a short time, however this class is intolerant to transmission errors. Applications in this traffic class only use resource transmissions when none of the other classes are active.

Just to keep it straight, these traffic classes are flexible, which means that a multimedia application with restrict time delays requirements can be included in Conversational class. QoS differentiation becomes useful for the network efficiency during high load when there are services with different delay requirements.

Getting into a detailed Services and Applications analysis, it is fundamental to know which kind of data is transmitted over the network and who require it. The usage profile of data services, is not linear and due this fact it has to be taken into account that users can be defined among several categories, more or less detailed. Become aware that, a residential one has different demands from a professional user or even from the youth ages. Applications characteristics are drawn in Table J.2 like volume of the most demanded services, QoS priority level needed to apply reduction strategies. Also, the delay presented is the start-up service delay and it is not taken into account the transport delay variation possible to occur in the transfer process.

Table J.2. Service differentiation and characteristics (adapted from [3GPP06] and [Seba07]).

Service	Bit Rate [kbps]		QoS Priority Level	Delay [s]	Average Size/Duration	DL	UL
	DL	UL					
Chat	[64, 384]		7	-	Message size [bytes]	50	
Email	[384, 1536]	[128, 512]	5	< 4	File size [kB]	200	
FTP	[384, 2048]	[128, 512]	6	< 10	File size [MB]	10	
P2P	[128, 1024]	[64, 384]	8	< 10	File size [MB]	12.5	
Streaming	[512, 1024]	[64, 384]	4	< 10	Video size [MB]	9.6	0.2
Video-Telephony	[32, 128]		2	< 0.4	Call duration [s]	240	
Voice	[4, 25]		1	< 0.4	Call duration [s]	120	
Web	[512, 1536]	[128, 512]	3	< 4 /page	Page size [kB]	300	20

Web sessions, Figure J.1 are composed of packet service session, whereas these, include several packet calls compiling bursts of packets. The correspondent packet arrival times are variable among the radio channel in use, and by the system TTI, and the reading time frequently between packet calls, stands for the user's data interpretation time.

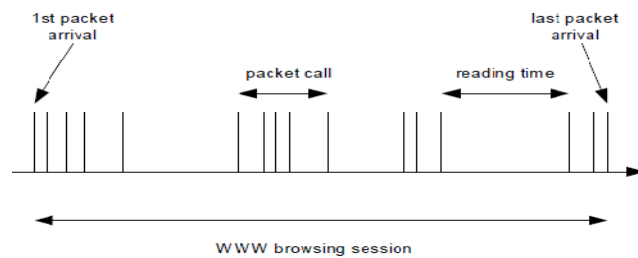


Figure J.1. Typical Web Session (extracted from [ETSI98]).

Remember that, with the evolution process of radio technologies, the rising of new demanding services is a constant new paradigm, which some can call as “killer applications”, hence the name, the service or application in which will use all the resources/capacity of the new technology or even require more then what can be offered. Nevertheless, nowadays there still exists some services which need a perfect RRM to be performed in a satisfactory way, like push-to-talk, video share and high definition video (DVB-H), multi-player games with low RTT and other person-to-person services.

DVB-H standards are European based, pointing towards to digital television contents on mobile devices. The possibility to receive these contents is able due an independent antenna working over the VHF (170 – 230 MHz) and UHF (470 – 862 MHz) bands. MBMS on the other hand, is one of many alternatives to the DVB-H, being an older mobile standard which uses the existing 2G, 3G networks and spectrum. Though, it has a weaker performance in terms of spectral efficiency, data rates and coverage. Notice that, a single DVB-H service data rate can be upon 10 Mbps along with scalable channel bandwidths between 5 to 8 MHz, in perfect handover conditions and over high moving speeds, [FuAh08], revealing a great business opportunity with the use of in-car systems.

Below, in Figure J.2, there is an evolution illustration between GSM and HSPA in terms of services.

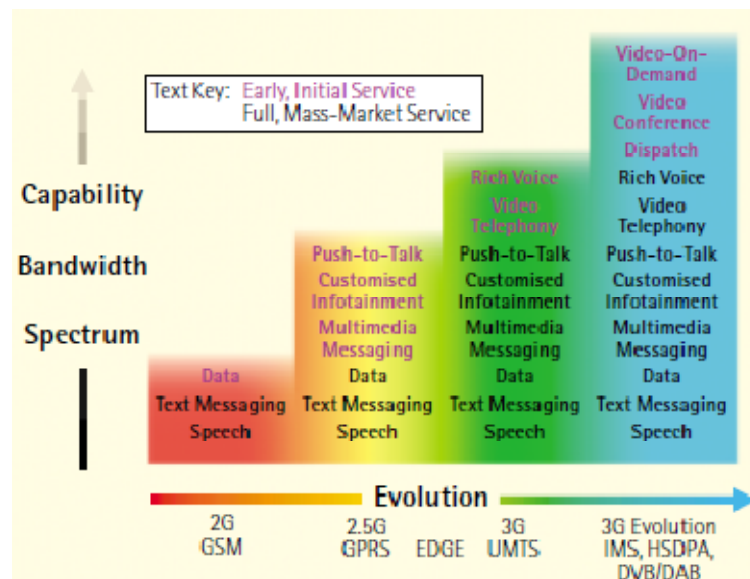


Figure J.2. Service differentiation between radio technologies (extracted from [UMTS09b]).

References

- [3GAM09a] 3G Americas, *HSPA to LTE-Advanced: 3GPP Broadband Evolution to IMT-Advanced (4G)*, Sep. 2009 (http://www.3gamericas.org/documents/3G_Americas_RysavyResearch_HSPA-LTE_Advanced_Sept2009.pdf).
- [3GAM09b] 3G Americas, *The Mobile Broadband Future: HSPA+ and LTE*, Sep. 2009 (http://www.3gamaricas.org/documents/3G_america.pdf).
- [3GPP01] 3GPP, Technical Specification Group Services and System Aspects, *Service aspects; Services and Service Capabilities (Release 99)*, Report TS 22.105, V3.10.0, Oct. 2001 (<http://www.3gpp.org/ftp/Specs/html-info/22105.htm>).
- [3GPP02a] 3GPP, Technical Specification Group Services and System Aspects, *Quality of Service (QoS) concept and architecture (Release 99)*, Report TS 23.107, V3.9.0, Sep. 2002 (<http://www.3gpp.org/ftp/Specs/html-info/23107.htm>).
- [3GPP02b] 3GPP, Technical Specification Group Radio Access Network, *Radio Interface Protocol Architecture (Release 99)*, Report TS 25.301, V3.11.0, Sep. 2002 (<http://www.3gpp.org/ftp/Specs/html-info/25301.htm>).
- [3GPP02c] 3GPP, Technical Specification Group – RAN WG1 (Radio Layer 1), *Revised CQI Proposal*, Report R1-02-0675, Paris, France, Apr. 2002 (http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_25/Docs/Zips/R1-02-0675.zip).
- [3GPP06] 3GPP, Technical Specification Group Services and System Aspects, *Service aspects, Services and Service Capabilities (Release 7)*, Technical Specification Group Services and System Aspects, Report TS 22.105, V7.1.0, Dec. 2006 (<http://www.3gpp.org/ftp/Specs/html-info/22105.htm>).
- [3GPP07a] 3GPP, Technical Specification Group Services and System Aspects; *Technical Specifications and Technical Reports for a UTRAN-based 3GPP system (Release 1999)*, Report TS 21.101, V3.17.0, Dec. 2007 (<http://www.3gpp.org/ftp/Specs/html-info/21101.htm>).
- [3GPP07b] 3GPP, Technical Specification Group Radio Access Network, *BS Radio transmission and Reception (FDD) (Release 99)*, Report TS 25.104, V3.14.0, Mar. 2007 (<http://www.3gpp.org/ftp/Specs/html-info/25104.htm>).
- [3GPP07c] 3GPP, Technical Specification Group Services and System Aspects; *Technical Specifications and Technical Reports for a UTRAN-based 3GPP system (Release 5)*, Report TS 21.101, V5.13.0, Dec. 2007 (<http://www.3gpp.org/ftp/Specs/html-info/22101.htm>).

- [3GPP07d] 3GPP, Technical Specification Group – RAN WG2 (Radio Layer 2), *HSPA+ User Plane Enhancements*, Report R2-070125, Sorrento, Italy, Jan. 2007 ([ftp://ftp.3gpp.org/tsg_ran/WG2_RL2/TSGR2_56bis/Documents/R2-070125.zip](http://ftp.3gpp.org/tsg_ran/WG2_RL2/TSGR2_56bis/Documents/R2-070125.zip))
- [3GPP08a] 3GPP, Technical Specification Evolved UTRA aspects, *Overall description (Release 8)*, Report TS 36.300, V9.1.0, Sep. 2009 (<http://www.3gpp.org/ftp/Specs/html-info/36300.htm>)
- [3GPP08b] 3GPP Communications Plan, PCG21_11 Late Contribution, *Setting the Standard for Mobile Broadband*, (http://www.3gpp.org/ftp/PCG/PCG_21/DOCS/PCG21_11r1.zip), Oct. 2008
- [3GPP08c] 3GPP, Technical Specification Group Radio Access Network, *Evolved Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 8)*, Report TS 36.211, V8.8.0, Sep, 2009 (<http://www.3gpp.org/ftp/Specs/html-info/36211.htm>).
- [3GPP09a] 3GPP, Technical Specification Group Radio Access Network; *UE Radio Access capabilities (Release 8)*, Report TS 25.306, V8.7.0, Jun, 2009 (<http://www.3gpp.org/ftp/Specs/html-info/25306.htm>)
- [3GPP09b] 3GPP, Technical Specification Group Radio Access Network, *Evolved Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities (Release 8)*, Report TS 36.306, V8.3.0, Mar, 2009 (<http://www.3gpp.org/ftp/Specs/html-info/36306.htm>)
- [3GPP09c] 3GPP, Technical Specification Group Radio Access Network, *Evolved Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 9)*, Report TS 36.101, V.9.0.0, Jun, 2009 (<http://www.3gpp.org/ftp/Specs/html-info/36101.htm>).
- [Alca09] Alcatel-Lucent, “*Alcatel-Lucent W-CDMA/HSPA Evolution*”, Public Brochure, Alcatel-Lucent, Paris, FR, 2009 ([http://www.alcatel-lucent.com/wps/DocumentStreamerServlet?LMSG_CABINET=Docs_and_Resource_Ctr&LMSG_CONTENT_FILE=Brochures/CAR7526081107_bro\(HSPA\).pdf](http://www.alcatel-lucent.com/wps/DocumentStreamerServlet?LMSG_CABINET=Docs_and_Resource_Ctr&LMSG_CONTENT_FILE=Brochures/CAR7526081107_bro(HSPA).pdf))
- [Agil07] Agilent Technologies, “*Agilent Technologies Solutions for 3GPP LTE*”, Technical Overview, USA, 2007 (<http://cp.literature.agilent.com/litweb/pdf/5989-6331EN.pdf>)
- [Agil08] Agilent Technologies, “*Agilent 3GPP Long Term Evolution: System Overview, Product Development and Test Challenges*”, Application Note, USA, 2008 (<http://cp.literature.agilent.com/litweb/pdf/5989-8139EN.pdf>)
- [Agil09] Agilent Technologies, *LTE and the Evolution to 4G Wireless: Design and Measurement Challenges*, John Wiley & Sons, Palo Alto, CA , USA , 2009.
- [Anac09] Anacom, “*Informação Estatística do Serviço de Acesso à Internet 1º Timestre de 2009*”, Public Report, Lisbon, PT, 2009 (http://www.anacom.pt/streaming/acesso_internet1trimestre2009.pdf?contentId=952500&field=ATTACHED_FILE)

- [BBSS04] Brouwer,F., Bruin,I., Silva,J., Souto,N., Cercas,F. and Correia,A., “Usage of Link-Level Performance Indicators for HSDPA Network-Level Simulations in E-UMTS”, in *Proc. of ISSSTA2004 - IEEE International Symposium on Spread Spectrum Techniques and Applications*, Sydney, Australia, Sep. 2004.
- [BEGG08] Bergman,J., Ericson,M., Gerstenberger,D., Göransson,B., Peisa,J. and Wager,S., “HSPA Evolution – Boosting the performance of mobile broadband access”, *Ericsson Review*, Vol 85, N°1, 2008.
- [BGG09] Bergman,J., Gerstenberger,D., Gunnarsson,F., Ström,S., “Continued HSPA Evolution of mobile broadband”, *Ericsson Review*, Vol. 86, N°1, 2009.
- [Carv09] Carvalho,G., *Data Rate Performance Gains in UMTS Evolution at the cellular level*, M.Sc. Thesis, Instituto Superior Técnico, Lisbon, Portugal, Oct. 2009.
- [CEGH02] Catreux,S., Erceg,V., Gesbert,D. and Heath,R.W. Jr., “Adaptive Modulation and MIMO Coding for Broadband Wireless Data Networks”, *IEEE Communications Magazine*, Vol. 40, No. 6, Jun. 2002, pp.108-115.
- [CiSy08] Cisco Systems, *Cisco Documentation, Overview of GSM, GPRS, and UMTS* (http://www.cisco.com/univercd/cc/td/doc/product/wireless/moblwrls/cmx/mmg_sg/cmxgsm.htm), Sep. 2008.
- [CoLa06] Costa,P. and Ladeira,D., *Planning of UMTS Cellular Networks for Data Services Based on HSDPA* (in Portuguese), Graduation Thesis, IST-UTL, Lisbon, Portugal, 2006.
- [Corr08] Correia,L.M., *Mobile Communication Systems – Course Notes*, IST-TUL, Lisbon, Portugal, Sep. 2008.
- [DaCo99] Damasso,E. and Correia,L.M., *Digital Mobile Radio Towards Future Generation*, COST231 Final Report, 1999 (<http://www.lx.it.pt/cost231/>).
- [DraJ07] Drajić,D., “60 Years of Shannon Information Theory”, in *Proc. Of 8th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services*, Niš, Serbia, Sep. 2007
- [Duar08] Duarte,S., *Analysis of Technologies for Long Term Evolution in UMTS*, M.Sc. Thesis, Instituto Superior Técnico, Lisbon, Portugal, Sep. 2008.
- [EFKM06] Ekström,H., Furuskär,A., Karlsson, J., Meyer,M., Parkvall,S., Torsner,J. and Wahlqvist, M., “Technical Solutions for the 3G Long-Term Evolution”, *IEEE Communications Magazine*, Vol. 44, No. 3, Mar. 2006, pp. 38-45.
- [Eric04] Ericsson, *Key Business Issues in the Service Layer*, White Paper, Stockholm, Sweden, 2004 (http://www.gsmworld.com/documents/service_wp_layer.pdf).
- [Eric08] Ericsson AB, Press Releases, http://www.ericsson.com/au/ericsson/press/2008/20080116_mobile_growth.shtml, Apr. 2009

- [Eric09] Ericsson AB, Long Term Evolution (LTE): an introduction (http://www.ericsson.com/technology/whitepapers/lte_overview.pdf), Jun. 2009.
- [ETSI98] ETSI, Universal Mobile Telecommunications System (UMTS); *Selection procedures for the Choice of Radio Transmission Technologies of the UMTS* (UMTS 30.03 version 3.2.0), TR 101 112, V3.2.0, France, Apr. 1998.
- [FuAh08] Furht, B. and Ahson, S., *Handbook of Mobile Broadcasting: DVB-H, DMB, ISDB-T, and MEDIAFLO*, CRC Press, Boca Raton FL, USA, 2008.
- [Gold05] Goldsmith, A., *Wireless Communications*, Cambridge University Press, UK, 2005.
- [GSMA09] GSM Arena, <http://www.gsmaarena.com>, Aug. 2009.
- [HEEE05] Helmersson, K., Englund, E., Edvardsson, M., Edholm, C., Parkvall, S., Samuelsson, M., Wang, Y. and Cheng, J., "System Performance of WCDMA Enhanced Uplink", in *Proc. of VTC'05 Spring – 61st IEEE Vehicular Technology Conference*, Stockholm, Sweden, June 2005.
- [HGMT05] Hagerman, B., Gunnarsson, F., Murai, H., Tadenuma, M., Karlsson, J., "WCDMA Uplink Parallel Interference Cancellation - System Simulations and Prototype Field Trials" in *EURASIP Journal on Applied Signal Processing*, Nov. 2005, pp 1725-1735.
- [HoTo04] Holma, H. and Toskala, A., *WCDMA for UMTS* (3rd Edition), John Wiley & Sons, Chichester, UK, 2004.
- [HoTo06] Holma, H. and Toskala, A., *HSDPA/HSUPA for UMTS*, John Wiley & Sons, Chichester, UK, 2006.
- [HoTo07] Holma, H. and Toskala, A., *WCDMA for UMTS – HSPA Evolution and LTE* (4rd Edition), John Wiley & Sons, Chichester, UK, 2007.
- [HoTo09] Holma, H. and Toskala, A., *LTE for UMTS - OFDMA and SC-FDMA Based Radio Access*, John Wiley & Sons, Chichester, UK, 2009.
- [Kath06] Kathrein-Werke KG, *UMTS Antenna Line Products from the World's largest Antenna Supplier*, Public Catalogue, Rosenheim, GER, 2006 (<http://www.kathrein.de/en/mcs/catalogues/download/99810446.pdf>)
- [Kath09] Kathrein-Werke KG, *LTE/WiMAX Antennas from the World's largest Antenna Supplier*, Public Catalogue, Rosenheim, GER, 2009 (<http://www.kathrein.de/en/mcs/catalogues/download/99811301.pdf>)
- [KePP03] Keskitalo, I., Page, J., Palin, A., "Ultra Wide Band (UWB) Compatibility with IMT-2000, Time for a Transform or Noisy Neighbours?", in *3G Mobile Communication Technologies, 2003. 3G 2003. 4th International Conference on (Conf. Publ. No. 494)*, 25-27 Jun. 2003, pp 304-308.
- [KuCo08] Kuipers, M., Correia, L.M., "Modelling the Relative MIMO Gain", in *Proc. of PIMRC'08 - IEEE Personal, Indoor and Mobile Radio Communications*, Cannes, France, Sep. 2008.

- [LLMP09] Larmo,A., Lindström,M., Meyer,M., Pelletier,G., Torsner,J. and Wiemann,H., "The LTE Link-Layer Design", Vol. 47, No.4, *IEEE Communications Magazine*, Vol , Apr. 2009, pp.52-59.
- [Lope08] Lopes,J., *Performance of UMTS/HSDPA/HSUPA at the Cellular Level*, M.Sc. Thesis, Instituto Superior Técnico, Lisbon, Portugal, 2008
- [Lync09] Lynch,D., *Verizon Communications*, Internal Presentation, NYC, NY, USA, 2009 (http://news.vzw.com/LTE/Dick_Lynch_MWC_Final.pdf)
- [Maćk07] Maćkowiak,M., *Geometrically Based Multibounce MIMO Channel Models*, M.Sc. Thesis, IST-UTL, Lisbon, Portugal, 2007.
- [Mark03] Marks,R., "The IEEE 802.16 WirelessMAN Standard for Broadband Wireless Metropolitan Area Networks", in *IEEE Computer Society Distinguished Visitors Program, IEEE C802.16-03/06*, CO, USA, Apr. 2003
- [MOME04] IST-MOMENTUM – Models and Simulation for Network Planning and Control of UMTS (<http://momentum.zib.de/>).
- [Moto07] Motorola, *Long Term Evolution (LTE): Overview of LTE Air-Interface*, Technical White Paper, USA, 2007 (<http://www.business.motorola.com/experienclte/pdf/LTEAirInterfaceWhitePaper.pdf>)
- [Moto08] Motorola, *Spectrum Analysis for Future LTE Deployments*, Technical White Paper, USA, 2007 (<http://business.motorola.com/experienclte/pdf/LTESpectrumAnalysisWhitePaper.pdf>)
- [MZDW04] Malladi,D., Zhang,X., Damjanovic,J. and Willenegger,S., "WCDMA Uplink System Performance", in *Proc. Of VTC2004-Fall – 60th IEEE Vehicular Technology Conference*, Los Angeles, USA, Sep. 2004.
- [NSNe09] Nokia Siemens Networks, Press Releases, http://www.nokiasiemensnetworks.com/global/Press/Press+releases/news-archive/Up_to_ten_times_faster_mobile_broadband_data_rates_a_step_closer_to_reality.htm , Jan. 2009
- [Nuay07] Nuaymi,L., *WiMAX – Technology for Broadband Wireless Access*, John Wiley & Sons, Chichester, UK, 2007.
- [Pede05] Pedersen,K.I., "Quality Based HSDPA Access Algorithms", in *Proc. of VTC'05 Fall – 62nd IEEE Vehicular Technology Conference*, Dallas, TX, USA, Sep. 2005.
- [Perg08] Perguiça,R., "Comparison between UMTS/HSPA+ and WiMAX/IEEE 802.16e in Mobility Scenarios", M.Sc. Thesis, Instituto Superior Técnico, Lisbon, Portugal, Sep. 2008.
- [PTIN06] PT Inovação, *Novos Interfaces Rádio (4G)*, Projecto IST WINNER, PT Inovação, Lisboa, PT, 2006 (http://www.ptinovacao.pt/actividade/proj_EST/fol_Winner.pdf)
- [PWST07] Peisa, J., Wager, S., Sågfors, M., Torsner, J., Göransson, B., Fulghum, t., Cozzo, C. and

- Grant, S., "High Speed Packet Access Evolution – Concept and Technologies", in *Proc. of Vehicular Technology Conference*, Dublin, Ireland, Apr. 2007.
- [Qual08] Qualcomm, *3G Leading the mobile broadband evolution*, Jun. 2008 ([http://www.huticce.org/2008/Keynotes/ICCE 2008 presentation revised \(keith\).pdf](http://www.huticce.org/2008/Keynotes/ICCE 2008 presentation revised (keith).pdf))
- [Qual09a] Qualcomm, *HSPA+ R7*, Public Document, San Diego, CA, USA, 2009 (http://www.qualcomm.com/common/documents/articles/HSPAplus_R7_Benefits_071009.pdf)
- [Qual09b] Qualcomm, *HSPA+ for Enhanced Mobile Broadband*, Public Document, San Diego, CA, USA, 2009
- [Qual09c] Qualcomm, *LTE and Release 8 and beyond*, Public Document, San Diego, CA, USA, 2009 (http://www.qualcomm.com/common/documents/articles/LTE_Benefits_072109.pdf)
- Ericsson, *Key Business Issues in the Service Layer*, White Paper, Stockholm, SWE, 2004 (http://www.gsmworld.com/documents/service_wp_layer.pdf)
- [RuHa05] Ruzicka,Z. and Hanus,S., "Radio Network Dimensioning in UMTS Network Planning Process", *Applied Electromagnetics and Communications, ICECom 2005, 18th International Conference*, Dubrovnik, Croatia, October 2005
- [RuYo08] Rumney,M. and Yokoyama,M., "3GPP LTE Downlink", *Agilent Measurement Journal*, Issue 5, May 2008, pp. 16-25
- [Salv08] Salvado,L., "*UMTS/HSDPA comparison with WiMAX/IEEE 802.16e in mobility scenarios*", M.Sc. Thesis, Instituto Superior Técnico, Lisbon, Portugal, Fev. 2008.
- [Sant04] Santo,L., *UMTS Performance in Multi-Service Non-Uniform Traffic Networks*, M.Sc. Thesis, Instituto Superior Técnico, Lisbon, Portugal, Dec. 2004.
- [Seba07] Sebastião,D., *Algorithms for Quality of Service in a WiFi Network*, M.Sc. Thesis, Instituto Superior Técnico, Lisbon, Portugal, Dec. 2007.
- [SeCa04] Sebastião,D. and Cardeiro,J., *Modelation and Traffic Dimensioning in the UMTS Radio Interface*, Graduation Thesis, Instituto Superior Técnico, Lisbon, Portugal, Oct. 2004.
- [SSOA07] Sternad,M., Svensson,T., Ottosson,T., Ahlén,A., Svensson,A. and Brunstrom,A., "Towards Systems Beyond 3G based on Adaptive OFDMA Transmission", *Proceedings of IEEE*, Vol.95, No. 12, Dec. 2007, pp. 2432-2455
- [TEK09] Portal TEK Sapo, http://tek.sapo.pt/noticias/telecomunicacoes/vodafone_estende_velocidade_movel_a_28_8_mbps_1007948.html, Jul. 2009.
- [UMTS09a] UMTS Forum, <http://www.ums-forum.org/content/view/2558/109/>, Jan. 2009.
- [UMTS09b] UMTS Forum, http://www.ums-forum.org/component/option,com_docman/task,doc_download/gid,1628/, Aug. 2009.

- [Voda09] Private Communication, Vodafone Portugal, 2009.
- [Veri09] Verizon, News Media Release, <http://news.vzw.com/news/2009/08/pr2009-08-14f.html>, Sep. 2009.
- [Wang04] Wang,X., *3G HSDPA Performance in Mobile Internet Connections*, M.Sc. Thesis, Royal Institute of Technology, Stockholm, Sweden, 2004.
- [Zimm80] Zimmermann, H., "OSI Reference Model – The ISO Model Architecture for Open Systems Interconnection", *IEEE Transactions on Communications*, Vol. 28, No. 4, Apr. 1980, pp. 425-432.