



INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

Performance Analysis of UMTS/HSDPA/HSUPA at the Cellular Level

João Manuel Cardoso Lopes

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

Jury

Supervisor: Prof. Luís M. Correia

President: Prof. António Topa

Members: Prof. António Grilo

Mr. Luís Santo

March 2008

To my parents and sisters

“Real difficulties can be overcome; it is only the imaginary ones that are unconquerable.”

Theodore Newton Vail

Acknowledgements

First of all, I would like to thank to Professor Luís Correia for the unique opportunity to perform this thesis and for the constant knowledge and experience sharing. His orientation, availability, guidelines, advising, opinion, and constant support, were a key factor for the completion of this work, and will also be useful for my professional future.

To Optimus, especially to Luís Santo and to David Antunes for all the suggestions, constructive critics, technical support and advice, and for having the time to answer all doubts with enormous patience. I also would like to thank the opportunity to perform measurements in both the Optimus test plant and in the live network, which gave me a better inside view of the technology, and allowed be to improve my technical knowledge.

To all GROW members for the clarifications, all the support and the contact with several other areas of wireless mobile communications. In particular I want to thank to Daniel Sebastião for sharing some results of his Master Thesis, and to Diana Ladeira for the patience and orientation in the critical software development phase.

I also want to thank to Mónica Antunes, Luís Salvado and Pedro Sobral for their friendship, the useful suggestions, different points of view, and the never ending discussions that allowed me to better understand several concepts. In a more personal level, I want to thank them for the good company, and for giving me strength that was essential for the completion of this journey.

I would like to thank to Ericsson, in particular to my colleagues from the SNA group, especially to Luís Anunciada, for the understanding and by providing the necessary availability for the conclusion of this thesis.

I also want to thank to all my friends for all the support, patience and encouragement. To Ivo Sousa, Filipe Tocha and Luís Ruivo for their opinions, good ideas, suggestions, and help provided during the conclusion of the thesis. A special thank to Bernado Borges for the company in the several running sessions that help me to lighten up the stress. I also want to thank to Liliana Baltazar and to Diana Martins for their friendship, caring, motivation and support throughout this demanding journey.

Finally, I also would like to thank to my family, and especially to my parents and sisters, for all the support and understanding throughout this last year, and to my sister Sara for all the good writing suggestions and revisions. Their love and care kept me going in the hardest times.

Abstract

The main purpose of this thesis was to analyse and compare UMTS HSDPA and HSUPA capacity and coverage. For this purpose, a single user model was developed for the calculation of the maximum cell radius. This model was adapted to a multiple users and multiple services scenario. The results from the single user model, as well as the ones from the multiple users simulator, were compared with measurements performed in both Optimus test plant and live network.

The results from the single user model show that, in an indoor scenario, HSUPA can serve 1.22 Mbps up to 0.19 km, while HSDPA with 10 HS-PDSCH codes can serve 6.0 Mbps up to 0.17 km. In a pedestrian environment, HSUPA can offer 1 Mbps up to 0.7 km, while at the same distance HSDPA can offer almost 3.0 Mbps.

The results from the multiple users simulator show an average cell radius of 0.28 km and 0.25 km for HSDPA and HSUPA, respectively. For HSDPA, one obtains 2.39 Mbps for the Node B throughput, and an average throughput per user of 0.55 Mbps, while for HSUPA, one gets a Node B throughput of 0.62 Mbps, and 0.21 Mbps for the average user throughput.

Keywords

UMTS, HSDPA, HSUPA, Coverage, Capacity, Multiservice Traffic

Resumo

Os objectivos principais desta tese foram a análise e a comparação da capacidade e cobertura do UMTS HSDPA e do HSUPA. Para isso, desenvolveu-se um modelo para monoutilizador com o objectivo de calcular o raio máximo da célula. Este modelo foi adaptado a um cenário de múltiplos utilizadores e de multisserviço. Os resultados do modelo de monoutilizador assim como os do simulador foram comparados com as medidas realizadas na *test plant* e na rede *live* da Optimus.

Os resultados do modelo de monoutilizador mostraram que, num cenário interior, o HSUPA consegue servir 1.22 Mbps até 0.19 km enquanto o HSDPA, com 10 códigos HS-PDSCH, consegue servir 6.0 Mbps até 0.17 km. Num cenário pedestre, o HSUPA consegue oferecer 1.0 Mbps até 0.7 km, enquanto o HSDPA oferece quase 3.0 Mbps.

Os resultados do simulador multisserviço mostram um raio médio da célula de 0.28 km e 0.25 km para HSDPA e HSUPA, respectivamente. No caso do HSDPA, o débito binário obtido para o *Node B* foi de 2.39 Mbps e de 0.55 Mbps por utilizador, enquanto que, para o HSUPA, se obteve um débito binário de 0.62 Mbps para o *Node B* e de 0.21 Mbps por utilizador.

Palavras-chave

UMTS, HSDPA, HSUPA, Cobertura, Capacidade, Tráfego Multisserviço

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List of Acronyms

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
16QAM	16 Quadrature Amplitude Modulation
A-DCH	Associated Dedicated Channel
ACK	Acknowledgment
AICH	Acquisition Indicator Channel
AP-AICH	Access Preamble Acquisition Channel
AMC	Adaptive Modulation and Coding
AMR	Adaptive Multirate
AMR-WB	Wideband AMR
ARP	Allocation Retention Priority
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BCH	Broadcast Channel
BER	Bit Error Rate
BLEP	Block Error Probability
BLER	Block Error Rate
BPSK	Binary Phase Shift Keying
CA-ICH	Channel Assignment Indicator Channel
CD-ICH	Collision Detection Indicator Channel
CDMA	Code Division Multiple Access
CN	Core Network
CPCH	Common Packet Channel
CPICH	Common Pilot Channel
CQI	Channel Quality Information
CRNC	Controlling RNC
CS	Circuit Switch
CSICH	CPCH Status Indication Channel
DCH	Dedicated Channel
DL	Downlink
DPCCH	Dedicated Physical Control Channel
DPCH	Dedicated Physical Channel
DPDCH	Dedicated Physical Data Channel

DRNC	Drift RNC
DS-CDMA	Direct Sequence CDMA
DSCH	Downlink Shared Channel
DT	Discard Time
DTX	Discontinuous Transmission
E-AGCH	E-DCH Absolute Grant Channel
E-DCH	Enhanced DCH
E-DPCCH	Enhanced Dedicated Physical Control Channel
E-DPDCH	Enhanced Dedicated Physical Data Channel
E-HICH	E-DCH HARQ Indicator Channel
E-RGCH	E-DCH Relative Grant Channel
E-TFCI	E-DCH Transport Format Combination Indicator
ECR	Effective Code Rate
ECSD	Enhanced Circuit Switch Data
EDGE	Enhanced Data rate for GSM Evolution
EGPRS	Enhanced GPRS
EIRP	Equivalent Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
F-DCH	Fractional DCH
FACH	Forward Access Channel
FDD	Frequency Division Duplex
FRC	Fixed Reference Channel
GBR	Guaranteed Bit Rate
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPRS	General Radio Packet System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HARQ	Hybrid ARQ
HLR	Home Location Register
HS-DPCCH	High-Speed Dedicated Physical Control Channel
HS-DSCH	High-Speed Downlink Shared Channel
HS-PDSCH	High-Speed Physical Downlink Shared Channel
HS-SCCH	High-Speed Shared Control Channel
HSDPA	High-Speed Downlink Packet Access
HSOPA	High Speed OFDM Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
IAO	Interactive Oriented
IBB	Interactive Background Balanced

IMS	IP Multimedia Sub-system
IMT-2000	International Mobile Telecommunications-2000
IP	Internet Protocol
IR	Incremental Redundancy
ISDN	Integrated Services Digital Network
ITU	International Telecommunication Union
LTE	Long Term Evolution
MAC	Medium Access Control
MAC-e	E-DCH MAC
MAC-hs	MAC high speed
max-Del	maximum Delay
ME	Mobile Equipment
MIMO	Multiple Input Multiple Output
min-GBR	minimum GBR
MMS	Multimedia Message Service
MSC	Mobile Switching Centre
MT	Mobile Terminal
NACK	Negative ACK
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On Off Keying
OVSF	Orthogonal Variable Spreading Factor
QoS	Quality of Service
QPSK	Quaternary Phase Shift Keying
P-CPICH	Primary CPICH
PCH	Paging Channel
PCCPCH	Primary Common Control Physical Channel
PDSCH	Physical Downlink Shared Channel
PF	Proportional Fair
PICH	Paging Indication Channel
PLMN	Public Land Mobile Network
PRACH	Physical Random Access Channel
PS	Packet Switch
PSTN	Public Switched Telephone Network
RACH	Random Access Channel
RLC	Radio Link Control
RLS	Radio Link Set
RNC	Radio Network Controller
RR	Round Robin
RRC	Radio Resource Control
RRM	Radio Resource Management

RSCP	Received Signal Code Power
RT	Real Time
RTT	Round Trip Time
RTWP	Received Total Wideband Power
SCCPCH	Secondary Common Control Physical Channel
SCH	Synchronisation Channel
SF	Spreading Factor
SGSN	Serving GPRS Support Node
SHO	Soft Handover
SINR	Signal to Interference plus Noise Ratio
SIP	Session Initiation Protocol
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
SPI	Scheduling Priority Indicator
SMS	Short Message Service
SRB	Signal Radio Bearer
SRNC	Serving RNC
TC	Traffic Class
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
THP	Traffic Handling Priority
TTI	Time Transmission Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UPH	UE Power Headroom
USIM	UMTS Subscriber Identity Module
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VLR	Visitor Location Register
VoIP	Voice over IP
WCDMA	Wideband CDMA

List of Symbols

α	DL orthogonality factor
β	Maximum interference value
Δf	Signal bandwidth
η_{DL}	DL load factor
η_{UL}	UL load factor
v	Activity factor
ρ	Application throughput
ρ_P	Physical layer throughput
ρ_{pilot}	P-CPICH energy per chip to interference ratio when HSDPA is active
Ψ	SINR
d	Distance between the user and the Node B
E_b	Energy per bit
E_c	Energy per chip
f	Frequency
F	Receiver's noise figure
G	Geometry factor
G_{div}	Diversity gain
G_t	Transmitting antenna gain
G_P	Processing gain
G_r	Receiving antenna gain
G_{rdiv}	Receiving antenna gain plus diversity gain
G_{SHO}	Soft handover gain
i	Inter- to intra-cell interferences ratio
I_0	Interference
k_d	Dependence of the multiscreen diffraction loss versus distance
k_f	Dependence of the multiscreen diffraction loss versus radio frequency
L_0	Free space loss
L_c	Cable losses between transmitter and antenna
L_{int}	Indoor penetration losses
L_p	Path loss between Node B and MT
L_{tm}	Approximation for the multiscreen diffraction loss
L_{tt}	Rooftop-to-street diffraction loss
L_u	Body losses

M	Total margin due to additional losses
M_{FF}	Fast fading margin
M_I	Interference margin
M_{SF}	Slow fading margin
N	Total noise power
N_0	Noise spectral density
N_u	Number of users
N_{rf}	Noise spectral density of MT receiver
P_{Sig}	Signalling power
P_t	Transmitting power at antenna port
P_{inter}	Inter-cell interference power
P_{intra}	Intra-cell interference power
$P_{HS-DSCH}$	Power of the HS-DSCH summing all active HS-PDSCH codes
P_{HSDPA}	HSDPA transmitter power
P_{pilot}	P-CPICH transmitter power
P_{noise}	Noise power
P_r	Available receiving power at antenna port
P_{Rx}	Received power at receiver input
P_{Tx}	Total Node B transmission power
R	Cell radius
R_b	Bit rate
R_c	WCDMA Chip rate
SF_{16}	HS-PDSCH SF of 16

List of Software

Borland C++ Builder

MapBasic

MapInfo

Matlab

Microsoft Excel

Microsoft Word

Microsoft PowerPoint

Microsoft Visio

TEMS

Chapter 1

Introduction

This chapter presents a brief overview of the work. Before establishing work targets and original contributions, the scope and motivations are presented. A brief state of the art in relation to the scope of the work is also presented. At the end of the chapter, the work structure is provided.

1.1 Overview

Mobile communications systems revolutionised the way people communicate, joining together communications and mobility. 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) phase I, were published in 1990 by the European Telecommunications Standards Institute (ETSI). In 1991, the first GSM system was launched in Finland. Nowadays mobile phone penetration exceeds 80%, and in some countries even the number of landline phones [HoTo04].

GSM is a digital system based on Time Division Multiple Access (TDMA) designed to offer voice communications and allowing at the same time data communications at low rate, 14.4 kbps, like Short Message Service (SMS) that became a huge success, being massively used by millions of users [HoTo04]. Due to the unexpected growth and interest achieved by data communications and multimedia services, General Packet Radio System (GPRS), and later Enhanced Data rates for GSM Evolution (EDGE), were introduced. These had the objective of enhance data communications experience, mainly by increasing packet data transfer rates over the air interface, with peak data rates up to 160 and 473.6 kbps, respectively [HoTo04]. More realistic data rates are obtained at the order of 30-40 kbps for GPRS and 120-160 kbps for Enhanced GPRS (EGPRS) – EDGE introduced Enhanced Circuit Switch Data (ECSD) for data over Circuit Switch (CS) and EGPRS for packet data, the latter being the most successful one, due to the higher interest in data communications using Packet Switch (PS), [HaRM03]. But both GPRS and EDGE were upgrades to a system originally designed for voice, with latency, important for low data rate application like online gaming, around 600 ms for GPRS and under 300 ms for GPRS. This fact aroused the need to develop a system designed from the beginning for data communications, with the ability to provide multimedia services, enhanced person-to-person communications, and access to data networks with higher throughput and capacity, [HoTo04]. GSM reached the second billionth users in the 2006 second quarter, with a mobile market share near 85%, being used by operators in more than 200 countries, [GSMW08]. In Figure 1.1, one shows the evolution of the number of mobile subscribers compared to the fixed ones.

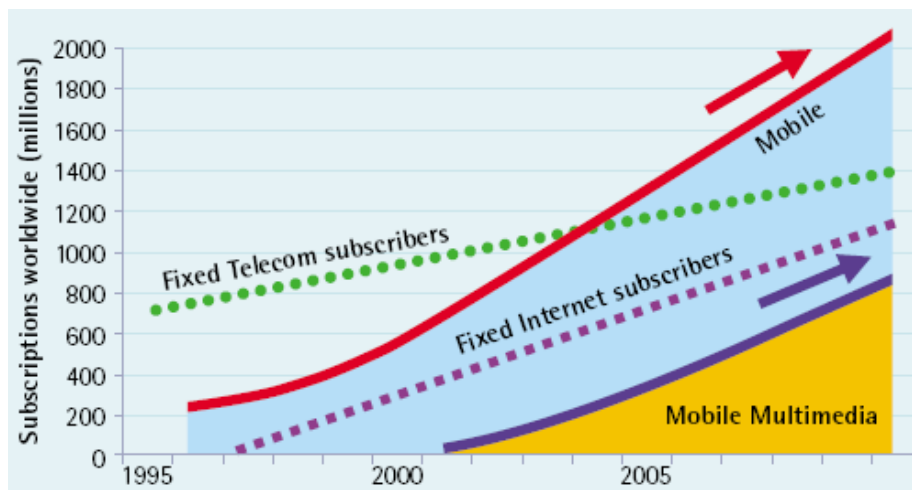


Figure 1.1 Evolution of the number of mobile subscribers (extracted from [UMFO03]).

In 1999, 3rd Generation Partnership Project (3GPP) launched Universal Mobile Telecommunications System (UMTS), a Third Generation (3G) first release, although EDGE had already been accepted by the International Telecommunication Union (ITU) as part of the International Mobile Telecommunications-2000 (IMT-2000) family of 3G standards since it has peak data rates above of 384 kbps (ITU's 3G definition). UMTS uses Wideband Code Division Multiple Access (WCDMA) as access technique, and was designed from the beginning to offer multiservice applications [HoTo04], unlike previous 2G systems, designed originally for voice communications. The variable bit rate and the mixture of traffic on the air interface presents new possibilities for both operators and users, as streaming traffic and voice over Internet Protocol (IP). New challenges in network planning and optimisation, for instances the higher delays, lead to the introduction of Quality of Service (QoS), [LaWN06]. WCDMA has higher hardware and spectral efficiency than GPRS/EGPRS, and at the same time, a reduced footprint [HoTo06]. The exponential growth of data communications over mobile phones forced a further development of systems that would be capable of offering higher capacity, throughput and enhanced multimedia services, available to consumers 'anywhere, anytime', [LaWN06].

High Speed Downlink Packet Access (HSDPA) was set as a standard in 3GPP Release 5 with the first specifications made available in March 2002. The initial peak data rate was 1.8 Mbps, increased to 3.6 Mbps during 2006. By the end of 2007, 7.2 Mbps are available, with the maximum peak data rate of 14.4 Mbps in a near future, starting the mobile IP revolution, [HoTo06]. Following the success accomplished by HSDPA, in December 2004, 3GPP launched Release 6 with E-DCH (Enhanced-Dedicated Channel), also known as High Speed Uplink Packet Access (HSUPA), first specifications. HSUPA started to be deployed at the end of 2007, with expected peak data rates up to 1.45 Mbps and around 3-4 Mbps in later releases [HoTo06]. In Figure 1.2, the evolution of the end user bit rates and Round Trip Time (RTT) of the systems introduced is presented.

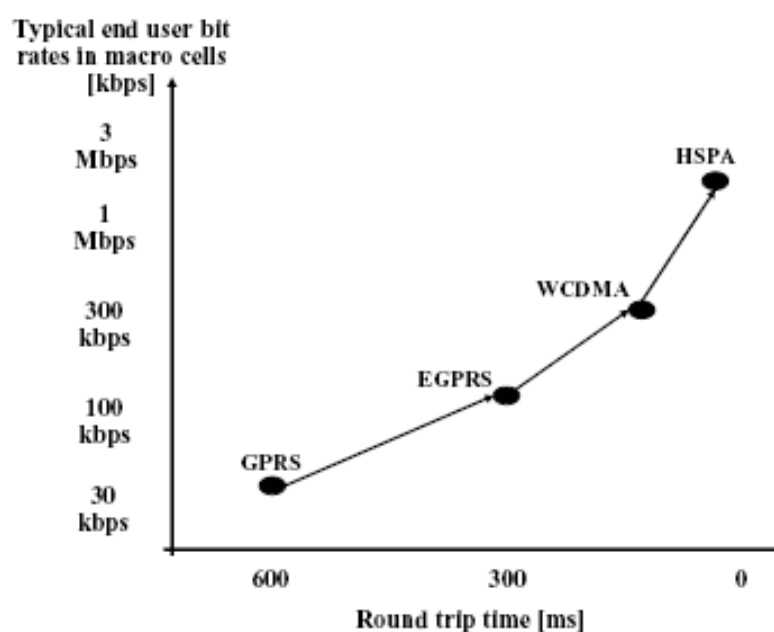


Figure 1.2. Radio capability evolution (extracted from [HoTo06]).

HSDPA and HSUPA deployed together are referred to as High Speed Packet Access (HSPA). HSPA is deployed on top of 3G networks, minimising equipment upgrade, with practical data rates beyond 2 Mbps in the Downlink (DL) and up to 1 Mbps in Uplink (UL), while keeping latency under 100 ms. This characteristics make HSPA attractive to low data rate application that require low latency, like Voice over IP (VoIP), which can be the driver application to the migration to an all-IP scenario, as well as to new packet-based applications to go wireless in an efficient way. This migration to IP will compel mobile operators to provide value to the subscribers, while maintaining control over resources.

In the beginning of 2008, there are more than 200 UMTS operators in 85 different countries and almost 70 networks are in the planning/deployment phase. Regarding HSPA, more than 170 operators spread over 74 countries offer HSDPA, and also 60 additional networks are expected to be launched in a near future. HSUPA, the latest 3GPP release is already available in 26 operators with 132 networks planned, [3GAM08]. In Figure 1.3, one presents a description of new services made available by HSPA, as well as the new services' requirements.

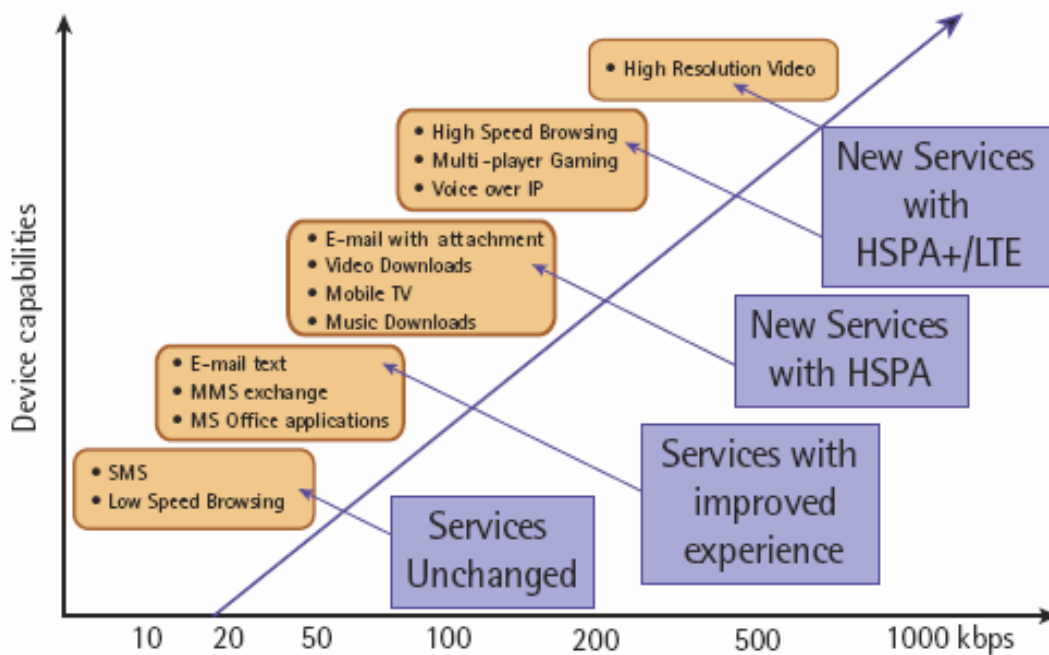


Figure 1.3. HSPA new services and enhanced user experience (extracted from [UMFO08a]).

Future developments comprise the use of Multiple Input Multiple Output (MIMO), which will improve capacity and throughput mainly in urban scenarios, as MIMO takes advantage of multipath propagation, and Orthogonal Frequency Division Multiplexing (OFDM), merged into High Speed OFDM Packet Access (HSOPA), being part of 3GPP Long Term Evolution (LTE). LTE has expected peak data rates of 100 Mbps in DL and up to 50 Mbps in UL, which will further improve the end user experience [HoTo06].

LTE will enable high mobile broadband capacity and services, providing an even higher cost efficiency mobile coverage. Future releases will offer DL peak data rates up to 326 Mbps and UL data rates up to 86 Mbps, with 20 MHz bandwidth in both UL and DL. It will allow operability in Frequency Division

Duplex (FDD) and Time Division Duplex (TDD) modes, scalability to operate in a range of bandwidth from 1.4 to 20 MHz, [UMFO08b], reduced latency and transaction time from inactive to active, [3GAM07]. In January 2008, LTE technical specifications were approved by 3GPP, being included in Release 8.

1.2 Motivation and Contents

The main purpose of this thesis is to study HSDPA and HSUPA at the cellular level in a multiple users and services scenario, in particular, addressing coverage and capacity aspects. Recent studies only analyse one of the systems, being difficult to compare both systems, due to the use of different propagation models. These thesis objectives were accomplished through the development and implementation of a single user model, which was afterwards adapted to a multiple users and multiple services scenario. Parameters like coverage, capacity and satisfaction grade, among others, were compared. A comparison of HSDPA performance for 5, 10 and 15 HS-PDSCH codes is addressed as well as the different capacity impacts of the increase of the number of codes. The method as well as the expressions to calculate both HSDPA and HSUPA's throughputs according to the distance, in a loaded multiple service network are presented. The results given by the simulator are also compared with the results of the measurements performed in both the test plant and in the live network.

This thesis was made in collaboration with the Portuguese mobile operator Optimus. Several technical details were discussed with the company, and one used the suggested values for several parameters throughout this thesis. The HSDPA and HSUPA measurements were performed at Optimus' test plant, and live measurements were made on Optimus' network. In both measurements, the equipment was supplied by the company.

This thesis' main contribution is the analysis and comparison of HSDPA and HSUPA in a multiple users and services scenario. A model to calculate the HSDPA and HSUPA user throughput as a function of distance for a single user scenario was implemented. These models were adapted to a multiple users simulator, allowing the analysis of HSDPA and HSUPA behaviour in a real network, by calculating several parameters, as the average network radius and throughput. The simulator permits evaluating the influence of the variation of the systems' parameters in network performance. Additionally, 3 reduction strategies, with different QoS requirements, were developed.

This thesis is composed of 5 chapters, including the present one.

In Chapter 2, one presents an introduction to UMTS, HSDPA and HSUPA. UMTS basic concepts are explained, and afterwards the HSDPA and HSUPA new features, in particular the new channels and radio resource management are presented. A brief analysis regarding performance is also performed. At the end of the chapter the state of the art is presented.

Chapter 3 starts with the introduction of the developed theoretical single service radius model. Later on, the simulator developed for multiple users and services, based on previous simulators, is

presented, the main modifications being pointed out. The HSDPA and HSUPA modules developed are described in detail. The input and output files are highlighted, and the simulator assessment is presented. At the end of the chapter, the modifications in the link budget for the measurement assessment are shown.

In Chapter 4, the default scenario with network architecture, profiles and application parameters for both HSDPA and HSUPA is introduced. The analysis concerning the number of users in the default scenario is also presented. Afterwards, the HSDPA and HSUPA main simulation results for both single and multiple users are presented. Later on, a comparison between the two systems concerning coverage and capacity, based on the simulator's results, is performed. The chapter concludes with HSDPA and HSUPA measurements, performed both in test plant and in live network, as well as a comparison between these measurements and the theoretical models.

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

A set of annexes with auxiliary information and results is also included. In Annex A, one presents the detailed link budget used throughout this thesis. In Annex B and D, one shows the user's interface to the single user model and to the multiple services simulator, respectively. In Annex C, information regarding the multiple services users' generation, as well as the default and alternative profiles characterisation, is presented. The flowcharts regarding the 3 used reduction strategies are shown in Annex E and F for HSDPA and HSUPA. In Annex G, one presents auxiliary results regarding the single user model, and in Annex H and Annex I additional results regarding the multiple users simulator are presented. In Annex J, the results regarding the HSDPA and HSUPA comparison are shown. Finally, in Annexes K and L, additional results from the HSDPA and HSUPA measurements are provided.

Chapter 2

UMTS Fundamentals

This chapter provides an introduction to UMTS. First, the UMTS Terrestrial Radio Access Network (UTRAN) system architecture is presented, followed by a brief description of the radio interface, the WCDMA. At the end of the section, concerning basic concepts, interference and capacity are analysed. Current services and applications in UMTS are also approached. Later in the chapter, HSDPA and HSUPA main features and characteristics are introduced. At the end of the chapter, the state of the art regarding this thesis main objective is presented.

2.1 Basic Concepts

In this section, Release 99 basic concepts are presented, based on [HoTo04]. The network architecture is presented in Subsection 2.1.1, and in Subsection 2.1.2 the radio interface is analysed. Interference and capacity are evaluated in Subsection 2.1.3.

2.1.1 Network Architecture

As specified by 3GPP, there are two radio interface modes for UMTS Terrestrial Radio Access (UTRA): FDD and TDD [3GPP02a]. In this thesis, only the UTRA FDD mode will be analysed.

Three high-level architecture modules compose the UMTS network [3GPP02a]: User Equipment (UE), UTRAN and Core Network (CN). The UE interacts with the user. UTRAN is responsible for the radio interface, and allows connections to the CN, which is responsible for interaction with external networks, such as other Public Land Mobile Networks (PLMNs), Public Switched Telephone Networks (PSTNs), Integrated Services Digital Networks (ISDNs), and Internet. The structure of the network architecture is presented in Figure 2.1.

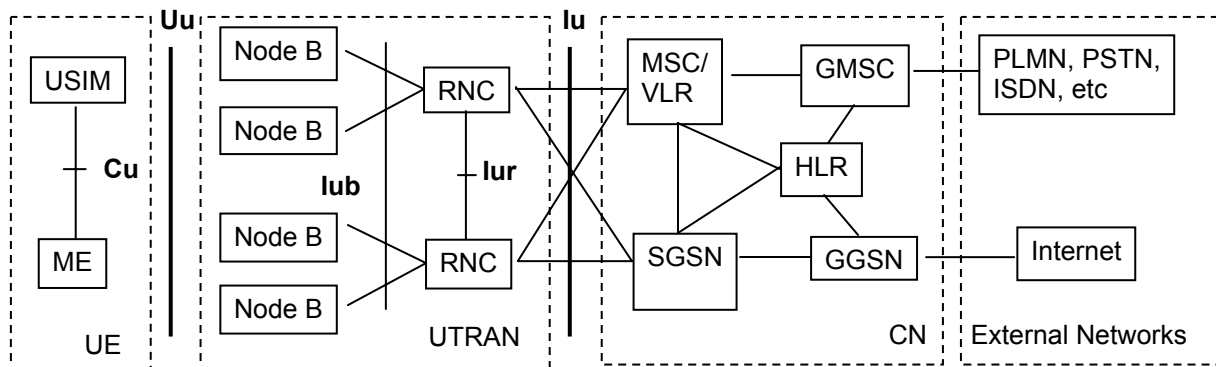


Figure 2.1. UMTS system architecture (extracted from [HoTo04]).

The UE is composed of:

- Mobile Equipment (ME) – responsible for the radio interface over the Uu interface, using WCDMA;
- UMTS Subscriber Identity Module (USIM) – a smart card that stores the subscriber identity, authentication information and encryption keys.

UTRAN elements are:

- Node B – performs the conversion of data flows from the Uu radio interface to the lub interface, and takes part in Radio Resource Management (RRM);
- Radio Network Controller (RNC) – controls Node Bs and performs RRM, such as code allocation, outer loop power control, packet scheduling, and handover control. The RNC has 3 logic roles: Controlling RNC (CRNC) controls the logical resources of UTRAN access points, Serving RNC (SRNC) ending the lub and Iu interfaces, and the Drift RNC (DRNC), which is any RNC, other than SRNC, controlling cells used by the Mobile Terminal (MT), being able to perform macro diversity and splitting. The Iur interface allows soft handover (SHO) between Node Bs belonging to different

RNCs.

The CN was adapted from the well-known GSM one. In UMTS, CN network elements are:

- Home Location Register (HLR) – database that stores user information, such as allowed services, user location for routing calls, and preferences. Every user of a network must be registered to that network's HLR;
- Mobile Switching Centre/Visitor Location Register (MSC/VLR) – is a network element with two functions: MSC is responsible for switching voice and data connections in the CS domain, the VLR being a database containing all active network users, as well as a more precise location of the UE;
- Gateway MSC (GMSC) – is a switch for connection to external networks on the CS domain;
- Serving GPRS Support Node (SGSN) – is a switch with the same functions as MSC/VLR, but for connections on the PS domain;
- Gateway GPRS Support Node (GGSN) – equivalent to GMSC on PS domain.

2.1.2 Radio Interface

UMTS uses WCDMA, a wideband Direct-Sequence Code Division Multiple Access (DS-CDMA) spread spectrum air interface, with a chip rate of 3.84 Mcps leading to a radio channel of 4.4 MHz and separation of 5 MHz. The UTRA/FDD frequency bands for Europe are [3GPP05]: [1920, 1980] MHz for UL and [2110, 2170] MHz for DL. WCDMA capabilities include: high bit rates, low delay, QoS differentiation, smooth mobility for voice and packet data, Real Time (RT) voice and capacity capability, and inter-working with existing GSM/GPRS networks.

Power control, soft and softer handover are key features in WCDMA air interface. Without power control, a single MT could block a whole cell. WCDMA applies two types of power control: closed loop, to avoid the use of excessive power, and thus, an increase of interference (the near-far problem), 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.

Softer handover happens when an MT is in the overlapping cell coverage of two sectors from the same Node B, having two different air interface channels. In SHO, the two sectors are associated to different Node Bs. In softer handover, the combining is done at the Node B, while in SHO it is done at the RNC. The main functionalities of channelisation and scrambling codes, used to separate physical channels and MT are summarised in Table 2.1.

Data from higher layers is carried in transport channels, which are mapped onto different physical channels. Two types of transport channels are defined, [3GPP02b]: dedicated channels, each one reserved for a single user, and common channels, shared among all users within the cell.

In UTRA specifications, [3GPP02b], there is only one dedicated transport channel, the Dedicated Channel (DCH), an UL or DL channel responsible for carrying all users' data, including the actual data for the required service, and also higher layer control information. DCH supports fast power control, fast data rate change on a frame-by-frame basis, the use of adaptive antennas, and SHO, being

mapped onto the Dedicated Physical Data Channel (DPDCH) for user data, and onto the Dedicated Physical Control Channel (DPCCH) for control information. Concerning the common channels, in DL one has the Broadcast Channel (BCH), the Forward Access Channel (FACH), the Paging Channel (PCH) and the Downlink Shared Channel (DSCH).

Table 2.1. Functionality of channelisation and scrambling codes (extracted from [Corr06]).

	Channelisation	Scrambling
Use	DL: MT separation UL: channel separation	DL: sector separation UL: MT separation
Duration	DL: 4 – 512 chip; UL: 4 – 256 chip	38 400 chip
Number	Spreading Factor	DL: 512; UL: > 1 000 000
Family	OVSF	Gold or S(2)
Spreading	Yes	No

The BCH is used to broadcast system and cell specific information, such as the available random access codes. It is transmitted with high power and low data rate, as it needs to be decoded by all MTs within the Node B's coverage area. BCH is mapped onto the Primary Common Control Physical Channel (PCCPCH). The FACH carries control information for the MT within the cell coverage area, and may also be used for packet data communications. It is transmitted with low data rate, so that it can be received by all MTs in the cell area, and does not use fast power control. It is mapped onto the Secondary Common Control Physical Channel (SCCPCH).

The PCH carries data necessary to the paging procedure, for example, when the network intends to initiate a communication with a specific user. It is always transmitted over the cells where the user is expected to be. Like the FACH, the PCH is also mapped onto the SCCPCH. The DSCH is used to carry dedicated user data and control information, being shared by several users. It supports fast power control and a variable data rate on a frame-by-frame basis, being always associated to a DL DCH. Contrary to the other common transport channels, the DSCH does not need to be received in the entire cell. It is mapped onto the Physical Downlink Shared Channel (PDSCH).

In UL, there are two common transport channels: the Random Access Channel (RACH) and the Common Packet Channel (CPCH) used to carry user packet data. The RACH is used to carry control information from the MT to the network, such as requests to set up connections, and may also be used to transmit small data packets. It is transmitted using open loop power control, and it is mapped onto the Physical Random Access Channel (PRACH). It is transmitted using fast power control, and uses collision techniques in order to avoid collisions when other users are also making packet-based connections.

From the six common channels presented, BCH, RACH, FACH and PCH are mandatory for the basic network operation, DSCH and CPCH being optional. When CPCH is present, four other physical channels, the CPCH Status Indication Channel (CSICH), the CPCH Collision Detection Indicator Channel (CD-ICH), the CPCH Channel Assignment Indicator Channel (CA-ICH) and the CPCH

Access Preamble Acquisition Channel (AP-AICH) are needed for CPCH access procedures.

There are also others physical channels, such as Synchronisation Channel (SCH), Common Pilot Channel (CPICH), Paging Indication Channel (PICH) and Acquisition Indicator Channel (AICH) that do not carry any transport channel. These channels carry relevant information to the physical layer procedures. The SCH is needed for cell search procedures, the CPICH aids the channel estimation at the MT, the PICH provides efficient MT sleep mode, being operated together with PCH, and AICH indicates to the MT the reception of the random access signature sequence.

2.1.3 Interference and Capacity

Interference and capacity in UMTS are analysed in this section, being significantly different from the ones associated to GSM, since, in UMTS, interference and capacity are user dependent. With WCDMA, a frequency reuse of 1 is used, meaning that the system is usually interference limited.

There are 3 main parameters limiting capacity, [HoTo04]: the number of available codes in DL, the system load (both UL and DL), and the shared DL transmission power. The number of available channelisation codes limits the number of simultaneous active users within the cell sector. As data rate increases, the Spreading Factor (SF) must decrease to allow higher data rates, leading to a decrease of the allowed users in the network. With an SF4, the maximum theoretical data rate would be 936 kbps and only 3 users could be served, since at least one branch of the Orthogonal Variable Spreading Factor (OVSF) code tree is reserved for network control information, where several control channels are transmitted with lower SF. The use of different scrambling codes in the same sector is not recommended, because it would decrease the orthogonality of the DL channels, and hence, increase interference. The maximum value for the SF is limited to assure a minimum QoS, since high SF values would increase interference.

Regarding system load, it is necessary to differentiate UL from DL, since in the latter there is a limit on the transmission power, and traffic flow is not symmetric between UL and DL. As the load increases in UL, a larger interference margin is needed, leading to a decrease of the cell coverage area. The UL load factor can be defined as:

$$\eta_{UL} = (1+i) \sum_{j=1}^{N_u} \frac{1}{1 + \frac{G_{P_j}}{(E_b/N_0)_j \cdot v_j}} \quad (2.1)$$

where:

- v_j : activity factor of user j (typically 0.67 for speech and 1.0 for data);
- E_b : energy per bit;
- G_{P_j} : processing gain of user j , defined as R_c/R_{bj} ;
- i : ratio of inter- to intra-cell interferences;
- N_0 : noise power density;
- N_u : number of users per cell;
- R_{bj} : bit rate of user j ;

- R_c : WCDMA chip rate.

For the DL load factor, one has:

$$\eta_{DL} = \sum_{j=1}^{N_u} v_j \frac{(E_b/N_0)_j}{G_{P_j}} [(1-\alpha_j) + i_j] \quad (2.2)$$

where:

- α_j : DL channel orthogonality of user j (between 0.4 and 0.9 in multipath channels);
- 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 power transmitter. Coverage in rural areas depends more 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.

The noise rise is defined by (2.3), and should be equal to the interference margin used in the link budget. When η_{UL} or η_{DL} approach one, the system reaches its pole capacity and the noise rise goes to infinity. One should use the load equations (2.1) and (2.2) to predict cell capacity, and the noise rise in the planning phase, to avoid the appearance of non-covered zones.

$$M_{I_{UL/DL[dB]}} = -10 \log(1 - \eta_{UL/DL}) \quad (2.3)$$

The DL transmission power is also a limiting factor in cell capacity; therefore, it is necessary to calculate the total transmission power of the Node B, which can be expressed as:

$$P_{Tx_{[W]}} = \frac{N_{rf} \cdot R_c \cdot \sum_{j=1}^{N_u} v_j \cdot \frac{(E_b/N_0)_j}{G_{P_j}} \cdot L_{p_j}}{1 - \overline{\eta_{DL}}} \quad (2.4)$$

where:

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

Increasing the Node B transmitter power, in order to increase cell capacity, is not an efficient technique. Splitting the transmitter power among several frequencies is an adequate approach to increase capacity, although it is only possible when more than 1 frequency can be allocated per cell.

Call admission and load control in RRM are the main responsible algorithms to control the parameters within the range that guarantees a stable network operation.

2.2 Services and Applications

As stated earlier, UMTS was designed to offer flexible services, instead of 2G systems that were

designed for an efficient delivery of voice. New services can emerge without any specific network optimisation. The adoption of IP Multimedia Sub-system (IMS) in combination with Session Initiation Protocol (SIP) allows the fast introduction of new services based on Internet applications and protocols, merging the Internet with the mobile world.

The services provided by UMTS networks were divided into four traffic classes, with different QoS requirements, [3GPP01] and [3GPP02c]: Conversational, Streaming, Interactive and Background. These four classes are basically distinguished by their delay sensitivity: the Conversational class is meant for voice traffic, being the most delay sensitive, while Background is meant for exchange of data information, being the most delay tolerant. Table 2.2 illustrates UMTS QoS classes. These traffic classes are not mandatory; for instance, a typically interactive application can use the Conversational class, if it has tight delay requirements.

Table 2.2. UMTS QoS traffic classes main characteristics (adapted from [3GPP01] and [3GPP02c]).

Traffic Class	Conversational	Streaming	Interactive	Background
Fundamental characteristics	-Preserve time relation (variation) between information entities of the stream -Conversational pattern (stringent and low delay)	-Preserve time relation (variation) between information entities of the stream	-Request response pattern -Preserve payload content	- Destination is not expecting the data within a certain time -Preserve payload content
Real-time	Yes	Yes	No	No
Symmetry	Yes	No	No	No
Switching	CS	CS	PS	PS
Guaranteed rate	Yes	Yes	No	No
Delay	Minimum and fixed	Minimum and variable	Moderate and variable	High variable
Example of application	Voice	Streaming video	Web browsing	E-mail

The Conversational class includes voice, since it is the class with tighter delay requirements, such as the preservation of time relations in data streams and low delay (less than 400 ms [HoTo04]) to assure good voice quality. The speech codec used in UMTS is Adaptive Multirate (AMR) with eight source data rates. It uses Discontinuous Transmission (DTX) to reduce the bit rate, leading to lower interference and consequently increase capacity. Another codec is also foreseen, the Wideband AMR (AMR-WB) with quality enhancements compared to the standard AMR or even fixed telephone line, due to an audio bandwidth between 50 and 7000 Hz. Another application that fits the Conversational class is VoIP, which, as the name suggest, is an application running over IP, being supposed to work on the PS domain, requiring IP header compression and QoS differentiation to meet the low delays needed for Conversational service requirements. Video telephony also fits the Conversational class, as it has similar delay requirements as voice, and even tighter Bit Error Rate (BER) requirements, due

to video compression. Video telephony can be transmitted in CS or PS, in a near future.

The Streaming class includes RT audio and video sharing, and can be considered a new application in telecommunications systems. Like the Conversational class, it requires preservation of time relation between packets, although supporting higher delay requirements. This is achieved through the used of buffers in the final applications. One-way video sharing can also be included in this class.

The Interactive class includes web browsing and online multiplayer gaming. This class is characterised by requesting response patterns and preservation of payload contents. For web browsing, large delays are supported; still, in order to accomplish a good experience, delay should be lower than 4 to 7 s [3GPP03]. In multiplayer video games, the RTT is a very important parameter, especially in multiplayer action games, where the end-to-end delay should be below 100 ms [AnLa04].

The Background class tolerates the highest delays, since virtually there are no delay requirements, being almost delay insensitive. Like the Interactive class, this class is intolerant to transmission errors. Applications in this traffic class only use resource transmissions when none of the other classes are active. The exchange of e-mails, Multimedia Message Service (MMS) and download of databases are typically applications in this class.

Among some of the current UMTS applications presented above, it is yet to determine the killer application or even if there will be one. With the introduction of HSDPA and HSUPA in recent releases, and their new features, the emerging of new applications is expected.

2.3 HSDPA

In this section, HSDPA main principles are presented, based on [HoTo06]. The main features and new channels are introduced in Subsection 2.1.1, performance, coverage and capacity are analysed in Subsection 2.3.2, while RRM techniques are covered in Subsection 2.3.3.

2.3.1 Main Features

With the demand for higher data rates, 3GPP launched Release 5 in March 2002, covering first HSDPA specifications, with expected peak data rates beyond 10 Mbps. HSDPA improves capacity and spectral efficiency, being deployed together with Release 99, sharing all network elements. It requires software upgrade of the network's elements, but a new MT on the user's side. Although designed for non-RT traffic, simulations show that HSDPA provides enough capacity for low bit rate and low latency applications, as VoIP.

While in Release 99 the scheduling control is based on the RNC, and the Node B only has power control functionality, in HSDPA, scheduling and fast link adaptation based on physical layer retransmissions were moved to the Node B, minimising latency and changing the RRM architecture. With HSDPA, RNC-based retransmission can still be applied on top of physical layer, using Radio Link

Control/Acknowledgment (RLC/ACK) in case of physical layer failure.

Another substantial change is the fact that HSDPA does not support SHO. Higher data rates are accomplished through the use of a new higher order modulation, the 16 Quadrature Amplitude Modulation (16QAM) with 4 bits per symbol, that can only be used under good radio channel conditions, due to the additional decision boundaries: phase and amplitude estimations. Quaternary Phase Shift Keying (QPSK) is mainly used to maximise coverage and robustness. HSDPA introduces Adaptive Modulation and Coding (AMC), which adjusts the modulation and coding scheme to the radio channel conditions, and, together with 16QAM, allows higher data rates.

As defined in Release 5, the DCH is necessary for HSDPA operation, since the Signal Radio Bearer (SRB) is carried on DCH for packet data, but HSDPA does not support DCH features, like fast power control or SHO. For Release 6, the Fractional-DCH (F-DCH) was created for handling power control when only packet services are active, allowing a larger number of users with lower data rates.

For HSDPA operation, a new user data channel, the High-Speed Downlink Shared Channel (HS-DSCH) mapped onto the High-Speed Physical Downlink Shared Channel (HS-PDSCH) was created. Two other channels, the High-Speed Shared Control Channel (HS-SCCH) in the DL, and the High-Speed Dedicated Physical Control Channel (HS-DPCCH) in the UL, were added for signalling.

The HS-DSCH is a transport channel for user's data, supporting the new 16QAM modulation. Node B scheduling with a Transmission Time Interval (TTI) of 2 ms, and fast physical layer transmission using Hybrid ARQ (HARQ) with two types of retransmission combining are used: identical retransmission, also called Chase (soft), or non-identical retransmission, also called Incremental Redundancy (IR). There is no power control or SHO, as there is only one HS-DSCH serving cell. Only a fixed SF16 is used, with a maximum of 15 codes per MT allowing a theoretical peak bit rate of 14.4 Mbps. Only turbo-coding is used, with better performance for high data rates than the convolutional one.

The HS-SCCH carries time critical signalling information, having a 2 slot offset compared to the HS-DSCH, to allow the MT to demodulate the correct codes. It uses QPSK modulation and a SF128 with 40 bits per slot, and does not have power control bits, even though power control can be used, based on Channel Quality Information (CQI) or on the associated Dedicated Physical Channel (DPCH). The HS-SCCH is divided into two parts: the first one carries information needed for de-spreading of the correct codes, and the second one carries less important information, such as the Automatic Repeat Request (ARQ) process being transmitted. For the use of code multiplexing, especially in the first deployment phase with limited MTs capabilities, more than one HS-SCCH needs to be transmitted, with the maximum number of HS-SCCH per MT being limited to 4.

The HS-DPCCH is the UL channel needed for physical layer feedback to support link adaptation and physical layer retransmissions. This channel was created to leave the DCH channels from Release 99 unchanged. It has a fixed SF256 and a three slot structure, the first slot being used for HARQ information, which is always sent when there is a correct decoding of the HS-SCCH, and the

remaining two slots for CQI. The CQI is sent from the MT to advise the Node B scheduler of the expected data rate to be received by the MT in the next TTI.

2.3.2 Performance, Capacity and Coverage

HSDPA performance depends on network algorithms, deployment scenarios, traffic generated, QoS and MT receiver performance and capability. As a shared channel used, end user performance is also dependent on the number of active users. There are 12 HSDPA MT categories, with different maximum DL bit rates, between 0.9 and 14.4 Mbps, Table C.3.

In order to evaluate HSDPA performance, the E_b/N_0 metric is not used, since the HS-DSCH bit rate varies every TTI with the use of different modulations and coding schemes, Effective Code Rate (ECR) and number of HS-PDSCH channels. The Signal to Interference plus Noise Ratio (SINR) is used instead of E_b/N_0 for HSDPA link budget planning and network dimensioning. The average HS-DSCH SINR for a single-antenna Rake receiver can be defined as:

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

where:

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

For performance analysis, the required instantaneous HS-DSCH SINR measurement is also used, defined as the SINR on the HS-DSCH channel to accomplish a specific Block Error Rate (BLER) target for the number of HS-PDSCH codes, modulation and coding scheme used.

While in Release 99, to achieve the necessary data rate for the type of service considered, voice or data, there is a requirement on E_b/N_0 , [Corr06], in HSDPA, due to the use of AMC, the data rate is a continuous function of the available HS-DSCH SINR. In Figure 2.2, one presents the average data rate as a function of the average HS-DSCH SINR, including the effects of link adaptation and HARQ with chase combining, for MTs with 5, 10 and 15 HS-PDSCH codes. For lower SINR values, QPSK is used, while for higher SINR values and hence, better radio channel conditions, 16QAM is used.

For network dimensioning, the pilot E_c/I_0 , standing for energy per chip to interference, based on the average wideband Primary-CPICH (P-CPICH), is also used to assess the average single user throughput. The average SINR can be expressed as a function of the average P-CPICH using (2.6) and the average throughput can then be calculated by using Figure 2.3.

The supported effective data rate achieved with 15 HS-PDSCH codes approaches the theoretical Shannon limit – the maximum error-free data rate that can be transmitted within a specific bandwidth

in the presence of noise and interference – with an approximate 2 dB difference.

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

where:

- P_{HSDPA} : HSDPA transmission power;
- P_{Tx} : total Node B transmission power;
- P_{pilot} : P-CPICH transmit power;
- ρ_{pilot} : P-CPICH E_c/I_0 when HSDPA is active.

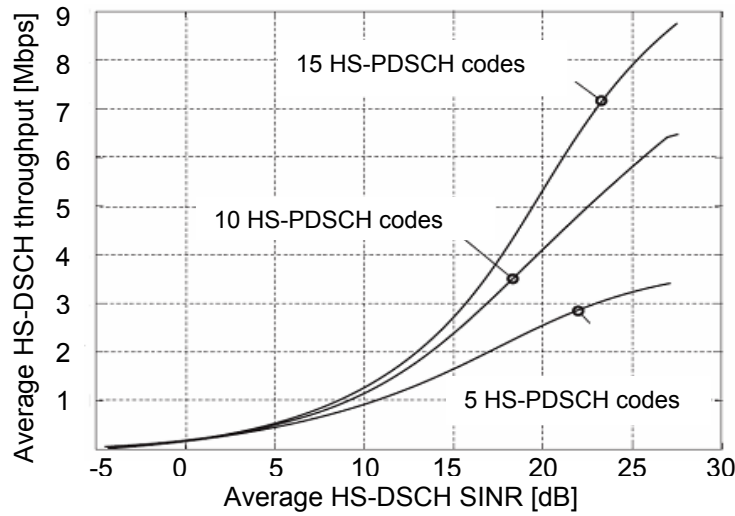


Figure 2.2. Data rate as function of the average HS-DSCH SINR for 5, 10 and 15 HS-PDSCH codes (extracted from [Pede05]).

The effect of the modulation used, QPSK or 16QAM, in the throughput is presented in Figure 2.3, as a function of the HS-DSCH SINR for two types of ITU channels: the pedestrian-A, for low MT velocity and micro-cellular environment, and the vehicular-A, for high speed MT and macro-cellular environment (higher delay power profile). For higher SINR values, the throughput improvement due to 16QAM is around 2 Mbps.

In the first HSDPA phase with MTs supporting only 5 HS-PDSCH codes, HSDPA is expected to provide a capacity gain in the order of 70%, mainly due to fast link adaptation, to HARQ, and to the multiple users capacity gain obtained with the use of Proportional Fair (PF) scheduling. With an HSDPA dedicated carrier, capacity depends on the number of HS-PDSCH codes used, on the type of scenario considered, type of service, and if code multiplexing is used (considering 5 code multiplexing). As expected, with a higher number of HS-PDSCH codes, a higher average throughput is achieved. The use of 5 codes multiplexing reduces the total capacity, due to the need of transmitting 2 HS-SCCH channels and having to schedule more than one user per TTI.

Considering VoIP, the number of users depends on the maximum tolerated delay. A higher delay tolerance increases the number of active users. With delays of 80, 100 and 150 ms, the capacity is 73,

87, and 105 users respectively [BPKM05]. These numbers of users can only be achieved in Release 99 by using AMR speech codec with low source rates, hence, worse quality, [HoTo04]. Link adaptation, HARQ and turbo-coding provide this capacity increase.

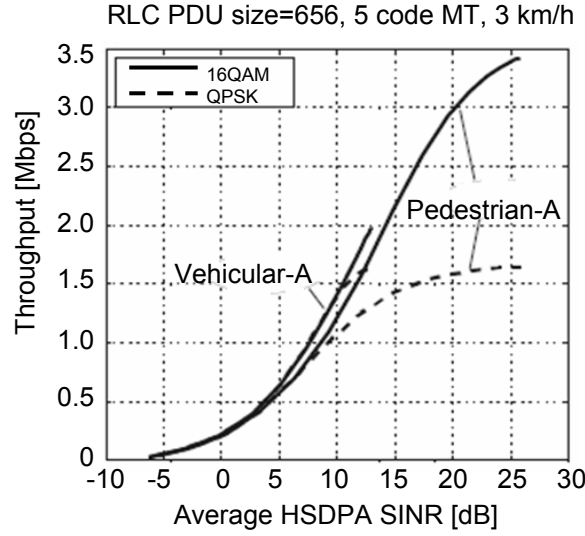


Figure 2.3. Throughput as function of the average HS-DSCH SINR for QPSK and 16QAM (extract from [HoTo06]).

Regarding coverage aspects, it is important to assure a minimum data rate at the cell edge. From Figure 2.3, the SINR is determined for a specific data rate. By using (2.7), it is possible to express the Node B HS-DSCH transmit power as a function of the SINR, and consequently as a function of the desired data rate at the cell edge.

$$P_{HS-DSCH} \geq SINR \left[1 - \alpha + G^{-1} \right] \frac{P_{total}}{SF_{16}} \quad (2.7)$$

where:

- G : geometry factor (wideband ratio of intra- to inter-cell plus noise interference), with -3 dB being a typically value at the cell edge; higher values are obtained when the MT is closer to the Node B.

Equation (2.7) can be used for a simplified network planning, to assure a minimum cell throughput in all Node B's coverage area, and also to define the cell radius according to the target services.

2.3.3 Radio Resource Management

RRM algorithms, using HSDPA physical layer enhancements, increase the capacity and end user performance, being also responsible for assuring network stability.

For the Node B, one has the HS-DSCH link adaptation to adapt the data rate every TTI and the Medium Access Control – high speed (MAC-hs) packet scheduling to control when and how each HSDPA user is served. Algorithms for Node B are not standardised, the strategies to be used being decide by manufacturers and operators. In the RNC, the resource allocation manages power and channelisation codes assigned to the Node B, with the admission control being used to decide if a new user is accepted in the cell, and to decide if it is going to be served using HSDPA or DCH (Release

99). Finally, the mobility management decides the HS-DSCH serving cell and manages Node B's buffer to minimise the loss of data packets, since there is no SHO in HSDPA. Next, Node B RRM algorithms and later, RNC's algorithms are explained in more detail.

The HS-DSCH link adaptation algorithm adjusts the transmission data rate based on the CQI reports in the UL HS-DPCCH. Even with constant transmitting power on the HS-DSCH, there are several time varying factors that are responsible for HS-DSCH SINR variations, namely, the total transmission power from the serving HS-DSCH cells, the DL radio channel, and inter-cell interference at the MT. Higher CQI reports, with values between 0 and 30, allow MTs to be served with higher bit rates.

Fast Node B scheduling is based on quality feedback, MT capability, resource availability, buffer status, QoS, and priority. There are several packet scheduler algorithms, the Round Robin (RR), based on "best effort" and PF, providing multiple users diversity, being the most representatives. The RR schedules all HSDPA users with equal probability, without considering radio channel conditions. The PF scheduler is based on feedback information, providing a fair split of resources among all users. PF parameters can be chosen to maximise the total cell throughput, only serving users with good radio quality, or to guarantee fairness, where users with worse radio quality are prioritised over time. Modifications in the PF scheduler can be introduced to provide the same average HSDPA data rates to all users in the cell [BaHo02]. Other scheduling algorithms with QoS differentiation, like minimum Guaranteed Bit Rate (min-GBR) or maximum Delay (max-Del), can be used. The MAC-hs scheduler at the Node B is also responsible for handling pending HARQ retransmissions.

In the initial phase, considering MTs supporting only 5 of the 15 available codes, code multiplexing should be used to schedule 3 simultaneous users, maximising spectral efficiency, but in this case, with 3 HS-SCCH codes, only 14 HS-PDSCH codes are available for traffic. Code multiplexing can also be used when there are several users with low data rate and delay sensitive applications, like VoIP. The use of code multiplexing reduces the multiple users diversity gain, and has the cost of transmitting one HS-SCCH per user.

The resource allocation algorithm at the RNC is responsible for HS-PDSCH Node B's code allocation. The spectral efficiency increases with the use of more HS-PDSCH codes, but the channelisation codes used for HS-PDSCH cannot be used for Release 99, which may lead to call blocking. In this case, the resource allocation is also responsible for deciding and releasing some of the HS-PDSCH codes to avoid voice call blocking in Release 99. This algorithm is also responsible for the allocation of multiple HS-SCCH codes in code multiplexing, and for power management of RT DCH connections.

The packet scheduler controls the power for non-RT channels. With HSDPA, it is necessary to control the power division between HSDPA and Release 99 channels, one approach being to let the RNC establish the amount of HSDPA power per Node B, and the other being to let the Node B allocate all non-used power to HSDPA transmission, the latter leading to better results, especially in coverage-limited scenarios. The state of the art solution is power allocation between HSDPA and non-HSDPA traffic based on QoS parameters: for DCH, one has Traffic Class (TC), Traffic Handling

Priority (THP), Allocation Retention Priority (ARP) and others on the Iu-PS interface, and for the HSDPA, one has Guaranteed Bit Rate (GBR), Scheduling Priority Indicator (SPI), and Discard Time (DT) on the Iub interface.

Admission control decides if a new user is admitted in the cell, and what type of service, DCH or HSDPA, the user will get. Voice or CS video users are served with DCH. For PS users, and considering QoS requirements, the algorithm chooses the type of service based on Node B's measurements, like total power, non-HSDPA and required HS-DSCH power, as well as pilot measurements from the MT. The RNC can then decide if the Node B has enough capacity to serve the new user with the required service, maintaining all other users with their specific QoS. An admission control algorithm using these measurements and new HSDPA QoS requirements to allocate HSDPA resources can provide attractive capacity for high quality VoIP users.

Mobility management is responsible for handovers. HSDPA does not support SHO, since there is only one serving HS-DSCH cell. HS-DSCH handovers are synchronised, allowing full coverage, mobility, and avoiding packet losses [PeTM04]. The RNC establishes the active set and makes handover decision normally based on MT CPICH measurements, even though the Node B can force an HS-DSCH cell change, due to a weak UL HS-DPCCH quality channel.

In HSDPA, one can consider several types of handover: inter Node B HS-DSCH to HS-DSCH, between different Node Bs, intra Node B HS-DSCH to HS-DSCH, between 2 sectors in the same Node B, and HS-DSCH to DCH. The last one happens when the MT moves to a non-HSDPA area. DCH to HS-DSCH handover is also possible for MTs entering HSDPA zones.

In inter Node B handover, packet losses due to changes in the HS-DSCH serving cell can be minimised with the RNC ACK mode, or the MT can signal the RNC to immediately change the HS-DSCH serving cell. In intra Node B handover, with MAC-hs preservation, packet losses can be avoided and UL coverage is improved, since HS-PDCCH is received simultaneously by both sectors.

2.4 HSUPA

In this section, HSUPA main aspects are presented based on [HoTo06]. HSUPA main features and channels are addressed in Subsection 2.4.1, performance, capacity and coverage aspects are addressed in Subsection 2.4.2, and in Subsection 2.4.3, RRM is analysed.

2.4.1 Main Features

After the improvement of HSDPA in DL, the same approach was taken in UL. In Release 6, the E-DCH was launched, although the term HSUPA was adopted by the wireless industry as a result of the HSDPA success. HSUPA main objectives were to improve UL capacity, and to achieve higher data rates, compared to Release 99's 384 kbps, reaching 1 to 2 Mbps in early phases. HSUPA improves the radio interface, maintaining all other network elements unchanged. As in WCDMA,

power control is essential for HSUPA operation, as well as support for SHO.

As in HSDPA, a faster physical layer, shorter TTI of 2 and 10 ms, and Node B scheduling were introduced. 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 SHO. The modulation used, Binary Phase Shift Keying (BPSK), was left unchanged since transmission with multiple channels was adopted, instead of using higher order modulation, avoiding complex implementations at the MT side.

Following the HSDPA strategy, scheduling was also moved to Node B. While in HSDPA one has a one-to-many structure, in HSUPA one has a many-to-one structure, and for that reason, the dedicated channel approach was chosen. In HSDPA, one of the criteria for admission of new users is the available power transmission, while in HSUPA, since each MT has its own transmitter, the shared resource is the UL noise factor, directly connected to the interference level. The scheduling main functionality is to keep the UL noise factor high enough, to allow a high cell capacity, assuring that cell overload does not take place.

For HSUPA operation, new channels were introduced: the Enhanced Dedicated Physical Data Channel (E-DPDCH) for user data, and the Enhanced Dedicated Physical Control Channel (E-DPCCH) for control information. For scheduling purposes, the E-DCH Relative Grant Channel (E-RGCH) and the E-DCH Absolute Grant Channel (E-AGCH) were created. The E-DCH HARQ Indicator Channel (E-HICH) was added for retransmission feedback. The DCH channels from Release 99 were left unchanged. For HSDPA, a shared channel approach was used, while for HSUPA the E-DCH is a dedicated channel, like DCH from Release 99, but with fast retransmission and scheduling. Each E-DCH is independent of E-DCHs and DCHs from MTs.

The E-DPDCH is an UL physical channel for transmitting user information bits, previously processed by the transport channel processing chain. Like the DCH from Release 99, this channel uses OVSF, supports multiple parallel transmissions, has fast power control loop, and uses BPSK modulation. The new properties are the fast physical layer HARQ and fast Node B scheduling. The E-DPDCH supports SF2, which allows a more power efficient MT amplifier for high data rates. There are 2 TTIs for the E-DPDCH: 10 and 2 ms. For the former, the frame is separated into five 2 ms sub-frames, each one corresponding to one E-DCH transport block. It needs the simultaneous transmission of the DPCCH for power and SIR estimation. The E-DPCCH is also required, to inform the Node B receiver of the E-DPDCH format. The theoretical maximum bit rate achieved is 5.76 Mbps, with parallel transmission of 2 SF2 and 2 SF4 codes.

The E-DPCCH is an UL physical channel that transmits E-DPDCH decoding information to the Node B. It has a fixed SF256 and transports 30 bits in a 2 ms sub-frame. For the 10 ms TTI, the 2 ms sub-frame is repeated 5 times, allowing reduced power transmission. The E-AGCH is a DL physical channel used to control the MT transmission power in relation to the DPCCH, and thus, control the available data rate for the MT. For the 2 ms TTI case, an additional bit, the absolute grant scope, may

be used to allow or disallow transmission for a specific HARQ process. It uses a fixed SF256.

The E-HICH is a DL physical channel to send HARQ feedback information for UL packet transmission. In case of correct decoding, an ACK is sent, otherwise, the Node B reports a Negative ACK (NACK). This ACK/NACK procedure is only valid for Node Bs belonging to the user's active set. For other Node Bs, only ACKs are sent, and in case of erroneous decoding, there is no transmission at all. This scheme reduces DL power transmission, since for these Node Bs, there is a high probability of incorrect packets reception. Until receiving an ACK, the MT will keep transmitting. The modulation, SF and structure are the same as for the E-RGCH, with 40-bit long orthogonal sequence, allowing up to 40 E-HICH/E-RGCH on a single code channel, the differentiation being done through high Radio Resource Control (RRC) signalling. All E-HICH transmitted from the same Radio Link Set (RLS) transport the same content and are soft combinable.

The E-RGCH is a DL channel for sending up, hold or down power commands, matching data rate adjustments. The modulation used is BPSK with On Off Keying (OOK) and SF128. The transmitted message depends on which cell is transmitting: for cells in the serving E-DCH RLS, the 3 power commands are valid while for the other cells, only the hold and down are valid, like ACK/NACK case in the E-HICH. For both cases, there is no transmission for the hold command. All E-RGCHs transmitted from the serving E-DCH RLS transport the same command, and are soft combinable.

2.4.2 Performance, Capacity and Coverage

As in HSDPA performance, HSUPA performance depends on parameters like network algorithms, deployment scenario, MT transmitter capability, Node B receiver performance and capability, and the type of traffic considered. For HSUPA, 6 MT classes are defined, with UL bit rates between 69 kbps and above 4 Mbps, for category 1 and 6, respectively, Table C.4. For testing purposes, a set of E-DCH channel configurations, the Fixed Reference Channel (FRC), were defined by 3GPP.

In HSUPA, since there is no AMC, the performance metric is similar to the Release 99 one, the E_c/N_0 , energy per chip to noise spectral density ratio. To achieve high data rates, a high E_c/N_0 at the Node B is required, which causes the UL noise to increase, and, as in WCDMA, leads to a decrease of the cell coverage area. For this reason, a maximum level for the UL noise may be defined for macro-cells, to assure the coverage area, hence, limiting high data throughputs. In Figure 2.4, the expected throughput for medium speed MTs as a function of the available E-DCH E_c/N_0 is presented, where FRC5 is representative for first MT releases, while FRC2 and FRC6 are representative for future MTs with advanced capabilities, such as the support for 2 ms TTI and higher coding rate.

As expected, FRC2 achieves a higher throughput, with the maximum just below 3 Mbps, although the higher data rates are only accomplished for high E_c/N_0 values, which in real networks may be difficult to achieve. The E-DPCCH must also be correctly received, and since there is no error correction for this channel, it should be transmitted with high power to reduce decoding errors.

For HSUPA, new measurements were introduced: the UE Power Headroom (UPH), informing the

Node B of the available power resources, and the E-DCH Transport Format Combination Indicator (E-TFCI), indicating the transport format being transmitted simultaneously on E-DPDCHs. The UPH measurement is similar to CQI in the HSDPA case, but due to delays and inaccuracy in measurements, it cannot be used with the same functionality as the CQI. In [HoTo06], several results from simulations comparing Release 99 to HSUPA are presented. As expected, HSUPA allows higher average throughput and improves the user bit rate, mainly due to fast physical layer HARQ retransmissions.

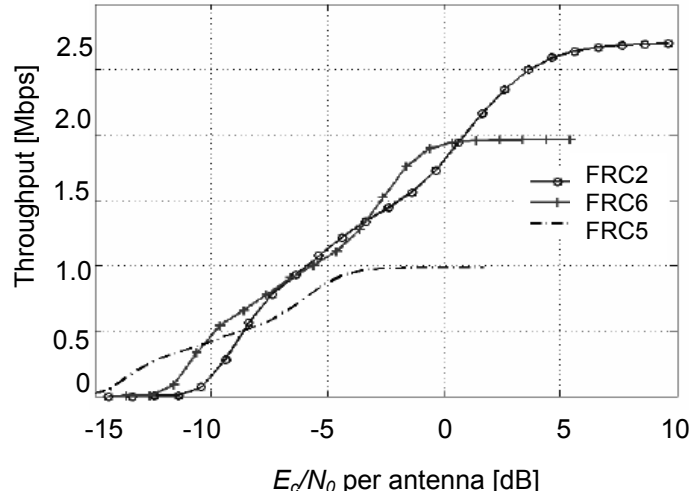


Figure 2.4. HSUPA throughput in Vehicular A at 30 km/h, without power control (extracted from [HoTo06]).

Considering HSUPA capacity, the use of HARQ and soft combination of HARQ retransmissions, allows to considerably decrease the necessary E_b/N_0 at the Node B, when comparing similar data rates with Release 99, which increases the UL spectral efficiency. Less delay and jitter in retransmissions is also accomplished, due to fast retransmissions. Increasing the Block Error Probability (BLEP) at first retransmission, leads to lower effective E_b/N_0 , and hence, to increase of UL's spectral efficiency. For realistic traffic, the capacity improvement due to the use of HARQ is expected to be around 15 to 20%.

The use of fast Node B scheduling allows fast adaptation to interference variations, and also a better resource sharing among users. The tighter UL noise factor control with Node B scheduling helps to avoid network overload and in case of overload situations, it reduces the necessary time to return to a stable state. Simulations predict an improvement of about 15 to 20%, due to the use this feature.

The adoption of HSUPA results in good coverage for high data rates, due to the use of low order modulation, which improves and simplifies the MT power amplifier. The use of fast HARQ and Node B scheduling introduces a capacity gain of 15 to 60%, depending on mobility, traffic and environment.

As stated earlier, there are 2 TTIs available: the 2 ms for high data rates, only achieved under good radio channel conditions, and the 10 ms, the default value, for cell edge coverage and when, due to increase in path loss, there is a high number of retransmissions. To extend HSUPA coverage, the user can be downgraded from the 2 ms TTI to the 10 ms one.

2.4.3 Radio Resource Management

HSUPA efficient RRM techniques allow capacity and available data rate improvement, while maintaining the network balanced. In HSUPA, RRM functions are divided among RNC, Node B and MT. For the RNC, admission control, resource allocation, QoS parameters, and mobility management are briefly described. For the Node B, the new functions compared to the ones from Release 99 are HARQ and fast packet scheduling.

Admission control is responsible for accepting new HSUPA users. For this decision, factors like the number of active HSUPA users, UL interference levels (based on Received Total Wideband Power (RTWP) measurements), SPI of new calls, GBR for new calls (while assuring GBR for all other existing calls), bit rates on both DCH and E-DCH, and also DL limitations, are analysed for new HSUPA users' admission. DCH connections, both CS and PS, are controlled by RNC admission control, while the Node B packet scheduler controls E-DCH PS connections.

For resource allocation, the received wideband power level at the Node B is determined by the RNC. Unused power from DCH connections can be allocated to HSUPA connections. UL noise measurements from the Node B are used to control active users, allowing a faster adjustment than decisions based on the RNC. For HSUPA, the UL interference can be set at higher values, since variations are smaller than in Release 99, and higher UL interference levels increases capacity. For congestion situations, RNC may send a congestion indication for a specific MT. Upon reception on the Node B, the bit rate of the specified MT can be downgraded. For QoS, parameters like SPI, GBR, and maximum number of HARQ retransmissions are sent from RNC to Node B, to be used in packet scheduling, the decision being taken at the Node B.

For mobility management, the RNC decides which cells belong to the active set, with a maximum of 4 Node Bs, and which one is the serving HSUPA. Usually, the same Node B acts as serving HSDPA/HSUPA, but this is not mandatory. When operated in SHO, each Node B handles MT's packets independently from other Node Bs, which requires packet re-ordering at the RNC, and consequently, a new MAC entity. This centralised approach reduces the number of packet retransmissions in SHO, since several Node Bs can receive the same data packet.

For the Node B, fast packet scheduling with HARQ retransmissions is the main innovation. There are 2 scheduling modes: one with HARQ control and signalling, and one non-scheduled mode controlled by RNC, which is similar to Release 99 DCH scheduling, but with physical layer retransmissions. The use of HARQ improves spectral efficiency, while Node B scheduling allows for operation with higher UL noise level, thus, increasing capacity. For the scheduling, the Node B considers resource feedback and availability, MT capability and buffer status, QoS and priority. For the Node B's scheduler, several MAC-e were introduced, each one of them connected to a single MT, the MAC-e being responsible for the HARQ operation. The bit rate allocated to an MT can be changed, based on the happy bit – which informs the Node B if the MT is satisfied with the present data rate, or if it desires higher power, and hence, higher data rate – MT buffer status, other MT measurements, or Node B available resources.

2.5 State of the Art

In this section, the state of art concerning this thesis' main objectives is presented. For HSDPA, several papers on performance and capacity analysis can be found, although they refer mainly to the improvement over Release 99, and not the influence of the number of HS-PDSCH codes on network throughput and capacity. Few papers are available on HSDPA, and even fewer on HSUPA.

The gain from using shared DCH/HSDPA carriers is evaluated under mixed traffic conditions in [PLSF04]. Through extensive dynamic simulations, network performance improvement and a capacity gain of 69% was accomplished for 6 to 7 W HSDPA transmission power and 5 HS-PDSCH codes. Several simulation results, like cell throughput sensitivity to the available HSDPA transmission power and user experienced throughput depending on the number of active HSDPA users, are presented. This work does not consider the feasibility of using more than 5 HS-PDSCH codes, namely, the use of 10 HS-PDSCH codes on shared carriers.

An analytical approach to HSDPA radio interface dimensioning is taken in [ZaSo05], based on specific requirements for throughput and HSDPA DL transmission power. It provides a link budget estimation that can be used to calculate HSDPA coverage. Several numerical results are presented, as available average HSDPA throughput when the non-HSDPA power is provided as input, HSDPA throughput as a function of the available HSDPA power, and the required HSDPA power to accomplish minimum HSDPA throughput at cell edge with a specified probability. In the simulations presented, only 5 HS-PDSCH codes were used, and the possibility of delivering 7.2 Mbps in shared carriers was not addressed, as well as the impact of deep indoor in HSDPA performance.

An analytical model for HSDPA cell radius calculation as a function of outage probability is presented in [AvMu05]. The maximum cell radius for MTs in the worst cell location, under full load is also presented. The numerical results allow determining the influence of several parameters, like the desire SINR threshold, the shadow fading, and the Node B transmit power. The results can be applied to both omni-directional and tri-sectorized antennas. In this paper, the MT receives signals from only 3 Node Bs, one transmitting the desired signal, and the other two being interferers. The path loss between all Node Bs is assumed to be identically distributed. For the cell radius, constraints on HSDPA throughput and code multiplexing were not considered. This paper does not consider the impact of shared carriers in the cell radius and the use of 5 or 10 HS-PDSCH codes.

The influence in capacity with the introduction of HSUPA, due to the use of shorter TTI, HARQ technique, and Node B scheduling is analysed in [HEEE05]. The results presented show a capacity gain in both delay and capacity optimised systems. Based on link and system levels simulations, the UL capacity gain achieved for rate scheduling is between 70 and 100%, compared to Release 5. This paper does not address the increase in the MT transmission power, and the comparison between HSUPA and Release 99 under different radio conditions.

End-to-end performance of enhanced UL is studied in [PEHP05]. The results demonstrate latency

times of 50 and 80 ms for TTIs of 2 and 10 ms. Enhancements in file upload were also presented for both large and small files, with higher performance improvement for the latter ones. Like in [HEEE05], a delay-optimised system can obtain a higher end-to-end performance compared to a capacity optimised one. It is shown that the use of 2 ms TTI can also improve end-to-end performance in file download, compared to HSDPA. In this paper, only 5 and 15 HS-PDSCH codes are considered when evaluating HSDPA performance. For the comparison between HSUPA and Release 99, different radio conditions, as well as the required MT transmission power, are not analysed.

In [SMRS05], measurements on an Ericsson test bed, based on enhanced UL applied on top of a commercial Release 99 cellular network integrated with HSDPA, are presented and compared to the results in [HEEE05] and [PEHP05]. The test bed supports a 2 ms TTI, fast retransmissions, HARQ and fast scheduling. Several performance parameters are analysed and compared over an Additive White Gaussian Noise (AWGN) channel and a fading Pedestrian A channel with MT's speed of 3 km/h. For lower data rates, measured and simulated results are similar, while, for higher data rates, the measured performance is deteriorated due to an error floor on the MT receiver. The test bed results can be used to validate the theoretical and simulation results. The presented simulations are mainly on HSUPA, while HSDPA performance, namely, the performance comparison between 5 and 10 HS-PDSCH codes is not analysed.

HSPA was introduced to improve data communications and to create a multiservice platform. Nevertheless, voice is still an essential service that must be provided by cellular operators, hence, papers considering VoIP are considered, mainly due to the importance that VoIP will have on the migration to an all-IP scenario based on HSPA. This migration will have impact on network's performance and capacity. Several papers show that in a wide-range, the use of VoIP will accomplish network enhanced performance.

VoIP performance under HSDPA is presented in [BPKM05]. This paper can be included in the focus of the present thesis, since it demonstrates the capacity increase obtained with VoIP calls, instead of CS voice calls in Release 99. Simulations results show a capacity increase compared to other studies for DCH calls, although these results are strongly dependent on various parameters, such as cell configuration, CQI delay, MT category, among others. The achieved improvement is strongly dependent on the tolerated delay. A code multiplexing of 4 was used. This paper does not consider limitations on the UL radio link, and only quasi-static network simulations focused on the air interface were carried out. Mobility, with the eventual losses due to changes in the HS-DSCH serving cell, was not considered.

System performance of VoIP on HSUPA is analysed in [ChKM06], with both a semi-analytical model and by system level simulations. The theoretical results, confirmed by simulations, show a capacity gain of VoIP over DCH. Analogous to VoIP on HSDPA, the UL capacity with non-scheduling is strongly dependent on the tolerated delay, and on the maximum number of HARQ retransmissions allowed. It is also shown that the use of HARQ and SHO can improve UL capacity, by reducing the MT transmission power.

Chapter 3

Models and Simulator Description

In this chapter, an overview of both the single user radius model and the HSDPA/HSUPA simulator are presented. The first one is intended to provide an overview of network planning, regarding cell radius for HSDPA and HSUPA, when a single user is at the cell edge requiring service. These models can be used in the first phase of network planning to estimate cell radius. The multiple users simulator, based on an existing one, has the objective of analysing a more realistic scenario, with users performing multiple services and randomly spread over the Node B's coverage area. The main outputs of this simulator are the average network radius and the average instantaneous cell throughput among others. Based on the instantaneous values, an analysis for the busy hour is also performed. Afterwards, the simulator assessment is shown. This chapter concludes with modifications introduced in the link budget for the measurements assessment.

3.1 Single User Radius Model

In this section, a functional description of the single user model for the radius calculation is presented. The user's interface is presented in Annex B. The maximum cell radius, being the maximum distance that allows the user to be served with the desired throughput, is calculated considering that there is only one user in the cell. Several parameters can be modified, namely for HSDPA:

- Total Node B transmission power;
- Frequency;
- Number of HS-PDSCH codes;
- Node B and MT antenna gains;
- Environment: pedestrian, vehicular, indoor with low and high losses and fading margins.

Other parameters, as the desired throughput according to the number of selected HS-PDSCH codes, additional losses, noise factor, activity factor and traffic power can also be modified. This model was developed in collaboration with [Salv08].

From (3.1), the maximum throughput at the physical layer, for 16QAM modulation, is 0.96 Mbps per HS-PDSCH code, being 4.8, 9.6 and 14.4 Mbps for 5, 10 and 15 codes, respectively. In real networks, only 14 HS-PDSCH codes are used for data, since usually 2 HS-SCCH codes must be reserved for signalling and control (HS-SCCH and Associated DCH (A-DCH)). Therefore, the maximum throughput at the physical level is 13.44 Mbps. From now on, one refers 15 HS-PDSCH codes, but the analysis performed considers that only 14 HS-PDSCH codes are available for traffic.

$$SF = \frac{\text{Chip rate}}{\text{Symbol rate}} \Leftrightarrow 16 = \frac{3.84}{\rho_P/4} \Leftrightarrow \rho_P = 0.96 \text{ Mbps} \quad (3.1)$$

Considering a codification rate of 75%, the maximum throughput at the physical layer is 3.6, 7.2 and 10.08 for 5, 10 and 15 HS-PDSCH codes, respectively. At the RLC layer, the maximum allowed throughput considered is 3.36, 6.72 and 9.4 Mbps for 5, 10 and 15 HS-PDSCH codes, respectively, considering 6.7% due to the overhead of the MAC and RLC layers. These are the available throughput at the application level, with more realistic values being around 3, 6 and 8.46 Mbps considering a BLER and application overhead of 10%.

For the HSDPA single user model, the only limiting factor is the available number of HS-PDSCH codes that restrain the maximum application throughput. The HSDPA receiver sensitivity, as well as the path loss, are calculated by using Annex A.

For HSUPA, the same radio parameters need to be introduced, with the exception of the number of HS-PDSCH codes. Additional parameters, like the inter- to intra-cellular interferences ratio, maximum UL load factor, diversity and SHO gains can be modified. Due to MT limitations, the maximum application throughput considered is 1.22 Mbps for category 2 MTs. This value is obtained considering that the maximum physical throughput is 1.45 Mbps, being 1.376 Mbps at the RLC layer, due to MAC

and RLC overheads. The maximum throughput at the application level, 1.22 Mbps [HoTo06], is obtained considering a 10% reduction for BLER and application overhead.

The objective of this model is to calculate the maximum cell radius for each throughput, introduced in the user interface. Using Figure A.1 and Figure A.2, the requested throughput is mapped onto SINR and E_c/N_0 for HSDPA and HSUPA, respectively, for the calculation, using (A.7) of the receiver's sensitivity, the minimum received power that allows the user to be served with the requested throughput. In this calculation, the interference margin was not considered, the maximum Node B antenna gain was used, and the lowest frequency in the frequency band was considered. Several considerations were taken into account, namely, perfect radio channel conditions were used, and interference due to both internal and external factors, and hence, noise rise, were not considered.

These results were obtained assuming the best radio conditions, but both slow and fast fading margins were considered in the environments margins. The total Node B transmission power, MT and Node B antenna gains, frequencies, and other parameters used in the link budget, are listed in Section 4.1, Table 4.2.

The path loss is calculated using the link budget detailed in Annex A, (A.1) and (A.11). From the COST-231 Walfisch-Ikegami propagation model, one has [DaCo99]:

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

where:

- L_o : free space loss;
- L_{tt} : rooftop-to-street diffraction loss;
- L_{tm} : approximation for the multiscreen diffraction loss;
- $EIRP$: equivalent isotropic radiated power, given by (A.3) or (A.4);
- P_r : available receiving power at the antenna port;
- G_r : receiving antenna gain;
- M : total margin, given by (A.10).

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

$$R_{[\text{km}]} = 10^{\frac{EIRP_{[\text{dBm}]} - P_{r[\text{dBm}]} + G_{r[\text{dBi}]} - M_{[\text{dB}]} - L'_{tt[\text{dB}]} - L'_{tm[\text{dB}]} - L'_{o[\text{dB}]}}{20 + k_d}} \quad (3.3)$$

where:

- $L'_{tt} = L_{tt} - k_d \cdot \log(d_{[\text{km}]})$;
- k_d : dependence of the multiscreen diffraction loss versus distance;
- d : distance between the user and the Node B;
- $L'_o = L_o - 20 \cdot \log(d_{[\text{km}]})$;
- R : maximum cell radius.

3.2 HSDPA/HSUPA Simulator

In this section, the HSDPA and HSUPA simulator developed is introduced. First, in Subsection 3.2.1, an overview of the simulator is presented, with the simulator's implementation being described in Subsection 3.2.2. In Subsection 3.2.3, the simulator input and output files are pointed out.

3.2.1 Simulator Overview

The simulator developed in this thesis, with the main structure being presented in Figure 3.1, was adapted from the one developed in [CoLa06], [Card06] and [SeCa04]. New HSDPA and HSUPA modules, highlighted in red, were added, while the main structure was left unchanged. The HSDPA simulator was elaborated in collaboration with [Salv08].

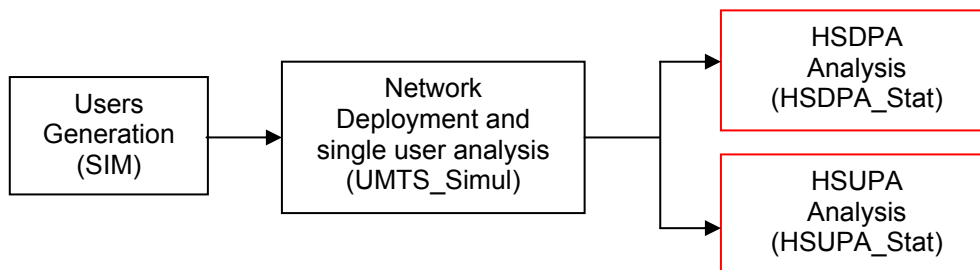


Figure 3.1. Simulator overview (adapted from [CoLa06]).

This simulator has the primary objective of analysing the performance of HSDPA and HSUPA. The simulator consists of 4 major modules:

- Users' generation;
- Network deployment without load;
- HSDPA analysis;
- HSUPA analysis.

The user generation module is described in detail in [CoLa06]. The only modification introduced was a new type of scenario, the indoor high loss scenario. This scenario was mainly introduced to establish a difference between low penetration indoor from the deep indoor one, with higher attenuation, due to the fact that most users access wireless networks in indoor scenarios. The input files for the traffic distribution and the services penetration percentage, as well as the QoS priority lists, are described in Annex C. This module was implemented in C++.

The network deployment module, implemented in MapBasic, is described in detail in [CoLa06]. This module places the users from the output file of the SIM program in the network, distributed throughout the most populated areas. After the user's placement, the network is deployed. Then a first network analysis is performed, the cell radius for a single user being calculated for each service and for the reference throughput. The link budget used in this analysis is the one presented in Annex A. All the users within the coverage area are the ones to be considered in the HSDPA and HSUPA modules. In Annex D, the user's manual for the UMTS_Simul application is presented.

3.2.2 HSDPA and HSUPA Implementation

These modules were implemented to enable the analysis of the impact of the HSDPA and HSUPA in the network, and were developed in C++. Its main objectives are the analysis of the network capacity and coverage, through a snapshot approach, calculating instantaneous network results as average radius, number of user per Node B as well as traffic and number of users' estimations per hour. This module performs analysis on a Node B basis, being executed in all Node Bs in the network. Afterwards the module computes averages regarding some of the parameters recorded for each Node B, and extrapolates some results for the busy hour analysis. The HSDPA and HSUPA implementations are presented together, since these are analogous, with the differences being pointed out.

To perform the network analysis, some parameters are considered. For HSDPA, one has:

- Node B DL transmission power;
- Frequency;
- MT antenna gain;
- User and cable losses;
- Noise figure;
- Signalling and control power percentage;
- Number of HS-PDSCH codes;
- Reduction strategies;
- Reference service;
- Interference margin;
- Environment.

Each of these parameters can be modified, and all have a different influence on the simulations' results. Radio parameters, such as Node B DL transmission power, frequency, MT antenna gain, user and cable losses, and noise figure, are the same as the ones considered in Section 3.1. The QoS priority, as well as the data volume for each service, can be modified, Figure D.6.

As HSDPA is not a stand alone system, being deployed on top of R99, even for an HSDPA dedicated carrier, such as the one considered in this thesis, a percentage of the total Node B DL transmission power is reserved for R99 signalling and control. Additionally, some power must be reserved for HSDPA signalling and control. The same procedure is applied to HSUPA, but in this case, the UL signalling and control power can be negligible, since the control is mainly performed by the Node B.

The number of HS-PDSCH codes is a key parameter for the evaluation of the network HSDPA performance, as it is responsible for the throughput increase of the end user. The maximum throughput associated to the number of HS-PDSCH codes also implies that the maximum instantaneous throughput at the Node B is 3 Mbps for 5 HS-PDSCH codes, 6 Mbps for 10 and 8.46 Mbps for 15. In the simulator, one did not consider a combination of MTs, i.e., for the 5 HS-PDSCH codes simulations only MTs supporting 5 codes are considered, and the same is valid

for the 10 and 15 codes simulations. The instantaneous throughput values at the Node B are the ones calculated in Section 3.1, adapted to the multiple users scenario, as in HSDPA, a shared channel being used. In this simulator, one did not consider shared transmission power, as this would require a per-TTI analysis, which is out of the scope of the present thesis. The multiple users influence is simulated by the introduction of the interference margin, specific for each Node B.

For HSUPA, the same aforementioned parameters are used, with the exception of the number of HS-PDSCH codes, an HSDPA specific parameter. For HSUPA, the throughput limitation is due to the number of E-DPDCH, and to the SF. For the MT category considered in this thesis – category 2 – the maximum application throughput is 1.22 Mbps, as explained in Section 3.1. Unlike HSDPA, for HSUPA, a dedicated channel is used, but the UL noise is shared among active users, leading to a shared throughput. For this reason, the same approach was taken for HSDPA and HSUPA, as in both systems, throughput is shared among users, although due to different features.

The considered reduction strategies are:

- “Throughput Reduction”, where the throughput of all users is reduced by a percentage defined in the HSDPA/HSUPA settings window;
- “QoS Class Reduction”, where all the users’ throughput of the same service is reduced by 10%, according to a list containing the services’ priorities;
- “QoS One by One Reduction”, where for a specific service, each user throughput is reduced one by one, also according to a priority list.

The same reduction strategies are used for both HSDPA and HSUPA, the difference being that for HSUPA, SHO must be taken into account. The 3 algorithms are detailed in Annex E and F, for HSDPA and HSUPA, respectively.

The reference service stands as an indicator for the number of users that are considered during simulations. A higher throughput considered for the reference service reduces the Node B nominal radius, with fewer users being considered. This analysis is for a single user only, with the purpose of considering the users that are in the Node B’s coverage area, meaning that these are the only users considered in the HSDPA and HSUPA modules.

The interference margin is a parameter used to emulate the load in the cell, as there is no specific interference margin in DL. This margin is only considered in the multiple users scenarios, being the main difference in the path loss calculation between the single and multiple users scenarios. Due to the interference margin, path loss decreases, leading to a lower cell radius or throughput, depending on the analysis, when one compares the single user with the multiple users scenarios. The same approach was taken for both HSDPA and HSUPA, regarding the interference margin calculation, explained in detail in Annex A.

The different environments influence the cell radius calculation, since each one has specific attenuation and fading margins, presented in Section 4.1. After all the explained parameters are set,

the radius for all the considered services in Figure D.5, as well as the radius for the reference service, is calculated, as shown in Figure D.8. For HSUPA, two additional parameters are considered: SHO and Node B antenna diversity.

The minimum and maximum service throughputs can also be modified, using the User Profile window, Figure D.5, for HSDPA and HSUPA. The maximum HSDPA throughput values are given by the system limitation, i.e., the number of HS-PDSCH codes chosen, Table 3.1. For HSUPA, the limitation is imposed by the MT category, as seen in Section 3.1.

Table 3.1. HSDPA and HSUPA maximum application throughput.

System	Maximum throughput [Mbps]
HSUPA	1.22
HSDPA 5 HS-PDSCH codes	3.0
HSDPA 10 HS-PDSCH codes	6.0
HSDPA 15 HS-PDSCH codes	8.46

In the beginning of the simulation, the number of users physically inside the Node B coverage area is calculated, as explained earlier. Two files with users' and network information are created. These files are going to be used in HSDPA_Stat and HSUPA_Stat modules:

- “data.dat”, which contains information of which Node B serves each user, the user distance, service requested, type of environment, and others;
- “definitions.dat”, with the radio parameters considered in the simulation, minimum and maximum throughput for each service, QoS priority, and other simulations' settings.

The next step is to associate each user to the Node B, according to the distance between them, the user being connected to the closest Node B, since in urban scenarios each user is usually within several Node Bs' coverage area. Regarding capacity, this is not the best approach, as the user should be connected to the Node B with more available resources, but at this point, the network is not yet created and so, that information is not available. Next, the throughput associated to the user distance is calculated, i.e., the maximum throughput that the Node B can offer to the user, considering the path loss (3.4). Using Figure A.3 and Figure A.4, the Signal to Noise Ratio (*SNR*) is mapped onto throughput. This algorithm is explained in detail in Annex A.

$$SNR_{[dB]} = P_{Rx_{[dBm]}} - N_{[dBm]} + G_{p_{[dB]}} = EIRP_{[dBm]} - L_{P_{[dB]}} + G_{r_{[dB]}} - L_{u_{[dB]}} - N_{[dBm]} + G_{p_{[dB]}} \quad (3.4)$$

where:

- *SNR*: signal to noise ratio;
- P_{Rx} : received power at receiver input;
- N : total noise power;
- G_p : processing gain;
- L_u : user losses.

The calculation of the cell radius in the multiple users simulator is different from the one used in the

single user model. In the latter, the main objective is to calculate the maximum cell radius, using the method described in Section 3.1, whereas in the multiple users scenario, the cell radius is defined as the distance of the user served further away from the Node B. Equation (3.4) is used to determine if the user can be served. One should mention that the capacity also limits the cell radius, since when the reduction strategies are executed, the users further away of the Node B have a higher probability of being delayed, and so, the Node B cell radius decreases.

When considering the throughput that can be offered to the user, there are 3 different situations:

- the user is served with the requested throughput – the throughput associated to distance is higher than the service's throughput;
- the user is served with the throughput associated to distance – this throughput is higher than the minimum service, and lower than the maximum service throughputs;
- otherwise the user is delayed, being considered in another TTI.

The procedure to calculate the user throughput for HSDPA is shown in Figure 3.2.

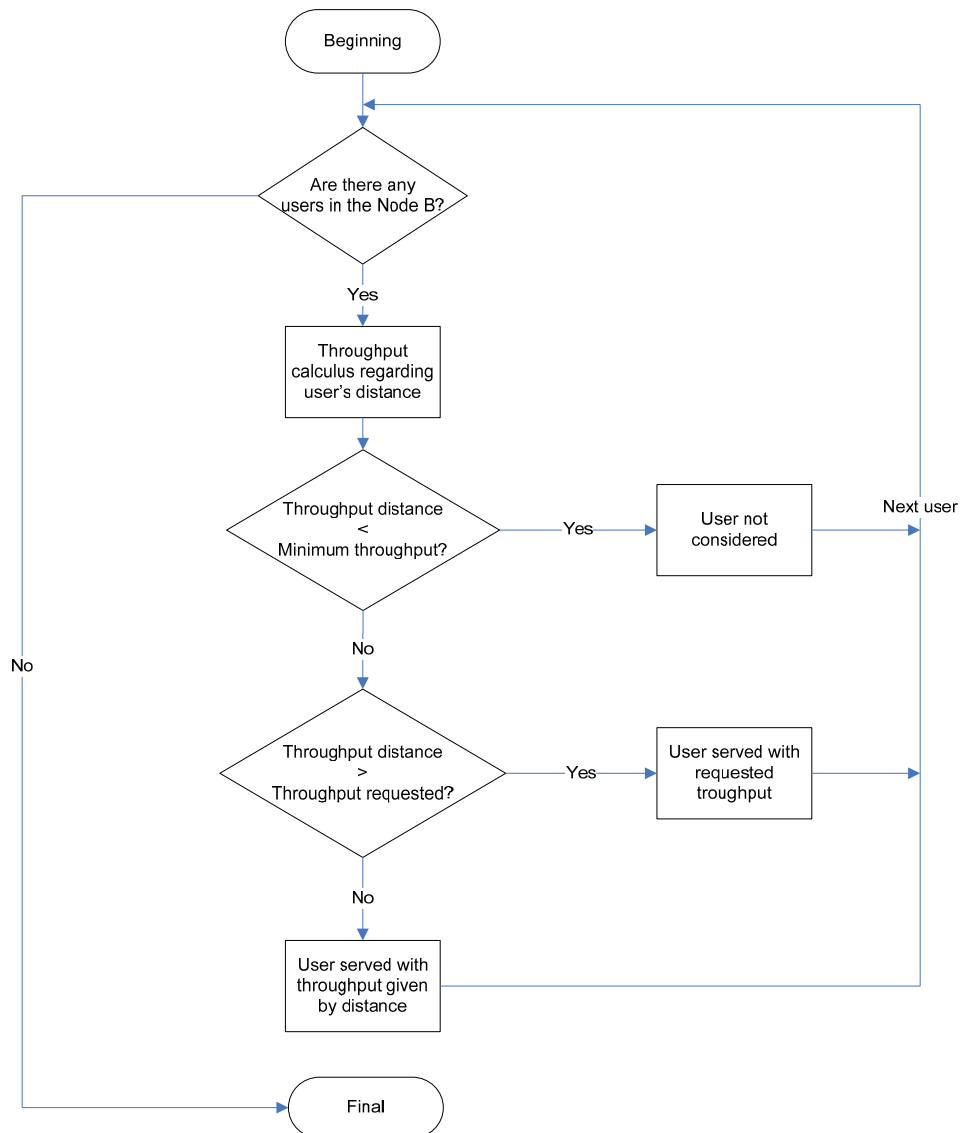


Figure 3.2. HSDPA user's throughput calculation algorithm.

The services' throughputs are obtained from the file "definitions.dat", and compared with the throughput given by the user distance, after being multiplied by a random function with values between 0 and 1. This randomness is a more realistic approach, since in several cases the throughput limitation is not imposed by the radio access network, but by the server's congestion.

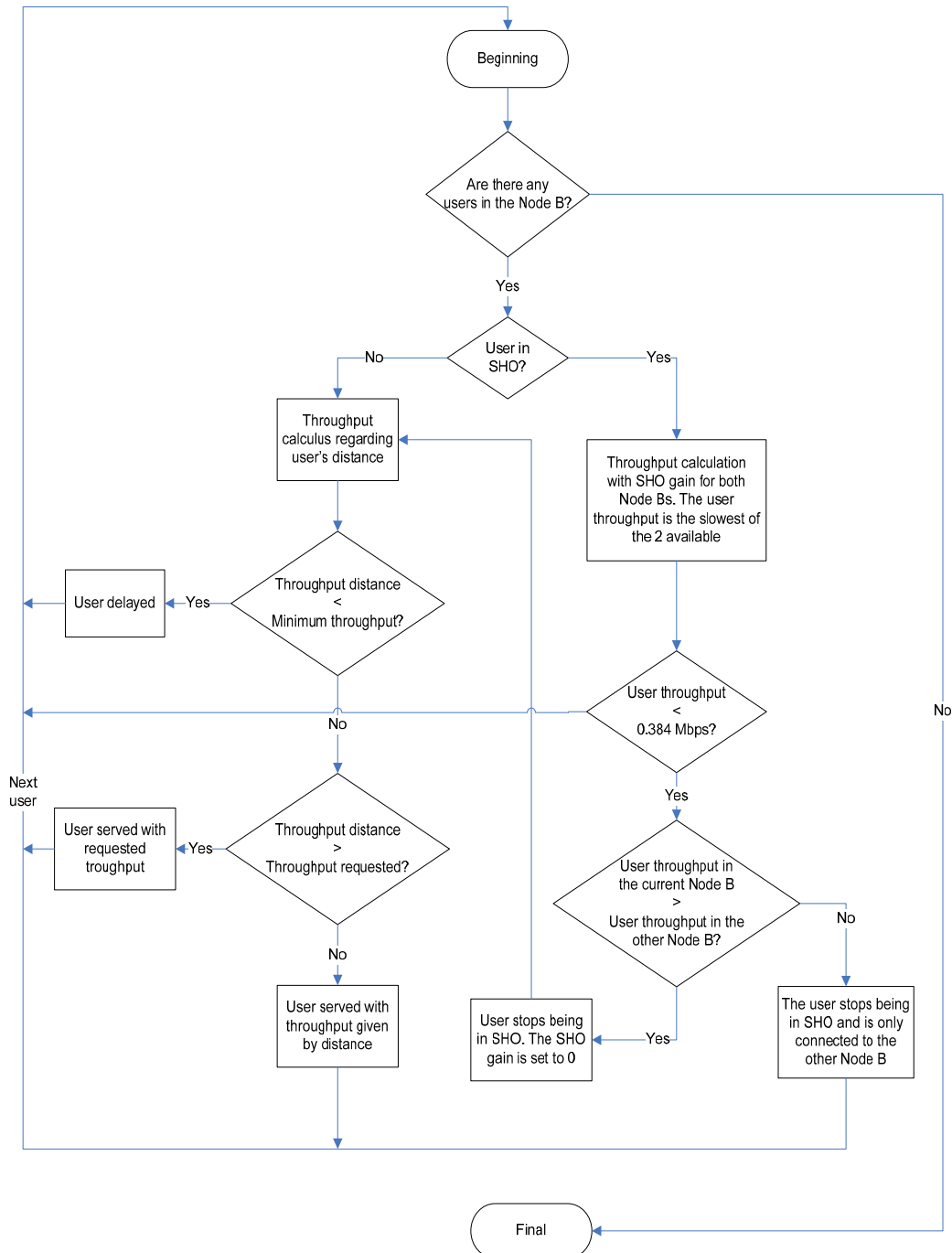


Figure 3.3. HSUPA user's throughput calculation algorithm.

The approach used for HSDPA is also used for HSUPA. For the latter, SHO gain must be considered, because each user can be connected to the two closest Node Bs. When the user is in SHO, the user throughput is the minimum throughput allowed by one of the two available throughputs from each Node Bs. SHO is only considered if the user throughput is higher than the SHO limit – which one

considers to be 0.384 Mbps. In Figure 3.3 the HSUPA users' calculation algorithm is shown.

The analysis of the system's capacity is carried out at the Node B's level, by summing the throughput of all served users. Two possible cases can occur:

- the sum is lower than the maximum allowed throughput for the Node B – all users are served without reduction;
- otherwise, one of the reduction strategies, shown in Annex E and F, are applied.

The maximum allowed throughput values considered for the Node B are shown in Table 3.1. The latter process is detailed in Figure 3.4 for HSDPA, and Figure 3.5 for HSUPA.

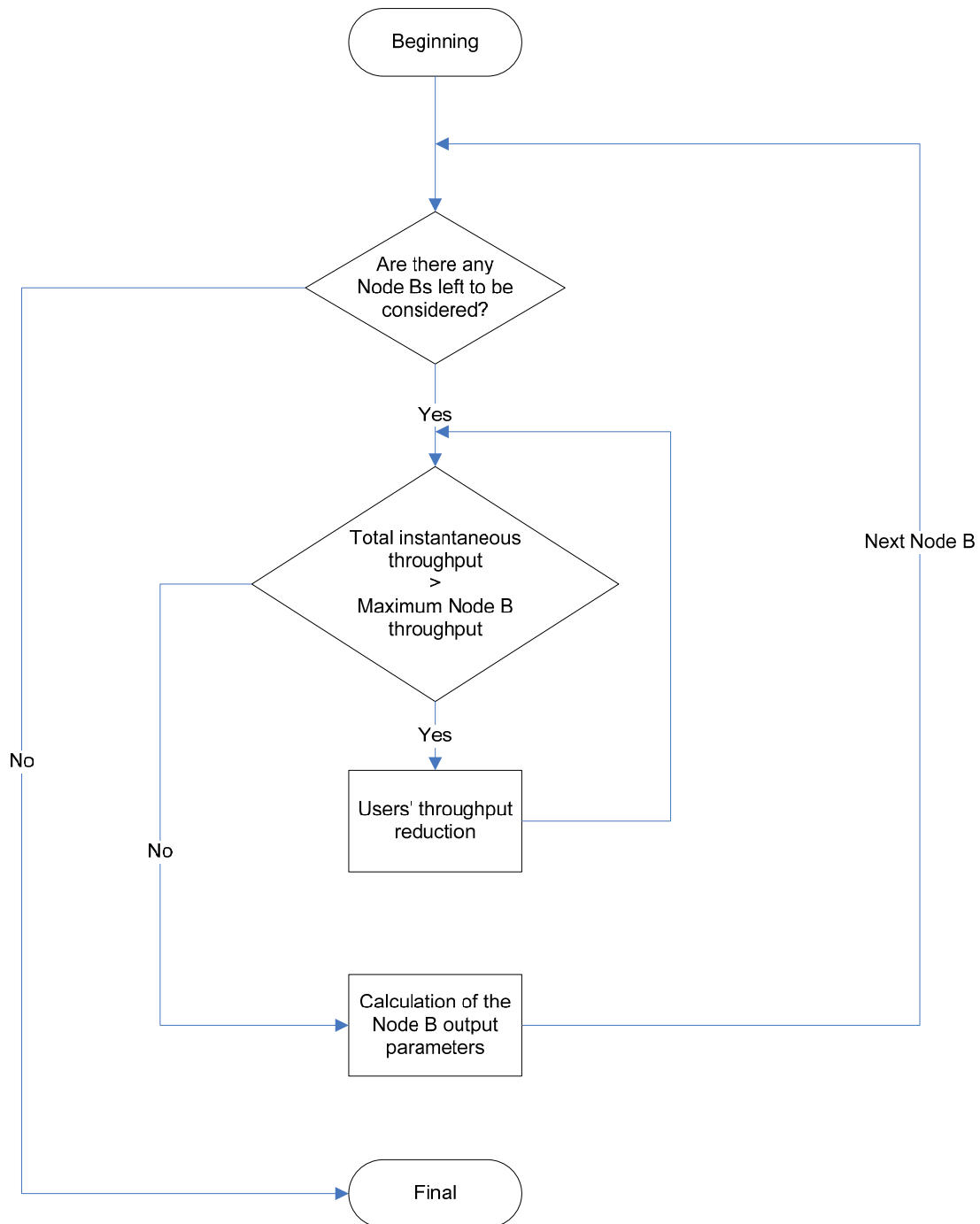


Figure 3.4. HSDPA algorithm to analyse the Node B limitation.

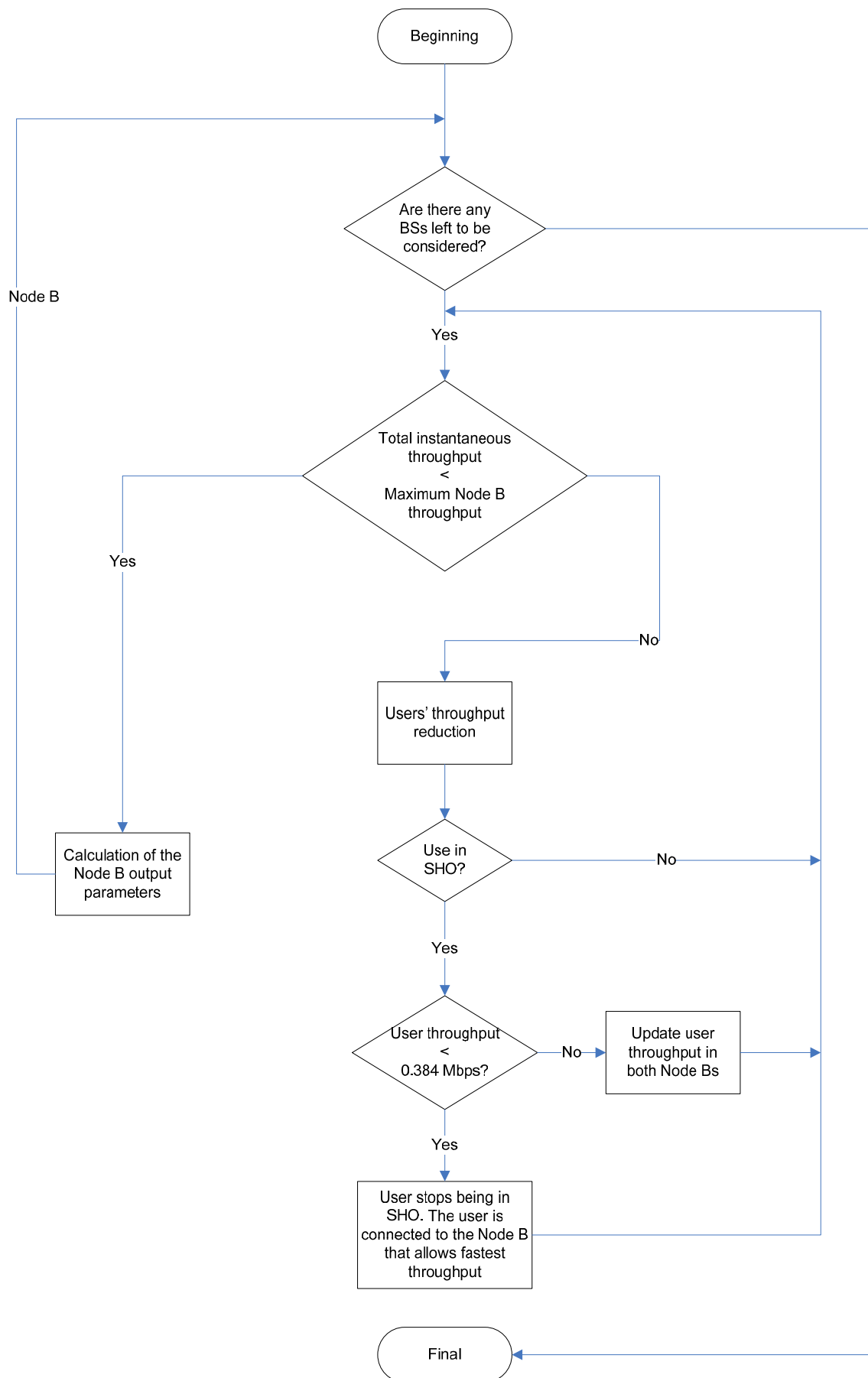


Figure 3.5. HSUPA algorithm to analyse the Node B limitation.

After the capacity analysis, several network parameters for each Node B are calculated:

- instantaneous served throughput, being the sum of all users' throughput;
- normalised throughput, being the ratio over the instantaneous served throughput and the maximum allowed throughput;
- radius, average of the user placed further away from the Node B for the 3 sectors;
- number of served and delayed users;
- percentage of satisfied and unsatisfied users, where a satisfied user is considered to be one being served with the requested throughput;
- average instantaneous throughput per user, the ratio between the sum of all users instantaneous throughput served and the number of served users;
- satisfaction grade, being the ratio between served and requested throughputs;
- total Node B traffic transferred in one hour;
- average data volume per user, the ratio of the total Node B data volume in one hour over the number of users served.

These parameters, except for the radius, are also presented in the services detail analysis, where all parameters are considered only for the users performing each one of the services. This analysis is then performed for all Node Bs in the network, and the average of each of the parameters is calculated for the entire network, taking the number of users of each service into account. The outputs for these results are shown in Figure D.10 and Figure D.11.

For the network analysis, the most relevant parameters for the instantaneous analysis are:

- percentage of served users, being the ratio between the number of served users and the total number of users in the network;
- average network satisfaction grade, the ratio of the served over the requested throughput;
- average network radius, being the average Node B individual radius in the network;
- average network throughput, the average of all Node B's instantaneous throughput for whole the network.

After the instantaneous analysis, the results are extrapolated for the busy hour analysis, Figure D.12. The parameters studied in the busy hour analysis are:

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

Considering each user throughput and file size, according to the type of service, the duration of the user's session is calculated. Based on this result, the number of sessions per hour is calculated according to the specified user. The total number of users in the busy hour is calculated as the summation of the number of sessions per hour of all users. Based on the number of users in the busy hour, the total traffic for each service is calculated, taking into account the volume, in MB, of each session, given by the traffic models. In this busy hour analysis, the total number of users, the total network traffic, the average volume and average number of users per Node B, as well as the average volume per user are calculated, Figure D.12.

3.2.3 Input and Output Files

In order to run the simulator, it is necessary to insert the following files in the UMTS_Simul application:

- “Ant65deg.TAB”, with the Node B’s 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, as streets, gardens, and others;
- “users.txt”, containing the users in the network, being the output of SIM module;
- “BSs_Lisbon_map.TAB”, with the information of the location of the Node Bs in the network.

The UMTS_Simul module creates 2 files that are going to be used by the HSDPA and HSUPA modules to perform the simulations:

- “data.dat”, a list with all users’ coordinates and Node Bs in the network, as well as the distance between them. For each user, additional information, such as the user scenario and requested service, is also present;
- “definitions.dat”, with the radio parameters considered, minimum and maximum throughputs for each service, QoS service’s priorities, and other simulations settings.

Based on these files, the HSDPA and HSUPA modules execute the network analysis and produce several output files, 2 of each are used by the UMTS_Simul to present the results in Map Info:

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

3.3 Simulator Assessment

In order to evaluate the simulator, all steps responsible for carrying out calculations were validated using several tools. The propagation model and link budget used were confirmed performing several calculations using Matlab and Excel, to assure that results were correct and according to the theoretical model.

Regarding the users’ insertion in the network, some validations were performed. As in HSDPA SHO is not considered, it must be assured that each user is only connected to one Node B. For this purpose, an output file was created containing the user’s information considering the Node Bs to which the user is connected. Even though the user may be in the coverage area of several Node Bs, the simulator only considers the nearest Node B to the user. The same procedure was taken for HSUPA, but in this case, the user can be connected to the two closest Node Bs.

The 3 reduction strategies were analysed through a controlled scenario, i.e., using a simulation with approximately 500 users and 3 Node Bs. After performing this simulation, the total instantaneous throughput was the parameter to be analysed. Forcing the situation where the total instantaneous throughput requested by all users is higher than the one allowed at the Node B, the list of user’s throughput was then placed in an Excel sheet, to monitor every step of the reduction strategies. This

analysis was performed for both HSDPA and HSUPA, separately, since due to SHO some modifications were introduced in the HSUPA reduction strategies.

After the simulation, all the output results, such as summations, averages and standard deviations were confirmed, by using the respective well-known formulas. This procedure was carried out for the Node B analysis as well as for the network.

Users' geographical positions, as well as the requested throughputs, are random variables, hence, several simulations must be taken to assure result validation. The default number of users considered per simulation is approximately 1600 – this result being justified in Section 4.1. Considering this value, 30 simulations were performed, executed in a Pentium D, CPU 3 GHz, 960 MB RAM, with an average simulation duration of 30 minutes, Table 3.2.

Table 3.2. Average and standard deviation values of the parameters considering 30 simulations.

Number of simulations	Ratio of served users		Satisfaction grade		Average network throughput [Mbps]		Average network radius [km]	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
5	0.51	0.08	0.86	0.04	2.39	0.11	0.29	< 0.01
10	0.51	0.01	0.87	0.04	2.39	0.08	0.28	< 0.01
15	0.51	0.01	0.87	0.04	2.39	0.08	0.29	< 0.01
20	0.52	0.01	0.86	0.03	2.41	0.09	0.29	< 0.01
25	0.52	0.01	0.86	0.03	2.39	0.09	0.29	< 0.01
30	0.52	0.01	0.86	0.03	2.39	0.09	0.29	< 0.01

The parameters considered in this analysis are:

- Percentage of served users;
- Satisfaction grade;
- Average network throughput;
- Average network radius.

The number of simulations is estimated based on the results presented in Figure 3.6 and Figure 3.7. From Table 3.2, one can observe that, for each parameter considered, there is almost no variation in the average, and the standard deviation presents smooth variations.

Taking the average simulation duration of around 30 minutes into account, and that when one increases the number of simulations there is no significant decrease of the standard deviation; one has concluded that 10 is the most suitable number of simulations – it allows a good precision, and at the same time, it does not require several hours of simulations. These results were obtained for HSDPA simulations. Although HSDPA and HSUPA are different techniques with specific features, the simulator principle is essentially the same, and so, the same number of simulations was used for HSUPA. For this analysis, HSDPA was chosen, since it is the system that is already deployed in the networks used, and on which more information is available.

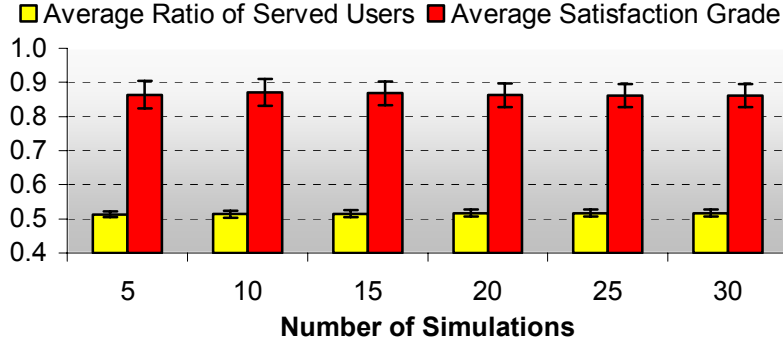
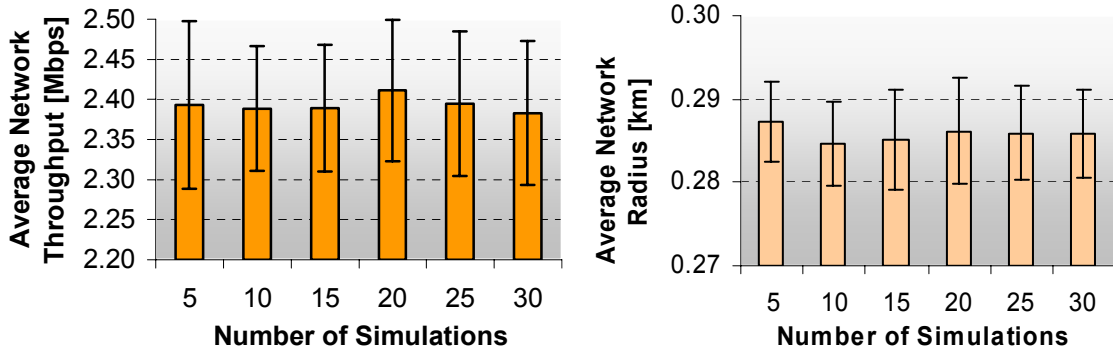


Figure 3.6. Evolution of the ratio of served user and satisfaction grade for 30 simulations.



(a) Average Network Throughput.

(b) Average Network Radius.

Figure 3.7. Evolution of the average network throughput and average network radius for 30 simulations.

In Figure 3.8, it is possible to examine the ratio of the standard deviation over the average value for each one of the analysed parameters. One can observe that there is no relevant decrease of this ratio when the number of simulations increases, and considering the average duration of each simulation, Figure 3.8 confirms that 10 simulations are enough. One can further notice that the satisfaction grade and the average network throughput present the higher values, even though the maximum value is below 0.05, meaning that there is a small variation among simulations, hence, increasing the number of simulations would have minimal impact on the results.

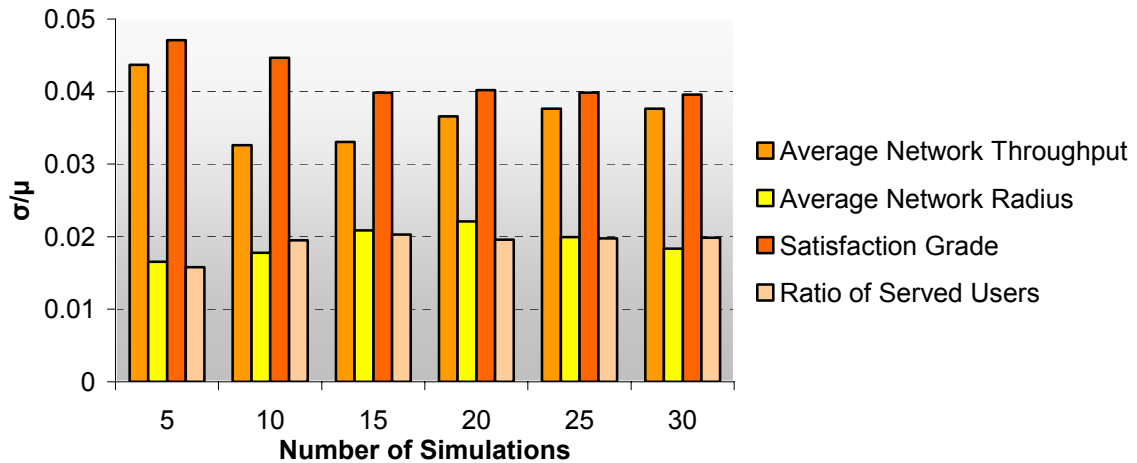


Figure 3.8. Standard deviation over average ratio for 30 simulations.

3.4 Measurement's Link Budget

In this section, one presents the modifications introduced in the link budget, described in Annex A, to allow a comparison between the results from the theoretical models and the ones from the measurements. One of the recorded parameters in the measurements is the Received Signal Code Power (RSCP), used to analyse the channel quality. For the measurements performed in both test plant and in the live network, there is no direct correlation between *RSCP* and distance. In both situations, the reductions on *RSCP* were accomplished by using attenuators. For the measurements in the test plant and in some cases for the measurements in the live network, *RSCP* variations between -70 and -115 dBm were performed by using the same distance between the MT and the Node B antenna. To compare the theoretical models and the measurements results, it is necessary to map the *RSCP* values onto the distance. For this purpose, one used the same link budget as the one used throughout this thesis with minor adaptations, pointed out in this section.

The mapping of *RSCP* onto distance is somehow similar to the process described for the single user model, the main difference being the calculation of the received power. In the single user model, the received power is calculated based on the user's requested throughput and the SINR curves from Figure 2.2, with the cell radius being calculated via (3.3). For the measurements, one used *RSCP* as the received power in the link budget, and so the user's distance is given by:

$$d_{[km]} = 10^{\frac{EIRP_{[dBm]} - RSCP_{[dBm]} + G_{r[dB]} - M_{[dB]} - L'_{a[dB]} - L_{tm[dB]} - L'_{p[dB]}}{20 + k_g}} \quad (3.5)$$

where:

- *RSCP*: Received Signal Code Power.

The same values as the ones defined in Section 4.1 were used for the link budget. The only changed values were the Node B antenna gain and the environment margin. In the HSDPA measurements, for an *RSCP* of -95 dBm, a distance of 200 m was obtained, using Global Positioning System (GPS). Using (3.5), one adjusted the Node B antenna gain and the environment margin, in order to obtain a distance of approximately 200 m for an *RSCP* of -95 dBm. For the Node B antenna gain, one used 12 dBi and for the environment margin one used 20.05 dB. It is curious to notice that the environment margin used is the weighted average of each of the environments used in the simulator and the environment's distribution percentage. In Annex A, one presents Figure A.5, Figure A.6 and Figure A.7 where the relationship between *RSCP* and distance is shown, for the measurements performed in test plant and in the live network, for HSDPA and HSUPA.

Chapter 4

Result Analysis

In this chapter, the results for both the single user radius model and for the multiple users simulator are presented. First, the single user radius model is analysed, separately for HSDPA and HSUPA. The results from the simulator introduced in Chapter 3 are then presented, considering several parameter variations, as the number of HS-PDSCH codes and Node B transmission power, for HSDPA, and alternative profiles, number of users and the reduction strategies, for both HSDPA and HSUPA. Later on, a comparison between HSDPA and HSUPA, focusing on coverage and capacity, for both single user and multiple users scenarios, is presented. At the end of the chapter, results from measurements performed in test plant and in live network are presented, and a comparison between the results given by the simulator and the real network measurements is carried out.

4.1 Scenarios Description

Two scenarios are considered throughout this thesis: the single user and the multiple users ones. The single user scenario considers that there is only one user in the cell, therefore, all the available resources are dedicated to this user. This scenario is used to calculate the maximum cell radius for the chosen throughput. In the multiple users scenario, one considers that the users are uniformly distributed along the coverage area of the Node B, performing different services with different associated throughputs.

The environments considered for both scenarios are pedestrian, vehicular, indoor low and high loss. The pedestrian environment stands for a user at the street level with low attenuation margins; the vehicular one stands for users performing services moving at high speed, where a large value for the slow fading, M_{SF} , and fast fading, M_{FF} , margin is considered; the indoor environment characterises users performing services inside buildings. There are two kinds of indoor environment: the low and high loss, where the latter is used for users in deep indoor locations with higher penetration attenuation, L_{int} . The percentages taken into account for the environments are:

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

The indoor environments represent the largest part of the overall percentage as it is, at the present, the most common environment for users performing the types of services analysed, mainly associated to laptops. In Table 4.1, one lists the attenuation margins associated to each type of environment.

Table 4.1. Slow and fast fading and penetration margin values (based on [CoLa06]).

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

The parameters for link budget estimation used for both scenarios, and the default values considered, are the ones listed in Table 4.2. For the single user scenario, the interference margin and the reduction strategy are not considered. The Node B antenna gain is 17 dBi, with a 65° half power beam width radiation pattern detailed in [CoLa06]. For the single user scenario, the maximum Node B antenna gain was used.

The maximum and minimum throughput values for the services considered in the default multiple users scenario in UL and DL, as well as the QoS priority list, are presented in Table 4.3. For the QoS priority list, the first services to be reduced are the ones with higher QoS value, according to the traffic

classes shown in Section 2.2. The services' penetration percentages for the default scenario as well as for the two alternative scenarios are presented in Annex C.

Table 4.2. Default values used in HSDPA and HSUPA link budget (based on [CoLa06] and [EsPe06]).

Parameter	HSDPA	HSUPA
Node B DL Transmission Power [dBm]	44.7	---
Frequency (single user) [MHz]	2112.5	1922.5
Frequency (multiple users) [MHz]	2142.5	1952.5
Number of HS-PDSCH codes	10	---
MT Antenna Gain [dBi]	0	
Maximum Node B Antenna Gain [dBi]	17	
User Losses [dB]	1	
Cable Losses between Transmitter and Antenna [dB]	3	
Noise Figure [dB]	9	5
Diversity Gain [dB]	---	2
SHO Gain [dB]	---	2
Interference Margin [dB]	6	
Percentage of power for signalling and control [%]	R99: 25 HSDPA: 10	---
Reduction Strategy	"QoS Class Reduction"	

Table 4.3. Maximum and minimum throughput for the default scenario.

Service	Maximum Throughput [Mbps]		Minimum Throughput [Mbps]		QoS
	DL	UL	DL	UL	
Web	1.536	0.512	0.512	0.128	1
P2P	1.024	0.384	0.128	0.064	6
Streaming	1.024	0.064	0.512	0.064	2
Chat	0.384	0.384	0.064	0.064	5
E-mail	1.536	0.512	0.384	0.128	3
FTP	2.048	0.512	0.384	0.128	4

The HSDPA and HSUPA traffic models characteristics' detailed by service are presented in Table 4.4. For HSUPA, the same traffic models cannot be used, due to the asymmetry of the services. For this reason, some of the traffic models characteristics must be redefined, namely the real asymmetric ones, like web browsing and streaming that use the UL channel mainly for signalling purposes. For web browsing, the same profile is used, but only 20 kB are considered for the UL data volume. The same data volume was considered for Streaming. For FTP, instead of 10, a 2 MB file was used. Chat and P2P are symmetric services and for this reason, the same traffic models were used.

To determine the number of users to use in the default scenario, several simulations were performed to analyse the impact of the variation of the number of users in several parameters, regarding network

performance as well as the average instantaneous throughput per user, Table 4.5. In this analysis, a network in the city of Lisbon was used, with 228 Node Bs spread along the city, according to the population distribution's in the city area: areas with higher population density have a higher number of Node Bs is present. In Figure D.9, the Node Bs deployment, together with the nominal Node B's coverage area for the simulated network is shown.

Table 4.4. HSDPA and HSUPA traffic models.

Service		DL	UL
Web	Average page size [OPTW06] [kB]	300	20
	Average reading time [Seba07] [s]	40	40
	Average number of pages per session	10	10
FTP	Average file size [SBER03] [MB]	10	2
	Average number of files per session	1	1
P" P	Average file size [MB]	12.5	12.5
	Average session initiation time [s]	30	30
Chat	Average MSN message size [CSEE06] [bytes]	50	50
	Average number of received messages during one session	25	25
E-mail	Average file size [Seba07] [kB]	100	100
	Average number of e-mails per session [Seba07]	1	1
Streaming	Average video duration [VNUN07] [s]	150	150
	Average video size [MB]	9.6	0.02
	Average number of videos per session [COMS07]	3	3

Table 4.5. Evaluation of the number of users considering several parameters.

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

As expected, the average network throughput increases with the number of users, since the system capacity limit is not achieved, but the parameters that evaluate the network quality, as the satisfaction grade, percentage of served users, and the average instantaneous throughput, decrease. The average network radius variation is not significant, but it can be seen that the increase of the number of users leads to a small increase in the network average radius. Analysing the evolution of the key parameters to evaluate network's performance shown in Table 4.5, the number of users considered for the default scenario throughout this thesis is 1600. It is a middle ground choice based on the evolution of all parameters shown on Table 4.5.

For the same reason as the one used for the analysis of the number of simulations, the analysis of the number of users was performed for HSDPA. To perform a fair comparison between HSDPA and HSUPA, the same number of users is used in both simulations, to assure that the result's variation is only due to the system chosen. Nevertheless it is important to emphasise that the services' throughput is limited by the type of system used, bearing in mind that HSDPA is a DL connection and HSUPA an UL one.

4.2 Single User Radius Model Analysis

In this section, the HSDPA and HSUPA results considering the single user analysis are presented.

4.2.1 HSDPA Evaluation

All the cell radius results in this section were calculated using the single user model described in Section 3.1, namely, the cell radius were computed using (3.3) and using the values from Section 4.1, Table 4.2. The HSDPA cell radii for the environments introduced in Section 4.1 are presented in Figure 4.1.

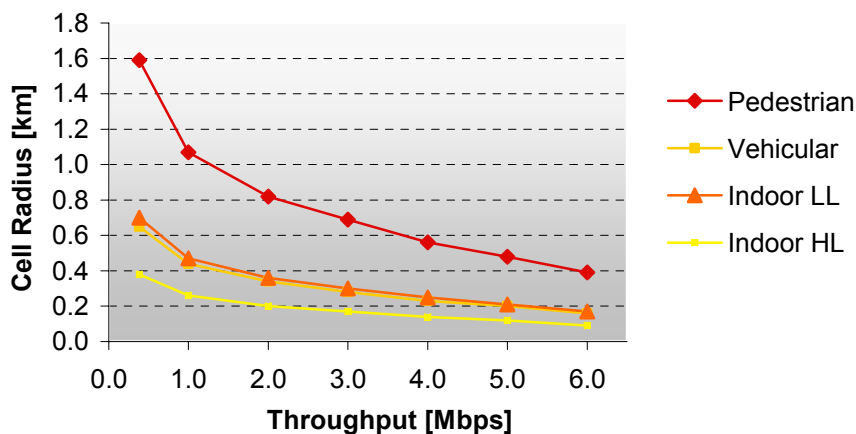


Figure 4.1. HSDPA cell radius for 10 HS-PDSCH codes, considering throughput and environment variations.

In Figure 4.1, one shows the variation of the cell radius as function of the throughput for each of the considered environments. For all environments, it is possible to observe that the cell radius decreases

with the increase of the throughput. This is due to the fact that higher throughputs require higher SINR values, Figure 2.2. With the increase of the SINR value, the path loss decreases, leading to a lower cell radius, (A.7), (A.1) and (3.3).

Considering the different environments, one can examine that the pedestrian one presents a higher cell radius, 0.69 km, compared to the other environments. The pedestrian environment allows an average increase of 128, 143 and 311% compared to the indoor low loss, vehicular and indoor high loss environments. In Table 4.1, one can observe that the pedestrian environment has lower attenuation margins, which justifies the higher cell radius, as the sum of the 3 margins is considered in the path loss, as seen in (A.10) and (A.11). This explains the similarity of the results for the vehicular and the indoor low loss environments, even though the environments have different characteristics. Considering the indoor low loss environment, it is observed that when the throughput ranges from 2 to 6 Mbps, the cell radius decreases from 0.4 to 0.2 km, while for the pedestrian environment the cell radius decreases from 1.6 to near 0.4 km.

In Figure 4.2, one shows the cell radius variation with the total Node B DL transmission power, considering a fixed throughput of 3 Mbps and the pedestrian environment, for 5, 10 and 15 HS-PDSCH codes. A 3 Mbps throughput is considered as it is the highest common throughput among the 3 set of HS-PDSCH codes analysed. Considering the maximum Node B transmission power, the cell radius difference between using 15 or 5 HS-PDSCH codes is around 50% for both pedestrian and indoor low loss environments. In these results, the influence of the CPICH was not considered, even though this is a key factor regarding cell coverage.

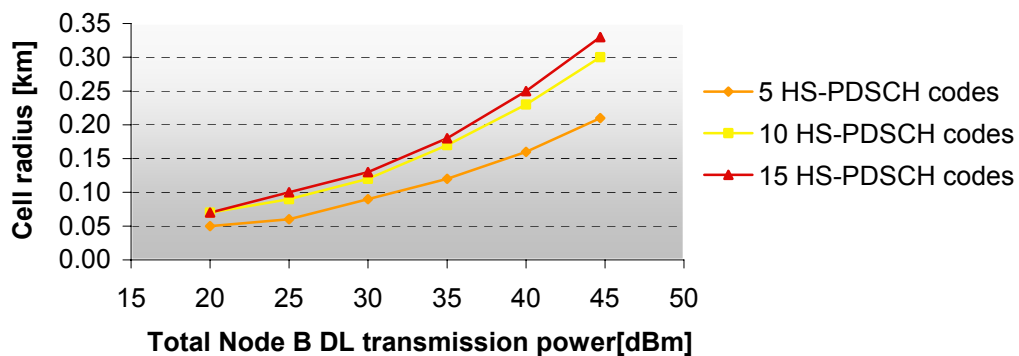


Figure 4.2. HSDPA cell radius for total Node B DL transmission power variation, for indoor low loss.

From Figure 4.2, it is possible to see that the increase of the transmission power leads to the increase of the cell radius, as there is a direct relation between these two parameters, as it can be seen from (A.3), (A.1) and (3.3). For 5, 10 and 15 HS-PDSCH codes, and considering the indoor low loss environment, the cell radius increases 320, 329 and 371% for an increase of the total Node B transmission power from 20 to 44.7 dBm. For the maximum Node B transmission power, and considering the maximum throughput of each set of HS-PDSCH codes, the cell radius is 0.48 km for 5 codes, and 0.39 km for both 10 and 15 codes, even though these set of codes have different maximum throughputs.

For each transmission power value, the same pattern repeats itself, i.e., a higher number of HS-PDSCH codes lead to a higher cell radius. This is due to the curves presented in Figure 2.2, where it is possible to observe that for the same throughput, the SINR value decreases for a higher number of HS-PDSCH codes. Therefore, by using (A.7), (A.1) and (3.3), one concludes that as expected, for the same throughput, the use of 15 HS-PDSCH codes allows a higher cell radius than the use of 5 or 10 codes. For a Node B transmission power of 44.7 dBm, and considering the indoor low loss environment, there is a gain of 57% by using 15 instead of 5 HS-PDSCH codes, while for 20 dBm, the same gain is reduced to 40%. The results presented in Figure 4.3 are only based in the SINR curves.

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

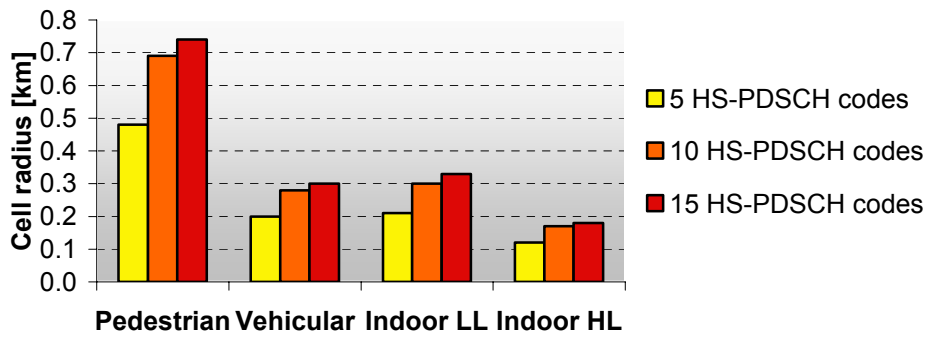


Figure 4.3. HSDPA cell radius for 3 Mbps and environment variation.

From Figure 4.3, one can confirm that for a fixed number of HS-PDSCH codes, the cell radius variation is due to the different margins associated to each environment, as in this thesis one did not considered the SINR variation with the type of environment. The difference in the cell radius for the 3 set of HS-PDSCH codes is not equal when one varies the type of environment, as there is an exponential relationship between the margins and the cell radius, (A.11) and (3.3). For the pedestrian environment, the cell radius is higher, and due to this fact, a higher difference between the results from 5 and 15 HS-PDSCH codes is observed. For 3 Mbps, HSDPA with 10 HS-PDSCH codes has a cell radius of 0.69 km for the pedestrian environment, of 0.28 km for vehicular, 0.30 for indoor low loss and 0.17 km for indoor high loss. For the pedestrian environment, and considering a reference throughput of 3 Mbps, there is a gain of 54% by using 15 instead of 5 HS-PDSCH codes while for the indoor low loss environment, the same gain is 57%. For both vehicular and indoor high loss the gain is 50%. A gain of 44% can be obtained by using 10 instead of 5 HS-PDSCH codes. In Annex G, one shows the tables with the main results regarding the single user analysis.

4.2.2 HSUPA Evaluation

In this subsection, the cell radius for HSUPA single user model is analysed, based on the single user model described in Section 3.1, namely, the cell radii were computed using (3.3) and the default values from Section 4.1, Table 4.2. Several parameters such as the UL inter-to-intra cell interferences, the UL load factor, or the activity factor, have limited influence in a single user scenario, below 5%, as

opposed to a multiple users one. For this reason, one chose not to present the results in this section, although these results are presented in Annex G. As, for the already mention parameters, frequency variations have limited influence in the cell radius calculation for both single and multiple users scenarios, since for HSUPA and for HSDPA, the maximum frequency separation is only 55 MHz, which leads to an average decrease of the cell radius of 4% when the highest frequency is used.

In Figure 4.4, the HSUPA cell radius results for several throughputs, considering the 4 environments are presented. As for HSDPA, when considering a fixed throughput, the pedestrian environment allows a higher cell radius, while the indoor high loss is the one with the shortest range, the reason being the same as the one presented for HSDPA. It can be further noticed from Figure 4.4 that all the environment curves present a negative value on the second derivative, contrary to the curves in HSDPA. This fact can be explained by using Figure 2.4, where the E_c/N_0 curve as function of the throughput variation is shown. Considering the throughput variation from 0.25 to 1.22 Mbps, the E_c/N_0 , in dB, presents an almost linear shape. The increase in E_c/N_0 is smoother than the one in SINR for the HSDPA curves, Figure 2.2. This justifies the fact that for HSDPA there is a cell radius decay of around 0.6 km, for 10 HS-PDSCH codes and pedestrian environment, when the throughput increases from 0.384 to 1 Mbps, while for HSUPA and considering the same throughput range, the cell radius decay is only 0.3 km. By considering the pedestrian environment, one gets an average increase of the cell radius of 145, 128 and 320% compared to the vehicular, indoor low loss and indoor high loss, respectively. Considering the maximum throughput, 1.22 Mbps, the cell radius is 0.44, 0.18, 0.19 and 0.10 km for pedestrian, vehicular, indoor low loss and indoor high loss, respectively. For a throughput of 0.75 Mbps, the pedestrian environment has a cell radius of 0.84 km, 0.34 km for both vehicular and indoor low loss, and 0.20 km for indoor high loss.

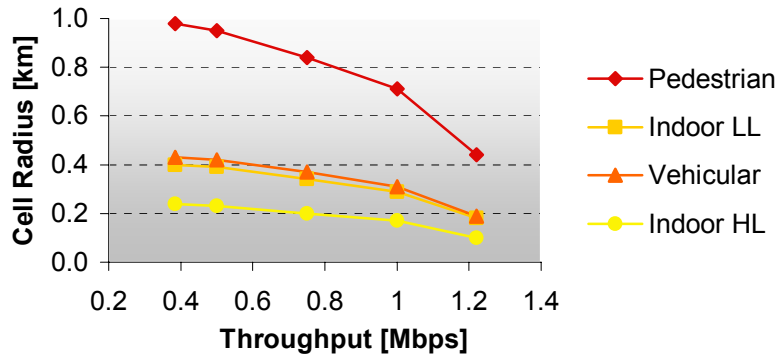


Figure 4.4. HSUPA cell radius evolution for the 4 considered environments as function of the throughput.

4.3 HSDPA Analysis in a Multiple Users Scenario

In this section, the HSDPA simulation results are analysed. First, the results of the default scenario introduced in Section 4.1 are examined. Afterwards, simulation results considering system parameter variations, as well as different scenarios, are studied. In Annex H, additional results are shown.

4.3.1 Default Scenario

All the results presented in this section were obtained using the multiple users simulator model introduced in Section 3.2. The link budget, detailed in Annex A, was used to calculate the path loss, with the user's SINR being calculated by (3.4), and the user's throughput using Figure A.1. The results on Figure 4.5 can be obtained by considering all the served users in all the simulations performed, where the distance and throughput for each user are shown. For all the users in Figure 4.5, one divided the distance in 10 m intervals, in order to calculate the average and standard deviation user throughput within each interval. This result is presented in Figure 4.6.

From Figure 4.6, one can notice that for distances further than 0.5 km, the user throughput starts to have an irregular behaviour. This fact can be explained by the reduced number of users that are served when the user's distance increases, as seen by the low standard deviation for distances above 0.6 km, meaning that few users are served and results have a small statistical relevance. This can also be justified by the fact that the average network radius is 0.28 km.

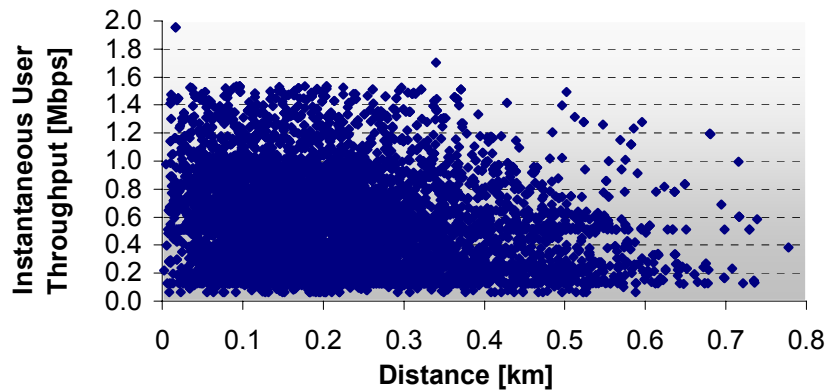


Figure 4.5. HSDPA instantaneous user throughput for all users variation with distance.

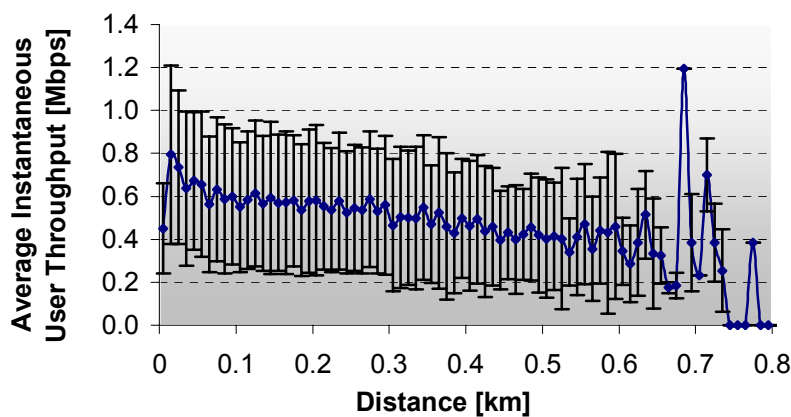


Figure 4.6. HSDPA average and standard deviation instantaneous throughput considering 10 m intervals.

Limiting the distance to 0.5 km, to eliminate the distances where there is a higher dispersion in the user throughput, (4.1) was computed, representing the network trend line regarding distance and the

average user throughput in a multiple users the default scenario, Figure 4.7.

$$\rho_{[\text{Mbps}]} = -0.521 \cdot d_{[\text{km}]} + 0.672 \quad (4.1)$$

where:

- d : distance between the Node B and the user.

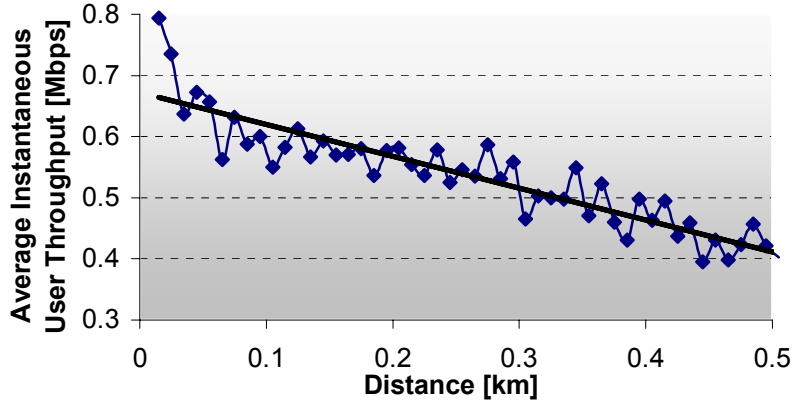


Figure 4.7. First order interpolation for HSDPA average instantaneous user throughput.

Other interpolation orders for the results in Figure 4.7 were studied and, as expected, the correlation values increased for higher interpolation orders. For the 6th order interpolation, a correlation of 0.95 is obtained, while for a linear interpolation, (4.1), a correlation of 0.90 is obtained, with a mean relative error of 5.5%. The increase of the correlation does not compensate the increase in the complexity of the interpolation expressions, hence, one chose the linear one.

The average instantaneous user throughput values shown in Figure 4.7 are obtained at the application level, and are dependent on the traffic profile chosen. These results do not represent the HSDPA maximum capacity in a multiple users scenario. One can observe, from Figure 4.7, that the average instantaneous throughput per user decreases with distance. For smaller distances, the influence of the interference margin is not noteworthy, as the SINR value is still above the threshold for the requested throughput, the latter being the limiting factor. For bigger distances, the SINR becomes the limiting factor, and the introduction of the interference margin due to the multiple users scenario causes an extra reduction on the SINR value, leading to a reduction of the user throughput. For the range of throughput values considered, between 0.064 and 2 Mbps, there is a variation in the SINR curves, as seen in Figure 2.2, leading to a fast reduction of the user throughput when SINR decreases. This behaviour is in accordance with the results from the single user model for indoor low loss environment, presented in Figure 4.28, and justifies the negative derivative of the average instantaneous user throughput in Figure 4.7. The average value in (4.1) is given by HSDPA capacity, and depends on the considered scenario. The results in Figure 4.7 were limited to 0.5 km, this being the maximum distance where (4.1) is valid. Via (4.1) and the average network radius, 0.28 km, the throughput in the cell edge is 0.52 Mbps, while the average instantaneous throughput per user is 0.56 Mbps.

In Figure 4.8, one represents the percentages of offered and served traffic. It is possible to observe that there is a difference in the referred percentages as not all users can be served by the network.

Figure 4.8b) shows the percentage of the 6 considered services, according to the final number of users effectively served by the network, while in Figure 4.8a) one shows the offered service percentages. The most significant difference is for Web, even though it is the service with the highest percentage of users and with the highest QoS priority. Web has a high minimum throughput, 0.512 Mbps, meaning that, when reductions are performed, Web users have a high probability of being delayed – they will be served later, to assure better service quality. On the other hand, P2P percentage of served users increases as fewer users are delayed due to the low minimum throughput, 0.128 Mbps, even though this is the service with the lowest QoS. The same explanation is valid for Streaming and Chat.

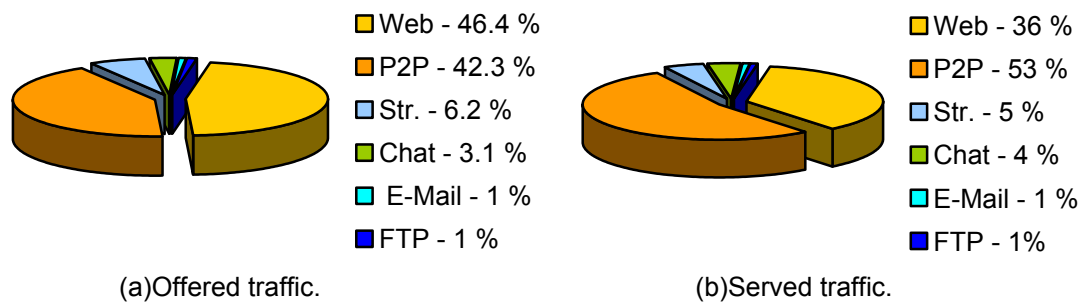


Figure 4.8. HSDPA percentage of traffic.

The average network throughput and average satisfaction grade detailed by service are shown in Figure 4.9. One can notice that P2P users have a high satisfaction grade, 85%, even though having a low average network throughput, meaning that this service has a low requested throughput. P2P users are the first ones to be reduced, but from Figure 4.9b) one can show that each user is reduced approximately only two times. Chat also has a low network average throughput, since this is the service with the lowest requested throughput. Web is the service with the lowest requested throughput. Web is the service with the highest QoS priority, and from Figure 4.9a), has the highest satisfaction grade, 93%, and an average throughput of nearly 0.8 Mbps. The high standard deviation values in E-mail and FTP services are explained by the fact that these services have a low percentage of users, approximately 1%, having a low statistical relevance. Figure 4.9 shows that the multiple users simulator can differentiate several services according to QoS's priority

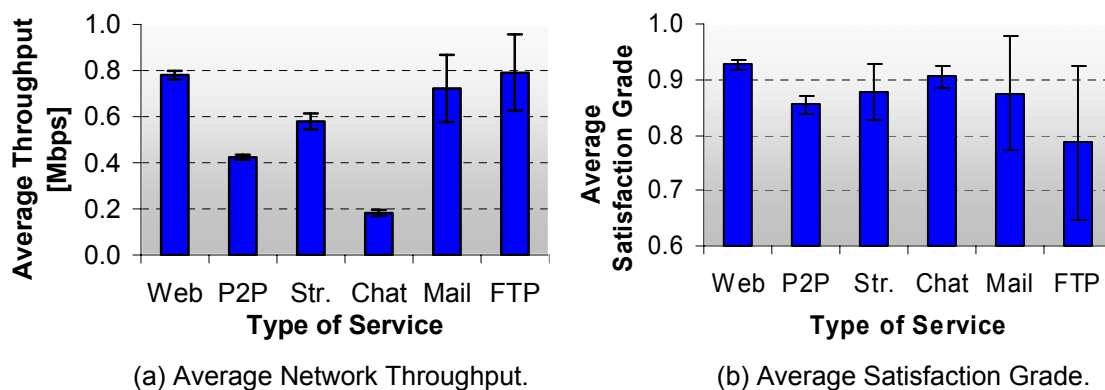


Figure 4.9. HSDPA network parameters (Throughput and Satisfaction Grade) detailed for services, for the default scenario.

Concerning the overall parameters, an average network throughput of 2.39 Mbps, and a satisfaction grade of 87% were obtained. In the analysis for the busy hour, average network traffic of 85 GB/h, with an average traffic of 0.37 GB/h per Node B were obtained. Regarding the number of users per hour, 32000 users can be served, with an average number of user per Node B of near 140.

4.3.2 Number of HS-PDSCH Codes

The influence of the number of HS-PDSCH codes in network performance is analysed in this subsection. An increase from 10 to 15 in the number of HS-PDSCH codes improves the average network throughput by approximately 9.2%, as the maximum throughput allowed for a single Node B is higher, due to the fact that more codes are available for data transmission. On the other hand, a reduction to 5 HS-PDSCH codes, means a reduction in the maximum throughput per Node B, and so, the average network throughput decreases almost 25%, Figure 4.10a). Due to the SINR curves, the same variation on the number of codes has different effects in the average network throughput. For the 3 set of HS-PDSCH codes studied, the average network throughput is less than 50% of the maximum network capacity. The variation on the average network radius is below 1%, Figure H.1a). The cell radius variations due to the use of 5 and 15 codes is lower than 1%, but while the use of 5 codes leads to a decrease, the use of 15 codes leads to an increase of the cell radius.

The impact of the variation of the number of HS-PDSCH codes can be seen in the average satisfaction grade, Figure 4.10b), as well as in the ratio of served users, Figure H.1b), as with the increase of the number of codes, more network resources, namely capacity, are available to users. The use of 10 HS-PDSCH codes instead of 5 HS-PDSCH codes leads to an increase of 18% in the satisfaction grade, and the use of 15 HS-PDSCH codes increases the satisfaction grade by only 4% compared to the default scenario.

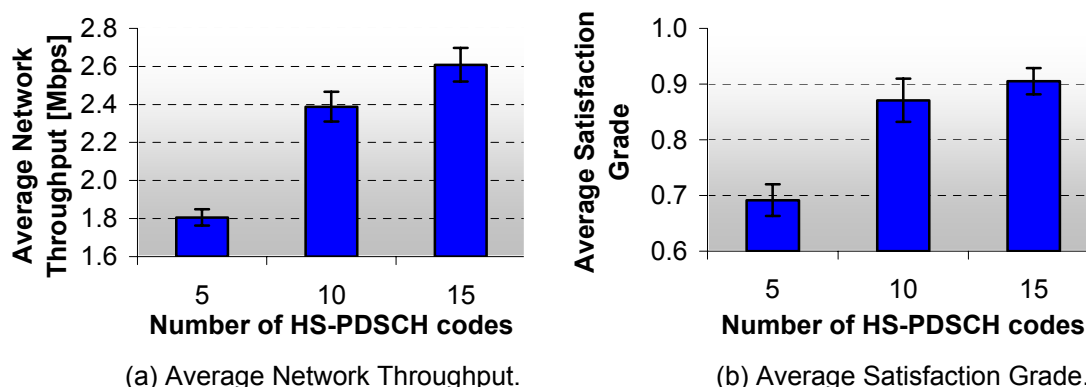


Figure 4.10. HSDPA network parameters (Throughput and Satisfaction Grade) for 5, 10 and 15 HS-PDSCH codes.

The use of 15 HS-PDSCH codes allows an increase of 4.5 and 5.5% for the total network traffic and for the total number of user served per hour compared to the default case, while the use of 5 HS-PDSCH codes reduces the network traffic and the number of user served per hour by 16 and 19%, Figure H.2. Regarding the average results per Node B for the busy hour analysis, the average

traffic per Node B for the default scenario is 0.37 GB/h. The use of 5 instead of 10 HS-PDSCH codes reduces the traffic by Node B by almost 16%, while the increase from 10 to 15 codes leads to an increase of 4.5%. For 5, 10 and 15 codes, the average number of users served per hour and per Node B is 112, 140 and 147, respectively. For 15 HS-PDSCH codes, these results are justified by a higher average network throughput, which leads to shorter user session's duration, thus increases the total network traffic and the total number of users per hour, whereas for 5 HS-PDSCH codes, the decrease is justified by the lower average network throughput.

In Figure 4.11, one shows the evolution of the average instantaneous throughput per user for 5, 10 and 15 HS-PDSCH codes. The user throughput as a function of the number of codes can be calculated by (4.2) and (4.3) for 5 and 15, respectively. The same method as the one described for the default scenario – 10 HS-PDSCH codes – was used. Therefore, a linear interpolation was adopted with the correlation for 5 and 15 codes being 0.89 and 0.86 with a mean relative error of 5.1 and 5.5%, respectively. For 5, 10 and 15 HS-PDSCH codes, the average instantaneous throughput per user increases from 0.52 Mbps to 0.56 Mbps and to 0.58 Mbps, respectively. For 5 HS-PDSCH codes, using (4.2) and considering an average network radius of 0.28 km, the instantaneous throughput at the cell edge is 0.47 Mbps, whereas for 15 HS-PDSCH codes and for the average network radius of 0.29 km, the instantaneous throughput at the cell edge is 0.56 Mbps.

$$\rho_{[\text{Mbps}]} = -0.382 \cdot d_{[\text{km}]} + 0.573 \quad (4.2)$$

$$\rho_{[\text{Mbps}]} = -0.387 \cdot d_{[\text{km}]} + 0.666 \quad (4.3)$$

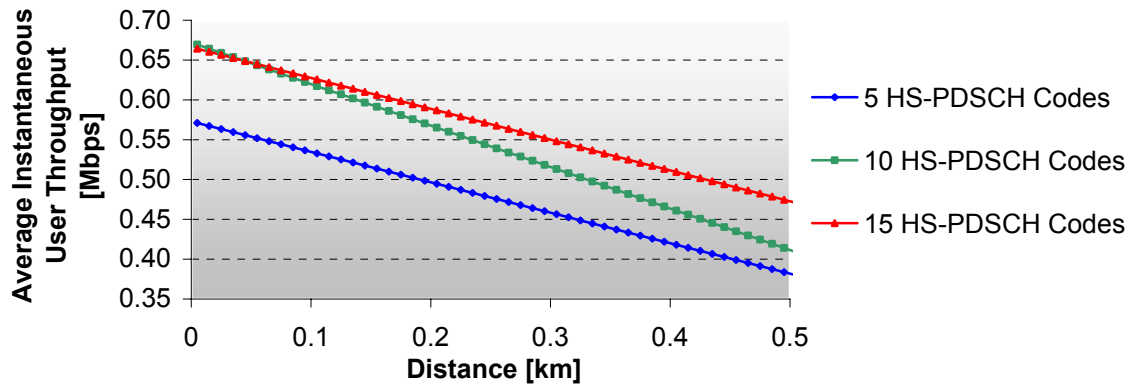


Figure 4.11. HSDPA average instantaneous throughput per user for 5, 10 and 15 HS-PDSCH codes.

From Figure 4.11, one can observe that the introduction of 10 and 15 HS-PDSCH codes has different effects, comparing the average instantaneous throughput per user. For the same reason as the one presented for the default scenario, the distance is limited to 0.5 km, this limitation being used throughout the HSDPA analysis. The introduction of 10 codes improves the average instantaneous user throughput by 0.1 Mbps, for distances up to 0.4 km, but beyond this distance, the improvement fades away. With 15 codes, the behaviour is somewhat different, as a significant improvement of the user throughput is obtained only for distances further than 0.25 km. The use of 15 HS-PDSCH codes increases the capacity near the cell edge, as seen in the instantaneous user throughput for 5 and 15 HS-PDSCH codes.

4.3.3 Total Transmission Power

As seen in the results for the single user model in Subsection 4.2.1, the total transmission power has a major influence in the path loss. In this subsection, the transmission power influence regarding several parameters is evaluated. A reduction of the total transmission power leads to a decrease of the average network radius, Figure 4.12a), thus, fewer users are served. For a 3 dB reduction of the total transmission power, the cell radius is reduced by 5.2%, 0.02 km. Since there is a reduction on the number of served users, a lower average network throughput is expected, Figure H.3a), where a reduction of 6.1% is obtained, and also a reduction of 10.3% of the average ratio of served users, Figure H.4a). One could expect a reduction on the average satisfaction grade, as there is a reduction of the transmission power, but from Figure H.3b), one can observe that instead there is a slight increase, 0.3%, in the satisfaction grade. This is due to the fact that, since there is a reduction of the cell radius, fewer users are served per Node B, meaning that each user is reduced fewer times.

The reduction of the number of served users, explains the reduction achieved in the hour analysis, where a 7.8%, near 6 GB/h, reduction of the total traffic is verified, Figure H.4b), and a reduction of nearly 10.3% of the number of users served per hour is obtained, Figure 4.12b). Regarding the busy hour analysis per Node B, there is a reduction of 7.8 and 10.3% for the traffic and number of users, respectively.

Using the same method as the one described for the default scenario, (4.4) can be obtained with a correlation of 0.91 for the linear interpolation and a mean relative error of 5.9%. Using (4.4) an instantaneous user throughput of 0.51 Mbps at the cell edge, 0.27 km can be obtained.

$$\rho_{[\text{Mbps}]} = -0.570 \cdot d_{[\text{km}]} + 0.665 \quad (4.4)$$

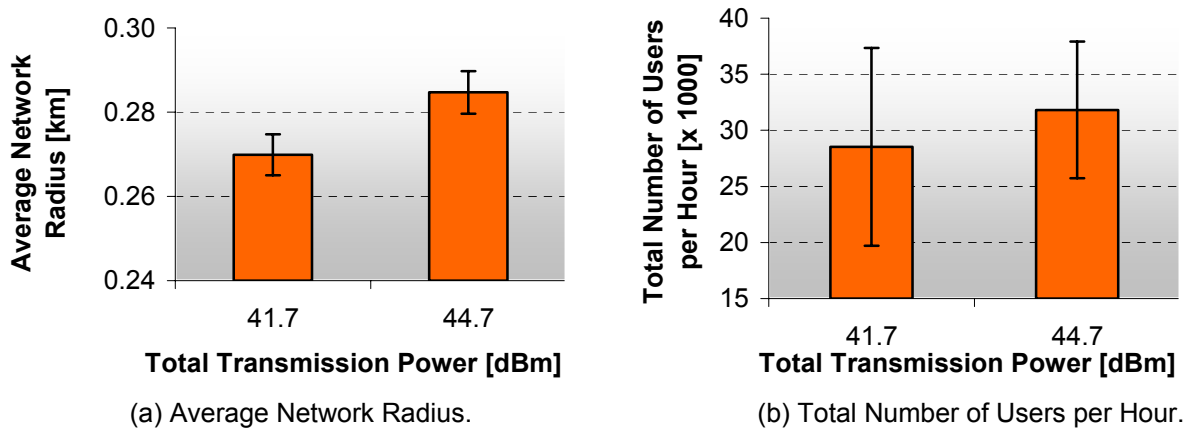


Figure 4.12. HSDPA network parameters (Radius and Number of Users) for 41.7 and 44.7 dBm of total Node B transmission power.

In Figure 4.13, one represents the average instantaneous throughput for a total Node B transmission power of 41.7 and 44.7 dBm. For the 44.7 dBm curve, (4.1) was used, while for 41.7 dBm, (4.4) was used. The decrease of the transmission power leads to a slight decrease of 2.3% in the average instantaneous throughput per user. For distances up to 0.2 km, SINR is not yet the limiting factor, as

the user is close enough to the Node B, and could even be served with higher throughputs. Beyond 0.2 km, SINR becomes the limiting factor, as already seen, and a higher transmission power is directly associated to a higher SINR, thus, to a higher user throughput.

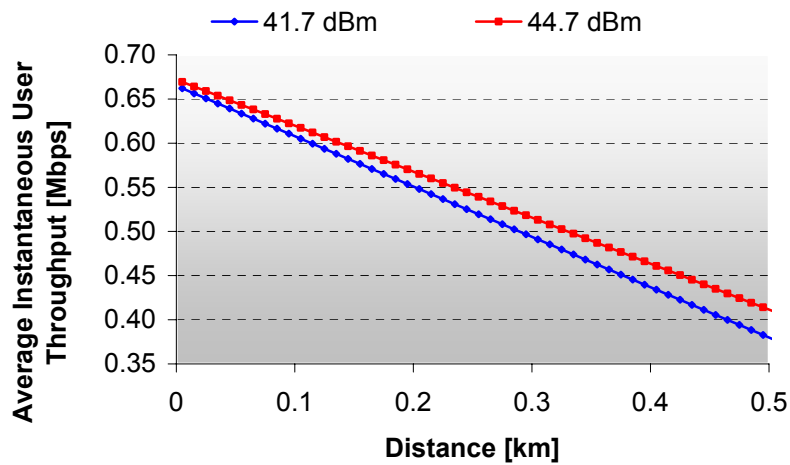


Figure 4.13. HSDPA average instantaneous user throughput for 41.7 and 44.7 dBm of total Node B transmission power.

4.3.4 Number of Users

When one increases the number of users offering traffic to the network, the average network throughput increases around 1.5 Mbps, almost 61%, as the system has not yet reached its full capacity, Figure 4.14a), and some of the extra users can still be served. However, this increase is mainly due to the higher number of users that are served in those Node Bs that are located outside of the areas with higher traffic, since the first Node Bs are already overloaded. The average network radius increases by 10.4%, as more users are spread over the coverage area, Figure H.5a), and the probability of the user being further away from the Node B increases. As more users are served, each Node B is more loaded, leading to a reduction of almost 18% of the average satisfaction grade, Figure H.5b), since the same capacity is now distributed to a higher number of users.

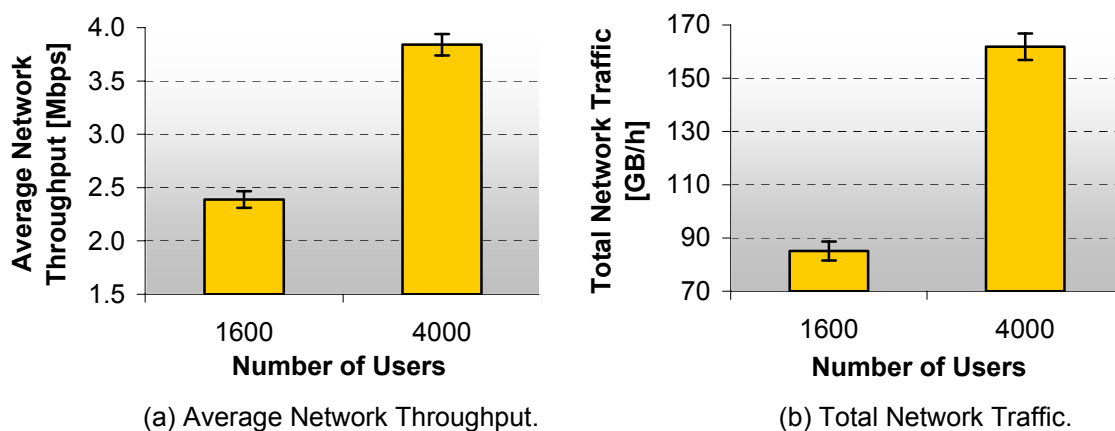


Figure 4.14. HSDPA network parameters (Throughput and Traffic) for 1600 and 4000 users.

Even though there is a reduction of the average ratio of served users, the total number of users

performing services for this scenario is still higher than the effective number of users served in the default scenario. For both the number of users served per hour and the network traffic, there is an increase of almost 90% compared to the values of the default scenario, Figure H.6. For the busy hour, and regarding the analysis per Node B, almost 265 user can be served per hour, generating an average traffic of 0.71 GB/h.

4.3.5 Alternative Profiles

In this subsection two other profiles, the Interactive Background Balanced (IBB) and the Interactive Oriented (IAO) profiles, with different services' penetration percentages and QoS priorities, are analysed, the results being compared with the ones from the default scenario. In these profiles, the influence of P2P is reduced to represent a more daytime approach, as the E-mail and Chat services are usually more used throughout the day. On the contrary, the P2P service is somehow a night service, as operators offer the so-called "Happy-Hour". In the alternative profiles, Streaming is considered the service with the highest QoS priority, followed by Web, while E-mail is considered the service with the lowest one. The modifications in the QoS priority list is an additional factor that influences the results presented in this subsection.

Analysing Table 4.6, where the services' characteristics are shown, one can notice that the alternative profiles present a significant reduction of the percentage of P2P users. P2P is highly demanding service, since it is characterised by high file size and, due to the low throughput tolerated, high session duration. On the other hand, there is an increase in the percentage of users performing Chat, E-mail and FTP. Both alternative profiles are more user throughput demanding, mainly due to the increase of E-mail and FTP users, since these services have a higher maximum, thus, a higher average throughput per user. The IBB profile is the most demanding one, as the reduction from IBB to IAO for P2P is more meaningful than the increase in the percentage of Chat in the IAO profile.

Table 4.6. Default and alternative scenarios characterisation.

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

One can notice from Figure H.7a) that the average network throughput remains approximately the same for the IBB profile, with a reduction below 1%, while for the IAO one, there is a reduction of 3.5%. In the default scenario, the average network throughput does not exceed 2.4 Mbps, as seen in Subsection 4.3.2. Regarding the alternative profiles, although being more throughput demanding, the

average throughput network does not increase. One can say that, for approximately 1600 users and using the randomly distributed user's throughput, the maximum average network throughput is 2.4 Mbps. The average network radius is reduced by 2.8 and 2.5% for the IBB and IAO profiles, respectively, Figure H.7b).

In both alternative profiles, there is a reduction of the average ratio of served users, of 6 and 10% for IAO and IBB, respectively, Figure 4.15a), mainly due to the fact that fewer P2P users are considered. P2P has the second lowest minimum throughput, hence, these users can be reduced several times before being delayed – when the user throughput crosses the minimum threshold – leading to a lower probability of the user being delayed. So, in a P2P dominant profile, as the default one, fewer users are considered delayed, and since P2P has a high percentage of users, this effect is more perceptible. The reduction of the number of users, together with the low reduction of the network throughput, leads to an increase of 13.9 and 3.6% for the IBB and IAO profiles, respectively.

For the difference observed in the alternative profiles regarding Chat and E-mail, the same justification is valid. In the IAO profile, there are more users performing Chat, which has the lowest minimum throughput, and so more users can be served than in the IBB one, Figure 4.15a). The average satisfaction grade increases to 89 and 90% for the IBB and IAO profiles, Figure H.8a), as the ratio of served users decrease and so, fewer users are served, allowing each one to be served with a higher throughput.

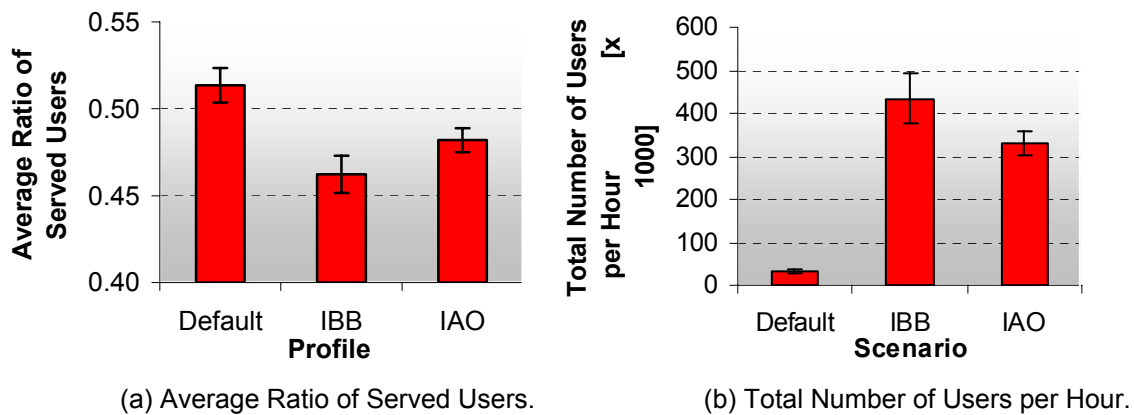


Figure 4.15. HSDPA parameters (Ratio of Served Users and Number of Users) for the 3 profiles studied.

Regarding the total network traffic per hour, and even though the alternative profiles have higher throughputs, there is an increase of near 18.5% for the IBB profile while in the IAO one, the average network traffic actually decreases 1%, Figure H.8b). For the Node B analysis, the traffic increases to 0.44 GB/h for the IBB profile, while being reduced to near 0.37 GB/h for the IAO one. This is due to the higher percentage of P2P users in the default scenario, whose sessions are characterised by high data volume data. In the IAO profile, there is a reduction of the carried traffic per hour, compared to the default scenario, since the P2P percentage is only 5%, and compared to the IBB profile, the former has more users performing chat, a low volume service, and fewer performing E-mail. The reduced

P2P percentage also explains Figure 4.15b), where there is a large difference in the number of user per hour. In the IAO profile, there is an increased of 943% regarding the number of user served per hour while for the IBB profile, this increase is even higher, 1265%. This difference to the default scenario is due to the higher percentage of services characterised by low data files, hence, shorter session durations. In the busy hour analysis per Node B, more than 1900 users are served in the IBB profiles, while for the IAO one, the number of users is near 1500.

The difference between the number of users per hour in the alternative profiles is also explained by the higher average instantaneous throughput per user of the alternative profiles, as a higher throughput per users leads to a lower average session duration, and to a higher number of users served per hour.

4.3.6 Strategies

To better notice the impact of the reduction strategies, one should consider a microscopic analysis rather than a macroscopic one, performed on all network's Node Bs. This is due to the fact that not all Node Bs in the network are overloaded, requiring reduction strategies to be performed. When considering the whole network, the "QoS One by One Reduction" strategy presents an improvement of only 2.2% Mbps of the average network throughput.

To perform the microscopic analysis, one selected 10 Node Bs in the most populated areas to assure that reduction strategies were executed. On those Node Bs, only 4 of the 6 services were active: Web, P2P, Streaming and Chat, since E-mail and FTP have a reduced penetration percentage. In these analyses, the randomly distributed throughput was not taken into account, to assure exactly the same conditions for the 3 strategies, and hence, to highlight the effect of the different reduction strategies.

In this subsection one presents the average results considering the referred Node Bs. One can verify that, as expected, the "QoS One by One Reduction" strategy is the best one, as it allows a higher Node B total throughput, Figure H.9. This is due to the fact that this reduction strategy performs a one by one user reduction and, after each reduction, the total throughput is recalculated and compared to the maximum allowed, as explained in Section 3.2. The improvement obtained by using the "QoS One by One Reduction" strategy instead of using the "QoS Class Reduction" one is approximately 2.2%, 0.15 Mbps, and compared to the "Throughput Reduction" one, it is nearly 0.25 Mbps, 4.5%. The same 2.2% gain can be obtained when the "QoS Class Reduction" strategy is used instead of the "Throughput Reduction" one. One can also notice a reduction of the standard deviation from the "Throughput Reduction" to the "QoS Class Reduction", and to the "QoS One by One Reduction", as the last one allows each Node B to be closest to the limit, independently of the user distribution, namely the percentage of users performing each service. The "QoS One by One" strategy allows the best use of the available HSDPA capacity.

A service by service analysis was also performed, where one detailed the effect of the reduction strategies within each service. For the same reason aforementioned, the "QoS One by One

Reduction” strategy presents the best results when analysing the average instantaneous throughput offered to each user, Figure H.10, and the overall satisfaction grade, Figure H.11.

The average instantaneous user throughput and average satisfaction grade for Chat are higher for the “Throughput Reduction” and “QoS Class Reduction” strategies than for the “QoS One by One Reduction” one. This is due to the fact that in the latter strategy, Chat is available in one more Node B than in the other two strategies. This fact leads to a reduction in both the average instantaneous user throughput and the satisfaction grade, since more users are considered – the same capacity is distributed to more users, leading to a lower user throughput and satisfaction grade.

4.3.7 Maximum Throughput

In this scenario, the randomly distributed throughput, described in Section 3.2, is also not used. The purpose of this analysis is to study the network behaviour in more demanding throughput scenarios, considering the same service percentages of the default scenario. One can observe that there is an increase of almost 41% of the average network throughput, Figure H.12a). Like for the number of users simulation, this gain was mainly achieved in the Node Bs outside the most populated areas. Both scenarios use the same users leading to marginal network radius reduction below 0.5%, Figure H.12b).

In Figure 4.16a), one can notice a reduction of almost 22% of the average satisfaction grade, as each user is now requesting a higher throughput, meaning that more reductions are performed. The ratio of served users is nearly 1% lower due to the higher users’ requested throughput, Figure H.13a). It is also interesting to notice that even though there is a reduction of the average satisfaction grade, this scenario has a higher average instantaneous throughput per user, 0.87 Mbps, an increase of 55% compared to the default scenario. On both parameters that one studied for the busy hour analysis, this scenario presents a significant increase of 36.4% on the total network traffic, Figure 4.16b), and almost 12000 more users can be served, an increase of 40%, Figure H.13b), as the average duration of each session is lower due to the higher instantaneous throughput per user. Concerning the busy hour analysis per Node B, the traffic increased to almost 0.51 GB/h while the number of user served per hour increase to 196.

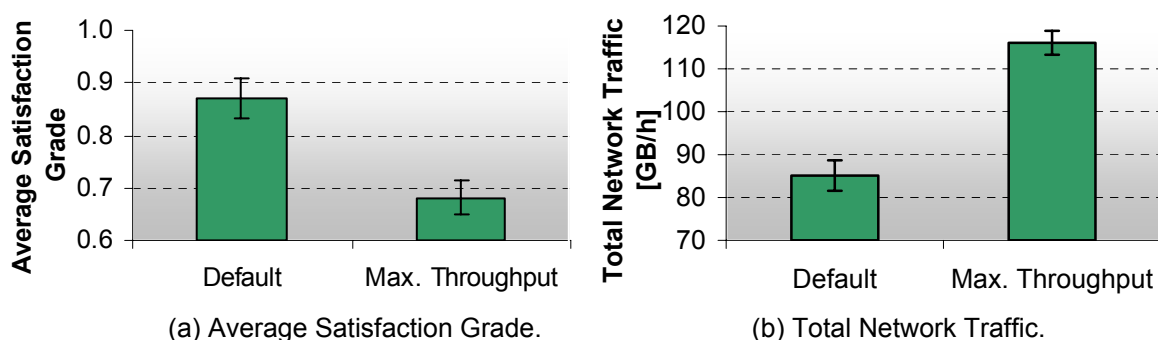


Figure 4.16. HSDPA network parameters (Satisfaction Grade and Traffic) for different throughput services.

4.4 HSUPA Analysis in a Multiple Users Scenario

In this section, the HSUPA main results are analysed. First, the results for the default scenario introduced in Section 4.1 are presented. Afterwards the results considering the different scenarios studied are presented. In Annex I, additional results regarding the HSUPA analysis are presented.

4.4.1 Default Scenario

All the results presented in this section were obtained using the multiple users simulator introduced in Section 3.2. The link budget detailed in Annex A was used to calculate the path loss, with the user's SINR being calculated by (3.4), and the user's throughput using Figure A.2. The results in Figure 4.17 and Figure 4.18 were computed using the same method as the one described for HSDPA.

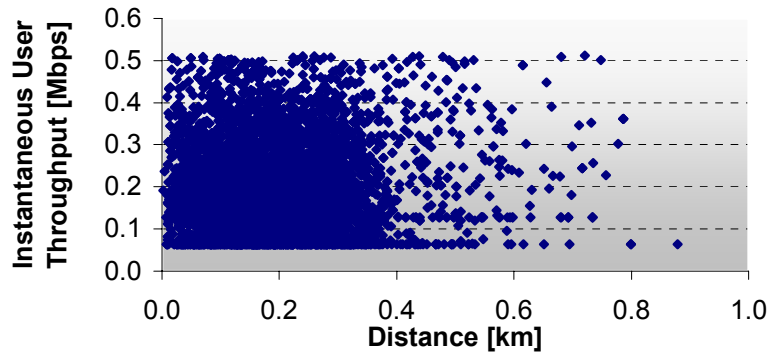


Figure 4.17. HSUPA instantaneous user throughput for all users as a function of distance.

From Figure 4.18, one can notice that, unlike HSDPA, in HSUPA the average instantaneous user throughput is approximately constant for distances up to 0.4 km. This is due to the fact that for the range of throughputs considered, between 0 and 0.512 Mbps, the E_c/N_0 value is always above the threshold, and the SF of the E-DCH channel used allows the maximum throughput, being independent of the user distance. As seen for the single user analysis, and considering the indoor low loss environment, HSUPA can deliver 0.7 Mbps to distances up to 0.4 km, Figure 4.28. Therefore, even when introducing the interference margin due to the multiple users scenario, the E_c/N_0 value does not cross the E_c/N_0 threshold. The use of SHO also helps to justify the constant throughput results, as when the distance increases and one would expect a reduction of the user throughput, the probability of the user being in SHO increases, as the user is more likely to be near the cell edge. For the default scenario, the average network radius is 0.25 km.

For distances further than 0.4 km, the average instantaneous user throughput curve starts to present oscillations and the standard deviation has an irregular behaviour, as fewer users are served at these distances. To interpolate the HSUPA user throughput curve, one limited the distance to 0.4 km, to avoid the distances where the users' throughput starts to oscillate. From Figure 4.18, one can easily recognise that the curve that best interpolates the user throughput, for distances up to 0.4 km, is a horizontal straight line, and so, a first order interpolation was performed:

$$\rho_{[\text{Mbps}]} = -0.019 \cdot d_{[\text{km}]} + 0.204 \quad (4.5)$$

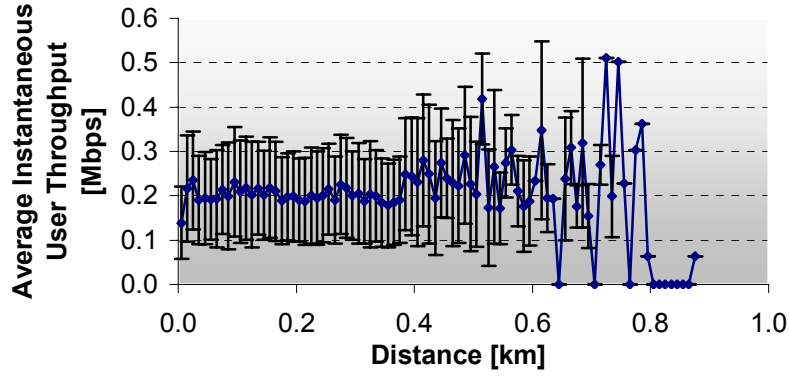


Figure 4.18. HSUPA average and standard deviation instantaneous throughput considering 10 metre intervals.

The correlation for the linear interpolation is 0.12. This low value is due to the fact that the derivative of the linear interpolation is close to 0, because from Figure 4.19 one can observe that (4.5) has a low mean relative error, 7.1%, close to the one for HSDPA. If the dependence with distance is not considered, as in (4.6), the mean relative error increases to only 7.4%.

$$\rho_{[\text{Mbps}]} = 0.204 \quad (4.6)$$

To compute Figure 4.19 the same method as the one described for HSDPA was used, the only difference being the distance limited to 0.4 km. HSUPA has an average instantaneous throughput per user of 0.21 Mbps with an average instantaneous throughput of 0.20 Mbps at the cell edge.

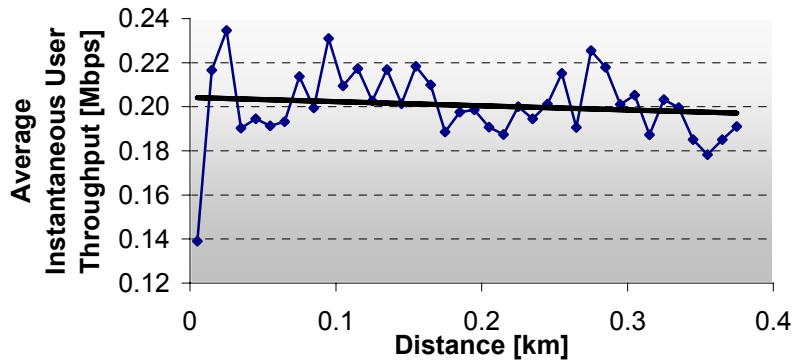


Figure 4.19. First order interpolation for HSUPA average instantaneous user throughput.

As for HSDPA, the results presented in Figure 4.19 do not represent HSUPA's maximum capacity. These results were obtained in a multiple users scenario, being dependent on the traffic profile chosen. HSUPA has an average network throughput of 0.62 Mbps with a 91% satisfaction grade. Regarding the busy hour analysis, 8900 user can be served, generating a network traffic of nearly 18 GB/h. Each Node B serves up to 39 users per hour, carrying almost 0.08 GB/h.

The percentages of offered and served traffic are represented in Figure 4.20. One can observe that, in a service by service analysis, both percentages are similar, meaning that HSUPA users are served

according to the offered traffic profile. The slight 3.7% increase of the P2P percentage is mainly due to the reduction of the percentage of users performing Web, since these have a higher minimum throughput. The 2.2% reduction of the percentage of users performing Streaming is explained by the fact that in this service, users are only served with the minimum throughput, and so, if reductions are performed more than one time, these users are always delayed.

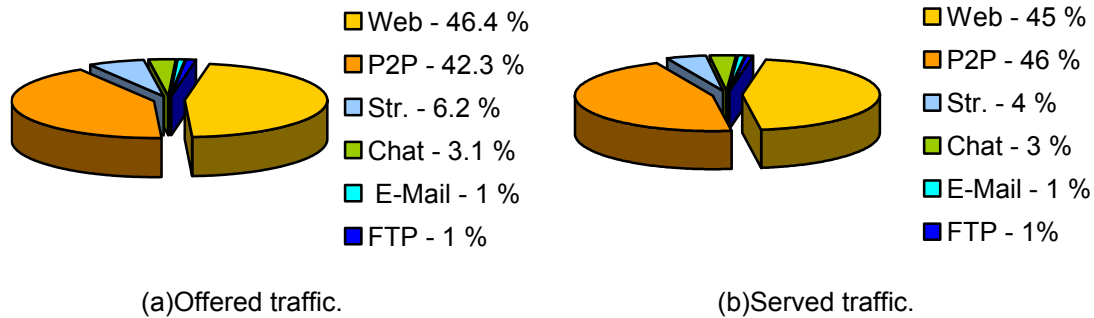


Figure 4.20. HSUPA percentage of traffic.

In Figure 4.21, the average network throughput and satisfaction grade are detailed by service, and one can notice that these parameters reflect the QoS differentiation as users performing services with higher throughput and QoS, Web, FTP and E-mail, are served with higher average throughputs. Web, the service with the highest QoS, has an average throughput per user of 0.26 Mbps and 92% satisfaction grade. The only exception is Streaming, but as already explained, this is a singular case, as the maximum and minimum throughput are equal which leads to a standard deviation of zero. E-mail and FTP have a higher standard deviation, as the percentages of served users are lower, compared to services like Web and P2P, and so have low statistical validity, this results being already seen in HSDPA.

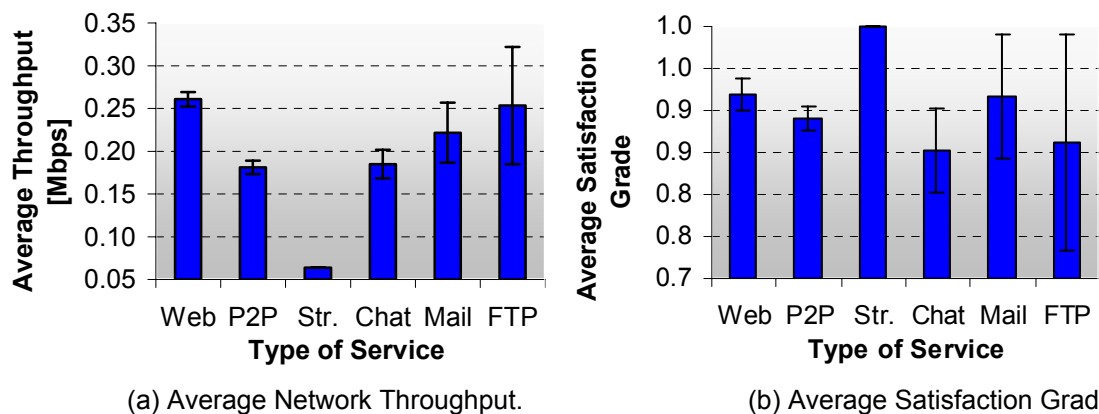


Figure 4.21. HSUPA network parameters (Throughput and Satisfaction Grade) detailed for services, for default scenario.

4.4.2 Number of Users

The average network throughput increases 35.2% to 0.84 Mbps when one increases the number of users offering traffic to the network, as the system can serve more users at the cost of a reduction of

9% of the satisfaction grade, Figure 4.22a) and Figure I.1b). The same phenomenon described for HSDPA is also valid in this analysis. It is also interesting to notice that even though the average network throughput increases in the 4000 users' scenario, the average instantaneous throughput per users decreases from 0.22 to 0.2 Mbps. The average network radius increases around 13.5%, as more users are in the Node B's coverage area, Figure I.1a).

The average ratio of served users decreases 28%, but the total number of users served for the 4000 users scenario increases 76%, compared to the 8900 users served in the default scenario, Figure I.2a) and Figure I.2b). The network traffic, Figure 4.22b), increases 60% to 28.9 GB/h, as more users are served instantaneously. The number of users per Node B increases to 69 and the traffic generated per Node B increases to near 0.13 GB/h.

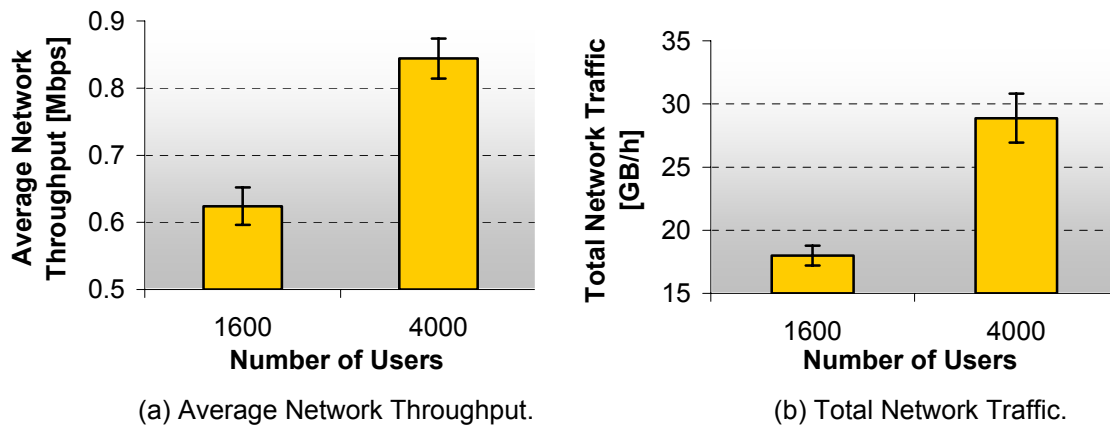


Figure 4.22. HSUPA network parameters (Throughput and Traffic) for 1600 and 4000 users.

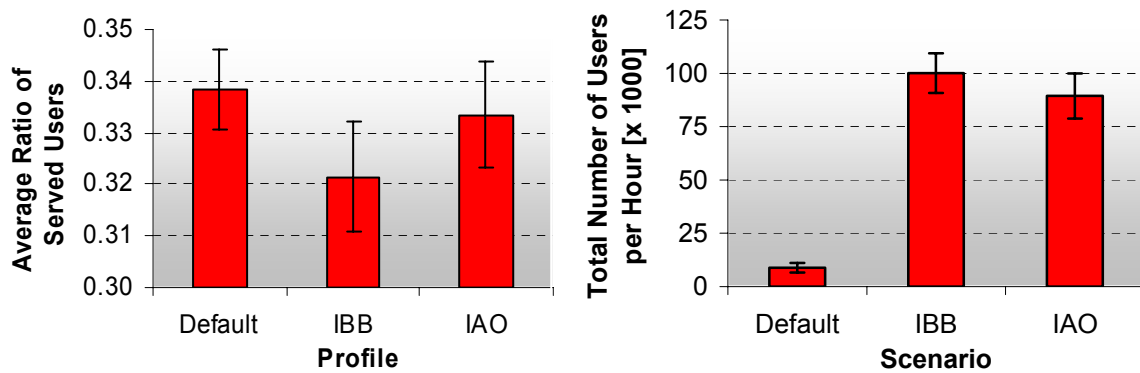
4.4.3 Alternative Profiles

In this subsection, the same profiles as the ones introduced for HSDPA are studied, this analysis being similar to the one presented for HSDPA. The alternative profiles are more throughput demanding, nevertheless, different behaviours regarding the average network throughput are observed. While in the IBB profile there is decrease of 1% in the average network throughput, the IAO one has an increase of 1.3%. These reduced variations are due to the fact that, HSDPA has reached its limit, around 0.62 Mbps per Node B, Figure I.3a) for these type of scenarios – around 600 users served, and with randomly distributed throughput. The increase of the average network radius for the 2 alternative scenarios is lower than to 3%, Figure I.3b). This cell radius invariance was also observed for HSDPA.

In both alternative profiles, there is a reduction of the average ratio of served users, 5 and 1.4% for the IBB and IAO profiles, Figure 4.23a), mainly due to the fact that fewer P2P users are considered in these profiles. This reduction is somehow similar to the one observed for HSDPA, but in this case, P2P, Streaming and Web have the lowest minimum throughput. By reducing the P2P service percentage and increasing the percentage of FTP and E-mail, with higher minimum throughput, Table 4.6, the probability of a user being delayed increases, as the users must be served with throughputs above the minimum. The default scenario has a high percentage of P2P users, whose minimum

service throughput is low, and so, fewer users are considered delayed. The average satisfaction grade increases 1.8% for the IBB profile and 0.7% for the IAO one, mainly due to the reduction of the ratio of served users, as the same capacity is distributed to fewer users. If the same users were considered, the average satisfaction grade would decrease. The IBB profile has a 3.6% lower ratio of served users, compared to the IAO one, because it has more users performing E-mail that has higher minimum throughput. The lower ratio of served users also helps to justify the higher average satisfaction grade of IBB profile, Figure I.4a).

The IBB profile has the highest total network traffic, 18.5 GB/h, Figure I.4b), with an average traffic per Node B of 0.08 GB/h, an increase of 2.9% compared to the default scenario. The total number of users per hour rose to around 100000 users, Figure 4.23b), 438 users per Node B. The increase of the traffic and the number of users depends mainly of the average instantaneous throughput per user, which increased near 5% for both alternative profiles.



(a) Average Ratio of Served Users.

(b) Total Number of Users per Hour.

Figure 4.23. HSUPA parameters (Ratio of Served Users and Number of Users) for the 3 profiles studied.

The IAO profile has the lowest total network traffic, 16 GB/h, and an average traffic per Node B of 0.07 GB/h, an 11% reduction compared to the default scenario, as it has the lowest P2P service percentage, whose users are responsible for most of the network's traffic. Nevertheless, the number of users per hour increased to near 89500 and to 392 for the total network and per Node B, respectively.

While the maximum variation of the total network traffic is the 11% reduction for the IAO profile, the total number of user per hour increases 1023% and 904% for the IBB and IAO profiles, respectively. This is due to the increase of the average throughput per user, but also due to the reduction of the percentage of Web and P2P users. The Web users' session time is dominated by the reading period, which one considered to be 40 s, while the P2P session is dominated by the size of the file and by the reduced user throughput, leading to higher session duration. By reducing the Web and P2P users and increasing the percentage of users performing other services with lower average session duration, one obtains a high increase of the total number of users. This increase does not have a direct influence in the total network traffic, as more user are served in the alternative profiles, but these users are performing services characterised by a low volume size.

4.4.4 Strategies

To evaluate the performance of the 3 reduction strategies, the same approach as the one defined for HSDPA was used for HSUPA, but unlike HSDPA, only 3 services were present. Due to HSUPA's reduced capacity, only Web, P2P and Streaming are analysed, as these are the services with a higher penetration percentage. As expected, and taking the results presented for HSDPA into account, the "QoS One by One Reduction" strategy shows the best results with an average network throughput of almost 1.21 Mbps, Figure I.5, near the system limit, 1.22 Mbps. The "QoS Class Reduction" strategy has an average network throughput of around 1.18 Mbps, while the "Throughput Reduction" strategy has 1.14 Mbps.

In the service by service analysis, Streaming has an average satisfaction grade of 100% and no standard deviation, even though Web is the service with the highest QoS priority. This is due to the fact that, for HSUPA, the maximum and minimum Streaming throughputs are equal, 64 kbps, meaning that all the served users have the same throughput. For the Web service, the expected behaviour can be observed, as the "QoS One by One Reduction" strategy has the best results, followed by the "QoS Class Reduction" and by the "Throughput Reduction" strategy, Figure I.6. For P2P, the "Throughput Reduction" strategy presents better results than the strategies implementing QoS differentiation. This is due to the fact that, in the "Throughput Reduction" strategy, all Streaming users are delayed, since they are initially served at the minimum service throughput, meaning that more capacity is available for users performing other services, even though these services may have lower QoS priority, as P2P. The strategies using QoS differentiation can serve Streaming users, since these are only reduced if the reductions are performed more than once, and due to this fact, P2P users are served with lower throughputs compared to the "Throughput Reduction" strategy.

4.4.5 Maximum Throughput

As for HSDPA, one also performed simulations in a more demanding scenario, by removing the randomly distributed user throughput, meaning that the user's average requested throughput is higher. In this scenario, there is an increase of almost 34% of the average network throughput, Figure I.7a). There is an increase in the cell radius of about 7.4%, since more users are considered, Figure I.7b), as the user throughput is higher, hence, even though the reduction strategy is executed more times, each user can also be reduced more times before being delayed.

The increase of the average network throughput is achieved by reducing the average satisfaction grade, since in this scenario more users are in the coverage area of the Node B. When one increases the requested throughput, the average satisfaction grade decreases around 27%, Figure 4.24a). One can notice from Figure I.7b) that the average ratio of served users is higher for the maximum throughput scenario, 6%, as the average instantaneous throughput per user is 52% higher, meaning that each user tolerates more reductions before being delayed.

In this scenario, both the total network traffic and the total number of users served per hour are higher

than the ones for the default scenario, Figure 4.24b) and Figure I.8b). For the total traffic, there is an increase of 52%, and an increase of 35% regarding the number of served users per hour. The average traffic per Node B rose to 0.12 GB/h, and the average number of users per Node B increased to almost 53. These results are mainly due to the higher user throughput per user, which reduces the average session duration and consequently more users are served and more traffic is generated.

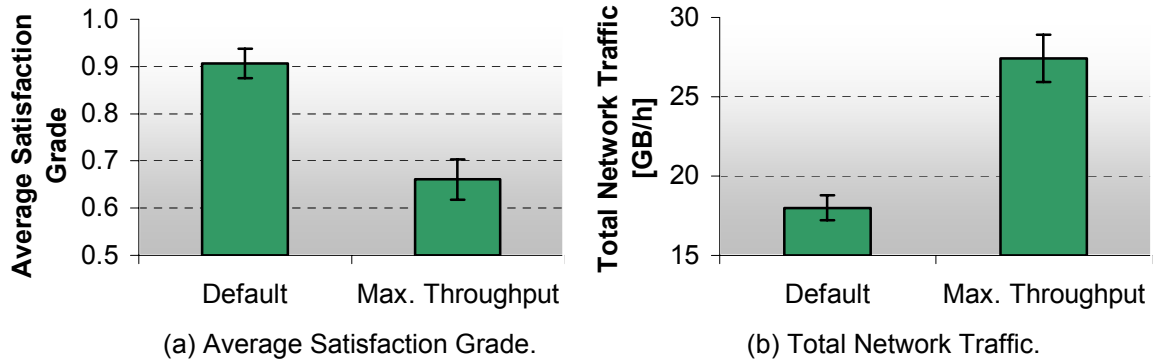


Figure 4.24. HSDPA network parameters (Satisfaction Grade and Traffic) for different throughput services.

4.5 HSDPA versus HSUPA

In this section, one presents a comparison between HSDPA and HSUPA. For both scenarios, the single user and the multiple users ones, the comparison is focused on coverage and capacity. First, the single user model results are compared, and later on, the results from the multiple users simulators are analysed.

4.5.1 Single User Scenario

Since HSDPA is a downstream connection and HSUPA an upstream one, a direct comparison between them is not performed, as DL and UL channels have different requirements, the maximum throughput being a good example. In Figure 4.25, the cell radius for the maximum throughput of HSUPA, 0.19 km, and for HSDPA, for 5, 10 and 15 HS-PDSCH codes, for the indoor low loss environment is presented. For the analysis of Figure 4.25, it is important to notice that different throughputs are being considered in the calculation of the cell radius for each system. As expected, HSDPA provides higher throughputs, and for the case where 5 HS-PDSCH codes are used, the cell radius is even higher than the one for HSUPA, even though HSDPA has a higher throughput.

From Figure 2.2, it can be noticed that for 5 HS-PDSCH codes the necessary SINR for 3.0 Mbps is 22 dB, while for 10 HS-PDSCH codes the SINR for 6.0 Mbps is 26.4 dB, and it is 26.5 dB for the maximum throughput, 8.46 Mbps, for 15 HS-PDSCH codes. When considering 5 HS-PDSCH codes, a lower SINR is required, and from (A.7) it can be seen that a higher cell radius is expected, compared to 10 and 15 HS-PDSCH codes, since both have higher SINR values. One could expect that the cell radius for 15 HS-PDSCH codes would be lower than the one for 10 HS-PDSCH codes, since the latter

has a lower maximum throughput. But from Figure 4.25, one can observe that 10 and 15 HS-PDSCH codes have equal cell radius, 0.17 km. This is due to the fact that 10 and 15 codes do not use the same SINR curves. In Figure 2.2, it can be seen that the SINR curve for 15 HS-PDSCH codes is always below the one for 10 HS-PDSCH codes for the same throughput, but when considering the maximum throughput for each curve, 6.0 and 8.46 Mbps for 10 and 15 HS-PDSCH codes, respectively, the SINR values are 26.4 and 26.5 dB. The SINR value justifies the fact that 10 and 15 HS-PDSCH codes have an equal cell radius. The SINR values from Figure 2.2 for HSDPA and from Figure 2.4 for HSUPA are used in (A.7), (A.11) and (3.3) successively to compute Figure 4.25.

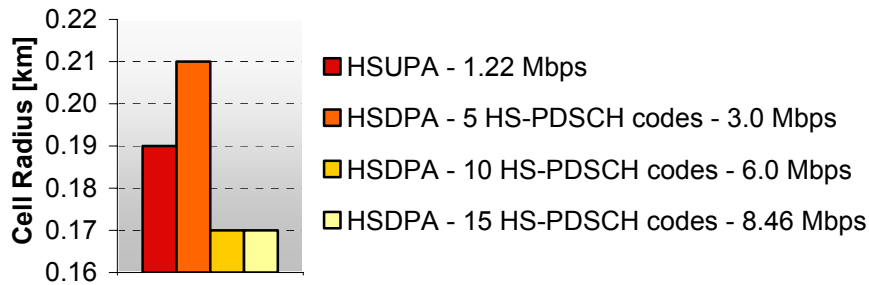


Figure 4.25. HSDPA and HSUPA cell radius for maximum throughput for indoor low loss environment.

In Figure 4.26, the cell radius for the common throughputs for HSDPA and HSUPA are presented. As expected, for the same throughput, HSUPA has a smaller cell radius compared to the HSDPA. It can be further noticed that for the range of throughputs considered in Figure 4.26, the average cell gain due to the use of 15 HS-PDSCH codes instead of 5 HS-PDSCH codes is 12%.

The maximum throughputs for different cell radius for the pedestrian environment are shown in Figure 4.27. For both HSDPA and HSUPA, the maximum throughput can be served to distances up to 0.4 km. For bigger distances, HSDPA with 15 HS-PDSCH codes has the fastest user throughput decay. For cell radius higher than 0.85 km, 10 and 15 codes have similar performance. One can also notice that up to 0.7 km HSUPA can serve a single user with up to 1 Mbps, presenting a small decay in the user's throughput when the cell radius is above this threshold. For HSUPA, the user throughput depends not only of the user distance but also of the SF of the E-DCH channel. This fact together with the lower sensitivity of the E_c/N_0 curves with distance, Figure 2.4, and the lower throughput range, explains the fact that HSUPA can deliver the maximum throughput at bigger distances.

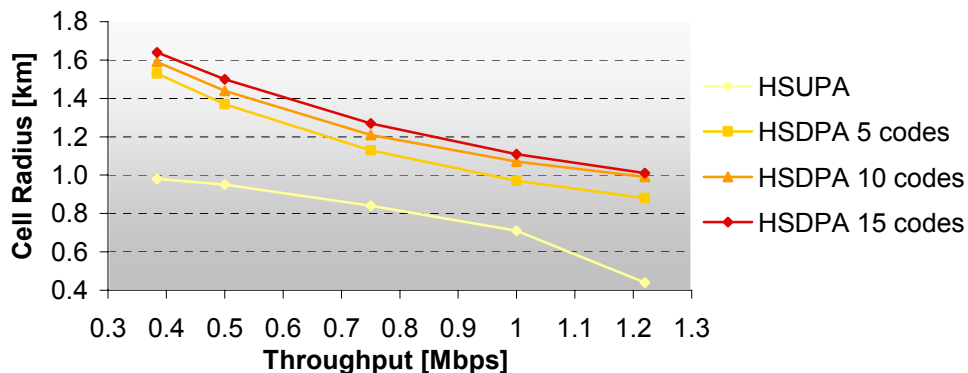


Figure 4.26. Cell radius for throughputs up to 1.22 Mbps for the pedestrian environment.

In the multiple users scenario, one considered that the major percentage of users were being served in indoor scenarios, due to the type of services considered. To allow a comparison between the single and multiple users scenarios, one presents in Figure 4.28 the throughput as function of the cell radius for an indoor low loss environment. The curves presented in Figure 4.28 have the same behaviour as the ones in Figure 4.27, for HSDPA, with the maximum throughput decreasing for distances around 0.2 km, as the indoor low loss scenario has higher environment margins. For HSUPA the maximum throughput can be served up to 0.3 km, showing the already mentioned lower sensitivity of HSUPA regarding the user's distance.

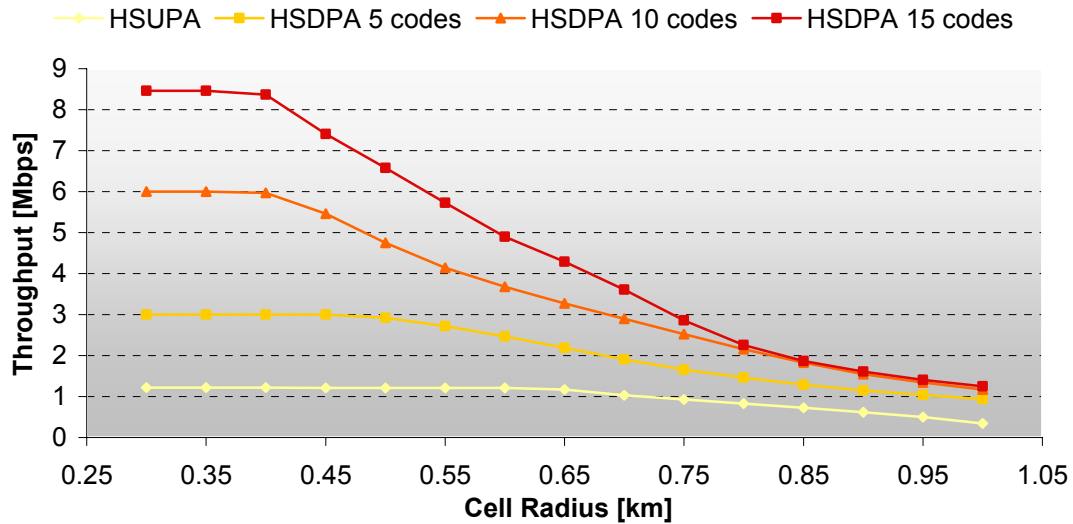


Figure 4.27. HSDPA and HSUPA throughput for different maximum cell radii for the pedestrian environment.

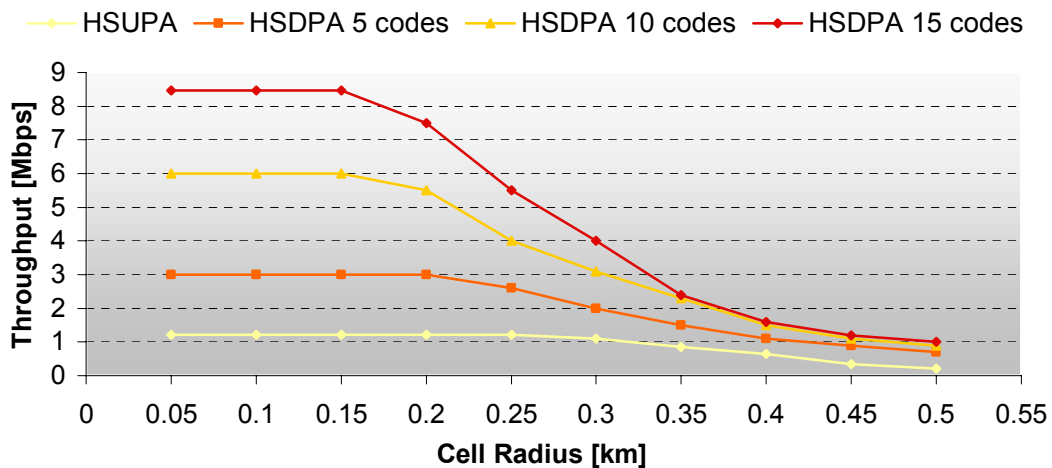


Figure 4.28. HSDPA and HSUPA throughput for different maximum cell radii for the indoor low loss environment.

4.5.2 Multiple Users Scenario

In the multiple users scenario, the UL and DL different characteristics pointed out in the single user model are also valid regarding the multiple users analysis. In this analysis, one focus the comparison

in the cell radius, number of served users per hour and per service and on the satisfaction grade. One focus on the default scenario analysis, as for the other scenarios and parameter variations, a thorough analysis was already performed. The findings for the default scenario are also valid for the previously studied scenarios.

In Figure 4.29a), a comparison between the HSDPA and HSUPA cell radius is shown, the difference between them being almost 0.04 km. Considering the default scenario presented on Section 4.1 for both DL and UL, the latter is the most restrictive, mainly due to the MT limitations – receiver sensitivity and transmission power. As mentioned earlier, capacity also influences the cell radius, since in a system with reduced capacity, as HSUPA, more reduction strategies are executed, leading to a reduction of the cell radius, since the user placed further away from the Node B have higher probability of being closer to the minimum throughput allowed for the service, hence, being delayed. It is important to notice that the results obtained for the radius, are average results, as both systems can serve users at higher distances, as seen in the single user model. The radius results in these simulations are also affected by the average distance between Node Bs, by the users' distribution among the Node Bs and also the users and services profiles used. For users performing both HSDPA and HSUPA, the latter system limits coverage.

The average ratio of served users is shown in Figure 4.29b) where 18% more users can be served by HSDPA. These results are also influenced by the fact that the network is currently dimensioned for HSDPA. To increase the ratio of served users, while keeping the same satisfaction grade, more Node Bs should be added to the network. This fact is even more relevant for HSUPA, since it has a lower average radius.

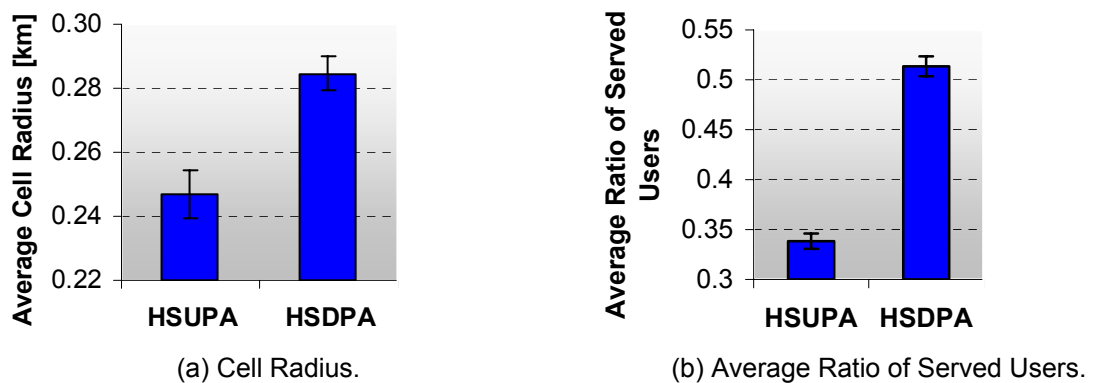


Figure 4.29. HSDPA and HSUPA comparison (Cell Radius and Ratio of Served Users).

The influence of the HSDPA higher throughput per user is most noticed in Figure 4.30, where the total number of user per hour is presented. HSDPA has the capacity to serve up to 3 times more users than HSUPA, as the HSDPA average instantaneous throughput per user, near 0.56 Mbps, which is almost three times higher than the one for HSUPA. In this analysis, it is also important the P2P influence, since this service is only size symmetric, with significant different throughputs. P2P has a high influence on the number of users served per hour, as it is the service with higher volume involved. This influence is also noticed for the alternative profile analysis for both HSDPA and HSUPA.

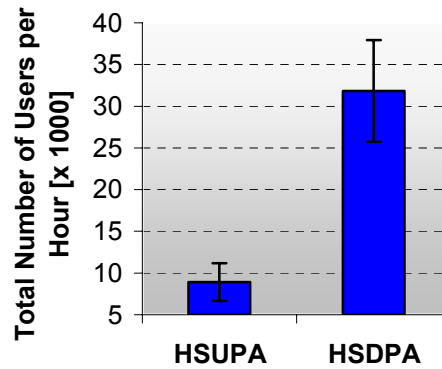


Figure 4.30. HSDPA and HSUPA total number of users served per hour comparison.

The average satisfaction grade for HSDPA and HSUPA detailed by service is shown in Figure 4.31a). In the majority of the considered services, HSUPA has a higher satisfaction grade, due to the lower throughput requested per user, although the differences are minimal. These results must be analysed together with the average number of served users, Figure 4.31b), where it can be seen that HSDPA can always serve more users than HSUPA. This fact is important for P2P, Streaming and Chat where HSUPA has a higher satisfaction grade, but a reduced number of served users, compared to HSDPA. For E-mail and FTP, the higher HSUPA satisfaction grade is mainly due to the lower required user throughput, since the difference in the number of served users is minimal.

When the difference between the HSDPA and the HSUPA satisfaction grade is analysed, FTP and E-mail are the services with the highest difference, excluding Streaming, as this service in UL has a fixed throughput of 0.064 Mbps and so a satisfaction grade of 1, because these services have the maximum difference between the UL and DL throughput. It is also interesting to notice that even though Web is a DL service with few UL requirements, it has a higher DL satisfaction grade. Chat, which is the most symmetric service, as it has the same volume and maximum throughput in both links, has a higher satisfaction grade and lower standard deviation in DL than in UL, mainly due to the higher HSDPA capacity.

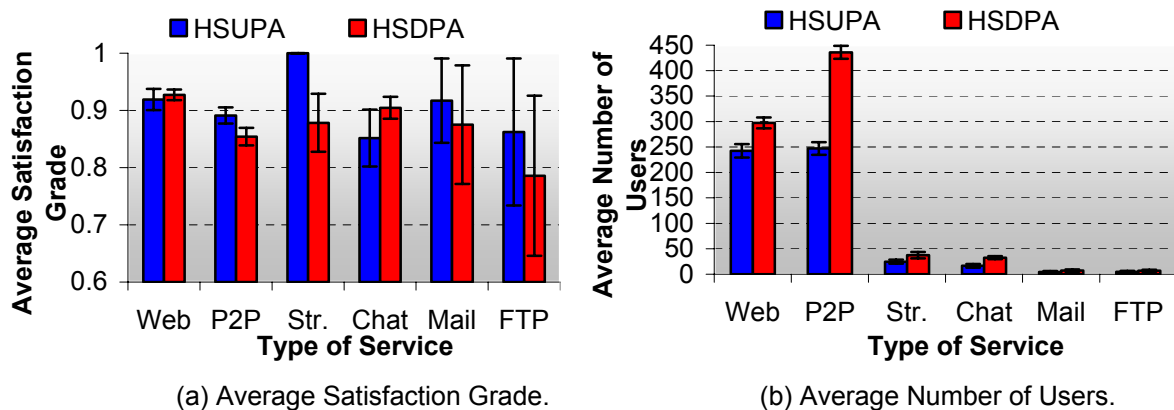


Figure 4.31. HSDPA and HSUPA comparison (Satisfaction grade and Number of Users).

The comparison of the average instantaneous throughput per user, based on (4.1) and (4.5) for HSDPA and HSUPA respectively, is presented in Figure 4.32. One limited the maximum distance to

0.4 km, the maximum valid distance for (4.5), although (4.1) is valid up to 0.5 km. For bigger distances these expressions are no longer valid. As expected, HSDPA can always serve a higher throughput, since HSUPA one is limited by the MT transmission power as well as the Node B's UL noise. For the distances considered in Figure 4.32, HSUPA presents an almost constant user throughput, but for bigger distances, the HSUPA throughput decreases due to the use of a lower SF. One can also add that HSDPA uses adaptive modulation, which helps to explain the decrease of the average user throughput, since when the user is closer to the Node B a higher SINR is obtained, and the user can be served with higher throughput. This fact does not occur in HSUPA, as BPSK modulation is used, and even though the user might obtain a higher E_b/N_0 , the throughput is limited by the SF used.

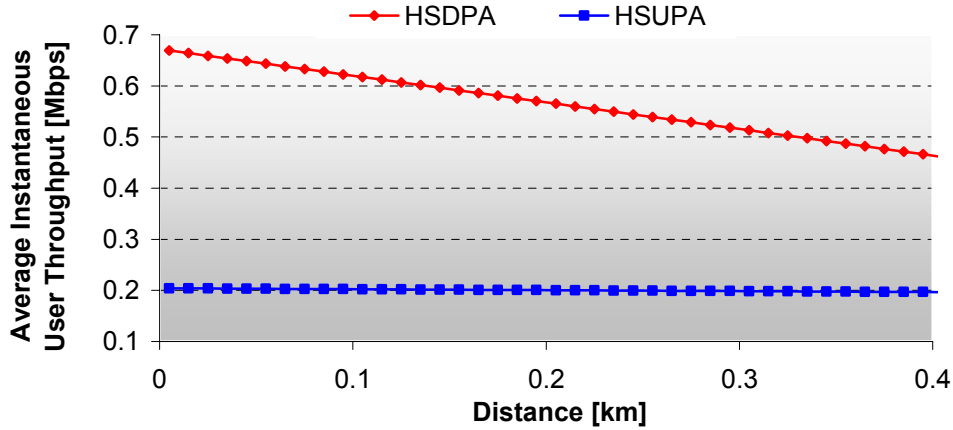


Figure 4.32. HSDPA and HSUPA average instantaneous throughput per user comparison.

In Annex J, one presents the comparison of the HSDPA and HSUPA average instantaneous user throughput for the other studied scenarios: number of users, alternative profiles and maximum throughput. A comparison for both HSDPA and HSUPA average instantaneous user throughput considering the difference scenarios is also shown. In Annex J, one also presents the average network radius and average throughput comparison for the several scenarios analysed.

4.6 HSDPA and HSUPA Measurements

In the present section, one presents HSDPA and HSUPA measurements performed in both test plant and in the live network. For HSDPA only 10 HS-PDSCH codes were considered.

4.6.1 Test Plant Measurements

In this subsection, the measurements performed in Optimus test plant are compared with the results from the single user model. As explained in Section 3.4, in these measurements as well as the ones performed in the live Network, one used *RSCP* to evaluate the radio channel conditions. To compare these results with the ones from the single user model, one mapped the *RSCP* values onto distance using the link budget described in Annex A with the modification introduced in Section 3.4.

The measurements were performed with a dedicated carrier reserved for the tests. One should mention that the radio interface was not the only limitation regarding the measurements performed, since, in some cases, the FTP server presented some instability, which affected some of the results. This fact was particularly important for the measurements with lower *RSCP* values.

For the FTP measurements, an average of 3 files, with approximately 13 MB each, were transferred from an FTP server located in the same IP network of the test plant. For the UDP measurements, a PERL scrip that forced the transfer of several files was used. Since there are no retransmissions in UDP and the server was continually transferring packets, UDP has significant better results than FTP. FTP is also a connection oriented protocol and implements mechanisms of flow control, retransmissions and slow start. The latter is particularly relevant for the measurements with lower *RSCP* values, since the radio connections were unstable leading to several re-connections and slow start was executed more often, reducing the average throughput.

In Figure 4.33, one presents a comparison regarding the results from the single user model and the ones from the measurements in the test plant. For the latter ones, the results for both FTP and UDP, using 2 data cards, are shown. One of the data cards had a Rake receiver and only 0.384 Mbps in the UL while the other had an equaliser and 1.42 Mbps in the UL (HSUPA). The Rake receiver combines the 3 best signals while the receiver with equaliser tries to capture the best signals, ignoring the remaining signals from multipath. The influence of the different receiver techniques in the received throughput is out of scope of this thesis.

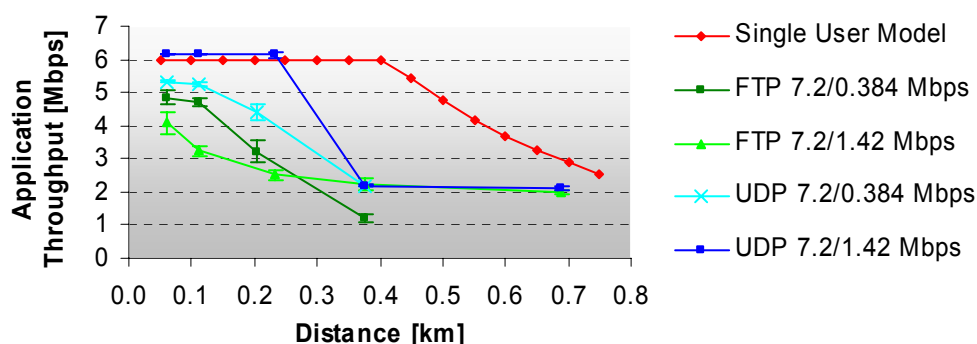


Figure 4.33. HSDPA measurements versus single used model results.

From the results in Figure 4.33, as expected, one can notice that the results obtained using UDP have higher throughput values compared to the ones obtained using FTP. This result is due to the different specification of the 2 protocols. It is interesting to notice that for distances up to 0.2 km, the UDP results with the 7.2/1.42 data card are above the ones from the theoretical model. This fact is explained by the fact that in the theoretical model one considered a 10% margin for BLER and retransmissions, while in UDP these mechanisms are not considered. One can also observe that throughput decreases from 7 Mbps to 2 Mbps for distances between 0.25 and 0.4 km, but maintains an approximately value of 2 Mbps up to 0.7 km. For distances up to 0.4 km, one can notice that for UDP the 7.2/1.42 Mbps data card provides higher throughput values than the 7.2/0.384 Mbps ones, while for FTP is the other way around. This is explained by the fact that FTP measurements with the

7.2/1.42 Mbps data card were the last ones being performed, with the FTP server presenting some instability, which affected these results.

From Figure 4.33, one can also notice that both FTP and UDP measurements curves present the same shape as the theoretical curve, but for the former ones, the throughput decays for smaller distances. For distances beyond 0.4 km the throughput values are similar for both data cards and for both protocols, except to FTP with 7.2/1.42 Mbps data card as already mentioned. For distances farther than 0.4 and up to 0.7 km, the application throughput is around 2 Mbps, which is a significant improvement compared to the maximum throughput, 0.384 Mbps, from Release 99. One only has measurements results up to 0.7 km, but beyond this value it is expected that the application throughput decreases, as it can be seen from the trend line of the theoretical model.

The analysis regarding the HSUPA measurements, shown in Figure 4.34, is similar to the one presented for HSDPA. For distances up to 0.15 km, the UDP throughput is above the theoretical model, as also occurred with HSDPA, although for the HSUPA case for smaller distances. The main differences between HSUPA and HSDPA are: HSUPA measurements follow the theoretical curve up to higher distances, and across the range of measurements covered, the UDP and FTP curves are closer to the theoretical model, for HSDPA, there is a significant reduction of the application throughput for distances further than 0.25 km, whereas that phenomenon is not verified for HSUPA.

The application throughput presents an almost constant value up to 0.7 km, which is in accordance with the results from the single user model, but a decrease of the application throughput is expected for bigger distances, following the theoretical model. Nevertheless, HSUPA can serve around 1 Mbps to distances up to 0.7 km. This data confirms the results of the single user model.

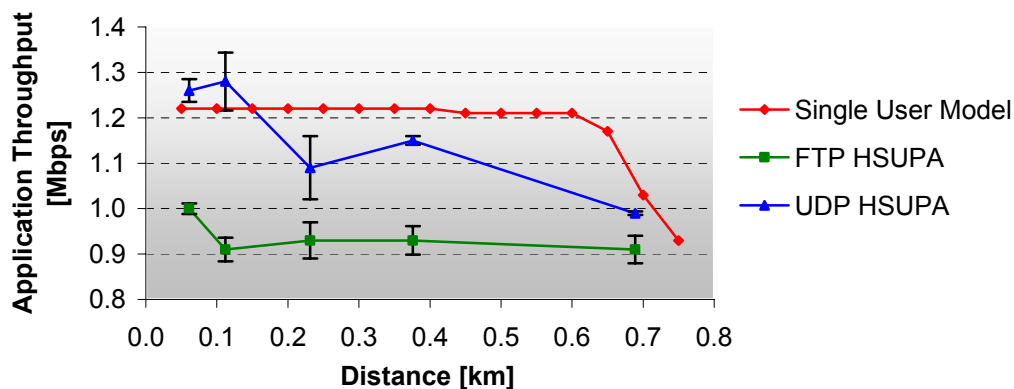


Figure 4.34. HSUPA measurements versus single used model results.

For both HSDPA and HSUPA was difficult to make measurements for distances larger than 0.7 km – mapped onto an RSCP value of -115 dBm – since for bigger distances, a low *RSCP* value in combination with a low E_c/N_0 will force the MT to try to connect to another cell, and in the handover zone, for HSDPA, and in SHO zone for HSUPA, the application throughput is reduced due to the increase of the signalisation messages.

As can be seen from Figure 4.33 and Figure 4.34, the HSUPA theoretical model, developed for the

calculation of the user's throughput, presents better results than the one developed for HSDPA. This result can be explained by the fact that, the models for HSDPA and HSUPA were adopted from the one used for Release 99. HSDPA has a fixed SF and adaptive modulation, while HSUPA has variable SF, like Release 99, hence, it functions in a similar way.

4.6.2 Live Measurements

In this section, the results from the live measurements are compared with the ones from the multiple users simulator introduced in Section 4.3. In this comparison, only the results from the default scenario are considered. In Annex K and Annex L, one presents additional results regarding the HSDPA and HSUPA measurements, respectively. In these measurements, only FTP was considered. In Annex K, Figure K.1, it can be seen a comparison between the results from the live measurement and the ones from the test plant. For the latter, only the FTP results are shown.

In Figure 4.35, one presents the physical requested throughput, the application throughput and the multiple users' simulator results for the default scenario. From Figure 4.35, one can notice that the curves for both the physical requested and the application throughput are above the curve regarding the results from the simulator. At the time of the measurements, Optimus had just launched HSDPA with 10 HS-PDSCH codes, hence, when the measurements were performed there were few users being served. This is one of the reasons that justifies the higher application throughput values regarding the measurements performed, since in HSDPA the throughput is shared among all the active users and if few users are connect, each user can be served with a higher average throughput.

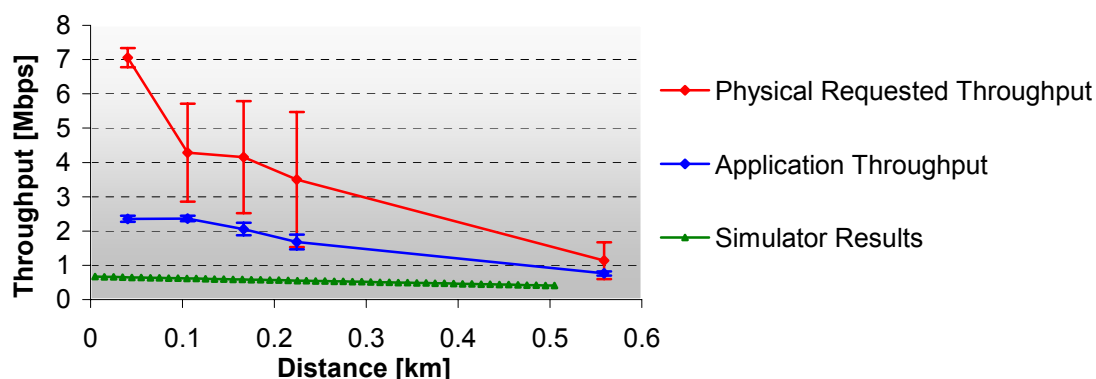


Figure 4.35. HSDPA throughput comparison.

From Figure 4.35, one can also observe a high difference between the physical requested throughput and the application throughput, starting with almost 4.5 Mbps that slowly fades away to 1 Mbps at 0.4 km. The physical requested throughput is the throughput that could be served to the user, if all the Node B resources were available. This throughput is based on the MT's CQI reports. The CQI values evolution regarding distance is shown in Annex H. In theory, the MT could be served with the physical requested throughput – as the name suggests, this throughput is considered at the physical layer, hence, at the application layer and considering a margin of 7.3% for the RLC layer and of 10% for BLER and retransmissions, approximately only 80% of the requested physical throughput would be

available to applications. But from Figure 4.35, the difference between the physical requested and the application curves is higher.

There are 2 main reasons that justify the difference between the results from the physical requested throughput and the application throughput: there were other users in the same cell (one had an average DTX of 70%), meaning that the available resources were shared and due to limitation of the Node B transmission that was limited to 5 Mbps at the time of the measurements. This fact limited the available throughput that is shared among users. Nevertheless, from Figure 4.35 one can notice that for distances up to 0.04 km the user can be served with the maximum physical throughput, 7.2 Mbps, while for bigger distances the maximum rapidly decreases to 0.1 Mbps.

As expected and predicted by the simulator results, both the requested physical throughput and the application throughput decrease with distance. It is interesting to notice that the higher decrease in the measured throughputs is for distances between 0.04 and 0.1 km, since for higher throughput values, even a small variation of the RSCP or of the E_c/N_0 are directly mapped onto CQI, leading to a reduction in the user's throughput. For bigger distances, the measured throughput continues to decrease, but at a lower rate. The difference between the requested physical throughput and the application throughput fades away with distance, since the requested throughput is closer to the one that can be served to the user. The limitation for the former is the conditions of the radio channel, while for the latter the limitation is the available resources at the Node B.

The results of the HSUPA measurements in the live network are similar to the ones performed in the test plant, since HSUPA was starting to be deployed at the time of the measurements, hence, there were almost no HSUPA users, meaning that almost all HSUPA Node B's resources were available.

In Figure 4.36, one presents the HSUPA measurement results compared with the ones from the multiple users service simulator. As measurements took place at 3 different locations, in Figure 4.36 one shows all 3 application throughput measures. In Annex L, one presents additional results regarding HSUPA measurements that help to understand the differences regarding the results for CCB, Luz and Firmino.

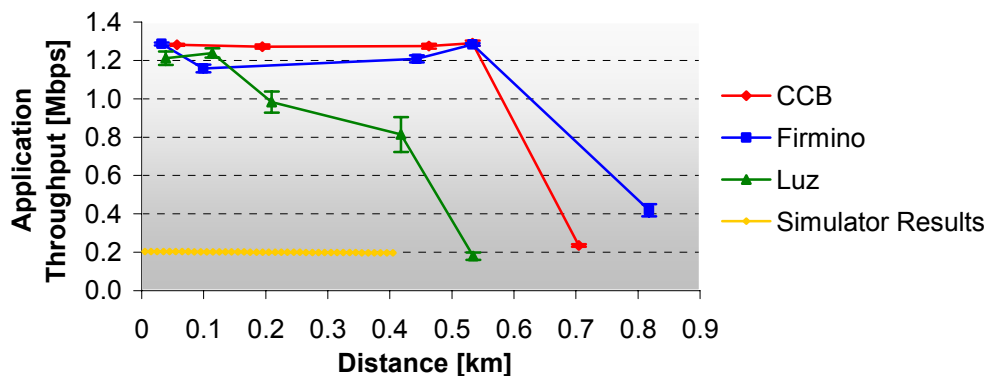


Figure 4.36. HSUPA throughput comparison.

Like for HSDPA, there is a significant difference between the results from the simulator and the ones

from the measurements. When the measurements took place, Optimus was still making some tests with HSUPA available in only 30 sites. For this reason, there is a small difference between the physical and the application throughput, as all HSUPA resources at the Node B were available and could be delivered.

With the exception of the measurements that took place in Luz, HSUPA can deliver the maximum throughput for distances up to 0.55 km. Beyond this distance, the application throughput begins to decrease at a higher rate, but for an urban scenario it is not expected to have cell radius higher than 0.55 km – the simulator results show an average cell radius of 0.25 km, hence, the maximum application throughput is available.

One should reinforce that even though the HSDPA and HSUPA measurements took place in the live network, these results cannot be extended to a multiple users scenario. This fact justifies the difference between the measured throughput and the one from the simulator. For HSUPA, the results from the live measurements can even be compared to the ones in the test plant.

It can be easily noticed from Figure 4.35 and Figure 4.36, that, as already stated in this subsection, the theoretical curves are above the ones from the measurements. This result can indicate that the results from the multiple users scenario are conservative. But one should also consider that while in the multiple users simulator there is real multiple users scenario, with several users offering traffic to the network, the measurements in the live network are characterised by a reduced number of users and for HSUPA, only one user was active. Nevertheless, for HSUPA, the model predicts throughput invariance with distance that was also observed in the measurements, the difference being only in the average value, again, due to the number of user active.

Chapter 5

Conclusions

In this chapter, one points out the main conclusions of this thesis, as well as some suggestions for future work.

The main objectives of this thesis were to study and analyse HSDPA and HSUPA performance, and compare both systems' capacity and coverage. These goals were accomplished through the development and implementation of 2 models: the single user and the multiple users one. First, a single user model was developed, and implemented in C++, with the purpose of calculating the maximum cell radius for HSDPA and HSUPA in a single user scenario, according to the user's requested throughput. The influence of the variation of several parameters was also studied. This model was afterwards adapted to a multiple users and services scenario, with several results being analysed considering the variation of both systems' parameters and type of scenarios. Measurements in Optimus test plant and live network were also performed, as well as a comparison between these measurements and the results from the theoretical models. For all the theoretical models, as well as for the measurements analysis, the COST 231 Walficsh-Ikegami model was used to calculate the cell radius, or the distance to the Node B, for the measurements, based on the path loss.

A single user model for HSDPA and HSUPA was developed, whose main purpose is to calculate the maximum cell radius when a single user is being served, in order to have a first approach regarding cellular planning. Several parameters were considered, namely, frequency, Node B and MT antenna gains, margins for indoor attenuation, and both slow and fast fading margins. For HSDPA, one also considered variations of the total transmission power and the number of HS-PDSCH codes. Regarding HSUPA, the UL load factor, the SHO gain among others can be changed. Cell radius is calculated based on the requested throughput, mapped onto SINR, and on the systems parameters' values.

For the multiple users analysis, the single user model was adapted by introducing the interference margin and by sharing the maximum available throughput among all users in Node B's coverage area. The multiple users model main goal is to assess the HSDPA and HSUPA performance in a real network, by simulating a multiple users scenario, through the individual analysis of HSDPA and HSUPA, and afterwards, a comparison between the 2 systems performance. For both HSDPA and HSUPA, the available throughputs are shared among all users. For HSDPA the sharing is due to the use of shared channels, while for HSUPA it is due to the share of the UL noise. Three reduction strategies, with different QoS requirements, were developed for the cases when the users' requested throughput exceeds Node B's capacity: the "Throughput Reduction", which reduces all users at the same time; the "QoS Class Reduction", which reduces all users of the same QoS class following the QoS priority list; and the "QoS One by One Reduction", reducing one user at a time, beginning by the users of the QoS class with the lowest priority.

For HSDPA and HSUPA multiple users simulator, the influence of the variation of the same parameters considered for the single used analysis was studied, as well as the influence of the increase of the number of users, offered traffic profile and increase of the requested throughput. The cell radius calculation in this model is different from the one in the single model. The Node B cell radius is calculated as the average of the user placed further away, while still being served, in the 3 Node B's sectors. If the sum of all users requested throughput in the Node B coverage area exceeds Node B's capacity, one of the reduction strategies, with different QoS requirements, is performed.

Some of the services used are typically DL services, hence, the traffic models were adapted for UL.

For the calculation of the users' distance to the Node B, regarding the measurements performed for both HSDPA and HSUPA, in the test plant and in the live network, the path loss calculation was adapted, in order to map the *RSCP* onto distance. This approach was implemented to allow a direct comparison between the theoretical results and the ones from the measurements.

For the default single user scenario, but considering the indoor low loss environment, the HSUPA cell radius is 0.19 km for the maximum throughput, 1.22 Mbps. For HSDPA with 5, 10 and 15 HS-PDSCH codes, the maximum cell radius, considering the maximum throughput for each number of codes is 0.21 km for 5 HS-PDSCH codes and 0.17 km for both 10 and 15 HS-PDSCH codes. Even though 10 and 15 codes have the same cell radius, the maximum throughputs considered are different, 6.0 and 8.46 Mbps, respectively. Due to the lower environment and fading margins, the pedestrian environment has higher cell radius than any of the other environments considered. For a throughput of 3.0 Mbps, HSDPA with 10 HS-PDSCH codes has a cell radius of 0.69 km for the pedestrian environment, of 0.28 km for vehicular, 0.30 km for indoor low loss and 0.17 km for indoor high loss. For HSUPA, considering a throughput of 0.75 Mbps, the pedestrian environment has a cell radius of 0.84 and 0.34 km for vehicular and indoor low loss, and 0.20 km for indoor high loss. The influence of the total Node transmission power in the HSDPA cell radius was also analysed. For 10 HS-PDSCH codes, there is a reduction of 78%, for a 3 Mbps throughput, when the total transmission power is reduced from 44.7 to 20 dBm, with the reduction of the cell radius being at an almost linear rate. For frequency variations, the reduced difference between the maximum and minimum, 55 MHz, leads to a reduction of only 4% for both HSDPA and HSUPA cell radius, when the highest frequency is used.

In the multiple users simulator, for the HSDPA default scenario, an average network radius of 0.28 km is obtained. The average network throughput is 2.39 Mbps, while the average instantaneous user throughput is around 0.56 Mbps, with a satisfaction grade of around 87%. Even though the single user model results, for the indoor low loss environment, indicated that HSDPA can maintain the maximum throughput for distances up to 0.2 km, the multiple users results show that the average instantaneous user throughput immediately decreases for shorter distances. This is due to the introduction of the interference margin in the link budget assessment. The comparison between the offered and served traffics show that there is a 10% reduction of Web users, which is compensated by an increase of about 10% of the percentage of P2P users. The offered and served percentages are similar for the other services. Due to the QoS differentiation introduced in the reduction strategy used, the service with the higher priority, Web, has the 2nd highest average instantaneous throughput per user and the highest satisfaction grade, almost 93%. The average network traffic is 85 GB/h and almost 32000 users can be served, these being the results obtained for the busy hour analysis. Regarding the busy hour analysis per Node B, in average, 139 users are served per Node B, generating 0.37 GB/h.

The variation of the set of HS-PDSCH codes in HSDPA was also studied. Due to the higher capacity, there is an increase of the average network throughput by 9.2% for an increase from 10 to 15 HS-PDSCH codes and a reduction of almost 25% when 5 are used instead of 10 codes, while the cell

radius variation is lower than 1%. The variation of the Node B's total transmission power was also analysed. A variation of 3 dB was considered, and when this reduction is performed, the average network radius decreases 5.2%, and there is a reduction of 6.1% of the average network throughput.

When considering the HSUPA multiple users default scenario, an average network radius of 0.25 km is obtained. The average network throughput is 0.62 Mbps, while the average user throughput is near 0.22 Mbps with a 91% satisfaction grade. Unlike HSDPA, both the single user model and the multiple users simulator results show that HSUPA delivers constant throughput up to 0.4 km in indoor scenarios, meaning that the introduction of the interference margin in the link budget for the multiple users analysis does not have the same influence as in HSDPA. Both offered and served traffic have very similar percentages – a Streaming 2% percentage reduction is compensated by the same 2% increase in the P2P percentage of served users. The service with highest QoS priority, Web, has an average throughput of 0.26 Mbps and 92% satisfaction grade. In the busy hour analysis, near 8900 users are served generating almost 18 GB/h. If one considers the busy hour analysis per Node B, an average of 39 users can be served and an average traffic of 0.08 GB/h is carried.

To evaluate the HSDPA and HSUPA behaviour in load situations, one increased the number of users offering traffic to the network. The average network throughput increases 61 and 35.3% for HSDPA and HSUPA, respectively. The increase of the average network throughput is not noticed at users' level, where there is even a reduction of the satisfaction grade and of the average instantaneous throughput per user, since the same resources are shared among a larger number of users. Regarding the average network radius, there is an increase of 10 and 13.5% for HSDPA and HSUPA.

The influence of the variation of the services' penetration percentages was also studied. Two alternative profiles were created with lower P2P penetration percentages and different QoS priorities. These alternative profiles are more throughput demanding, due to the lower P2P penetration percentage, since this service has one of the lowest minimum throughput. For HSDPA, the IBB profile has an average network throughput increase lower than 1%, while for the IAO profile there is a decrease of 3.5%. HSUPA has a different behaviour, as there is a reduction of 1% for the IBB profile and an increase of 1.3% for the IAO profile. Regarding the average network radius, for HSDPA, there is a reduction of around 2.5% for both alternatives scenarios compared with the default one, while for HSUPA there is an increase of 2.7 and 2.3% for the IBB and the IAO profiles. From the set of parameters analysed, the one that most differs from the default scenario is the number of users served per hour, mainly due to the increase of the average instantaneous throughput per user, leading to shorter user sessions, hence, more users can be served per hour.

In the overall network analysis, the advantages of using the different reduction strategies is almost unnoticed, since these strategies are not executed in all networks' Node Bs. To perform this analysis, a group of 10 Node Bs, where these strategies are executed, was chosen. For HSDPA and HSUPA, different Node Bs were used, since the reduction strategies are not executed in all Node Bs for both HSDPA and HSUPA. For HSDPA, only 4 of the 6 services are active, while for HSUPA, only 3 services are considered. The use of the "Throughput Reduction QoS Class Reduction" strategy

reduces the average Node B throughput by 2.2 and 3.5%, for HSDPA and HSUPA, compared to the “QoS Class Reduction”. When the “QoS One by One Reduction” strategy is used, instead of the “QoS Class Reduction” one, there is an average increase of 2% for both HSDPA and HSUPA Node B’s throughput. “QoS One by One Reduction” strategy also has the lowest standard deviation, as this strategy allows Node B’s throughput to be the closest to the maximum – 6.0 Mbps and 1.22 Mbps for HSDPA and HSUPA, respectively. This reduction strategy has also the highest satisfaction grade.

One also studied the influence of increasing the user’s requested throughput, which leads to an increase of the average network throughput by almost 41 and 33.5% for HSDPA and HSUPA. The HSDPA average network radius decreases almost 0.5%, while the HSUPA one increased 7.4%. This different behaviour is due to capacity and path loss. For HSUPA, the reduction strategies are executed several times, leading to a higher probability of delaying the users closer to the minimum service threshold. In this scenario, all users request the maximum throughput, meaning that they tolerate more reductions to be performed, before being delayed. This phenomenon can be seen on the reduction of the satisfaction grade by almost 27% for HSUPA, and 22% for HSDPA.

When comparing HSDPA and HSUPA in a single user scenario, for throughputs between 0.384 Mbps and 1.22 Mbps and the pedestrian environment, HSUPA has always a smaller cell radius compared to HSDPA. For this range of throughputs, the advantage of using higher number of HS-PDSCH codes is minimal. This analysis may be interesting for symmetric applications where it can be seen that HSUPA limits coverage. For the comparison of HSDPA and HSUPA, one calculated the maximum throughput of each system at the cell edge for both the pedestrian and the indoor low loss environments. For the pedestrian environment and HSDPA with 5, 10 and 15 HS-PDSCH codes, the maximum throughput can be delivered for distances up to 0.4 km. For distances further than 0.4 km, the throughput at the cell edge decreases at a faster rate for 15 HS-PDSCH codes. For a distance of 1.0 km, the maximum HSDPA throughput is around 1.0 Mbps for the 3 HS-PDSCH sets of codes considered. HSUPA can deliver the maximum throughput up to 0.6 km, and can keep delivering throughputs above 1.0 Mbps up to 0.7 km. For distances of 1.0 km, HSUPA throughput is below 0.384 Mbps. For the indoor low loss environment the same study was performed. The curves for both HSDPA and HSUPA present the same shape and evolution as the ones for the pedestrian environment, but for indoor low loss the maximum HSDPA throughput can only be delivered up to 0.2 km, while HSUPA maximum throughput can only be delivered for distances up to 0.3 km.

The comparison of HSDPA and HSUPA multiple users simulator results show that, for the default scenario, HSDPA has a bigger cell radius, near 15.3%, than HSUPA. This means that the latter system is the one that limits coverage when both systems are deployed together. As expected, HSDPA has higher capacity, as it can be seen by the higher average network throughput, and by the higher value for the maximum throughput at the Node B, and most importantly, by the number of users served. HSDPA can serve up to 32000 users, while HSUPA can only serve 8900. If new services, with higher UL demands, are to be launched, more Node Bs should be placed in the network, in order to increase networks performance, mainly HSUPA, hence, serving more users. Regarding the traffic

carried by the network, HSDPA carries 85 GB/h, while HSUPA carries 18 GB/h. This difference is due to the different capacity of the 2 systems, but also due to the different characterisation of the traffic models used for DL and UL, since the majority of the services have lower UL file sizes. HSDPA has a satisfaction grade of 87%, while HSUPA has a satisfaction grade of 91%. The higher HSUPA satisfaction grade is due to the fewer number of user served per cell, and due to the lower requested throughputs per service – Streaming has a requested throughput of only 0.064 Mbps.

The test plant measurement results show that the HSDPA single user model can approximate with low relative error UDP measurements for distances up to 0.23 km, but only up to 0.12 km for FTP. For HSUPA, the results show that the single user model approximates the measured curves with a low relative error for distances up to 0.7 km for both UDP and FTP. The HSUPA single user model can better fit the measurement results. Throughputs measured in the live network are considerably higher than the ones from the multiple users simulator. Even though the measurements took place in a live network, both systems were in the initial launching phase, with few users being served simultaneously. For HSUPA, the measurements in the live network are actually equivalent to the ones performed in the test plant, since all Node B resources were available to a single user.

The results from the single user model indicate that HSUPA can deliver the maximum throughput for bigger distances than HSDPA, but the latter allows higher throughputs. The advantages of having a higher number of HS-PDSCH codes available, bigger cell radius and higher cell capacity, hence, higher user throughput, fade away rapidly in indoor scenarios for distances further than 0.45 km. The multiple users simulator results show an average cell radius of 0.28 km for HSDPA and of 0.25 km for HSUPA. It can also be seen that, considering the parameter's variations studied, the cell radius variation is minimal. The parameters that have higher influence in HSDPA the cell radius are the Node B transmission power, with a reduction of 8.2% and the higher number of users, with an increase of 10.4%. For HSUPA, the increase of the number of users leads to an increase of 13.5% of the cell radius. The increase of the number of users and of the requested throughput per user increased the Node B throughput by 61 and by 41%, for HSDPA and HSUPA, respectively. However, this difference is only noticed at the user level for the latter scenario. The alternative scenarios have a major influence in the number of user served per hour.

For future work, one would suggest an analysis considering code multiplexing as well as terminal supporting 5, 10 and 15 HS-PDSCH codes for HSDPA and category 6 MTs for HSUPA, supporting up to 4.0 Mbps. The introduction of new features from the latest 3GPP releases as MIMO, OFDM and other LTE techniques could also be interesting. At the RRM level, it could be interesting to analyse the optimisation of the user's connection to the Node B based not only on the users' distance but also on the Node B's available resources. A reduction strategy based on both the QoS priority and on the users' requested resources could also be a challenge to consider in future researches. Regarding measurements in the live network, one could suggest measurements in a truly multiple users scenario, and considering aspects as mobility and indoor performance. One could also suggest an improvement of the HSDPA model to better fit the measurement results, especially the ones from the test plant.

Annex A – Link Budget

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

The path loss can be calculated by [Corr06]:

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

where:

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

If diversity is used (only diversity in UL is considered, since there is no space in the MT for spatial diversity, and polarisation diversity requires doubling the transmit equipment at the Node B [Sant04]), G_r in (A.1) is replaced by

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

where:

- G_{div} : diversity gain.

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

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

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

where:

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

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

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

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

where:

- P_{Rx} : received power at receiver input.

The UMTS receiver sensitivity can be approximated by:

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

where:

- N : total noise power given by (A.8);
- G_p : processing gain, Table A.1;
- SNR : signal to noise ratio, Table A.1.
- R_b : bit rate;
- R_c : WCDMA chip rate;
- E_b/N_0 : energy per bit to noise spectral density ratio.

Table A.1. HSDPA and HSUPA processing gain and SNR definition.

System	Processing Gain	SNR
HSDPA	Fixed and equal to 16	SINR
HSUPA	R_c/R_b	E_b/N_0

The total noise power is:

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

where:

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

The interference margin, not considered in the single user model, is calculated based on the total number of users of the Node B coverage area. It is most likely that the Node B with the higher number of users in its coverage area is the Node B with more served users. To calculate the number of served users, the interference margin is necessary to evaluate the throughput due to the user distance and so, the latter approximation was considered. For the Node B with the higher number of users connected to, one assigns the maximum interference margin value, defined in Section 4.1, and for the other Node Bs, the interference margin for both HSDPA and HSUPA at a given Node B is estimated by:

$$M_{I_j [dB]} = \frac{N_{u_j}}{N_{u_{max}}^{NodeB}} \cdot \beta_{[dB]} \quad (A.9)$$

where:

- β : maximum interference value considered;
- N_{u_j} : number of users in the Node B j ;
- $N_{u_{max}}^{NodeB}$: number of users of the most populated Node B.

Some margins must be taken into account, to adjust additional losses due to radio propagation and others:

$$M_{[dB]} = M_{SF_{[dB]}} + M_{FF_{[dB]}} + L_{int_{[dB]}} - G_{SHO_{[dB]}} \quad (A.10)$$

where:

- M_{SF} : slow fading margin;
- M_{FF} : fast fading margin;
- L_{int} : indoor penetration losses;
- G_{SHO} : soft handover gain, for HSUPA only.

The total path loss can then be calculated by:

$$L_{p\ total[dB]} = L_{p[dB]} - M_{[dB]} \quad (A.11)$$

The total path loss is used as input in the COST 231 Walfisch-Ikegami propagation model, described in [DaCo99], to calculate the cell radius, R , for the single user model. In Section 3.1, this calculus is briefly exposed. The HSDPA frequency, f , values used ([2110, 2170] MHz) exceed the frequency validation values and some of the calculated cell radius are below the distance validation values, namely for high data rates. Nevertheless, the model was used, since it is adjusted to urban non-line of site propagation.

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

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

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

Table A.2. Values used in the COST 231 Walfisch-Ikegami propagation model (based on [CoLa06]).

Parameter name	Value
Street Width [m]	24
Building Separation [m]	48
Node B height [m]	26
Building height [m]	24
MT height [m]	1.8
Orientation angle [°]	90

For HSDPA, using Figure 2.2, the values for SINR and throughput for 5, 10 and 15 HS-PDSCH codes were collected to create the real curves in Figure A.1. For the 15 HS-PDSCH codes, it is considered that the user is using a category 10 MT, being able to receive all the 15 codes.

For HSDPA, the values of SINR, Ψ , as function of the throughput, ρ , were calculated by polynomial interpolation, using Matlab and Excel, assuring that the relative error was below 5%, Table A.3.

Considering 5 HS-PDSCH codes, one has:

$$\Psi_{[\text{dB}]} = 0.1856 \cdot \rho_{[\text{Mbps}]}^5 - 1.6176 \cdot \rho_{[\text{Mbps}]}^4 + 6.7608 \cdot \rho_{[\text{Mbps}]}^3 - 16.7997 \cdot \rho_{[\text{Mbps}]}^2 + 27.3903 \cdot \rho_{[\text{Mbps}]} - 4.9847 \quad (\text{A.12})$$

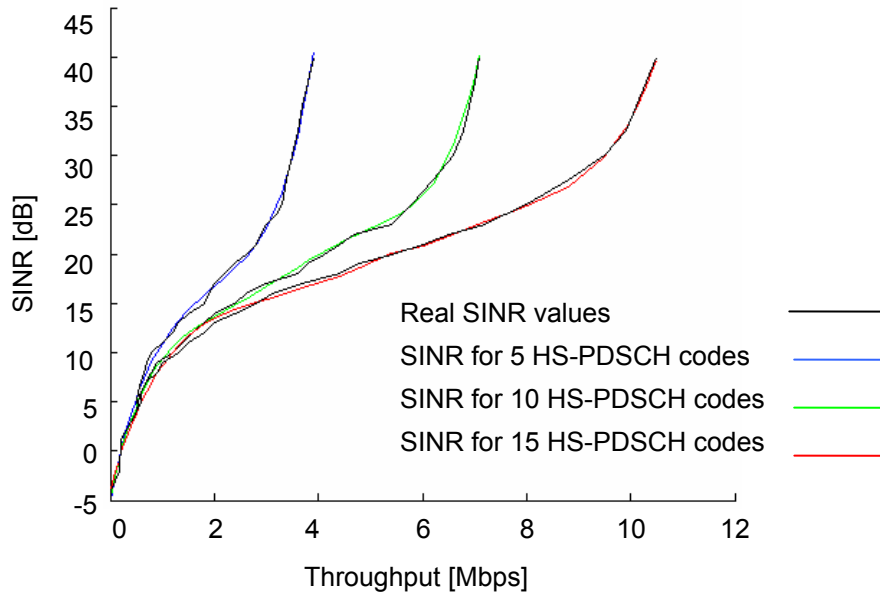


Figure A.1. Interpolation for 5, 10 and 15 HS-PDSCH codes.

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

$$\Psi_{[\text{dB}]} = 0.0382 \cdot \rho_{[\text{Mbps}]}^5 - 0.6722 \cdot \rho_{[\text{Mbps}]}^4 + 4.4891 \cdot \rho_{[\text{Mbps}]}^3 - 14.2023 \cdot \rho_{[\text{Mbps}]}^2 + 24.3795 \cdot \rho_{[\text{Mbps}]} - 4.6875 \quad (\text{A.13})$$

In 15 HS-PDSCH codes case, the SINR can be calculated by:

$$\Psi_{[\text{dB}]} = \begin{cases} 0.0061 \cdot \rho_{[\text{Mbps}]}^5 - 0.1663 \cdot \rho_{[\text{Mbps}]}^4 + 1.6581 \cdot \rho_{[\text{Mbps}]}^3 - 7.8530 \cdot \rho_{[\text{Mbps}]}^2 + 18.9881 \cdot \rho_{[\text{Mbps}]} - 3.9237, & \rho_{[\text{Mbps}]} \leq 5.4 \\ 0.0952 \cdot \rho_{[\text{Mbps}]}^4 - 2.7432 \cdot \rho_{[\text{Mbps}]}^3 + 29.4923 \cdot \rho_{[\text{Mbps}]}^2 - 138.1340 \cdot \rho_{[\text{Mbps}]} + 257.0166, & 5.4 < \rho_{[\text{Mbps}]} \leq 8.46 \end{cases} \quad (\text{A.14})$$

Table A.3. HSDPA and HSUPA mean relative error and standard deviation.

	Number of HS-PDSCH Codes	Relative Error [%]	Standard Deviation [Mbps]
HSDPA	5	2.9	0.24
	10	2.1	0.20
	15	3.4	0.23
HSUPA	---	0.4	<0.01

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

For HSUPA the $SINR$ used is the required E_b/N_0 , and as with HSDPA, the E-DPDCH throughput is a continuous function of the E_b/N_0 at the Node B. The values of the E_b/N_0 , energy per chip to noise spectral density ratio, as function of the throughput, Figure A.2, were calculated by interpolating the

FRC6 curve in Figure 2.4. The results presented are for Vehicular A channel, but since there are no results for other channel types, the same values were used for all environments, the difference in the cell radius being due to the different values for the slow fading, fast fading and the indoor margin considered, Section 4.1.

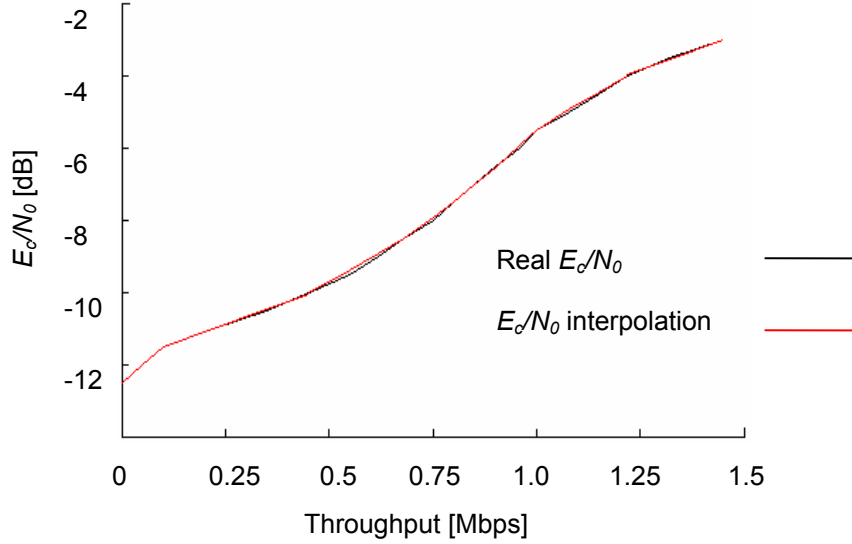


Figure A.2. Interpolation for the HSUPA FRC6 curve.

To minimise approximation errors, the interpolated function is stepwise:

$$E_c / N_0 \text{ [dB]} = \begin{cases} 10 \cdot \rho_{\text{[Mbps]}} - 12.5, & 0 \leq \rho_{\text{[Mbps]}} \leq 0.1 \\ 4.2 \cdot \rho_{\text{[Mbps]}} - 11.9334, & 0.1 < \rho_{\text{[Mbps]}} \leq 0.45 \\ 5.187 \cdot \rho_{\text{[Mbps]}}^2 + 0.659 \cdot \rho_{\text{[Mbps]}} - 11.3473, & 0.45 \leq \rho_{\text{[Mbps]}} \leq 1.0 \\ 6.8 \cdot \rho_{\text{[Mbps]}} - 12.3, & 1.0 < \rho_{\text{[Mbps]}} \leq 1.22 \end{cases} \quad (\text{A.15})$$

To assure the approximation validity, the mean relative error value and standard deviation were calculated, being depicted in Table A.3. The values are within the acceptable interval, hence, the approximation was used to obtain the E_c / N_0 as a function of the intended throughput.

For the sensitivity calculation, the E_b/N_0 should be used, which can be obtained from E_c/N_0 :

$$E_b / N_0 \text{ [dB]} = E_c / N_0 \text{ [dB]} + G_{P_{\text{[dB]}}} \quad (\text{A.16})$$

Regarding the situation where it is necessary to calculate the throughput due to the distance between the user and the Node B, the first step is to determine the path loss associated to the user distance, described in [CoLa06] and [Sant04]. After the path loss calculation, the receiver sensitivity is determined, resulting:

$$P_{R_{\text{[dBm]}}} = EIRP_{\text{[dBm]}} - L_{P_{\text{[dB]}}} + G_{r_{\text{[dB]}}} - L_{u_{\text{[dB]}}} \quad (\text{A.17})$$

For HSDPA, rearranging (A.7), the SINR associated to a certain user distance is calculated by:

$$SINR_{[dB]} = P_{Rx_{[dBm]}} - N_{[dBm]} + G_{\rho_{[dB]}} \quad (A.18)$$

The expressions of the interpolation curves in Figure A.3 are given by (A.19), (A.20) and (A.21) for 5, 10 and 15 HS-PDSCH codes respectively. These expressions are step-wise due to the fact that all polynomial expressions given by Matlab and Excel presented relative errors higher than 5%. In Table A.4, the relative error and standard deviation are presented for these curves.

$$\rho_{[Mbps]} = \begin{cases} 0, \psi_{[dB]} < -4 \\ 0.095 \cdot \psi_{[dB]} + 0.38, -4 < \psi_{[dB]} \leq -2 \\ 0.0464 \cdot \psi_{[dB]} + 0.2828, -2 < \psi_{[dB]} \leq 9 \\ 0.15 \cdot \psi_{[dB]} - 0.65, 9 < \psi_{[dB]} \leq 15 \\ 0.2 \cdot \psi_{[dB]} - 1.4, 15 < \psi_{[dB]} \leq 22 \\ 3.0, \psi_{[dB]} > 22 \end{cases} \quad (A.19)$$

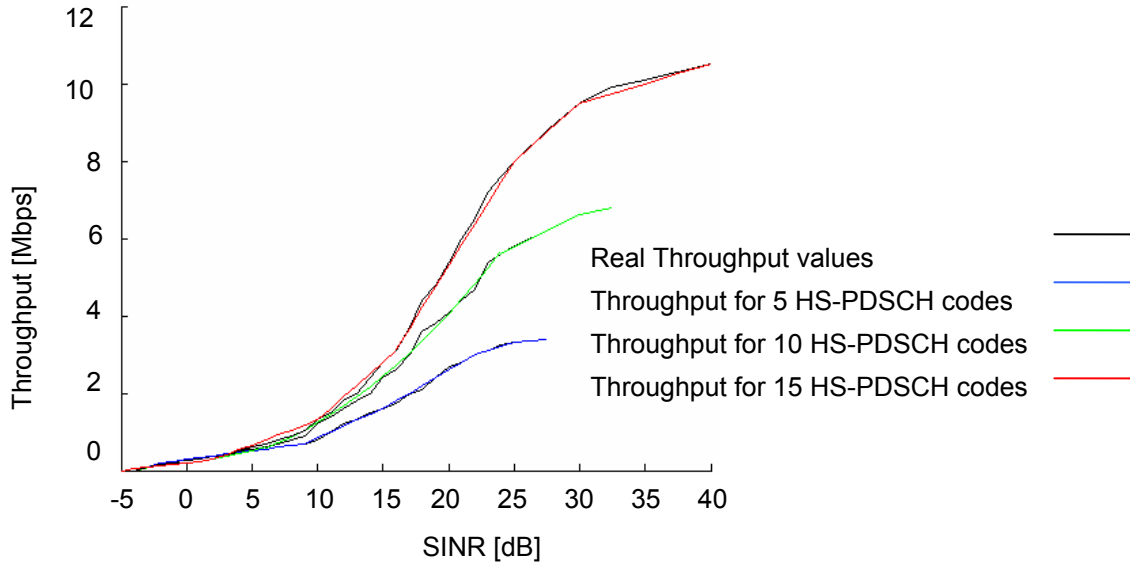


Figure A.3. HSDPA throughput as function of the SINR.

$$\rho_{[Mbps]} = \begin{cases} 0, \psi_{[dB]} < -4 \\ 0.085 \cdot \psi_{[dB]} + 0.34, -4 < \psi_{[dB]} \leq -2 \\ 0.0167 \cdot \psi_{[dB]} + 0.2034, -2 < \psi_{[dB]} \leq 1 \\ 0.076 \cdot \psi_{[dB]} + 0.65, 1 < \psi_{[dB]} \leq 6 \\ 0.0085 \cdot \psi_{[dB]}^2 + 0.0271 \cdot \psi_{[dB]} + 0.1141, 6 < \psi_{[dB]} \leq 24 \\ 0.1667 \cdot \psi_{[dB]} + 1.599, 24 < \psi_{[dB]} \leq 26.4 \\ 6.0, \psi_{[dB]} > 26.4 \end{cases} \quad (A.20)$$

$$\rho_{[\text{Mbps}]} = \begin{cases} 0, & \psi_{[\text{dB}]} < -5 \\ 0.0367 \cdot \psi_{[\text{dB}]} + 0.183, & -5 < \psi_{[\text{dB}]} \leq 1 \\ 0.09 \cdot \psi_{[\text{dB}]} + 0.13, & 1 < \psi_{[\text{dB}]} \leq 3 \\ 0.1296 \cdot \psi_{[\text{dB}]} + 0.014, & 3 < \psi_{[\text{dB}]} \leq 10 \\ 0.3 \cdot \psi_{[\text{dB}]} - 1.7, & 10 < \psi_{[\text{dB}]} \leq 16 \\ 0.54 \cdot \psi_{[\text{dB}]} - 5.5, & 16 \leq \psi_{[\text{dB}]} \leq 25 \\ 0.3 \cdot \psi_{[\text{dB}]} + 0.5, & 25 < \psi_{[\text{dB}]} \leq 26.5 \\ 8.46, & \psi_{[\text{dB}]} > 26.5 \end{cases} \quad (\text{A.21})$$

In HSUPA, considering (A.7) and (A.16), the E_c/N_0 given by the user distance is:

$$E_c/N_{0[\text{dB}]} = P_{Rx[\text{dBm}]} - N_{[\text{dBm}]} \quad (\text{A.22})$$

Using Figure A.4, it is now possible to calculate the user's throughput considering the user's distance.

Table A.4. Relative error and standard deviation for the interpolated curves in Figure A.3.

System	Number of HS-PDSCH Codes	Relative Error [%]	Standard Deviation [Mbps]
HSDPA	5	2.2	0.03
	10	3.0	0.04
	15	4.9	0.03
HSUPA	---	0.7	0.02

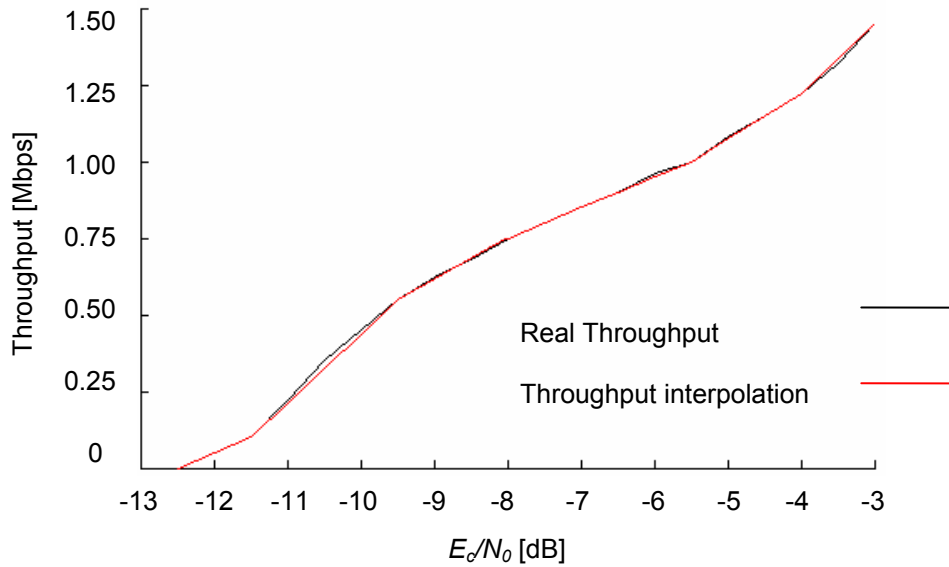


Figure A.4. HSUPA throughput as function of the E_c/N_0 .

The expressions in (A.23) were determined using linear interpolation for the curves in Figure A.4 and limiting the error to ensure an error below 5%, Table A.4.

$$\rho_{[\text{Mbps}]} = \begin{cases} 0, & E_c/N_{0[\text{dB}]} < -12.5 \\ 0.1 \cdot E_c/N_{0[\text{dB}]} + 1.25, & -12.5 < E_c/N_{0[\text{dB}]} \leq -11.5 \\ 0.225 \cdot E_c/N_{0[\text{dB}]} + 2.6875, & -11.5 < E_c/N_{0[\text{dB}]} \leq -9.5 \\ 0.1333 \cdot E_c/N_{0[\text{dB}]} + 1.8167, & -9.5 < E_c/N_{0[\text{dB}]} \leq -8 \\ 0.1 \cdot E_c/N_{0[\text{dB}]} + 1.55, & -8 < E_c/N_{0[\text{dB}]} \leq -5.5 \\ 0.1467 \cdot E_c/N_{0[\text{dB}]} + 1.8067, & -5.5 \leq E_c/N_{0[\text{dB}]} \leq -4.02 \\ 1.22, & E_c/N_{0[\text{dB}]} > -4.02 \end{cases} \quad (\text{A.23})$$

One presents in Figure A.5 the relation between *RSCP* and distance for the measurements performed in the test plant, using the link budget defined in this annex with the changes introduced in Section 3.4. In these measurements, TEMS was not available, hence, the standard deviation could not be calculated.

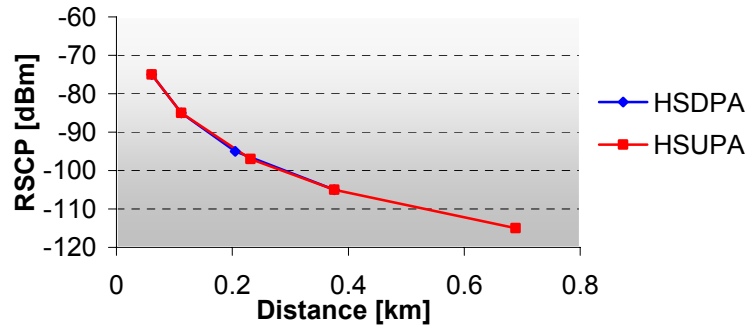


Figure A.5. HSDPA and HSUPA *RSCP* versus distance for the test plant measurements.

In Figure A.6 and Figure A.7, one presents the relation between *RSCP* and distance for the measurement performed in the live network for both HSDPA and HSUPA. For the latter, one presents 3 curves, since measurements were performed at 3 different locations. The standard deviation increases with the distance since the radio channel is more unstable. The only exception to this result is the measurement with a lower *RSCP*. One can also notice that HSUPA has lower standard deviations than HSDPA, probably due to the “single user environment” of the HSUPA measures.

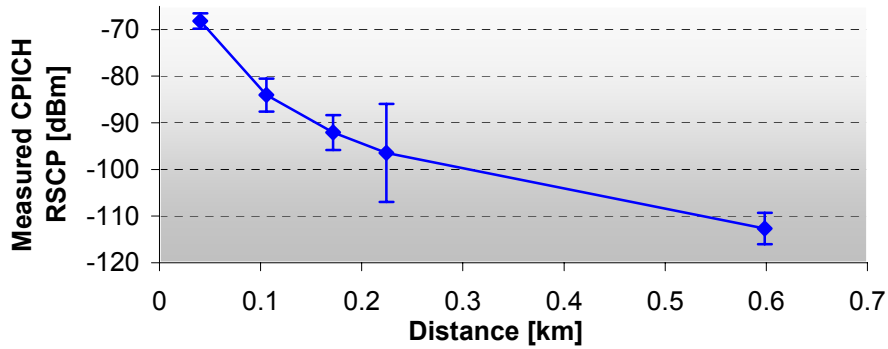


Figure A.6. HSDPA *RSCP* versus distance for the measurements performed in the live network.

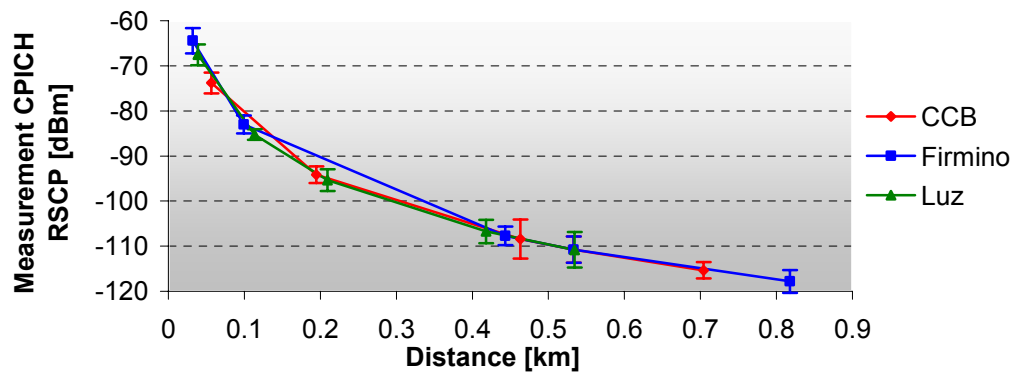


Figure A.7. HSUPA *RSCP* versus distance for the measurements performed in the live network.

Annex B – Single User Model Interface

In this annex, the single user and single service model interface for HSDPA, Figure B.1, and for HSUPA, Figure B.2 are shown.

The screenshot shows the 'UMTS-HSDPA Single User' window. It contains various input fields for parameters like DL Tx Power (44.7 dBm), DL Frequency (2112.5 MHz), and antenna gains. There are also dropdown menus for the number of HS-DSCH codes (set to 10) and radio environment selection (Pedestrian). A 'Result' box at the bottom states: 'HSDPA: The cell radius for 6.00 Mbps is 0.39 km.' Buttons for 'Run' and 'Exit' are at the bottom right.

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

The screenshot shows the 'UMTS-HSUPA Single User' window. It includes input fields for UL Tx Power (24 dBm), UL Frequency (1922.5 MHz), and throughput (1.22 Mbps). It also features fields for various gains and losses, and a radio environment selection (Pedestrian). The 'Result' box at the bottom states: 'HSUPA: Load factor: 0.274. The cell radius for 1.22 Mbps is 0.63 km.' Buttons for 'Run' and 'Exit' are at the bottom right.

Figure B.2. HSUPA single service user model interface.

Annex C – Services’ Characterisation and MT classes

The user’s generator program is based on parameters provided by the MOMENTUM project, [MOME04]. The previously existing profiles were adapted to the new services, Table C.1. There is a correspondence between the services traffic distribution files used in this thesis and the ones from MOMENTUM, with similar service percentages. All the other input parameters were left unchanged, being the ones used in [CoLa06]. In Table C.2, the services’ penetration percentages and QoS priority list for the scenarios studied are presented.

Table C.1. Traffic distribution files correspondence.

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

Table C.2. Default and alternative scenarios characterisation.

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

In Table C.3 and Table C.4 one presents the HSDPA and HSUPA MT category and capability categories. For HSDPA 12 MT categories were defined while for HSUPA, only 6 were considered.

Table C.3. HSDPA terminal capability categories (adapted from [HoTo06]).

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

Table C.4. HSUPA terminal capability categories (adapted from [HoTo06]).

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

Annex D – User’s Manual

In this annex, one presents the simulator’s user manual. To start the application, it is necessary to introduce 3 input files:

- “Ant65deg.TAB”, with the Node B 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 D.1.

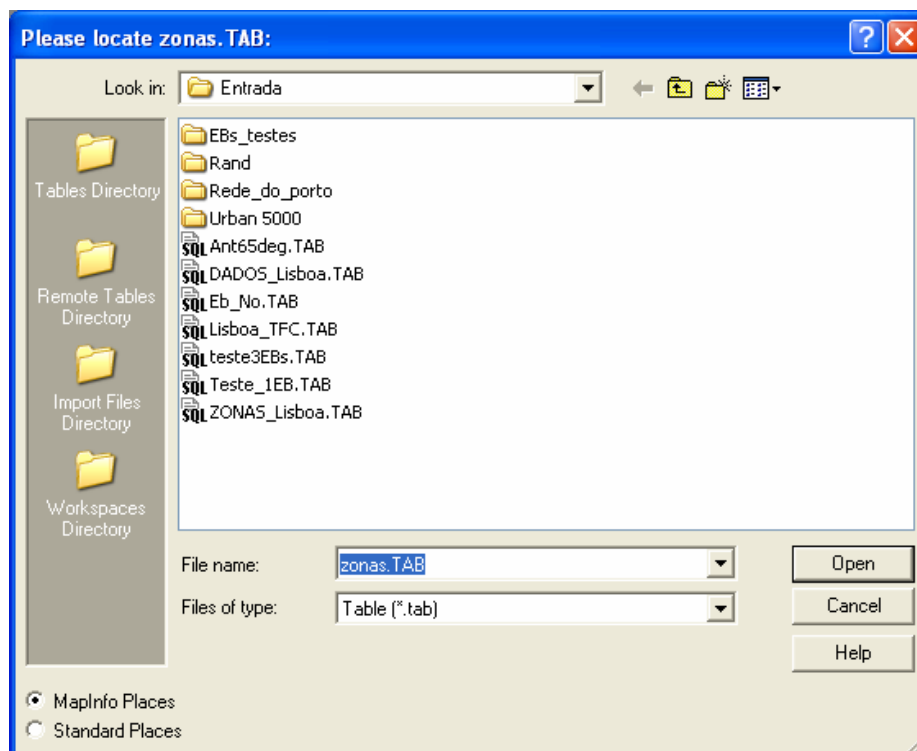


Figure D.1. Window for the introduction of ZONAS_Lisboa.TAB file.

After the introduction of the geographical information, a new options bar is displayed in MapInfo, where it is possible to choose between HSDPA and HSUPA, Figure D.2, and define the simulation’s characteristics.

Among the several options that are available for HSDPA and HSUPA, the windows for the propagation model and services’ colours are common for both systems, Figure D.3 and Figure D.4, respectively, since the propagation model parameters used are the same and the service’s colour are only a graphical information.

In both HSDPA and HSUPA User Profile windows’, Figure D.5, it is possible to change the maximum and minimum desired throughput for each service. The values for the minimum throughput are the ones presented in Figure D.5, not being possible to define a minimum service throughput lower than the ones presented.

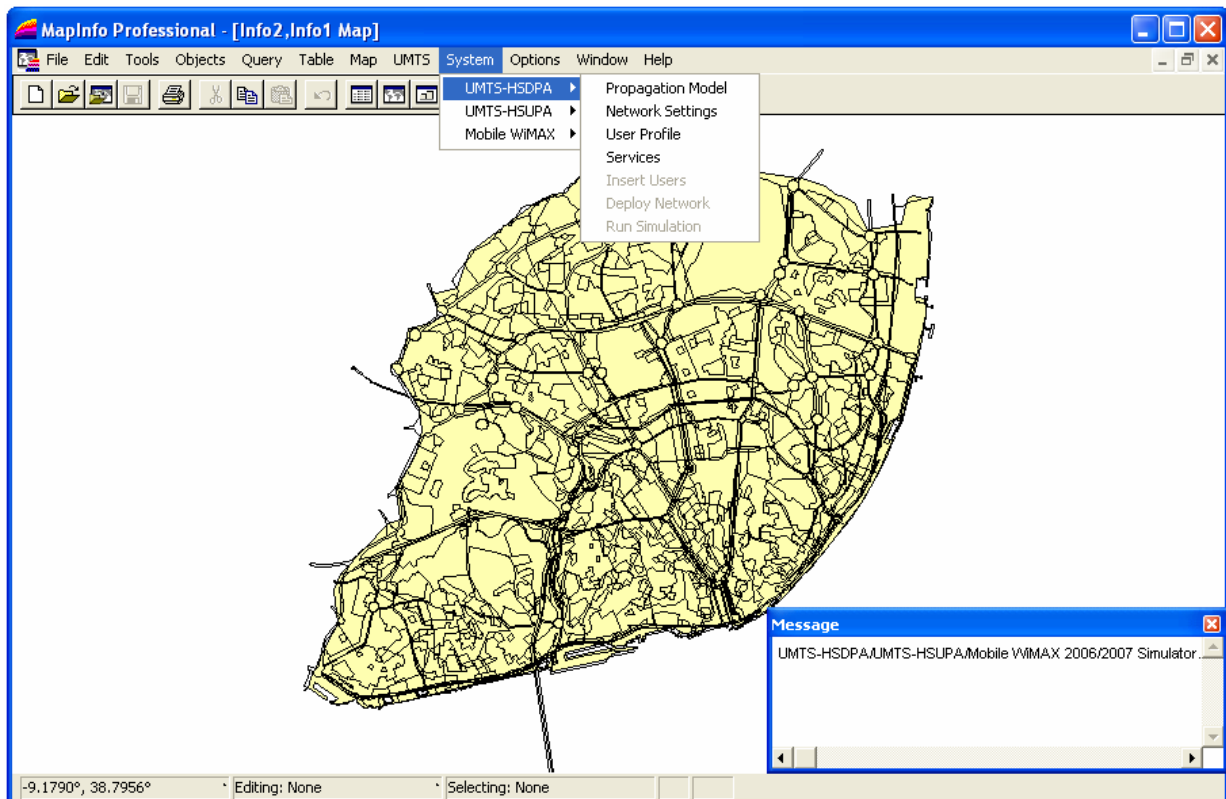


Figure D.2. View of the simulator and menu bar with the several options for each one of the systems.

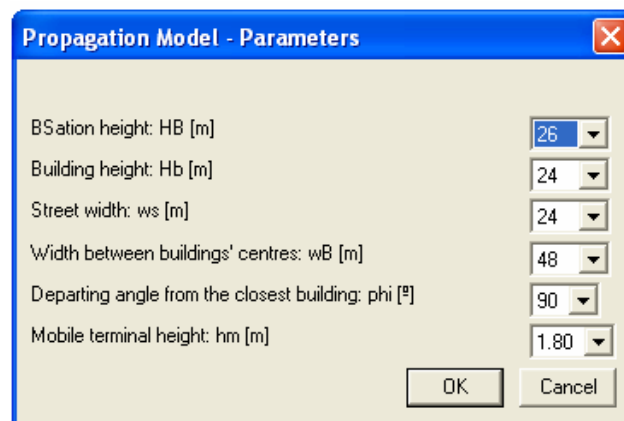


Figure D.3. Propagation model parameters.

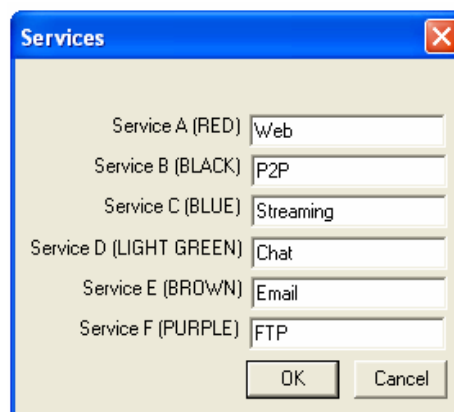


Figure D.4. Services' colour assignment.

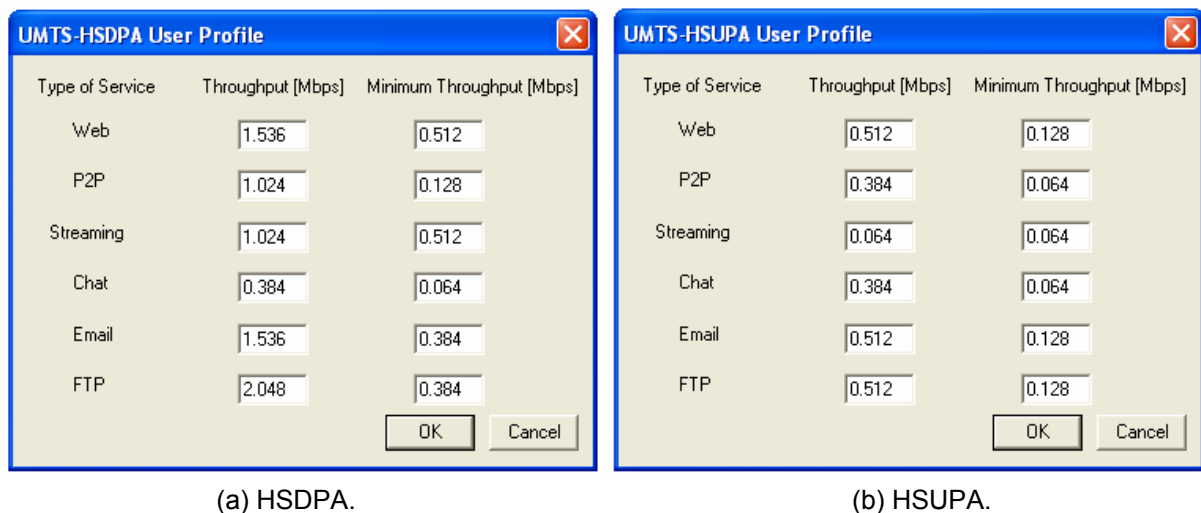


Figure D.5. HSDPA and HSUPA maximum and minimum service throughput.

Traffic properties, like the volume and service QoS priorities, can be modified, Figure D.6. As explained in Section 4.1, UL and DL traffic models are not identical, justifying the 2 different windows with different default values.

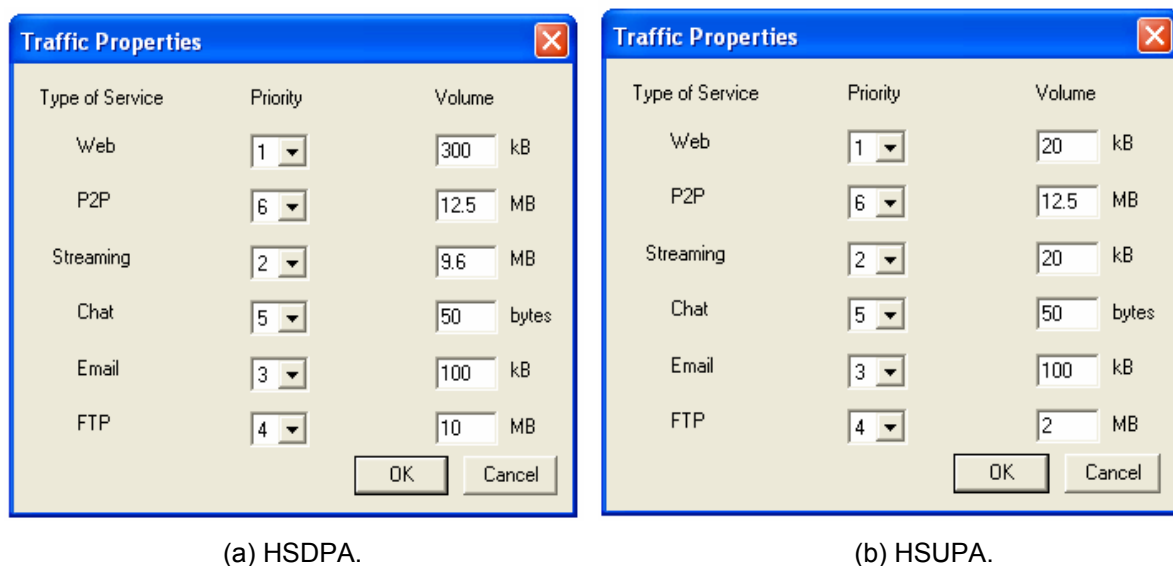


Figure D.6. HSDPA and HSUPA traffic properties window.

Regarding HSDPA and HSUPA Settings and windows', Figure D.7, it is possible to modify the different radio parameters of both systems, along with the reference scenario, reference service and reduction strategy. The default values are presented in Section 4.1.

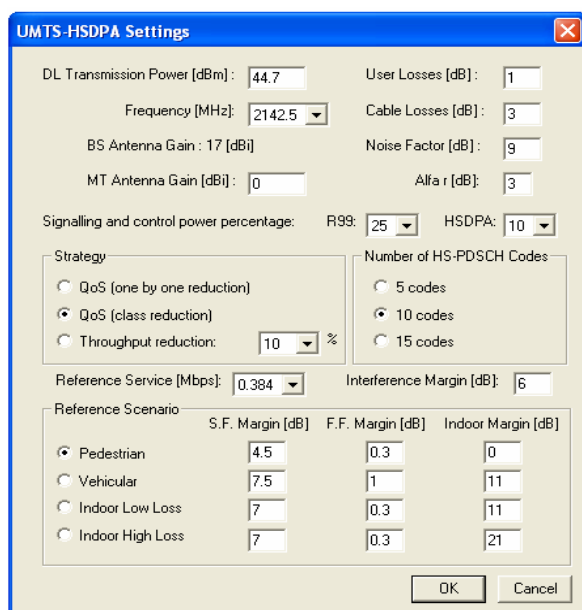
In Table D.1, one presents the relation between the number of users effectively considered and the ones that are necessary to consider as input parameter in the SIM program, as there are some users that are placed outside of the network area, not being considered in the analysis.

After pressing the "OK" button, it is displayed in the "Message" window the results regarding the cell radius for the reference service and the different services considered in Figure D.5. The window in

Figure D.8 presents HSDPA results. From now on, only HSDPA windows will be presented, since the procedures are identical to both systems.

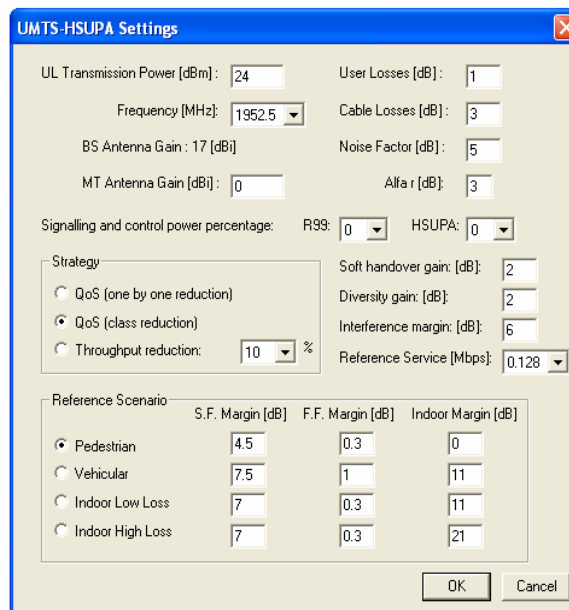
Table D.1. Evaluation of the number of users considered taking into account several parameters.

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



UMTS-HSDPA Settings window showing various parameters for HSDPA simulation. The window includes fields for DL Transmission Power (44.7 dBm), Frequency (2142.5 MHz), BS Antenna Gain (17 dBi), MT Antenna Gain (0 dBi), User Losses (1 dB), Cable Losses (3 dB), Noise Factor (9 dB), and Alpha r (3 dB). It also features a Signalling and control power percentage section with R99 (25) and HSDPA (10) options. The Strategy section includes QoS (one by one reduction), QoS (class reduction), and Throughput reduction (10%). The Reference Service (0.384 Mbps) and Interference Margin (6 dB) are also specified. A Reference Scenario table is provided with options for Pedestrian, Vehicular, Indoor Low Loss, and Indoor High Loss, each with S.F. Margin, F.F. Margin, and Indoor Margin values.

(a) HSDPA.



UMTS-HSUPA Settings window showing various parameters for HSUPA simulation. The window includes fields for UL Transmission Power (24 dBm), Frequency (1952.5 MHz), BS Antenna Gain (17 dBi), MT Antenna Gain (0 dBi), User Losses (1 dB), Cable Losses (3 dB), Noise Factor (5 dB), and Alpha r (3 dB). It also features a Signalling and control power percentage section with R99 (0) and HSUPA (0) options. The Strategy section includes QoS (one by one reduction), QoS (class reduction), and Throughput reduction (10%). The Reference Service (0.128 Mbps) and Interference Margin (6 dB) are also specified. A Reference Scenario table is provided with options for Pedestrian, Vehicular, Indoor Low Loss, and Indoor High Loss, each with S.F. Margin, F.F. Margin, and Indoor Margin values.

(b) HSUPA.

Figure D.7. HSDPA and HSUPA simulations' parameters.

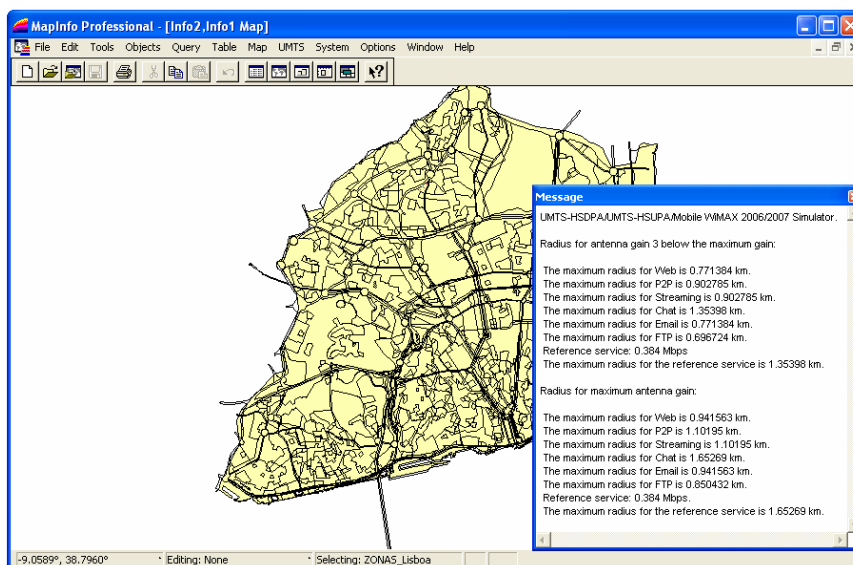


Figure D.8. Visual aspect of the application after running the HSDPA settings window.

Later, in the network setting window, the functionality “Insert Users” is activated, to introduce the users in the network, by choosing one of the user files from the SIM application. Afterwards, the menu “Deploy Network” becomes active, requesting a file containing the Node Bs’ location, so that these can be placed in the city area, Figure D.9.

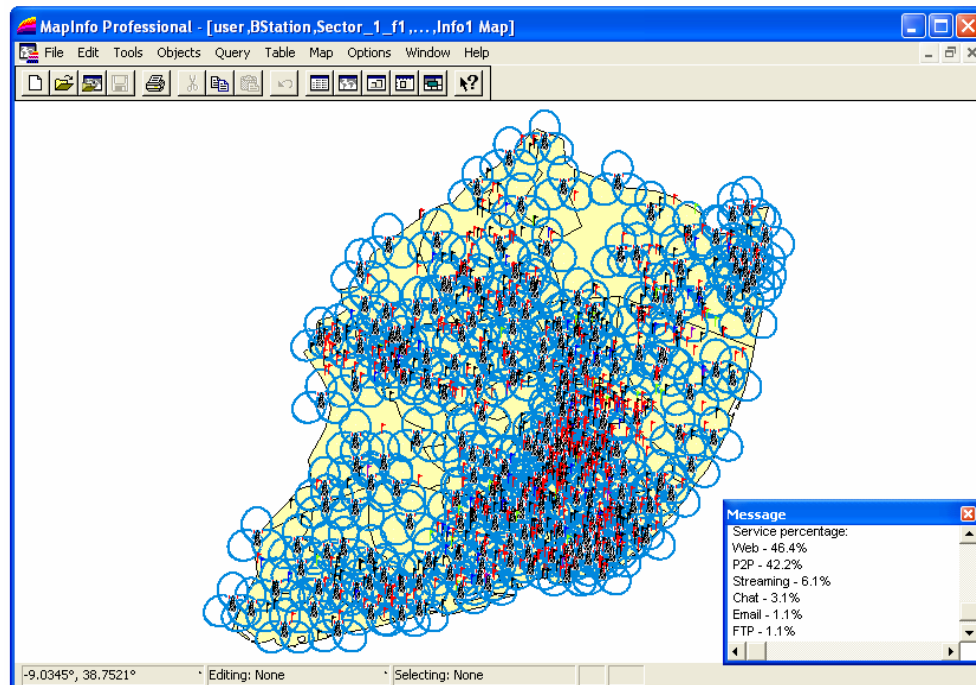


Figure D.9. Result of the “Network Deployment” with 228 tri-sectored Node Bs’ coverage area.

After showing Figure D.9, the menu “Run Simulation” is switched on, and when executed, the simulation takes place with the various simulations’ results being displayed by pressing the “OK” button. In Figure D.10, Figure D.11 and Figure D.12 the results for 228 Node Bs and around 2000 users are presented.

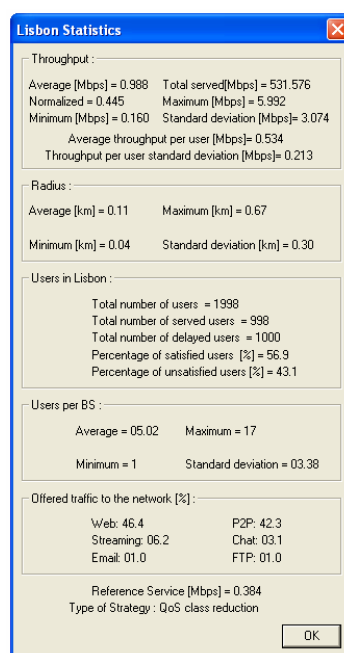


Figure D.10. HSDPA instantaneous results for the city of Lisbon.

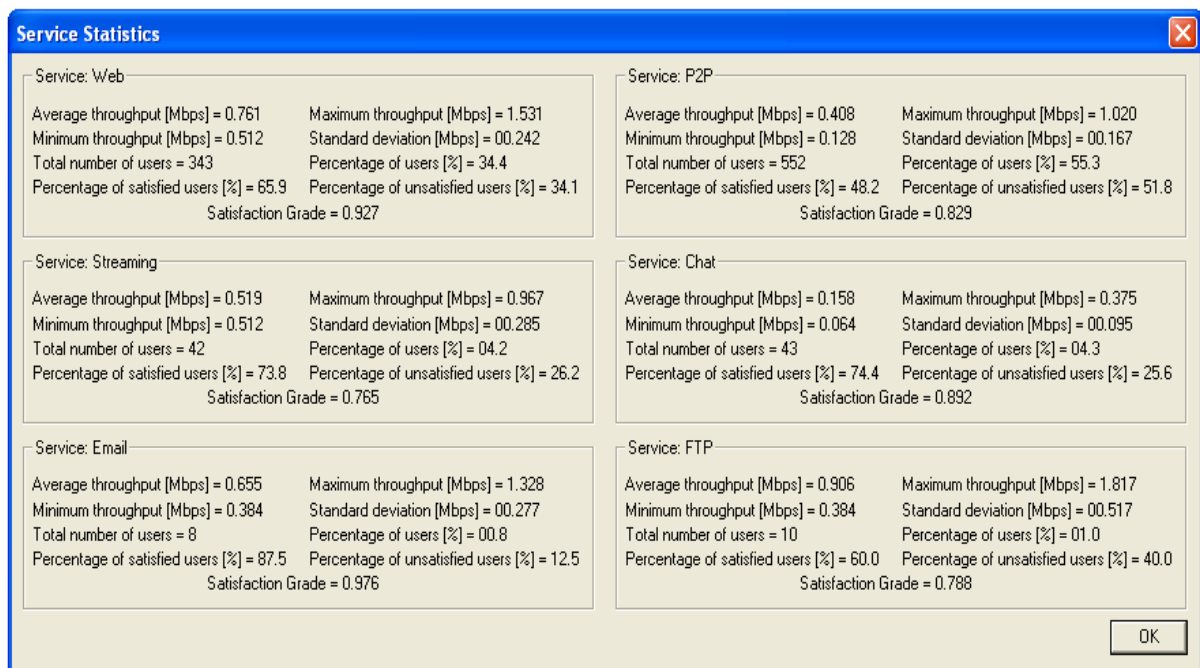


Figure D.11. HSDPA instantaneous results detailed by service for the city of Lisbon.

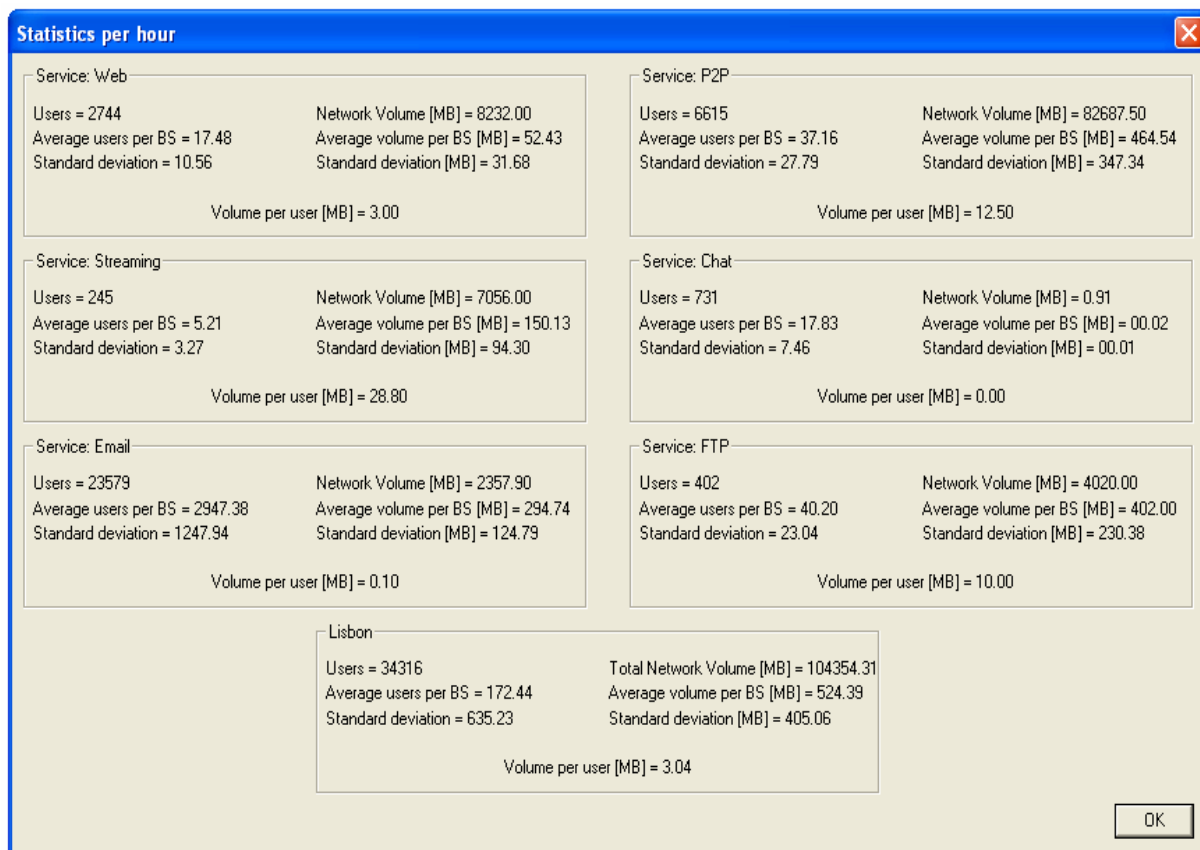


Figure D.12. HSDPA extrapolation results for the hour analysis.

Annex E – HSDPA Reduction Strategies

In this annex, the flow charts regarding the HSDPA reduction strategies are presented. The three reduction algorithms are: “Throughput reduction”, Figure E.1, “QoS class reduction”, Figure E.2 and “QoS one by one reduction”, Figure E.3.

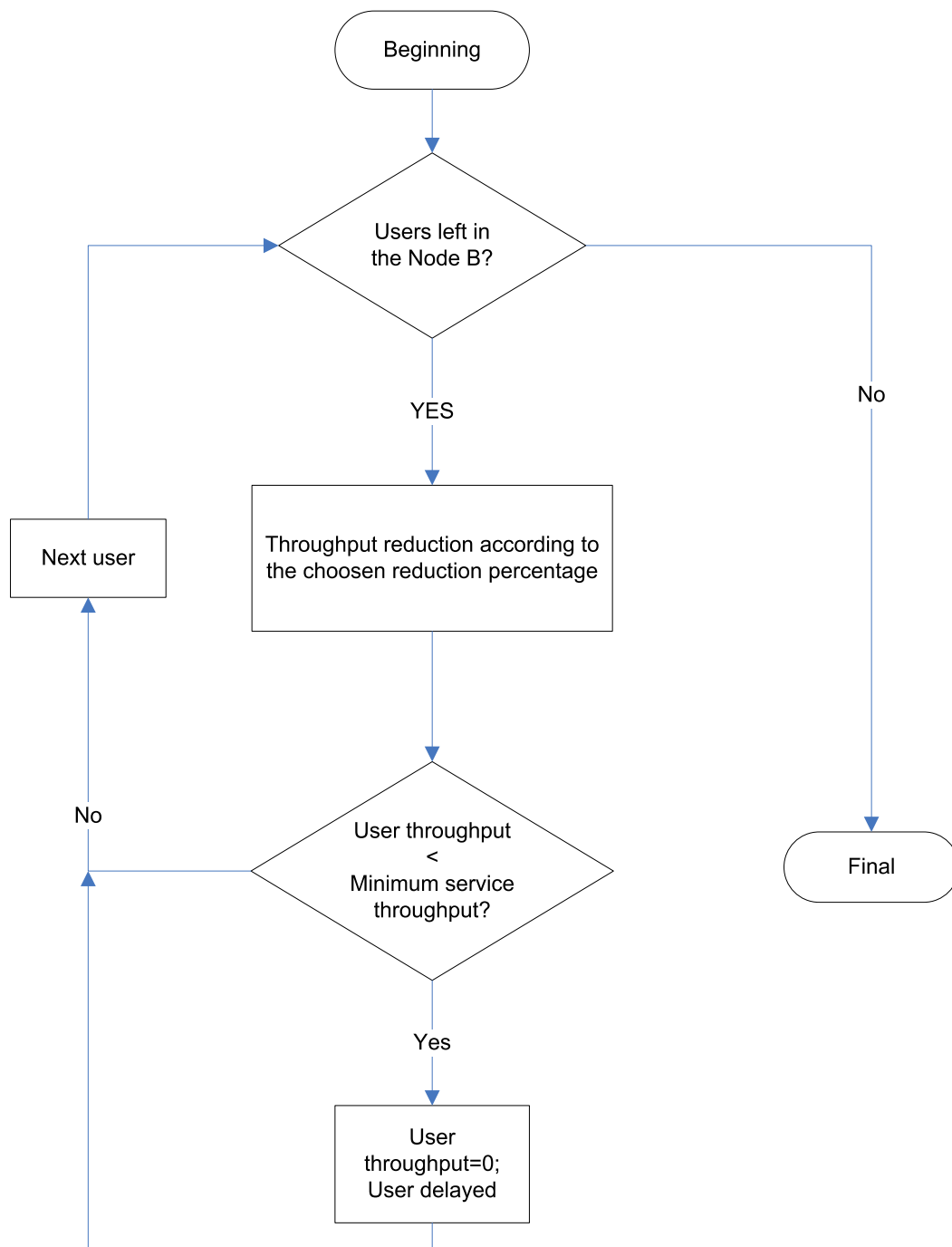


Figure E.1. HSDPA algorithm for the “Reduction throughput” strategy.

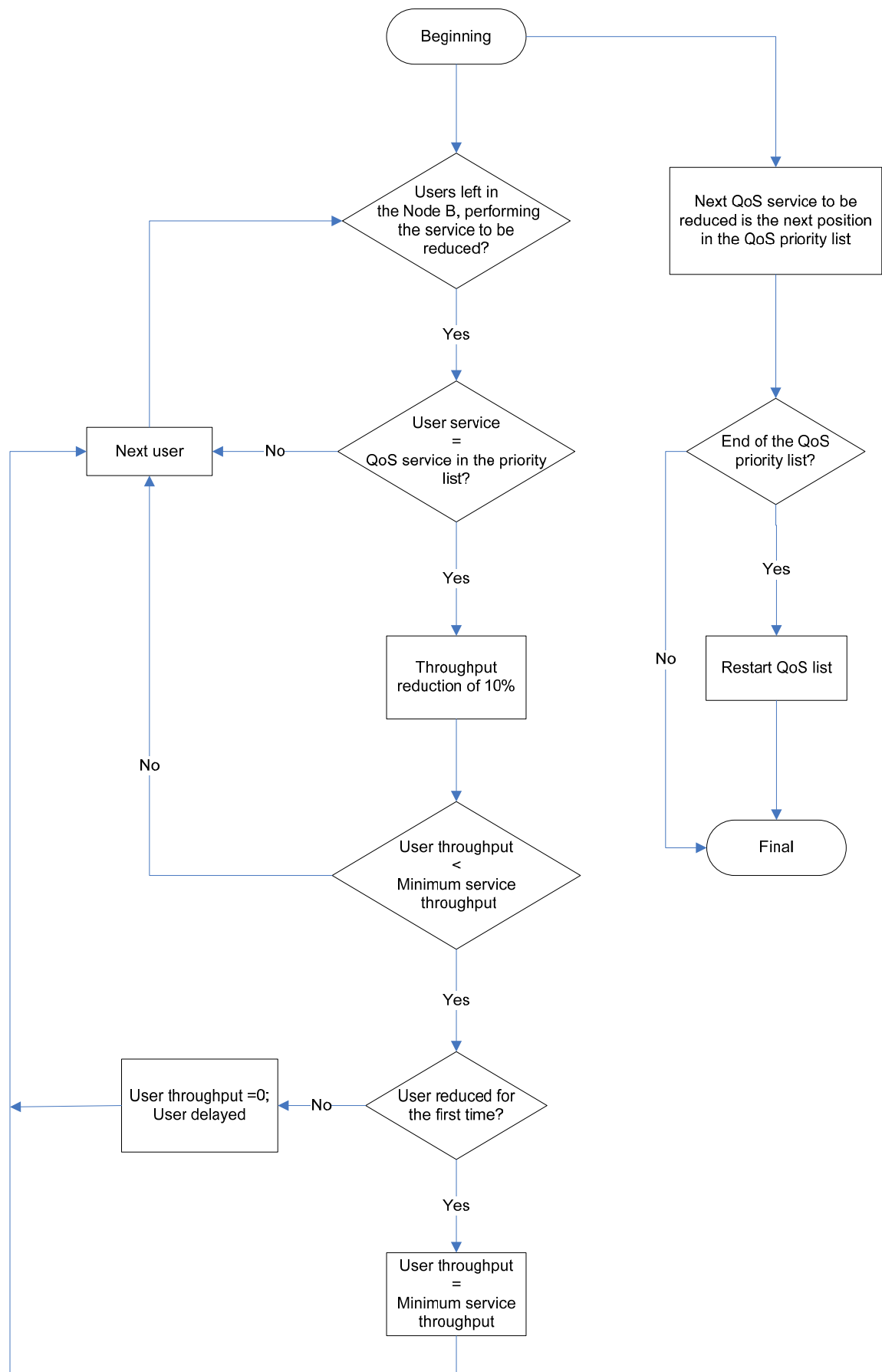


Figure E.2. HSDPA algorithm for the “QoS class reduction” strategy.

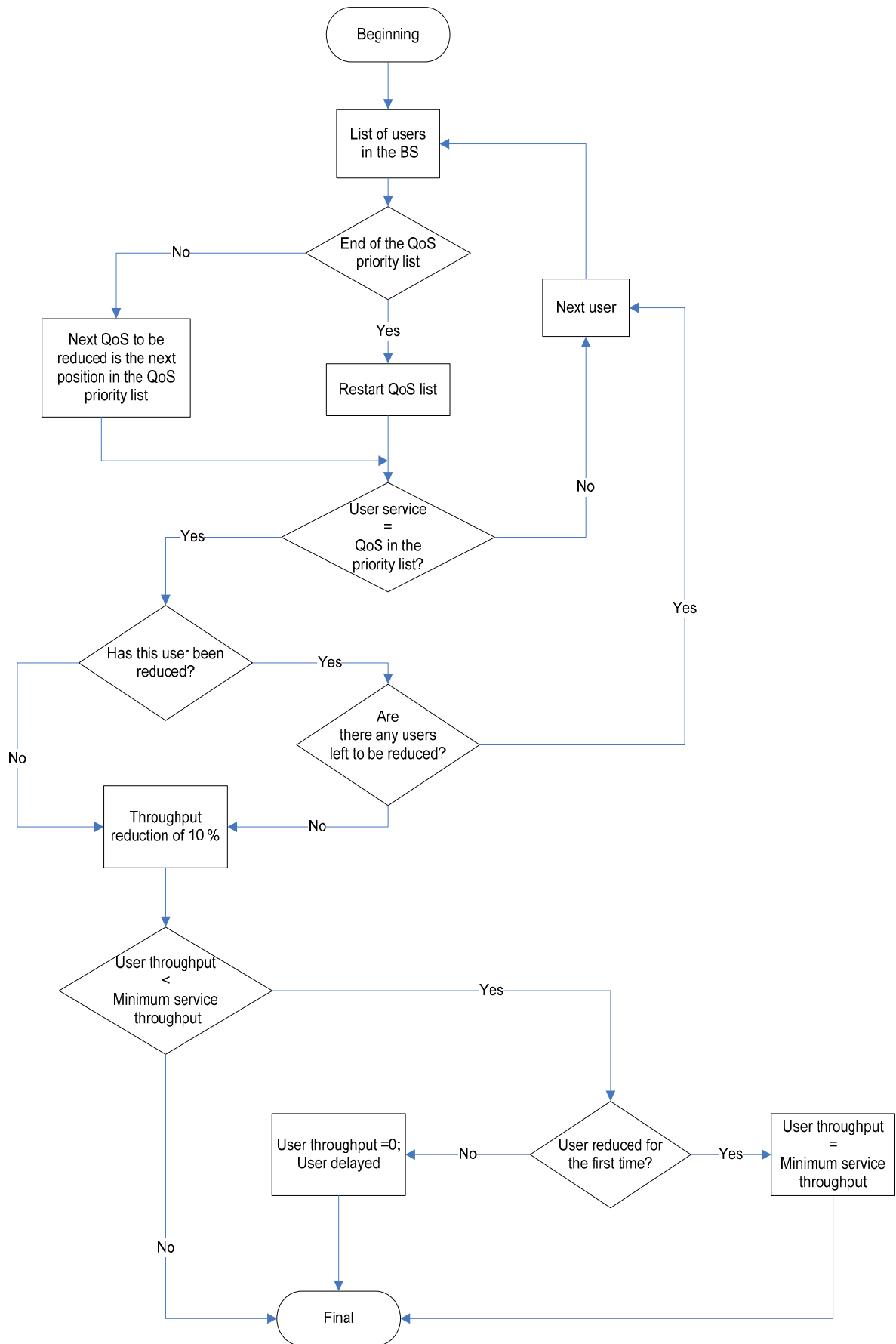


Figure E.3. HSDPA algorithm for the “QoS one by one reduction” strategy.

Annex F – HSUPA Reduction Strategies

In this annex, the flow charts regarding the HSUPA reduction strategies, with the addition of the SHO feature, are presented. The three reduction algorithms are: “Throughput reduction”, Figure F.1, “QoS class reduction”, Figure F.2 and “QoS one by one reduction”, Figure F.3.

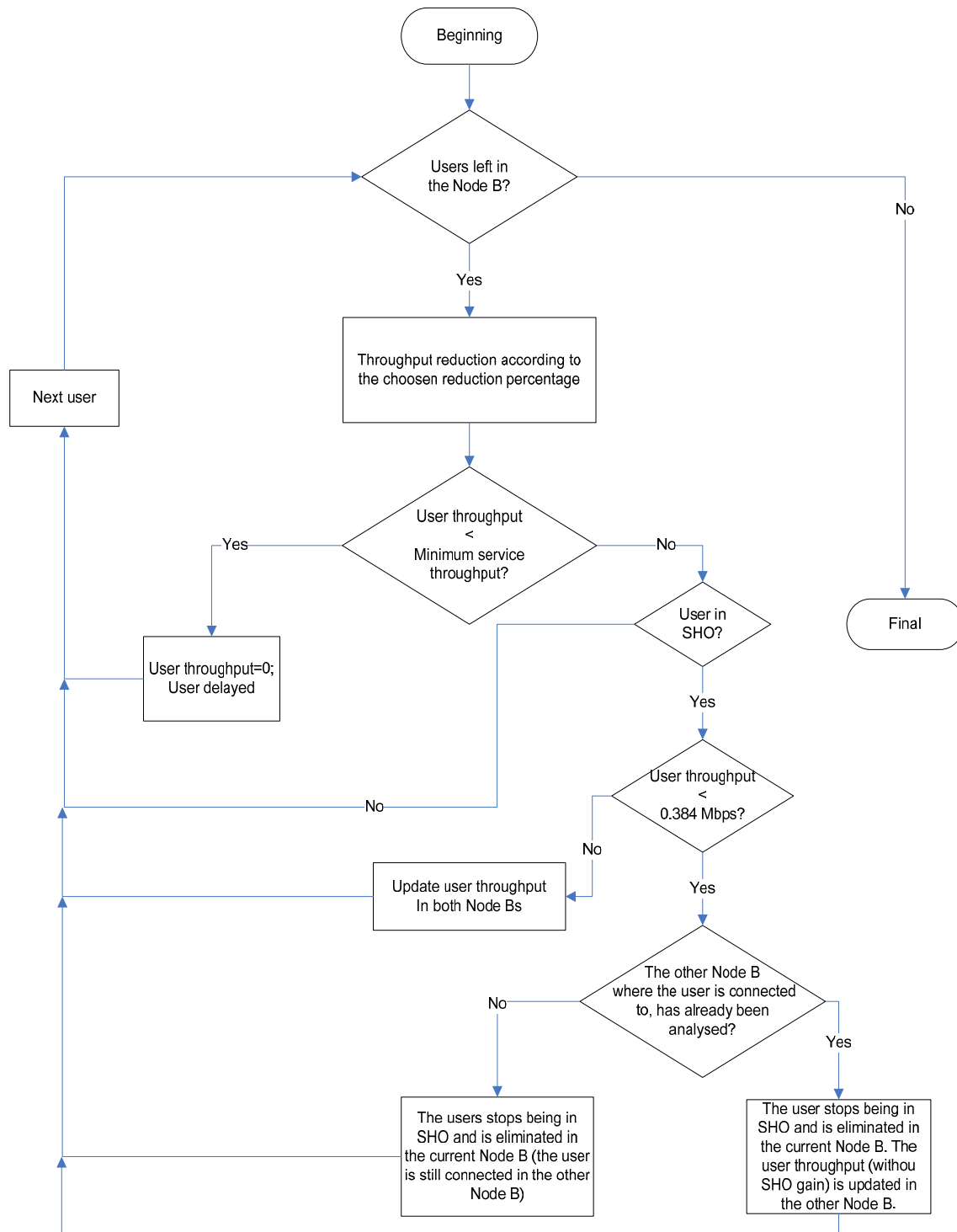


Figure F.1. HSUPA algorithm for the “Reduction throughput” strategy.

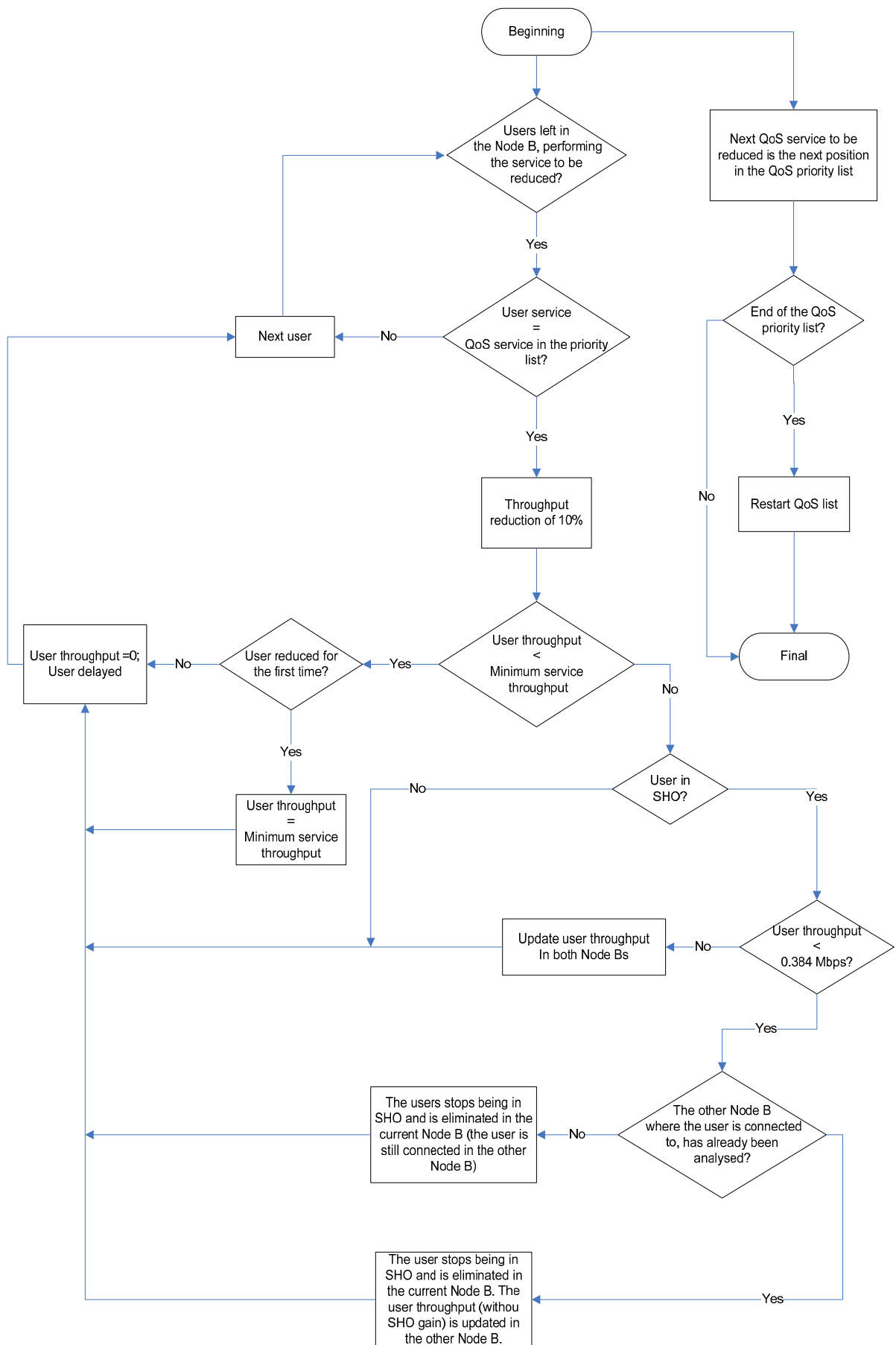


Figure F.2. HSUPA algorithm for the "QoS class reduction" strategy.

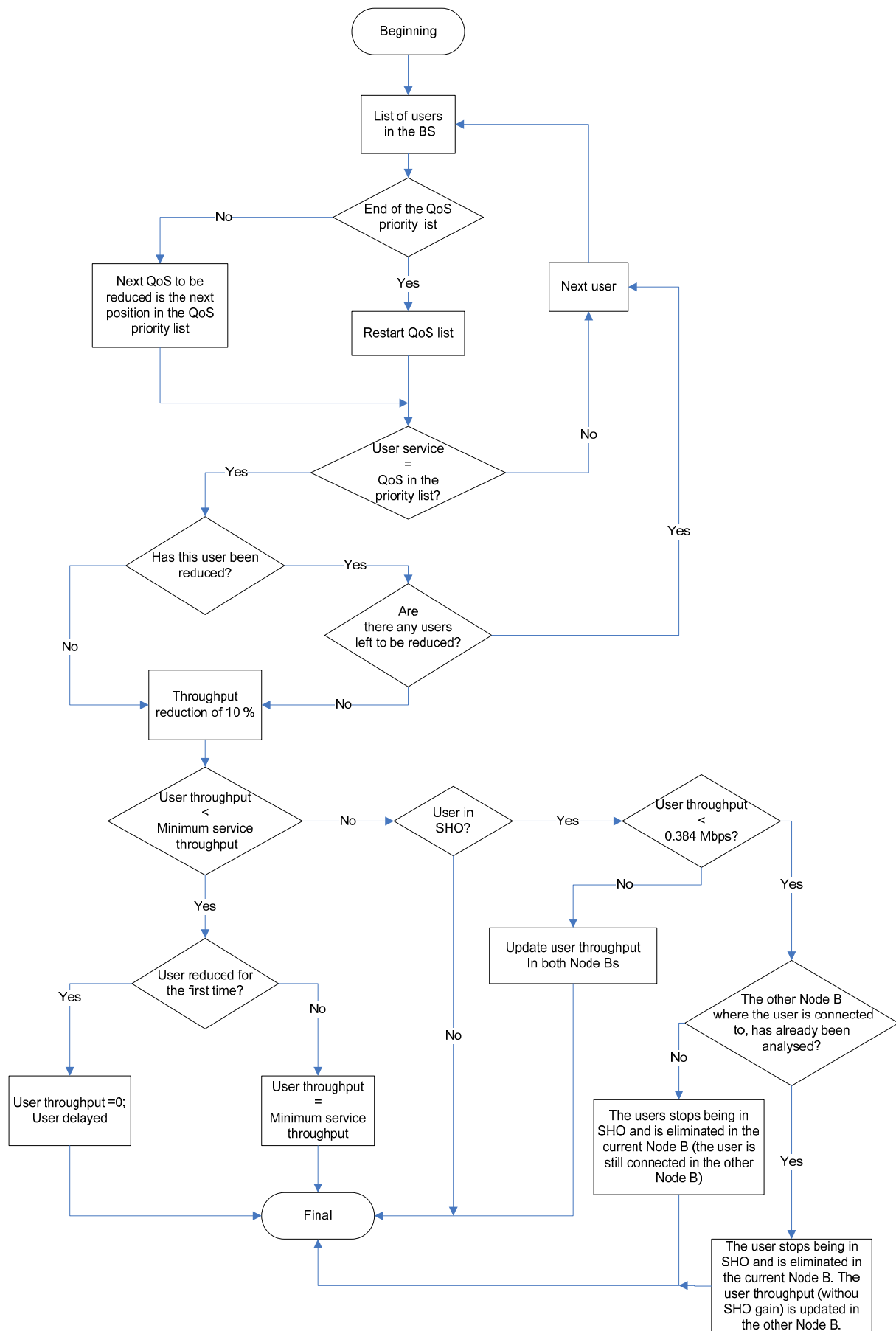


Figure F.3. HSUPA algorithm for the “QoS one by one” strategy.

Annex G – Single User Results

In this annex, the HSDPA, Table G.1, and HSUPA, Table G.2, single cell radius results for the model presented in Section 3.1 are detailed.

Table G.1. HSDPA single user cell radius for different throughputs and frequency variations.

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

Table G.2. HSUPA single user cell radius considering throughput, frequency, environment and inter- to intra-cell variations.

			Cell Radius [km]				
i	Frequency [MHz]	Environment	Throughput [Mbps]				
			0.384	0.5	0.75	1.00	1.22
0.65	1922.5	Pedestrian	0.98	0.95	0.84	0.71	0.44
		Vehicular	0.40	0.39	0.34	0.29	0.18
		Indoor LL	0.43	0.42	0.37	0.31	0.19
		Indoor HL	0.24	0.23	0.20	0.17	0.10
0.391		Pedestrian	0.99	0.95	0.84	0.71	0.46
		Vehicular	0.41	0.39	0.35	0.29	0.19
		Indoor LL	0.44	0.42	0.37	0.31	0.20
		Indoor HL	0.24	0.23	0.20	0.17	0.11
0.65	1977.5	Pedestrian	0.95	0.91	0.81	0.68	0.42
		Vehicular	0.39	0.37	0.33	0.28	0.17
		Indoor LL	0.42	0.40	0.36	0.30	0.18
		Indoor HL	0.23	0.22	0.19	0.16	0.10
0.391		Pedestrian	0.95	0.91	0.81	0.69	0.44
		Vehicular	0.39	0.38	0.33	0.28	0.18
		Indoor LL	0.42	0.40	0.36	0.30	0.19
		Indoor HL	0.23	0.22	0.20	0.17	0.11

Annex H – HSDPA Additional Results

In this annex, supplementary results regarding the HSDPA analysis for the multiple users scenario are presented. Concerning the number of codes analysis, the average network radius and the average ratio of served users are presented in Figure H.1, and in Figure H.2 the total network traffic and the total number of users served per hour is shown.

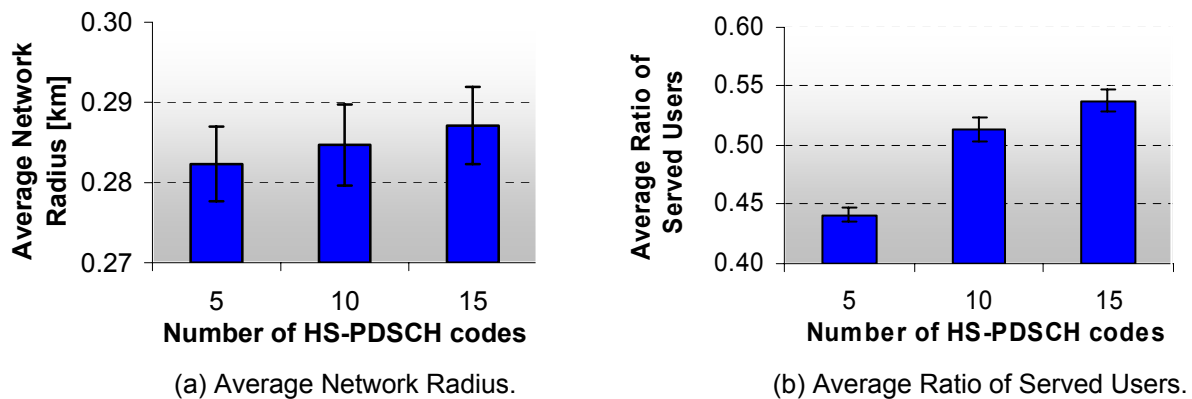


Figure H.1. HSDPA network parameters (Radius and Ratio of Served Users) for 5, 10 and 15 HS-PDSCH codes.

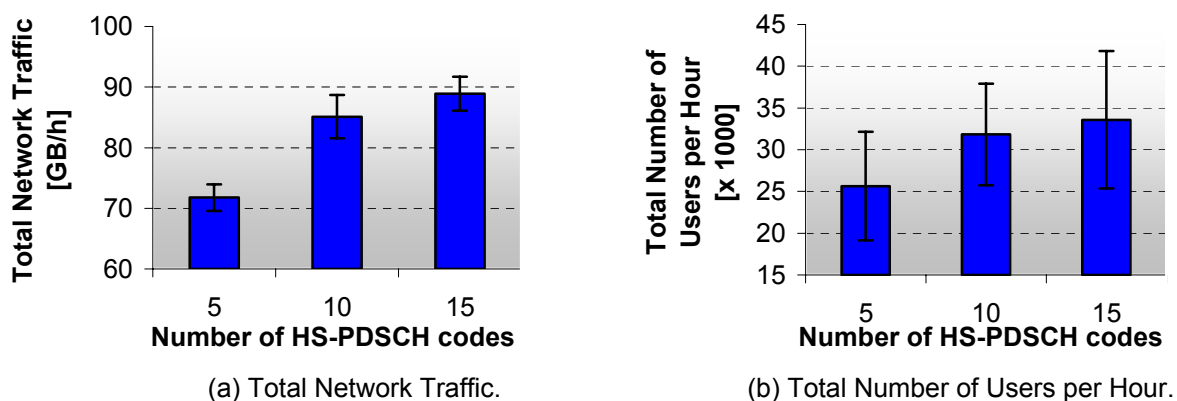


Figure H.2. HSDPA network parameters (Traffic and Number of Users) for 5, 10 and 15 HS-PDSCH codes.

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

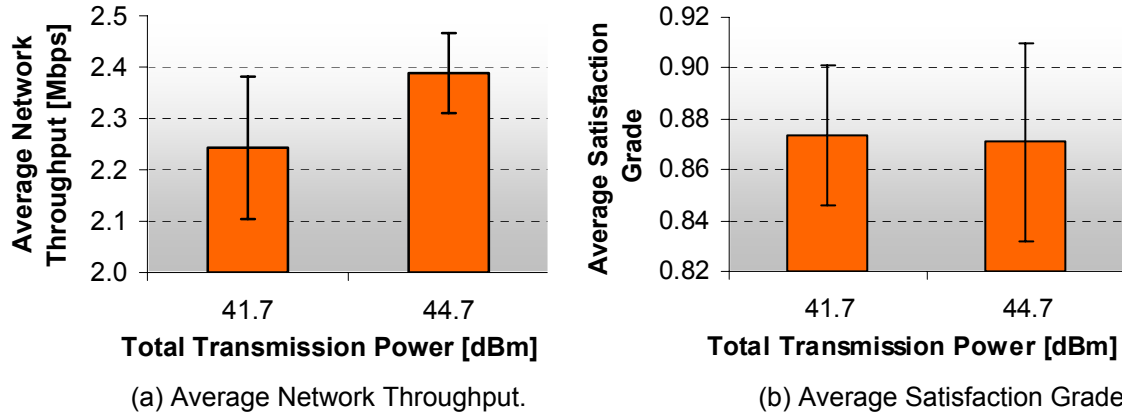


Figure H.3. HSDPA network parameters (Throughput and Satisfaction Grade) for 41.7 and 44.7 dBm of total Node B transmission power.

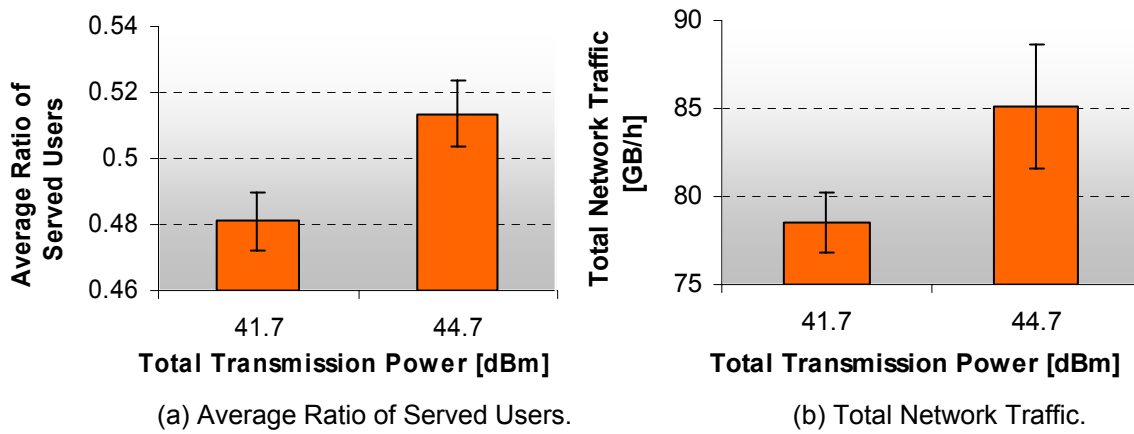


Figure H.4. HSDPA network parameters (Ratio of Served Users and Traffic) for 41.7 and 44.7 dBm of total Node B transmission power.

The average network radius and the average satisfaction grade for the variation of the number of users are shown in Figure H.5 and the average ratio of served users and the total number of users per hour in Figure H.6

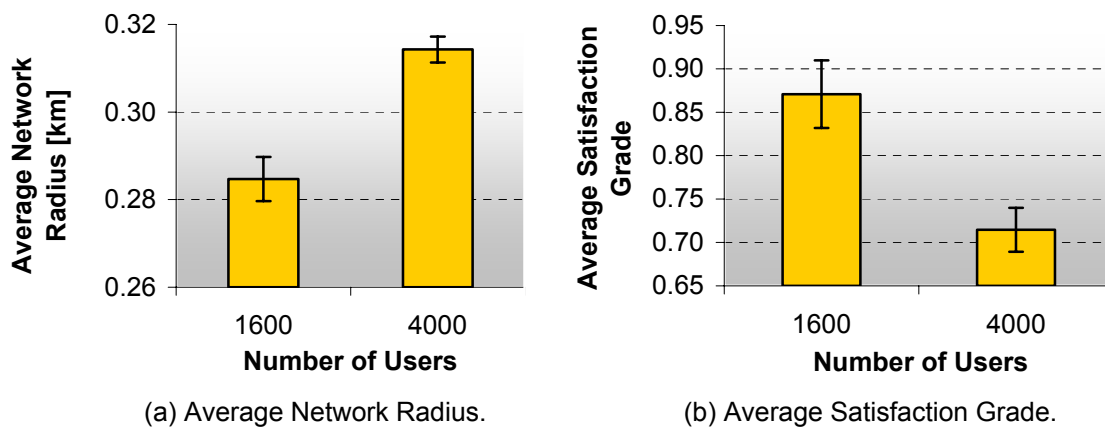
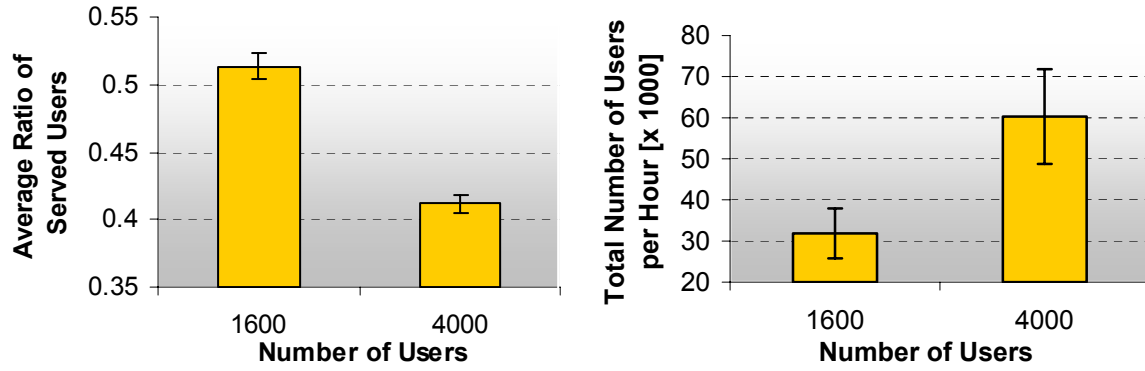


Figure H.5. HSDPA network parameters (Radius and Satisfaction Grade) for 1600 and 4000 users.

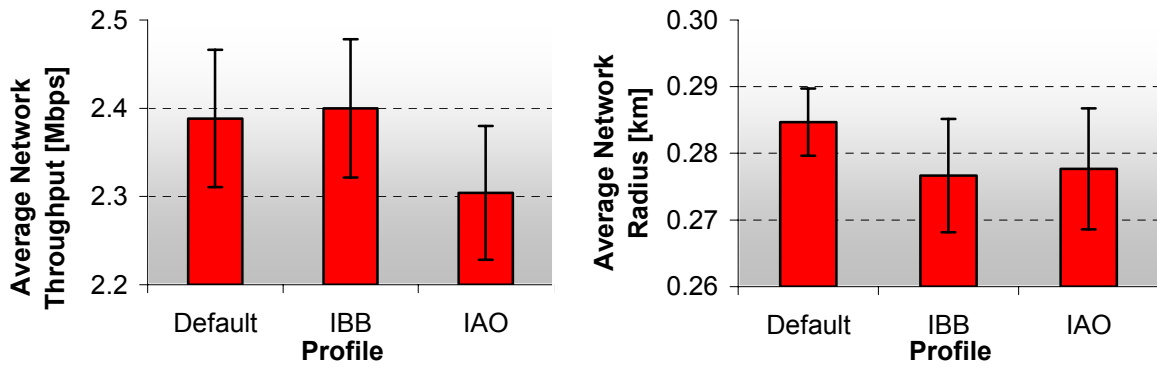


(a) Average Ratio of Served Users.

(b) Total Number of Users per Hour.

Figure H.6. HSDPA network parameters (Ratio of Served Users and Number of Users) for 1600 and 4000 users.

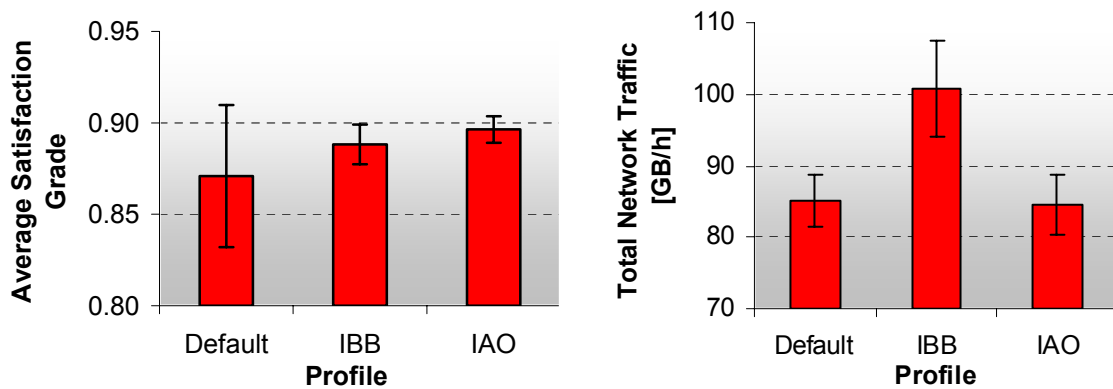
Regarding the alternative profiles studied, the results for the average network throughput and the average network radius are presented in Figure H.7 and the results for the average satisfaction grade and the total network traffic in Figure H.8



(a) Average Network Throughput.

(b) Average Network Radius.

Figure H.7. HSDPA parameters (Throughput and Radius) for the 3 profiles studied.



(a) Average Satisfaction Grade.

(b) Total Network Traffic.

Figure H.8. HSDPA parameters (Satisfaction Grade and Traffic) for the 3 profiles studied.

Concerning the analysis performed for the 3 reduction strategies studied, in Figure H.9 one presents the average throughput for the 10 Node Bs considered in this analysis, in Figure H.10 the average instantaneous throughput per Node B detailed by service, and in Figure H.11 the average satisfaction

grade of the users being served in the Node Bs considered.

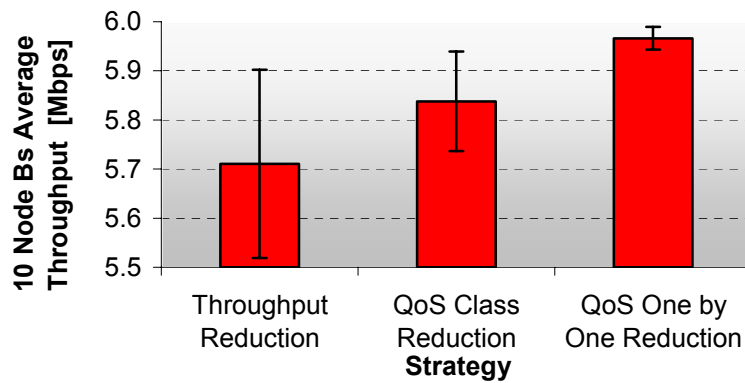


Figure H.9. HSDPA 10 Node Bs average throughput.

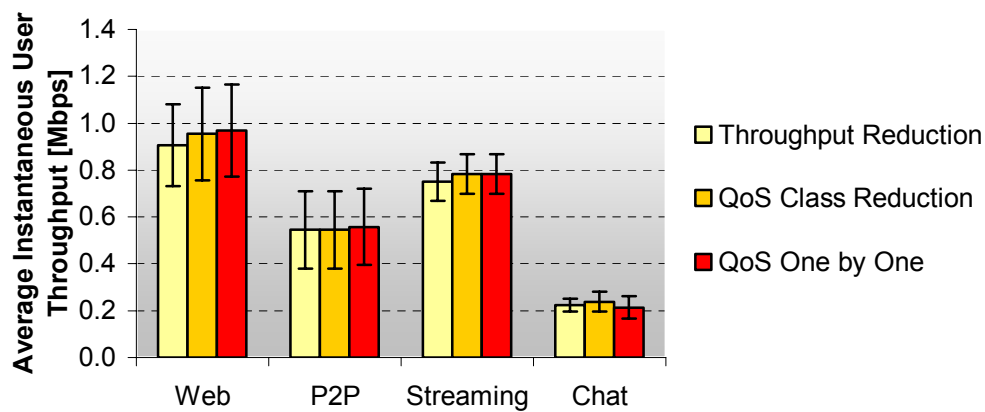


Figure H.10. HSDPA average instantaneous throughput per Node B, for the 10 Node Bs sample, detailed by service.

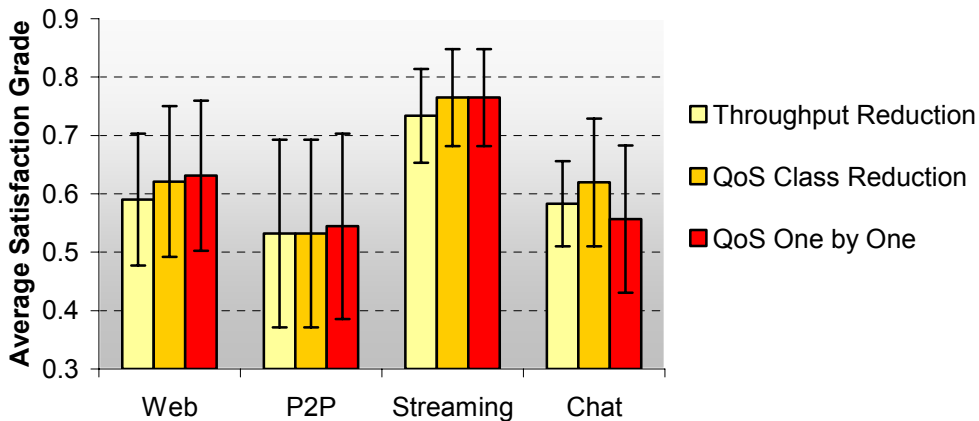


Figure H.11. HSDPA average satisfaction grade per Node B, for the 10 Node Bs sample, detailed by service.

For the maximum throughput analysis, the results regarding the average network throughput and the average network radius are presented in Figure H.12. In Figure H.13, one presents the average ratio of served users and the total numbers of users served per hour.

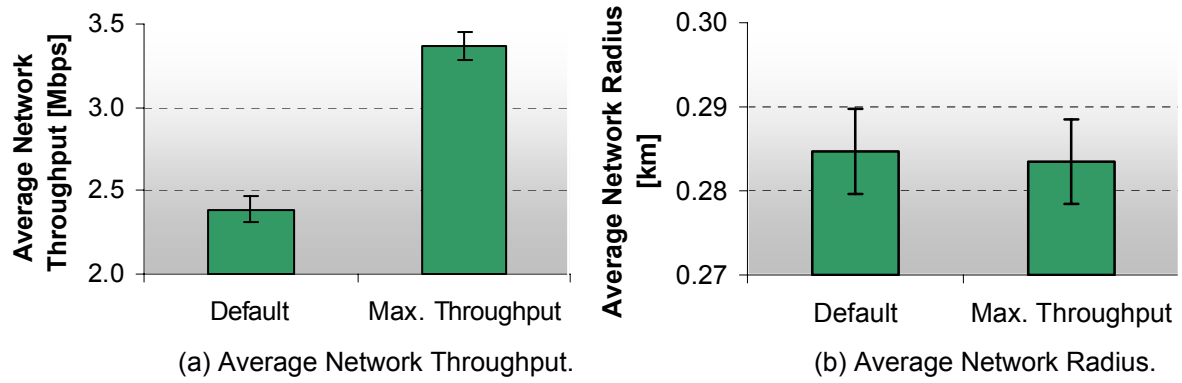


Figure H.12. HSDPA network parameters (Throughput and Radius) for different throughput services.

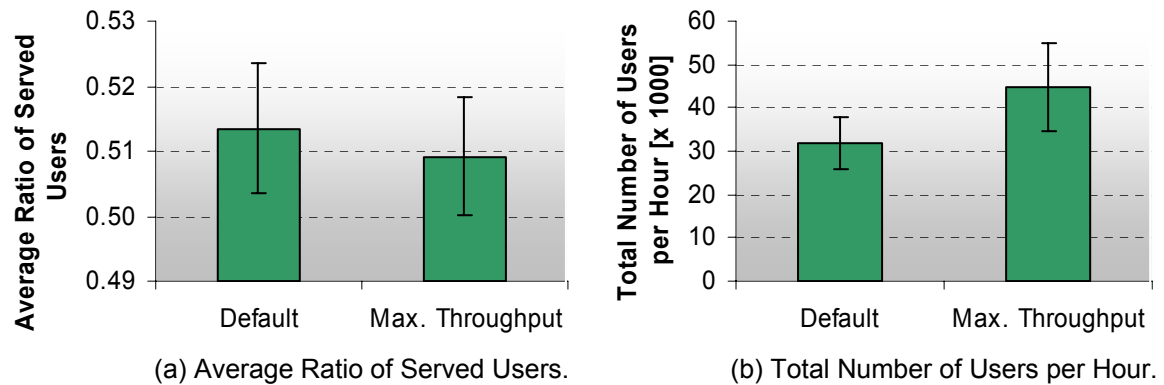


Figure H.13. HSDPA network parameters (Ratio of Served Users and Number of Users) for different throughput services.

In Figure H.14, one shows the variation of the HSDPA average instantaneous throughput per user regarding the several parameters variation studied. As it can be seen, only the analysis regarding the maximum throughput presents a higher increase, 55%, of the average instantaneous throughput per user.

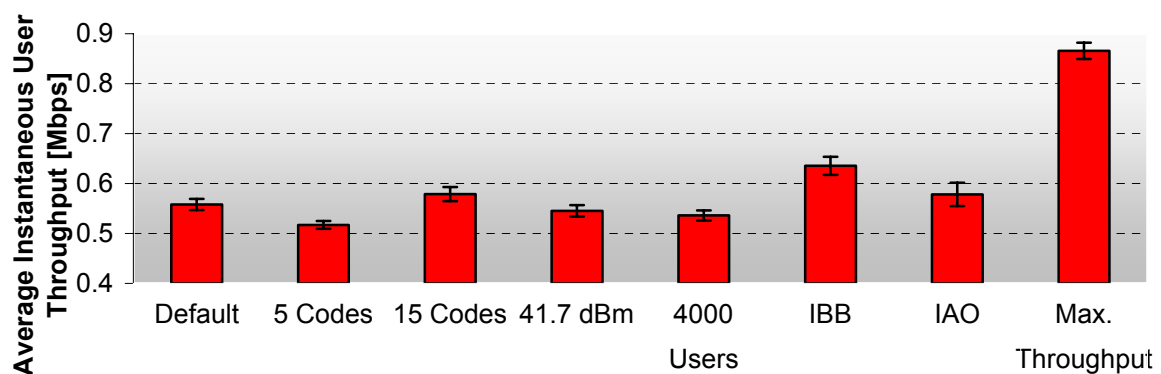


Figure H.14. HSDPA average instantaneous throughput evolution for the several parameters variation analysed.

Annex I – HSUPA Additional Results

Extra results regarding the HSUPA analysis for the multiple users simulator are presented in this annex. For the number of users analysis, the results for the average network radius and the average satisfaction grade are presented in Figure I.1, and the average ratio of served users and total number of user served per hour are shown in Figure I.2

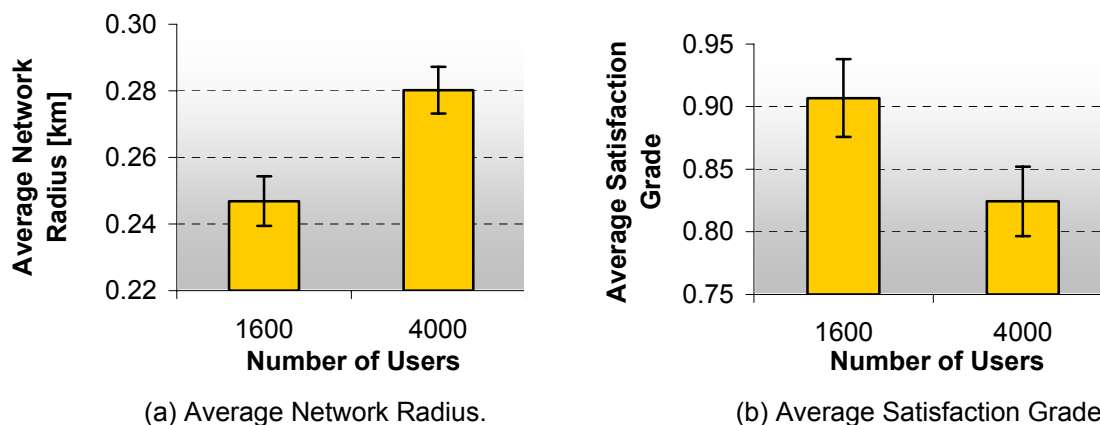


Figure I.1. HSUPA network parameters (Radius and Satisfaction Grade) for 1600 and 4000 users.

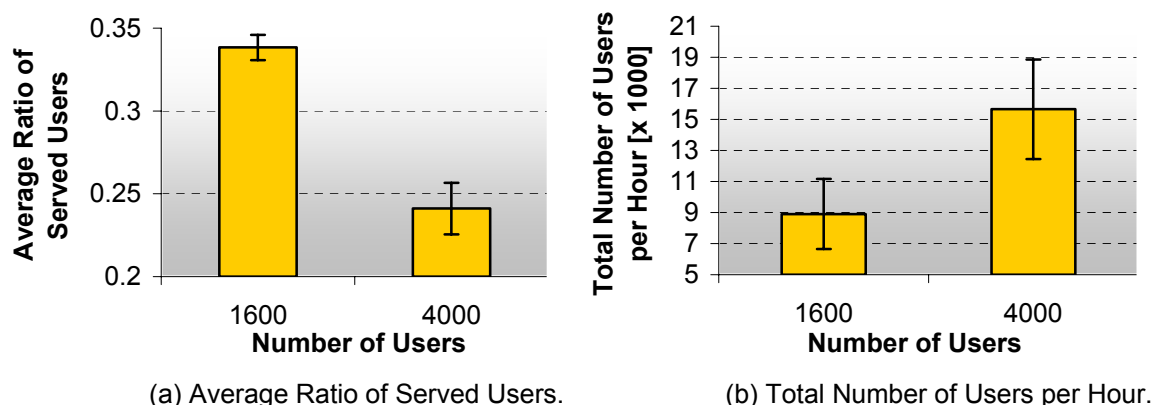
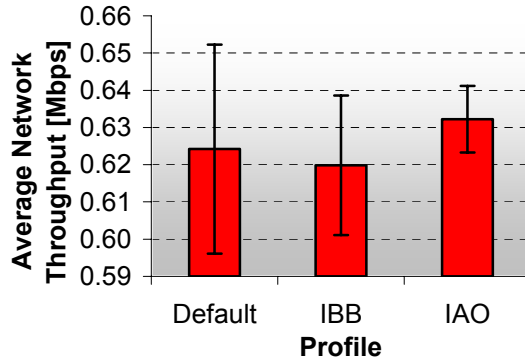
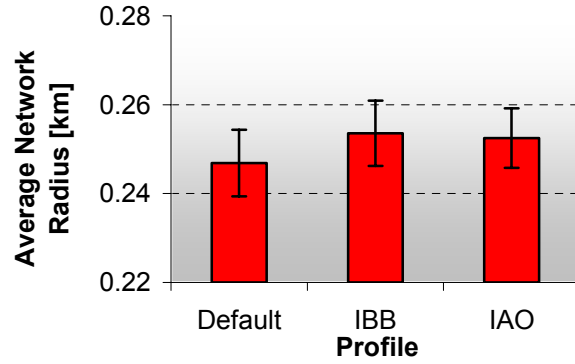


Figure I.2. HSUPA network parameters (Ratio of Served Users and Number of Users) for 1600 and 4000 users.

Regarding the alternative profiles, one shows in Figure I.3 the results for the average network throughput and the average network radius, whereas in Figure I.4 the results for average satisfaction grade and total network traffic are shown.

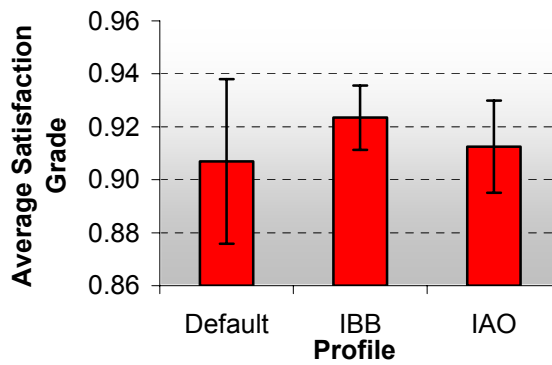


(a) Average Network Throughput.

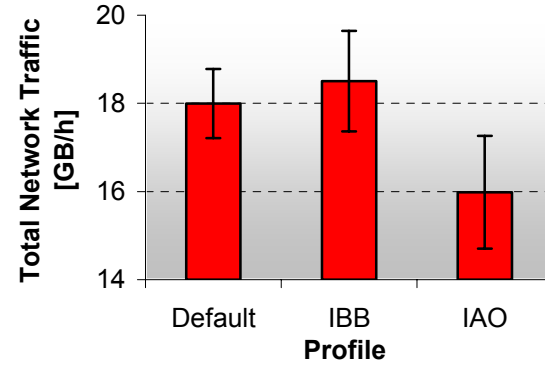


(b) Average Network Radius.

Figure I.3. HSPA parameters (Throughput and Radius) for the 3 profiles studied.



(a) Average Satisfaction Grade.



(b) Total Network Traffic.

Figure I.4. HSPA parameters (Satisfaction Grade and Traffic) for the 3 profiles studied.

Regarding the analysis for the 3 reduction strategies studied, in Figure I.5 one presents the average throughput for the 10 Node Bs considered, and in Figure I.6 the average instantaneous throughput per Node B as well as the users' satisfaction grade, both detail by service.

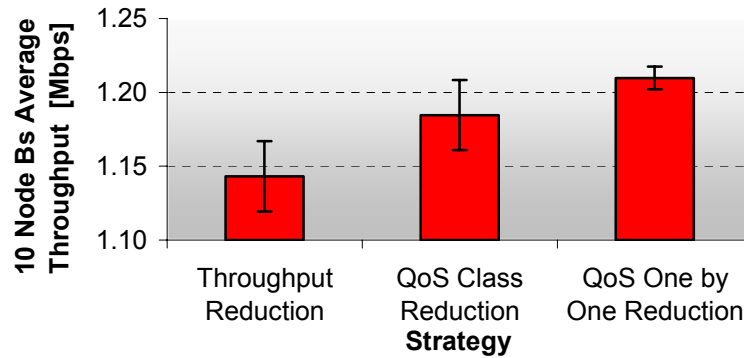


Figure I.5. HSPA 10 Node Bs average throughput.

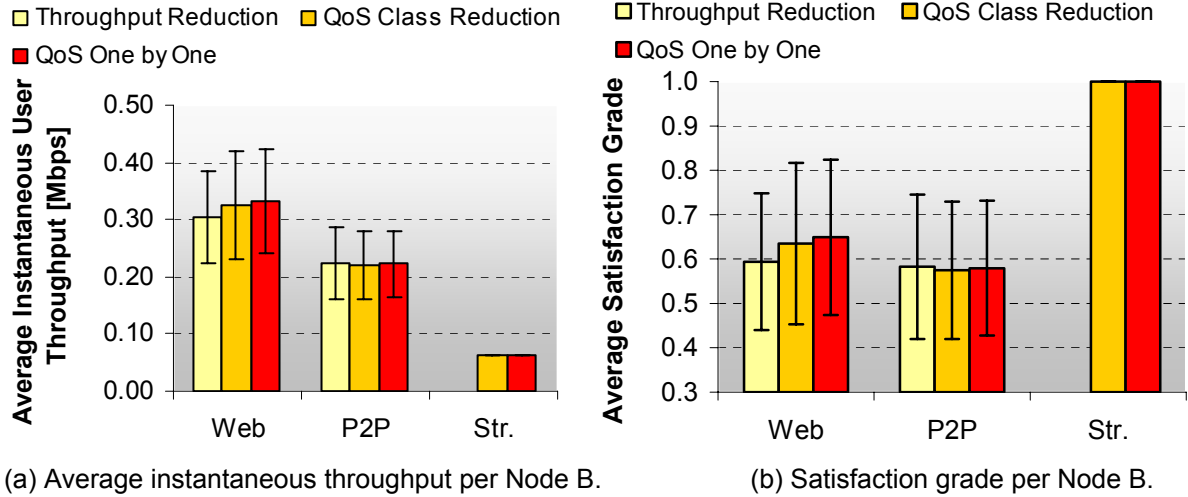


Figure I.6. HSUPA parameters (throughput and satisfaction grade) for the 10 Node Bs sample, detailed by services.

For the maximum throughput analysis, one illustrates in Figure I.7 the average network throughput and the average network radius, while in Figure I.8, the average ratio of served users and the total number of users served per hour are shown.

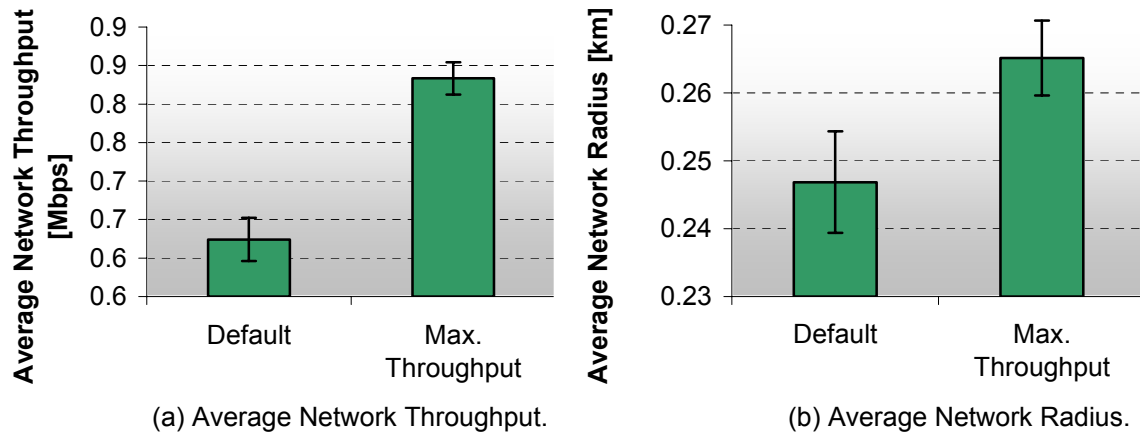


Figure I.7. HSUPA network parameters (Throughput and Radius) for different throughput services.

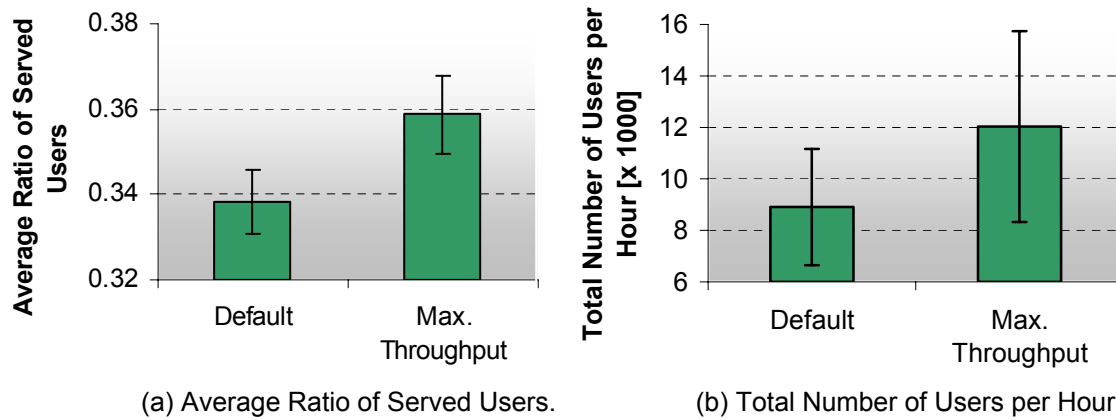


Figure I.8. HSUPA network parameters (Ratio of Served Users and Number of Users) for different throughput services.

In Figure I.9 the variation of the HSUPA average instantaneous throughput per user is shown. As for HSDPA the average instantaneous throughput per user is almost constant with the exception of the analysis regarding the maximum throughput where there is an increase of 52%.

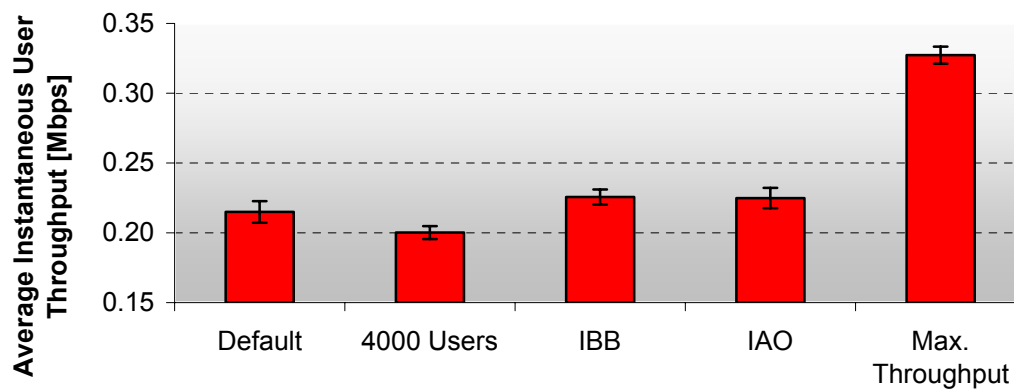


Figure I.9. HSUPA average instantaneous throughput evolution for the several parameters variation analysed.

Annex J – HSDPA/HSUPA Evaluation

In this annex, additional results regarding the HSDPA and HSUPA comparison regarding the multiple users analysis are presented. The expression for the average instantaneous user throughput for both HSDPA and HSUPA for the number of users, alternative profiles and maximum throughput scenarios are presented. As mentioned previously in Subsection 4.5.2, the distance was limited to 0.4 km, even though for HSDPA the validity distance is 0.5 km. A comparison for both HSDPA and HSUPA average instantaneous user throughput considering the difference scenarios is also shown. These results are presented in Figure J.1, being computed by using the method described in Subsection 4.3.1.

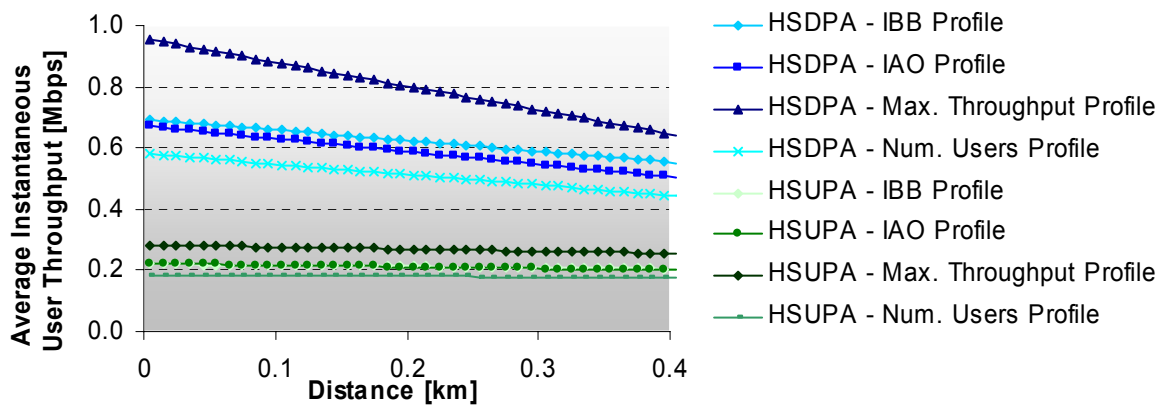


Figure J.1. Average instantaneous user throughput for HSDPA and HSUPA for the several profiles.

Equations (J.1) and (J.2) for HSDPA and HSUPA for the IBB profile can be obtained from Figure J.1:

$$\rho_{[\text{Mbps}]} = -0.352 \cdot d_{[\text{km}]} + 0.697 \quad (\text{J.1})$$

$$\rho_{[\text{Mbps}]} = -0.032 \cdot d_{[\text{km}]} + 0.221 \quad (\text{J.2})$$

Equations (J.3) and (J.4) for HSDPA and HSUPA for the IAO profile can be obtained from Figure J.1:

$$\rho_{[\text{Mbps}]} = -0.417 \cdot d_{[\text{km}]} + 0.672 \quad (\text{J.3})$$

$$\rho_{[\text{Mbps}]} = -0.055 \cdot d_{[\text{km}]} + 0.222 \quad (\text{J.4})$$

Equations (J.5) and (J.6) for HSDPA and HSUPA for the maximum throughput profile can be obtained from Figure J.1:

$$\rho_{[\text{Mbps}]} = -0.779 \cdot d_{[\text{km}]} + 0.958 \quad (\text{J.5})$$

$$\rho_{[\text{Mbps}]} = -0.069 \cdot d_{[\text{km}]} + 0.284 \quad (\text{J.6})$$

Regarding the scenario with higher number of users, from Figure J.1, the HSDPA and HSUPA throughput can be estimated by:

$$\rho_{[\text{Mbps}]} = -0.340 \cdot d_{[\text{km}]} + 0.581 \quad (\text{J.7})$$

$$\rho_{[\text{Mbps}]} = -0.021 \cdot d_{[\text{km}]} + 0.185 \quad (\text{J.8})$$

As it can be seen in, only for the maximum throughput scenario, there is a significant difference in the average instantaneous throughput, regarding the results from the default scenario. One can also mention that the IBB has a lower derivative, hence, presents better results at the cell edge. In Table J.1, one presents the correlation and the mean relative error values for both HSDPA and HSUPA. As mentioned earlier, the correlation values for HSUPA are low due to the close to zero slope of the HSUPA expressions, even though the mean relative errors are similar to HSDPA ones.

Table J.1. Correlation and mean relative error values.

Scenario	Correlation		Mean Relative Error [%]	
	HSDPA	HSUPA	HSDPA	HSUPA
IBB Profile	0.682	0.258	5.2	5.8
IAO Profile	0.776	0.388	6.5	5.6
Max. Throughput	0.927	0.348	4.7	7.3
Maximum number of users	0.800	0.200	6.2	5.2

As can be seen from (J.1), (J.3), (J.5) and (J.7) for HSDPA and for (J.2), (J.4), (J.6) and (J.8) for HSUPA the average instantaneous user throughput varies according to the chosen scenario. The IBB and IAO profiles are more throughput demanding than the default one and that fact is observed in the higher average value of the expression present in this annex. The maximum throughput scenario is the most demanding one, and this fact is confirmed by the highest average throughput of 0.86 Mbps and 0.28 Mbps for HSDPA and HSUPA, respectively.

In Figure J.2 and Figure J.3 one presents a comparison of the average instantaneous user throughput for HSDPA and HSUPA, for the common scenarios.

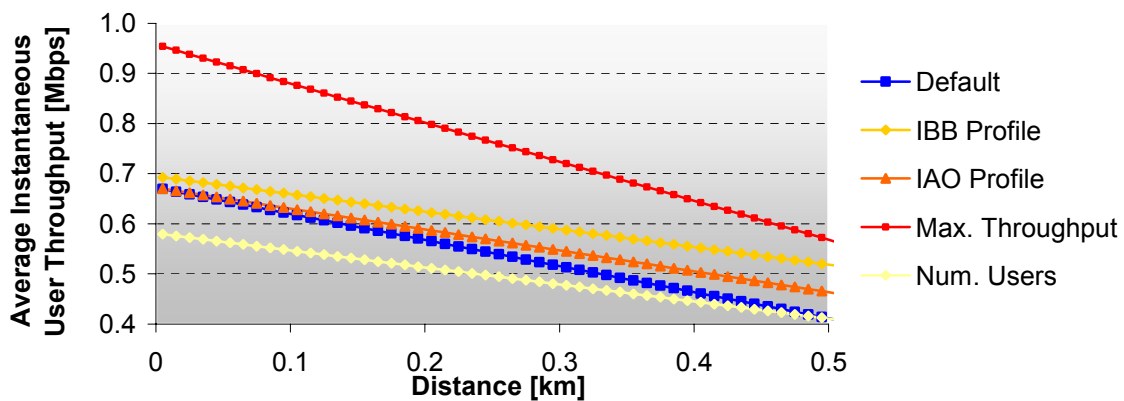


Figure J.2. HSDPA average instantaneous user throughput for the scenario studied.

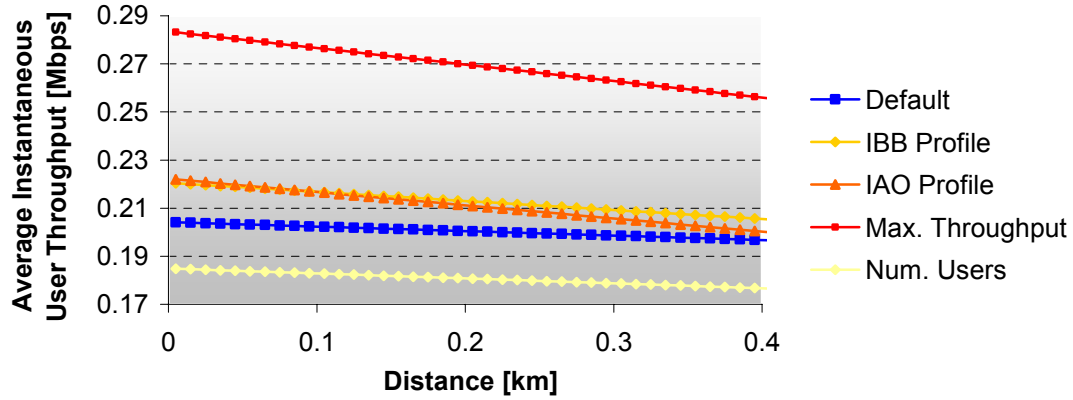


Figure J.3. HSUPA average instantaneous user throughput for the scenario studied.

In Figure J.4, one represents the HSDPA and HSUPA average network radius variation for all the analysed scenarios. As already stated, and it can be easily observed in Figure J.4, the HSDPA average network radius presents an almost constant value of 0.28 km while the HSUPA has an average network radius of 0.25 km. The reduction of 3 dB in the total Node B transmission power and the increase of the number of users are the HSDPA scenarios where one can notice the bigger variation whose explanation is given in Subsections 4.3.3 and 4.3.4, respectively. For HSUPA, only in the increased number of users scenario one can notice a noteworthy network radius variation, with this fact justified in Subsection 4.4.2.

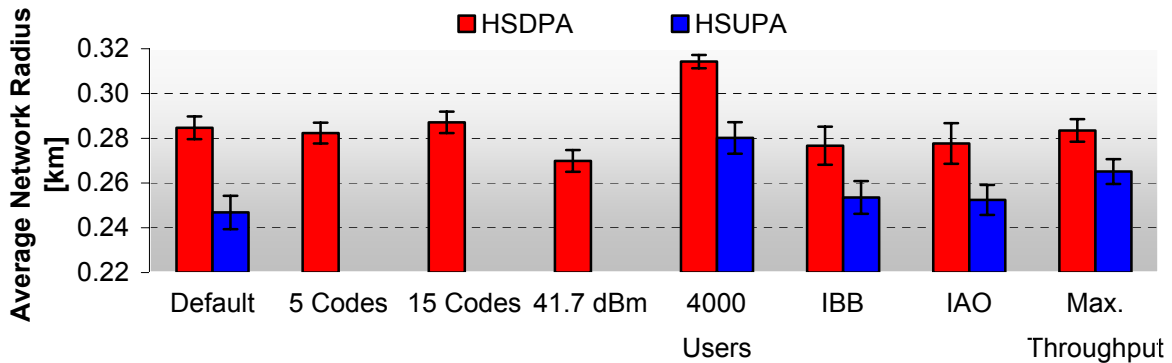


Figure J.4. HSDPA and HSUPA average network radius comparison.

In Figure J.5, one shows the average network throughput for all HSDPA scenarios. Unlike the results for the network radius, this parameter has a higher variation for the studied scenario. Nevertheless, these variations do not have influence in the HSDPA average instantaneous throughput, except for the maximum throughput, as seen in Annex H. In Figure J.6, the same result is presented for HSUPA with the same observations being valid.

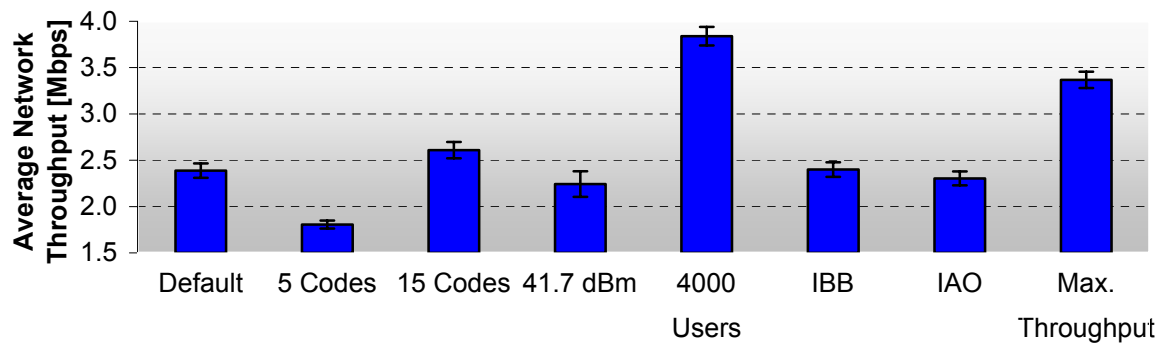


Figure J.5. HSDPA average network throughput.

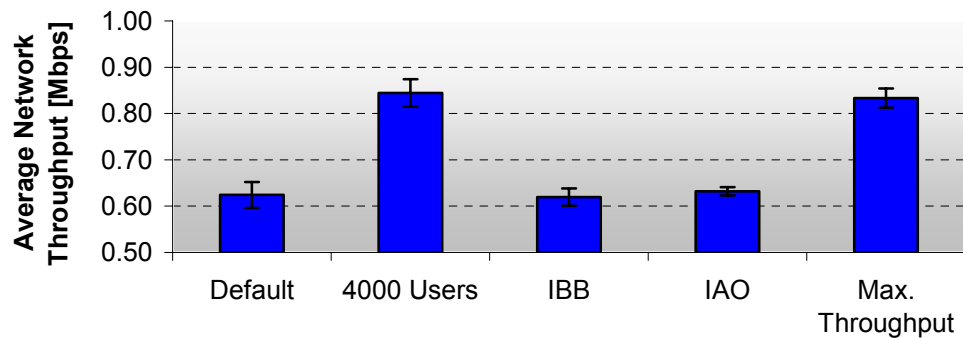


Figure J.6. HSUPA average network throughput.

In Figure J.7, Figure J.8, Figure J.9 and Figure J.10, one shows the comparison between the HSDPA and HSUPA results for the satisfaction grade, ratio of served users, total number of users and total network traffic regarding the several analysed scenarios. For HSDPA, the satisfaction grade varies between 68%, for the maximum throughput scenario, and 91% for the 15 HS-PDSCH codes scenario. HSUPA satisfaction grade varies between 66 and 92%. Due to the reduced number of users served, and to the lower throughputs of the UL services, HSUPA has higher satisfaction grades than HSDPA. Only for the maximum throughput scenario HSDPA can provide a satisfaction grade higher than HSUPA, meaning that HSUPA is more sensitive to an increase of the offered traffic, being capacity limited.

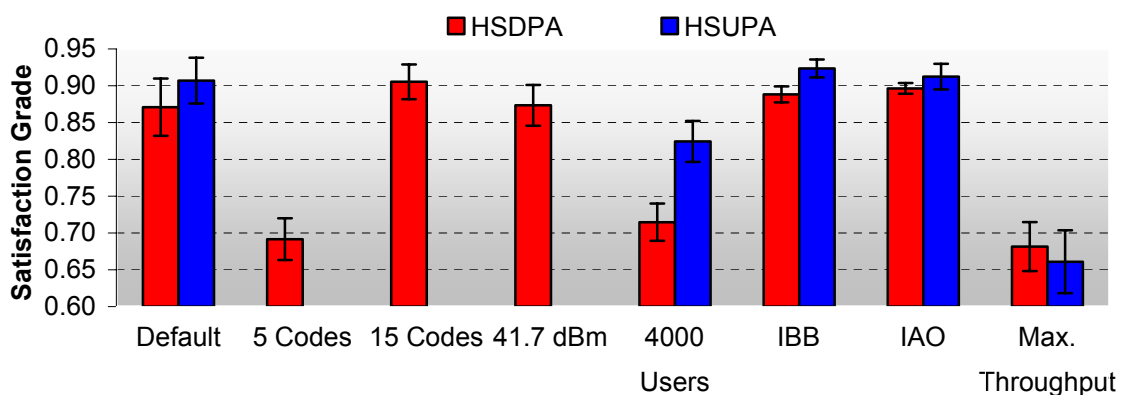


Figure J.7. HSDPA and HSUPA average satisfaction grade.

The higher HSDPA capacity justifies the higher ratio of served users, Figure J.8, hence, the higher number of users served instantaneously and in the busy hour.

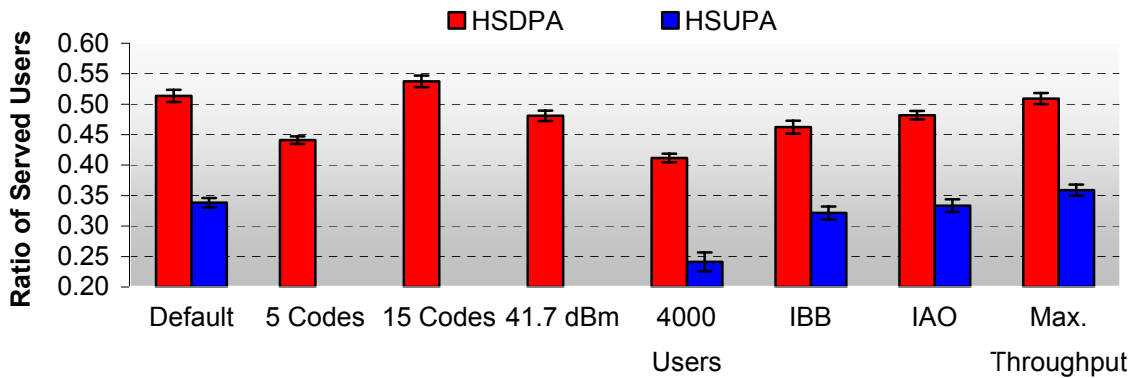


Figure J.8. HSDPA and HSUPA average ratio of served users.

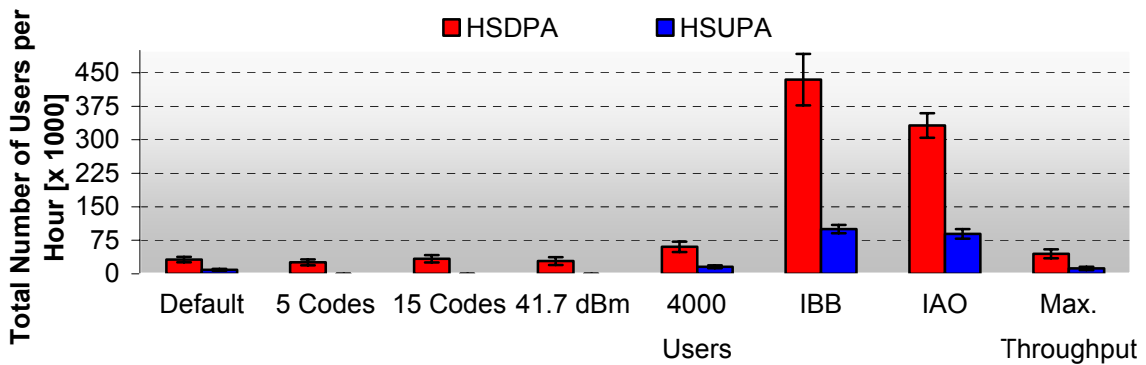


Figure J.9. HSDPA and HSUPA total number of users per hour.

The total network traffic is presented in Figure J.10. As expected, HSDPA carries more traffic than HSUPA, but these results also reflect the asymmetry of the different services considered for UL and DL, the latter being characterised by services with higher throughputs and file sizes.

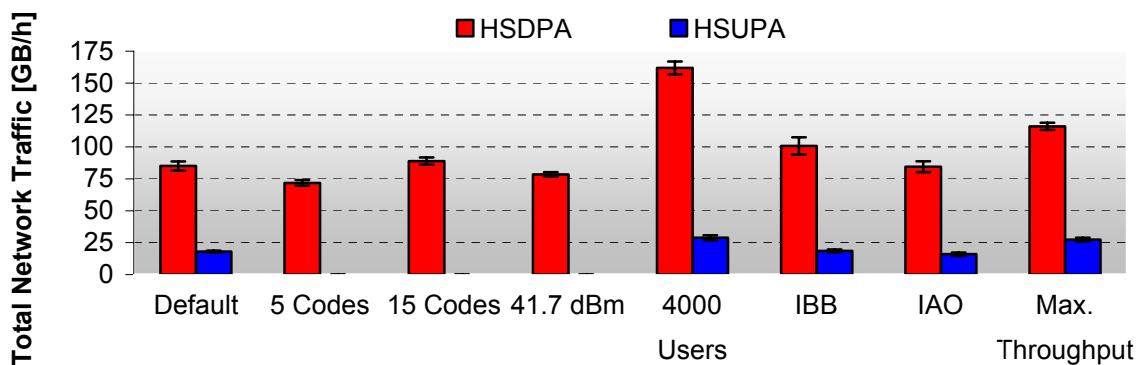


Figure J.10. HSDPA and HSUPA total network traffic.

Annex K – HSDPA Measurements

In this annex, one presents additional results regarding the HSDPA measurements performed in the Optimus live network. For the measurements performed in the test plant, TEMS was not available, hence, the additional results are only shown for the measurements performed in the live network.

In Figure K.1, the requested physical throughput from the live measurements is compared with the FTP application throughput from the measurements in the test plant. In this case, the difference between the requested and the application throughput is smaller, since there was only one user being served, and there was no transmission limitations. One can also notice that the standard deviation for the requested throughput is higher than the one for the application throughput, since the latter was performed in a controlled environment.

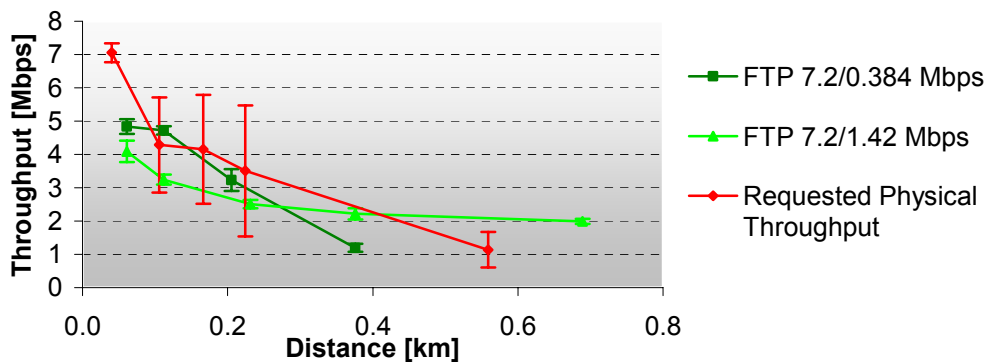


Figure K.1. Requested physical throughput *versus* FTP application throughput.

In Figure K.2, one shows the E_c/N_0 evolution according to distance. These results for E_c/N_0 were measured during file transfer, and for 16 QAM modulation one measured a degradation of near 6 dB in the E_c/N_0 value, when the MT passed from idle to active mode.

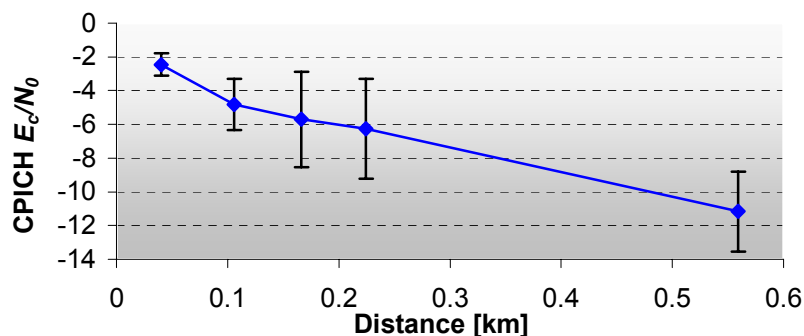


Figure K.2 HSDPA E_c/N_0 evolution.

The E_c/N_0 decrease rate presents an almost constant value, but one can see from Figure 4.35 that a small reduction in E_c/N_0 for smaller distances causes a higher reduction on the user throughput. The CQI, with values between 0 and 30, is directly related to the channel quality, being shown in Figure

K.3. Both curves in Figure K.2 and Figure K.3 have the same shape and behaviour, since they represent 2 different measures of the radio channel quality. The Node B only uses 16 QAM modulation for CQI values above 16 and 10 HS-PDSCH codes for MTs reporting CQI values above 25. From Figure K.3, 10 HS-PDSCH codes can only be used up to 0.05 km while the 16 QAM modulation can be used up to 0.45 km. For CQI values between 16 and 24, the number of HS-PDSCH codes dynamically varies between 5 and 10, [HoTo06].

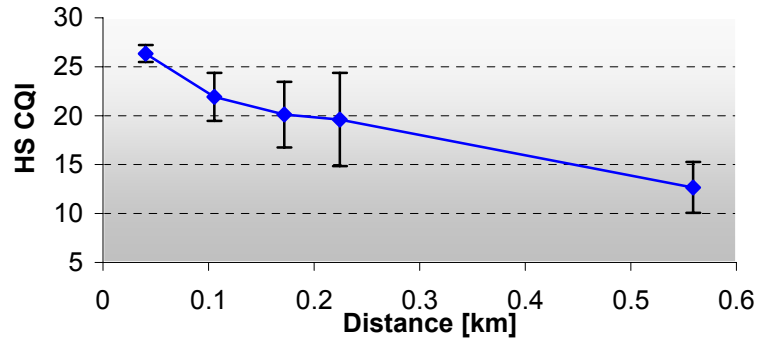


Figure K.3. HS-CQI evolution.

In both Figure K.2 and Figure K.3, there is an increase of the standard deviation with distance, since there is a degradation of the radio channel, leading to higher variations of E_c/N_0 and CQI. For the measure at 0.55 km, the standard deviation is actually smaller than the ones for smaller distances. These results have also occurred for the requested physical throughput in Figure K.1. For the measures at larger distances, the poor radio channel quality only allowed small range variations, leading to a smaller standard deviation, whereas for shorter distances the radio channel presents higher variations.

Annex L – HSUPA Measurements

The HSDPA and HSUPA test plant measurements were performed on the same day. For this reason the results presented in this annex are also only for the measurements performed in the live network. Three curves are shown in each figure, since one performed measurements in 3 different locations.

In Figure L.1, one shows a comparison between the physical (E-DCH throughput) and the application throughput for the measures in CCB and in Luz. In Figure L.1, one does not include the measurements from Firmino to help visualise the relation between both layer's throughputs. One can observe that for both CCB and Luz, the application throughput curves track the physical throughput curves with a minor offset. For the same reason as the one presented for HSDPA, the throughput application curves are below the physical ones, but for HSUPA the difference between the 2 curves is smaller, since there was only one user being served, hence, all Node B's resources were available.

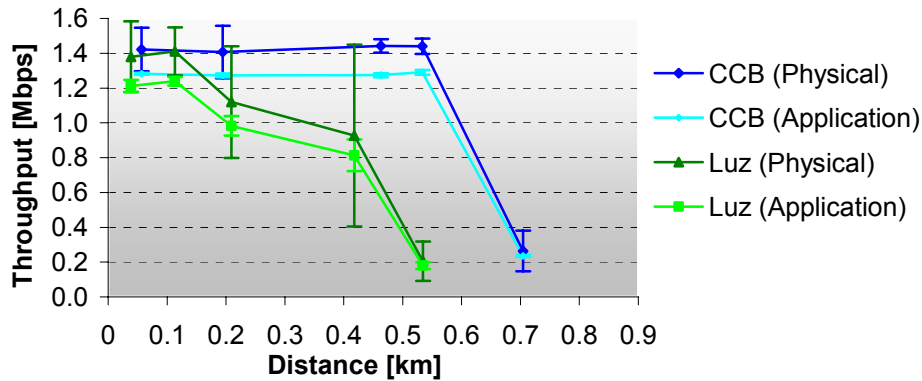


Figure L.1. Physical versus application throughput.

In Figure L.2, one shows the E_c/N_0 measures, and like for HSDPA, these values were recorded during active mode. Even though E_c/N_0 is a DL measurement, it can also be used to evaluate the UL radio channel quality. To perform a real evaluation of the UL radio channel, it would be necessary to have access to the Node B's statistics.

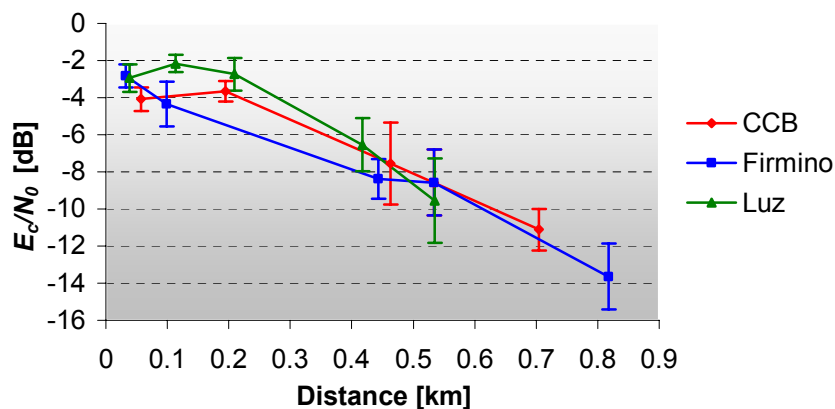


Figure L.2. HSUPA E_c/N_0 measurements.

From Figure L.1 and Figure L.2, one can observe that for E_c/N_0 values up to -8 dB, HSUPA can serve the user with approximately 1 Mbps at distances of 0.5 km.

In Figure L.3, one shows the 3 E-DCH throughput curves. As it can be seen, for the measurements in Luz, the E-DCH throughput presents lower values than the ones for CCB and Firmino, which justifies the lower application throughput recorded in Luz. The lower values for the E-DCH throughput in Luz are explained by the results in Figure L.4, where the E-TFCI, with values between 0 and 97, is shown – for this measurement, the E-TFCI value of 53 was not considered, since this value corresponds to a base band limitation. The E-TFCI has a similar function as CQI, but for UL, hence, the E-TFCI has a direct relation with the E-DCH throughput. The maximum E-TFCI value is 97, being mapped onto the maximum E-DCH throughput – 1.42 Mbps. Even though the MT may be reporting the maximum E-TFCI value, the maximum E-DCH throughput is only mapped onto the maximum application throughput if there are enough available resources at the Node B side, otherwise the available throughput is shared among all users.

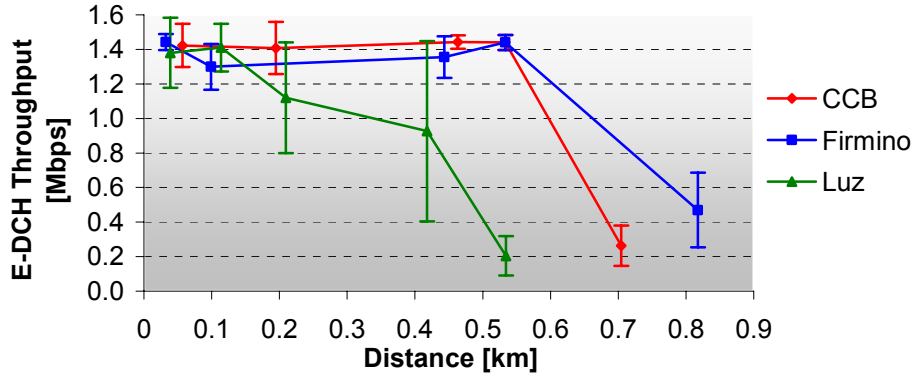


Figure L.3. E-DCH Throughput measurements.

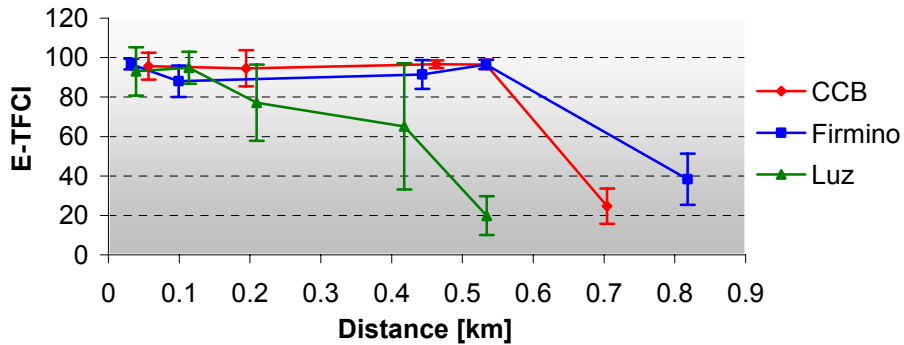


Figure L.4. E-TFCI measurements.

In Figure L.5, the MT transmission power is shown. These results are related to the ones from Figure L.4. One can observe that the MT transmission power curve for the measurements in Luz is above the curves for the measurements in CCB and Firmino. In Luz, for distances beyond 0.2 km, the MT transmission power reached 20 dBm, the maximum allowed. For this reason, for larger distances the MT cannot increase the transmission power to compensate for the degradation of the radio channel quality, leading to a reduction of the E-TFCI, E-DCH channel, hence, the application throughput. For

the measurements in CCB and Firmino, the MT transmission power is always below the maximum value, except for the last measure. For this reason, in these locations, one had higher E-TFCI values.

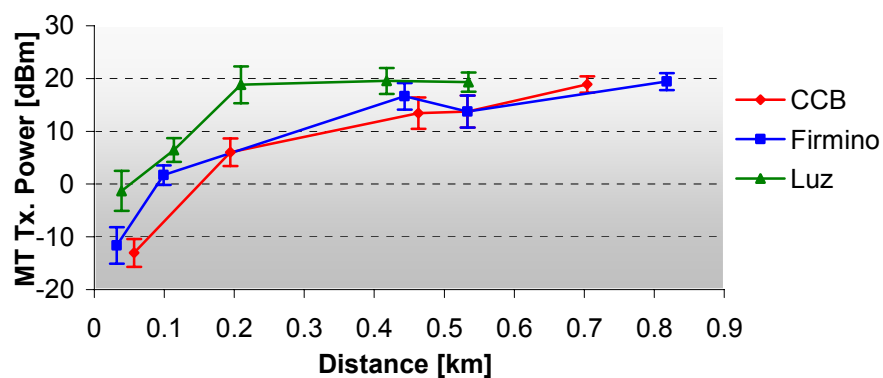


Figure L.5. MT transmission power measurements.

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