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Analysis of Radio Repeaters in UMTS

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To my family and friends

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Abstract

This thesis analyses repeaters in UMTS and their impact on coverage, capacity and Quality of Service. For this purpose, a single user model was developed in order to calculate the maximum repeater radius. A more realistic approach was taken with the development of a multiple users simulator. Using these tools, the impact of the variation of several parameters was analysed. The single user results show that, in Release 99 and for a pedestrian environment, the increase in the repeater gain leads to an increase in the repeater radius of up to 2.2 times. In HSDPA and HSUPA this value is 2.8 and 3.5 times, respectively. The multiple users results show that, in Release 99, the repeater increases the number of covered users by 7.3%, in the most favourable conditions. In HSDPA this growth can go as far as 5.0%, and in HSUPA up to 20.0%. Results also show that the repeater has no impact on both capacity and Quality of Service.

Keywords

UMTS, Repeaters, Coverage, Capacity, Quality of Service

Resumo

Esta tese analisa repetidores em UMTS e o seu impacto na cobertura, capacidade e qualidade de serviço. Para tal, um modelo de utilizador único foi desenvolvido, de modo a calcular o raio máximo do repetidor. Para uma abordagem mais realista desenvolveu-se um simulador com múltiplos utilizadores. Com a ajuda destas ferramentas, foi analisado o impacto da variação de vários parâmetros. Os resultados de monoutilizador mostram que, em Release 99 e num cenário pedestre, aumentar o ganho do repetidor conduz a um aumento no raio do repetidor de até 2,2 vezes. Em HSDPA e HSUPA este valor é de 2,8 e 3,5 vezes, respectivamente. Os resultados do simulador de múltiplos utilizadores mostram que, em Release 99, o repetidor aumenta o número de utilizadores cobertos em 7,3%, nas condições mais favoráveis. Em HSDPA, este crescimento cifra-se nos 5,0% e em HSUPA nos 20,0%. Os resultados também mostram que o repetidor não tem impacto na capacidade nem na qualidade de serviço.

Palavras-chave

UMTS, Repetidores, Cobertura, Capacidade, Qualidade de Serviço

Table of Contents

List of Figures

List of Tables

List of Acronyms

16-QAM	16 Quadrature Amplitude Modulation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
AGC	Automatic Gain Control
AMC	Adaptive Modulation and Coding
AOS	Automatic On-off Switching
AWGN	Additive White Gaussian Noise
BER	Bit Error Ratio
BPSK	Binary Phase Shift Keying
BS	Base Station
BS-R	BS-Repeater
CN	Core Network
CS	Circuit Switched
DL	Downlink
DS-CDMA	Direct-Sequence Code Division Multiple Access
EIRP	Equivalent Isotropic Radiated Power
ETSI	European Telecommunication Standards Institute
FDD	Frequency Division Duplex
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPRS	General Packet Radio System
GSM	Global System for Mobile Communications
HLR	Home Location Register
HSDPA	High-Speed Downlink Packet Access
HS-DSCH	High-Speed Downlink Shared Channel
HSPA	High-Speed Packet Access
HS-PDSCH	High-Speed Physical Downlink Shared Channel
HS-SCCH	High-Speed Shared Control Channel
HSUPA	High-Speed Uplink Packet Access
ISDN	Integrated Services Digital Networks
ME	Mobile Equipment
MIMO	Multiple Input Multiple Output
MRC	Maximum Ratio Combining

MSC	Mobile Switching Centre
MT	Mobile Terminal
OFDMA	Orthogonal Frequency-Division Multiple Access
O-H	Okumura-Hata
OVSF	Orthogonal Variable Spreading Factor
PDP	Power Delay Profile
Ped	Pedestrian
PLMN	Public Land Mobile Networks
PSTN	Public Switched Telephone Networks
QoS	Quality of Service
QPSK	Quaternary Phase Shift Keying
R-MT	Repeater-MT
RNC	Radio Network Controller
Rx	Receiver
SF	Spreading Factor
SGSN	Serving GPRS Support Node
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
SMS	Short Message Service
SNR	Signal to Noise Ratio
Tx	Transmitter
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
USIM	UMTS Subscriber Identity Module
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
Veh	Vehicular
VLR	Visitor Location Register
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
W-I	Walfisch-Ikegami

List of Symbols

α	DL orthogonality factor
α_j	Orthogonality of channel of user *j*
β	Distance ratio
δ_τ	Differential propagation delay between two signals
Δf	Signal bandwidth
Δh	Terrain undulation height
η_{DL}	DL load factor
η_{UL}	UL load factor
θ	Average angle of slope
ν_j	Activity factor of user *j*
ρ_{IN}	SINR
ρ_{IN10}	SINR considering 10 HS-PDSCH codes
ρ_{IN15}	SINR considering 15 HS-PDSCH codes
ρ_{IN5}	SINR considering 5 HS-PDSCH codes
ρ_N	SNR
σ_d	Delay spread of the direct path
σ_r	Delay spread of the path through the repeater
σ_s	Standard deviation for suburban environments
σ_u	Standard deviation for urban environments
τ	Delay
$\tau_{pBS\text{-}MT}$	Propagation delay between the BS and the MT
$\tau_{pBS\text{-}R}$	Propagation delay between the BS and the repeater
$\tau_{pR\text{-}MT}$	Propagation delay between the repeater and the MT
τ_R	Repeater internal delay
φ	Road orientation with respect to the direct radio path
Ω_r^R	Repeater's receiving antenna front-to-back ratio
Ω_t^R	Repeater's transmitting antenna front-to-back ratio
A_{cov}	Covered area
c	Speed of light
d	Distance
$d_{BS\text{-}MT}$	Distance between the BS and the MT
$d_{BS\text{-}R}$	Distance between the BS and the repeater

$d_{R\text{-}MT}$	Distance between the repeater and the MT
E_b	Energy per bit
E_c	Energy per chip
F	Receiver's noise figure
g	Ratio of intra- to inter-cells interference plus noise (geometry factor)
G_t^{BS}	BS's transmitting antenna gain
G_{cov}	Coverage antenna gain
G_{div}	Diversity gain
G_{donor}	Donor antenna gain
G_t^{MT}	MT's transmitting antenna gain
G_P	Processing gain
G_r	Receiving antenna gain
G_{amp}^R	Repeater's amplifier gain
G_{rdiv}	Receiving antenna gain plus diversity gain
G_{t-BS}^R	Gain of the repeater's antenna transmitting to the BS (donor antenna)
G_{t-MT}^R	Gain of the repeater's antenna transmitting to the MT (coverage antenna)
G_{SHO}	Soft handover gain
h_b	BS height
H_B	Building height
h_{be}	BS effective height
h_m	MT height
i	Intra- to inter-cell interferences ratio
I	Interference power
I_{inter}	Received inter-cell interference
I_{intra}	Received intra-cell interference
i_j	Intra- to inter-cell interferences ratio for user j
k_a	Increase of the path loss for BS antennas below the rooftops of the adjacent buildings
K_{ac}	Across streets correction factor
K_{al}	Along streets correction factor
k_d	Dependence of the multi-screen diffraction loss versus distance
k_f	Dependence of the multi-screen diffraction loss versus frequency
K_{hp}	Position in terrain undulation correction factor
K_{ih}	Isolated hill correction factor
K_{mp}	Mixed paths correction factor
K_{oa}	Open areas correction factor
K_{qo}	Quasi open areas correction factor
K_{sp}	Average slope correction factor
K_{su}	Suburban areas correction factor

K_{th}	Terrain undulation correction factor
L_0	Path loss in free space propagation
L_c^{BS}	Cable losses between BS's transmitter and antenna
L_{bsh}	Losses due to the fact that BS antennas are above or below the rooftop level
L_{ind}	Indoor penetration losses
$L_{O\text{-}H}$	Path loss obtained via the COST 231 O-H model
L_{ori}	Street orientation loss
L_p	Path loss
$L_{p\,max}$	Maximum allowable path loss
$L_{pBS\text{-}R}$	Path loss between the BS and the repeater
L_{pj}	Path loss between the BS and user *j*
$L_{pR\text{-}MT}$	Path loss between the repeater and the MT
L_c^R	Cable losses between repeater's transmitter and antenna
L_{rm}	Rooftop-to-street diffraction and scatter loss
L_{rt}	Multiple screen diffraction loss
L_u	Body losses
M	Total margin due to additional losses
M_{FF}	Fast fading margin
M_{SF}	Slow fading margin
$M_I^{UL/DL}$	Interference margin
N	Total noise power
N_0	Noise spectral density
N_U	Number of users per cell
N_{ucov}	Number of covered users
N_{userv}	Number of served users
$\mathcal{P}$	Power delay
P_b	Blocking probability
P_C^{BS}	BS transmission power allocated to the common channels
P_{EIRP}^{BS}	EIRP from the BS
P_r^{BS}	Available receiving power at BS's antenna port
P_{Tot}^{BS-R}	Total BS transmission power to a user within the repeater's coverage area
P_{Tot}^{BS}	Total BS transmission power
P_{Tx}^{BS}	BS transmission power allocated to the traffic channels
$P_{carrier}$	Total carrier transmit power
P_{EIRP}	Equivalent Isotropic Radiated Power
$P_{HS\text{-}DSCH}$	HS-DSCH transmit power
$P_{HS\text{-}SCCH}$	Power allocated to the transmission of the HS-SCCH
P_{EIRP}^{MT}	EIRP from the MT

P_r^{MT}	Available receiving power at MT's antenna port
P_{Rx}^{MT}	Power at MT's receiver input
P_{Tx}^{MT}	MT transmission power
P_C^R	Repeater transmission power allocated to the common channels
$P_{EIRP-BS}^R$	EIRP from the repeater to the BS
$P_{EIRP-MT}^R$	EIRP from the repeater to the MT
P_{FB}^R	Repeater's feedback signal power
P_{r-BS}^R	Available receiving power, from the BS, at repeater's antenna port
P_{r-MT}^R	Available receiving power, from the MT, at repeater's antenna port
P_{Rx-BS}^R	Power from the BS at repeater's receiver input
P_{Rx-MT}^R	Power from the MT at repeater's receiver input
P_{Tot}^R	Total repeater transmission power
P_{Tx}^R	Repeater transmission power allocated to the traffic channels
P_{Tx-BS}^R	Repeater transmission power to the BS allocated to the traffic channels
P_{Tx-MT}^R	Repeater transmission power to the MT allocated to the traffic channels
P_{Rx}	Power at receiver input
$P_{Rx\,\min}$	Receiver sensitivity
P_{Sig}	Signalling power
P_t	Transmitting power at antenna port
R	Cell radius
R_b	Bit rate
R_{b10}	Bit rate considering 10 HS-PDSCH codes
R_{b15}	Bit rate considering 15 HS-PDSCH codes
R_{b5}	Bit rate considering 5 HS-PDSCH codes
R_{bj}	Bit rate of user *j*
R_c	WCDMA chip rate
R_{breqj}	Requested throughput of user *j*
R_{bservj}	Served throughput of user *j*
S_G	Satisfaction grade
SF_{16}	SF of 16
w_B	Distance between middle points of adjacent buildings
w_s	Street width
X_d	Instantaneous signal level of the direct signal
X_r	Instantaneous signal level of the signal at the input of the repeater

List of Software

Borland C++ Builder	ANSI C++ Integrated Development Environment
MapBasic	Programming software and language to create additional tools and functionalities for MapInfo
MapInfo	Geographic Information Systems Software
Matlab	Computational math tool
Microsoft Excel	Calculation tool
Microsoft Visio	Design tool
Microsoft Word	Text editor tool

Chapter 1

Introduction

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

The history of mobile communications systems goes back to analogue cellular systems, commonly referred to as first-generation ones, which provided only voice service. Second Generation (2G) systems are already digital and have enabled voice communications to go wireless – the number of mobile phones exceeds the number of landline phones and the mobile phone penetration rounds 100% in several markets – and provided new services, like text messaging and internet access [Hoto07].

The most notable example of a 2G system is Global System for Mobile Communications (GSM), which was published in 1990 by the European Telecommunication Standards Institute (ETSI). GSM offered a low rate, 9.6 kbps, so General Packet Radio System (GPRS) was introduced, allowing average data rates of approximately 40 kbps [HaRM03].

In the year of 1999, the Third Generation Partnership Project (3GPP) launched the first standard specifications for Universal Mobile Telecommunications System (UMTS), called Release 99, which provides bit rates up to 384 kbps. UMTS, the first Third Generation (3G) system, uses Wideband Code Division Multiple Access (WCDMA) as air interface. Unlike 2G systems, originally designed for voice communications, UMTS was developed from the beginning for multimedia communications, bringing new business opportunities not only for manufacturers and operators, but also for the providers of content and applications using these networks [HoTo07]. Although, according to regulatory authorities, the first UMTS networks should have started operating in 2002, the real start of operation was delayed to the beginning of 2004, due not only to technical problems, but also to the fact that the market for mobile high data rate applications had to be developed first [Moli05]. The exponential growth of wireless broadband communications, along with expanded customer demands, stimulated the development of systems capable of offering higher capacity, throughput and enhanced multimedia services, available to consumers 'anywhere, anytime' [LaWN06].

High Speed Downlink Packet Access (HSDPA) was standardised in 3GPP's Release 5, with the first specifications being available in March 2002. HSDPA was commercially deployed in 2005, initially with a peak data rate of 1.8 Mbps, increased to 3.6 Mbps in 2006, and to 7.2 Mbps in 2007; currently, some operators already provide a data rate of 14.4 Mbps. The Uplink (UL) counterpart of HSDPA, High Speed Uplink Packet Access (HSUPA), was set as standard in December 2004 by Release 6 of 3GPP, commercially deployed during 2007, pushing peak data rates to 5.76 Mbps [Hoto07]. HSDPA and HSUPA deployed together are referred to as High Speed Packet Access (HSPA).

There is one more evolution step, specified by 3GPP in Release 7, on top of WCDMA: HSPA evolution, or HSPA+. It introduces new features, like Multiple Input Multiple Output (MIMO) and brings a number of further substantial enhancements to end-user performance and network capacity [HoTo07]. HSPA+ is already commercially available. The next emergent technology uses a new access technique called Orthogonal Frequency-Division Multiple Access (OFDMA), and is called Long Term Evolution (LTE), specified in 3GPP's Release 8, pushing peak data rates even higher. The roadmap for the 3GPP technologies discussed above is presented in Figure 1.1.

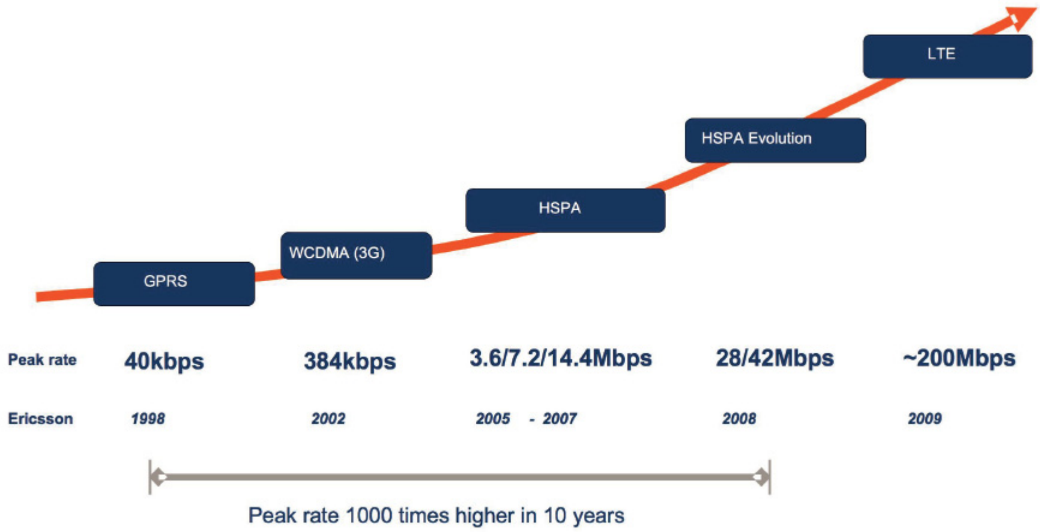


Figure 1.1 – Continuous evolution of 3GPP capabilities (extracted from [Eric09]).

In August 2009, there were 295 UMTS operators in service, spread over 126 countries, and 57 more were planned or in deployment. From these, 277 operators offer HSDPA (with more 44 planned) and 87 have HSUPA in service (with an additional 11 planned) [3GAM09a].

Considering the global cellular technology market, that is considering GSM – which still has the largest market share –, UMTS and other less significant technologies, in February 2009 it was announced that the mobile communications world reached the four billionth connection [GSMW09], and it is forecasted that the global market reaches six billion connections by 2013, Figure 1.2.

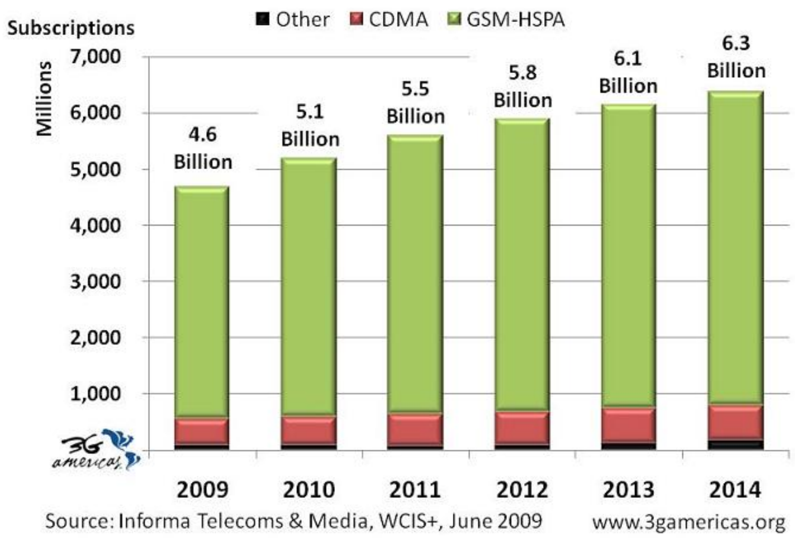


Figure 1.2 – Global cellular technology forecast (extracted from [3GAM09b]).

As stated earlier, mobile phones are, today, an indispensable tool for the majority of the population, and mobility is a key word, as consumers expect that good coverage exists wherever they are. Hence, operators have to find ways to optimise coverage. However, this optimisation is not just a technical challenge, as the intense competition among operators means that they need to expand and improve their networks as cost effectively as possible [Loza08]. This can pose some problems, since, sometimes, coverage holes appear and filling in these dead spots with the installation of a new Base Station (BS) may not be a feasible solution as they are very expensive equipments.

That is when repeaters come as an equipment of special interest, as they are a cost-efficient way to increase coverage, being much cheaper equipments than a BS. Also, in what concerns the systems presented before, repeaters are very flexible devices, as they are currently used in GSM and UMTS networks, and there are already repeaters for LTE.

The main scope of this thesis is to study repeaters in UMTS Release 99 and HSPA networks and their impact on coverage, capacity, and Quality of Service (QoS). These objectives are accomplished through the development and implementation of a single user model, and a simulator with multiple users and multiple services.

This thesis was made in collaboration with Celfinet, a mobile communications consulting company.

The main contribution of this work is the analysis of the impact of a repeater in coverage, capacity, and QoS, in a realistic scenario, in both Downlink (DL) and UL. A model to calculate the maximum repeater radius under different circumstances was developed, and simulation tools for Release 99, HSDPA and HSUPA are also an important outcome of this work. They both allow the variation of several parameters, like the repeater gain and the distance between the BS and the repeater.

This work is composed of five chapters, including the present one, followed by a set of annexes. In Chapter 2, an overview of UMTS is provided, with a brief introduction to the network architecture and the radio interface. Then, coverage, capacity and QoS are analysed. After that, an introduction to repeaters is provided, and the state of the art is presented. Chapter 3 presents the link budget used, followed by the single user radius model. Repeaters' delay and capacity are then approached. Later on, the simulator and its respective assessment are presented. In Chapter 4, the default scenario is presented, describing the environments considered and the parameters used in the link budget, for Release 99, HSDPA and HSUPA. Afterwards, the single user results are analysed, followed by the ones of the multiple users, where the influence of the variation of some parameters is analysed. Chapter 5 concludes this work, drawing the main conclusions and pointing out some suggestions for future work. A set of annexes with auxiliary information and results is also included. It includes expressions for the models, simulator's interface and user guide, and additional results, among others.

Chapter 2

Aspects of UMTS and Repeaters

This chapter provides an overview of the basic aspects of UMTS and repeaters. Firstly, the UMTS network architecture is briefly introduced, followed by a description of the radio interface. Then, coverage, capacity, and Quality of Service are analysed. An introduction to repeaters is provided, starting with the general issues, and then focusing on repeaters in UMTS networks. Finally, the state of the art regarding coverage and capacity with repeaters is presented.

2.1 Network Architecture

UMTS network elements are, functionally, grouped into three high-level architecture modules [HoTo04]: the UMTS Terrestrial Radio Access Network (UTRAN), the Core Network (CN) and the User Equipment (UE) – also known as Mobile Terminal (MT). UTRAN handles all radio-related functionalities, and CN is responsible for switching and routing calls and data connections to external networks, such as other Public Land Mobile Networks (PLMN), Integrated Services Digital Networks (ISDN), Public Switched Telephone Networks (PSTN) or the Internet. The network architecture is depicted in Figure 2.1.

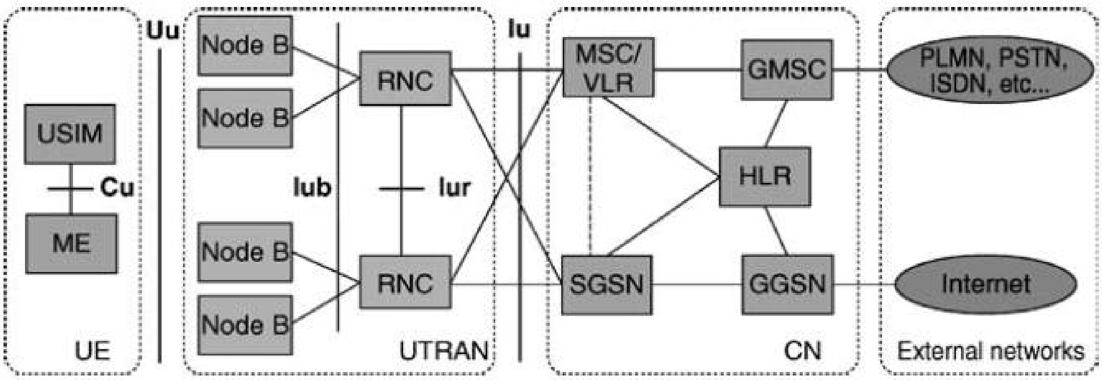


Figure 2.1 – UMTS network architecture (extracted from [HoTo04]).

The UE, i.e., the MT, consists of two parts:

- Mobile Equipment (ME): responsible for radio communications over the Uu interface.
- UMTS Subscriber Identity Module (USIM): a smartcard that holds information about the subscriber, and the subscription, authentication and encryption keys.

The UTRAN consists of two parts:

- Node B: converts the data flow between the Iub and Uu interfaces and takes part in radio resource management. It is the BS.
- Radio Network Controller (RNC): responsible for the control of the radio resources of UTRAN.

One of the main requirements for the design of the UTRAN architecture was to support soft handover, which occurs when the call is connected to more than one BS on the same carrier frequency. UTRAN also supports hard and softer handovers.

The definition of CN is adopted from GSM, and its elements are:

- Home Location Register (HLR): database that stores information on the user's service profile, like information on allowed services or forbidden roaming areas. It must remain stored as long as the user's subscription to the system is active.

- Mobile Switching Centre/Visitor Location Register (MSC/VLR): the MSC switches connections in the Circuit Switched (CS) domain; the VLR stores the visiting user's service profile as well as a more precise location of the UE.
- Gateway MSC (GMSC): it is the switch at the connection to external CS networks.
- Serving GPRS Support Node (SGSN): similar function to that of the MSC/VLR, but used for Packet Switched (PS) services.
- Gateway GPRS Support Node (GGSN): equivalent to GMSC, but on the PS domain.

2.2 Radio Interface

In the radio interface (identified as Uu in Figure 2.1), UMTS uses WCDMA, a wideband DS-CDMA (Direct-Sequence Code Division Multiple Access) air interface. It has a chip rate of 3.84 Mcps, which leads to a channel bandwidth of 4.4 MHz, with a channel separation of 5 MHz. Currently, UMTS uses only Frequency Division Duplex (FDD), UMTS Terrestrial Radio Access (UTRA)-FDD occupying the band [1920, 1980] MHz for UL and [2110, 2170] MHz for DL [Moli05].

WCDMA uses two types of codes for spreading and multiple access: channelisation and scrambling. The former spreads the signal by extending the occupied bandwidth, while the latter does not lead to bandwidth expansion, but distinguishes among cells and users. Channelisation codes in WCDMA are Orthogonal Variable Spreading Factor (OVSF) ones, which allow the Spreading Factor (SF) to be changed and orthogonality between codes to be maintained. Scrambling codes can be either short (based on the extended S(2) code family) or long (a 10 ms code based on the Gold family). Table 2.1 summarises the functionality and characteristics of channelisation and scrambling codes.

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	38400 chip
Number	Spreading Factor	DL: 512 UL: > 1 000 000
Family	OVSF	Gold or S(2)
Spreading	Yes	No

The aspects mentioned so far are common to Releases 99, 5 and 6. However, Releases 5 and 6 did introduce some changes in order to implement HSDPA and HSUPA, respectively. Some of the changes that are worth mentioning concern features like SF, modulation, power control and the support of soft handover, which are summarised in Table 2.2. One of these changes should be pointed out, as it is important in the context of this thesis: in HSDPA, the modulation is no longer fixed, and Adaptive Modulation and Coding (AMC) is introduced. AMC adjusts the modulation and coding scheme to the radio channel conditions and, together with the 16 Quadrature Amplitude Modulation (16-QAM) – also introduced with HSDPA, and that can only be used under good radio channel conditions –, allows higher data rates. Also, HSDPA introduces a fixed SF of 16, which means that 15 codes can be allocated for data transmission. From the BS point of view, all 15 codes can be allocated, while the MT can only allocate 5, 10 or 15 codes.

Table 2.2 – Comparison of fundamental properties of Releases 99, 5 and 6.

	Release 99	**Release 5 / HSDPA**	**Release 6 / HSUPA**
SF	Variable	Fixed and equal to 16	Variable
Modulation	Fixed (BPSK for the UL and QPSK for the DL)	Variable (16-QAM or QPSK)	Fixed (BPSK)
Power control	Yes	No	Yes
Soft handover	Yes	No	Yes
Maximum data rates [Mbps]	0.384	14.4	5.76

Data generated at higher levels is carried over the air interface with transport channels, which are mapped onto different physical ones. UTRA channels use a 10 ms radio frame structure, each frame corresponding to 15 slots, resulting in a slot duration of 667 μs [LaWN06]. Releases 5 and 6 introduced some new channels, essential to implement HSDPA and HSUPA features, respectively. Three of them worth mentioning – as they are of importance later in this text – are the High-Speed DL Shared Channel (HS-DSCH), which is mapped onto the High-Speed Physical DL Shared Channel (HS-PDSCH), and the High-Speed Shared Control Channel (HS-SCCH), all relative to HSDPA.

2.3 Performance Parameters

In this section, coverage and capacity are analysed in Subsection 2.3.1 and, in Subsection 2.3.2, QoS is addressed.

2.3.1 Capacity and coverage

Capacity and coverage are closely related in UMTS [Lope08], therefore, both must be considered simultaneously in the dimensioning of such networks.

Capacity depends on the number of users and their type of service. There are three main parameters that limit capacity [HoTo04]: the number of available codes in DL (although the lack of codes rarely occurs), the network load, and the shared DL transmission power.

The network load affects another parameter: the interference margin. The more loading is allowed in the network, the larger the interference margin is, and the smaller the coverage area becomes. The interference margin is defined by:

$$M_{I[\mathrm{dB}]}^{UL/DL} = -10 \cdot \log(1 - \eta_{UL/DL}) \tag{2.1}$$

where:

- $\eta_{UL/DL}$: UL/DL load factor

The load factor is not the same for UL and DL, since codes are used differently in UL and DL. So, for the UL load factor one has:

$$\eta_{UL} = (1 + i) \cdot \sum_{j=1}^{N_U} \frac{1}{1 + \frac{G_{Pj}}{\rho_{Nj} \cdot \nu_j}} \tag{2.2}$$

where:

- N_U: number of users per cell
- ν_j: activity factor of user j
- G_{Pj}: processing gain of user j
- i: intra- to inter-cell interferences ratio
- ρ_{Nj}: Signal to Noise ratio (SNR) of user j

As for the DL load factor, one has:

$$\eta_{DL} = \sum_{j=1}^{N_U} \nu_j \cdot \frac{\rho_{Nj}}{G_{Pj}} \cdot [(1 - \alpha_j) + i_j] \tag{2.3}$$

where:

- α_j : orthogonality of channel of user j
- i_j : intra- to inter-cell interferences ratio for user j

When η_{UL} or η_{DL} approach unity, the network reaches its pole capacity, and the noise rise goes to infinity. The main difference between the two load factors has to do with the fact that, in DL, the transmission power does not vary with the number of users, being shared among them, whereas in UL, each MT has its own transmitter power. Therefore, coverage depends more on the load in DL; even with a low load in DL, coverage decreases as a function of the number of users.

The DL transmission power also limits cell capacity. Therefore, one should be able to calculate the total BS transmission power, which can go up to 20 W – or 43 dBm – in Release 99, and up to 40 W – 46 dBm – in Release 5 [HoTo07]. But part of that power has to be allocated to the common channels that are transmitted independently of traffic ones. Hence, the total BS transmission power can be separated into two components:

$$P_{Tot}^{BS} = P_{Tx}^{BS} + P_{C}^{BS} \tag{2.4}$$

where:

- P_{C}^{BS} : BS transmission power allocated to common channels
- P_{Tx}^{BS} : BS transmission power allocated to traffic channels, given by:

$$P_{Tx}^{BS} = \frac{N_0 \cdot R_c \cdot \sum_{j=1}^{N_U} \nu_j \frac{\rho_{N\,j}}{G_{Pj}} \cdot \overline{L_{pj}}}{1 - \overline{\eta_{DL}}} \tag{2.5}$$

- N_0: noise spectral density
- R_c: WCDMA chip rate (3.84 Mcps)
- $\overline{L_{pj}}$: average path loss between the BS and user j
- $\overline{\eta_{DL}}$: average DL load factor

In Release 99, typically, 3.6 W are allocated for DL common channels [HoTo07]. The power allocated to common channels in Release 5 adds to the power allocated to these channels in Release 99, to the transmission of HS-SCCH ($P_{HS\text{-}SCCH}$) – usually between 0.2 and 0.5 W – and HS-DSCH ($P_{HS\text{-}DSCH}$), which can be defined as follows [HoTo06]:

$$P_{HS-DSCH} \geq \rho_{IN} \cdot (1 - \alpha + g^{-1}) \frac{P_{Tot}^{BS}}{SF_{16}} \tag{2.6}$$

where:

- ρ_{IN}: Signal to Interference plus Noise Ratio (SINR), to be defined ahead
- α: DL orthogonality factor
- SF_{16}: SF of 16
- g: ratio of intra- to inter-cells interference plus noise at the user, geometry factor, defined as:

$$g = \frac{I_{intra}}{I_{inter} + N} \tag{2.7}$$

- I_{intra}: received intra-cell interference
- I_{inter}: received inter-cell interference
- N: total noise power

As an example, the HS-DSCH transmission power should be equal to 5.6 W, if the required throughput at the cell edge needs to be 200 kbps [HoTo06].

Increasing DL transmission power is not an efficient approach to increase DL capacity. By contrast, the splitting of the DL power between two carriers increases DL capacity, without any extra investment in power amplifiers. A trade-off between DL capacity and coverage can be made: if there are fewer users, more power can be allocated to one user allowing a higher path loss.

As for the MT transmission power, it can go up to 33 dBm, but typical values are 21 dBm for voice and 24 dBm for data. This is valid for both Releases 99 and 6 [HoTo07].

Release 99 typically uses E_b/N_0 as an approximation to SNR:

$$\rho_N \approx E_b / N_0 \tag{2.8}$$

where:

- E_b: energy per bit
- N_0: noise spectral density

However, to evaluate HSDPA performance the E_b/N_0 metric is not used. The HS-DSCH SINR is used instead, which can be expressed, for a single antenna Rake receiver, as [HoTo06]:

$$\rho_{IN} = SF_{16} \frac{P_{HS-DSCH}}{(1-\alpha)\cdot I_{intra} + I_{inter} + N} \tag{2.9}$$

For lower SINR, QPSK is used, while 16-QAM is employed for a higher SINR, as it is necessary to provide higher data rates.

The performance metric used by HSUPA is the energy per chip to noise spectral density ratio, E_c/N_0. A high E_c/N_0 at the BS is necessary to achieve higher data rates, leading to an increased UL noise and, consequently, a decreased cell coverage area. The relation between E_b/N_0 and E_c/N_0 is given by:

$$E_b / N_{0[\text{dB}]} = E_c / N_{0[\text{dB}]} + G_{P[\text{dB}]} \tag{2.10}$$

where:

- E_c: energy per chip
- G_P: processing gain, defined as:

$$G_{P[\text{dB}]} = 10 \cdot \log\left(\frac{R_c}{R_b}\right) \tag{2.11}$$

- R_b: Bit rate

Table 2.3 shows how the processing gain varies with the bit rate.

Table 2.3 – Relation between bit rate and processing gain.

Bit rate [kbps]	Processing gain [dB]
12.2	25.0
64	17.8
128	14.8
384	10.0

Annex A contains the expressions of the throughput as a function of SINR and E_c/N_0, [Lope08].

2.3.2 Quality of Service

QoS is defined, in the context of UMTS, as the collective effect of service performances that determine the degree of satisfaction of a user of a service [3GPP01].

In order to prioritise different services according to their requirements, especially when the network load gets higher, 3GPP defined four traffic classes, based on their QoS requirements [3GPP02]: Conversational, Streaming, Interactive and Background. The main distinguishing factor among these QoS classes is how delay sensitive traffic is: the Conversational class is meant for very delay-sensitive traffic, while the Background one is the most delay insensitive traffic class. Table 2.4 summarises QoS classes' main characteristics.

Table 2.4 – UMTS QoS classes and their main parameters (adapted from [3GPP01], [3GPP02], [HoTo04] and [LaWN06]).

<table>
<tr><th>Traffic Class</th><th>Conversational</th><th>Streaming</th><th>Interactive</th><th>Background</th></tr>
<tr><td>Fundamental characteristics</td><td>Preserve time relation (variation) between information entities of the stream
Conversational pattern</td><td>Preserve time relation (variation) between information entities of the stream</td><td>Request response pattern
Preserve payload content</td><td>Destination is not expecting the data within a certain time
Preserve payload content</td></tr>
<tr><td>Real-time</td><td colspan="2">Yes</td><td colspan="2">No</td></tr>
<tr><td>Symmetric</td><td>Yes</td><td colspan="3">No</td></tr>
<tr><td>Guaranteed bit rate</td><td colspan="2">Yes</td><td colspan="2">No</td></tr>
<tr><td>Delay</td><td>Low and stringent</td><td>Low; tolerates some variation</td><td>Low round-trip delay</td><td>Practically delay insensitive</td></tr>
<tr><td>Switching</td><td colspan="2">CS/PS</td><td colspan="2">PS</td></tr>
<tr><td>Example of application</td><td>Voice</td><td>Streaming Video</td><td>Web browsing</td><td>Emails</td></tr>
</table>

The Conversational class is the one that raises the strongest and most stringent QoS requirements, as it is the only one where the required characteristics are strictly given by human perception. Therefore, the maximum end-to-end delay has to be less than 400 ms [HoTo04]. Although the most well known use of this scheme is telephony speech over CS, there are a number of other applications that fit this scheme, e.g., Voice over IP (VoIP) and video conferencing.

The Streaming class includes real-time audio and video sharing, and is one of the newcomers in data communications. Like the Conversational class, it requires bandwidth to be maintained, but tolerates some delay variations that are hidden by a buffer in the receiver.

The Interactive class includes, e.g., web browsing, and is characterised by the request response pattern of the end user. At the message destination there is an entity expecting the message (response) within a certain time. Round trip delay time is therefore one of the key attributes. Also, the content of the packets must be transparently transferred, i.e., with low bit error rate.

The Background class assumes that the destination is not expecting the data within a certain time; therefore, it is the least delay sensitive class (there is no special requirement for delay). Like in the Interactive class, the content of the packets must be transparently transferred. Examples are the background delivery of e-mails or Short Message Service (SMS).

UMTS QoS classes are not mandatory for the introduction of any low delay service. It is possible to support streaming video or conversational VoIP from an end-to-end performance point of view by using just the Background class. QoS differentiation becomes useful for the network efficiency during high load, when there are services with different delay requirements.

It is also important to know the usual bit rates and typical file dimensions associated to the different services. Table 2.5 shows some examples, which also includes the QoS priority list. If reduction strategies are applied, the first services to be reduced are the ones with the lower QoS priority (that corresponds to a higher priority value), according to the traffic classes shown in Table 2.4.

Table 2.5 – Bit rates and applications of different services (adapted from [Lope08] and [3GPP05]).

Service	**Bit rate [kbps]**		**QoS priority**	**Characteristics**		
	DL	**UL**		**Average volume/duration**	**DL**	**UL**
Voice	12.2		1	Call duration [s]	120	
Web	[512, 1536]	[128, 512]	2	Page size [kB]	300	20
Streaming	[512, 1024]	[64, 384]	3	Video size [MB]	9.6	0.02
Email	[384, 1536]	[128, 512]	4	File size [kB]	100	
FTP	[384, 2048]	[128, 512]	5	File size [MB]	10	
Chat	[64, 384]		6	MSN message size [B]	50	
P2P	[128, 1024]	[64, 384]	7	File size [MB]	12.5	

2.4 Repeaters

In this section, the main aspects of repeaters are presented. Their general issues are addressed in Subsection 2.4.1, and in Subsection 2.4.2 one focuses on repeaters in UMTS networks.

2.4.1 General Issues

Because BSs are expensive, repeaters – which are considerably cheaper and easier to install – are sometimes used to fill in areas not properly covered by the BSs. The repeater coverage area may be either outdoor or indoor, including situations like filling in coverage holes (also known as dead spots) in valleys, Figure 2.2, tunnels and buildings, or extending the service area beyond cell boundaries.

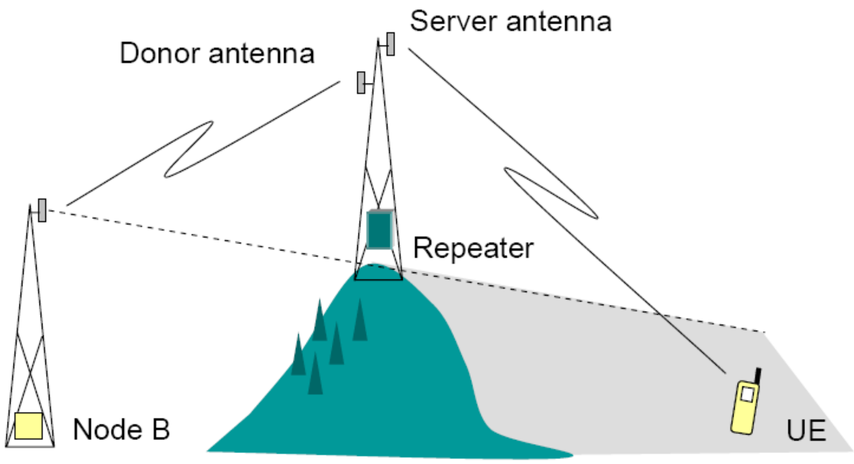
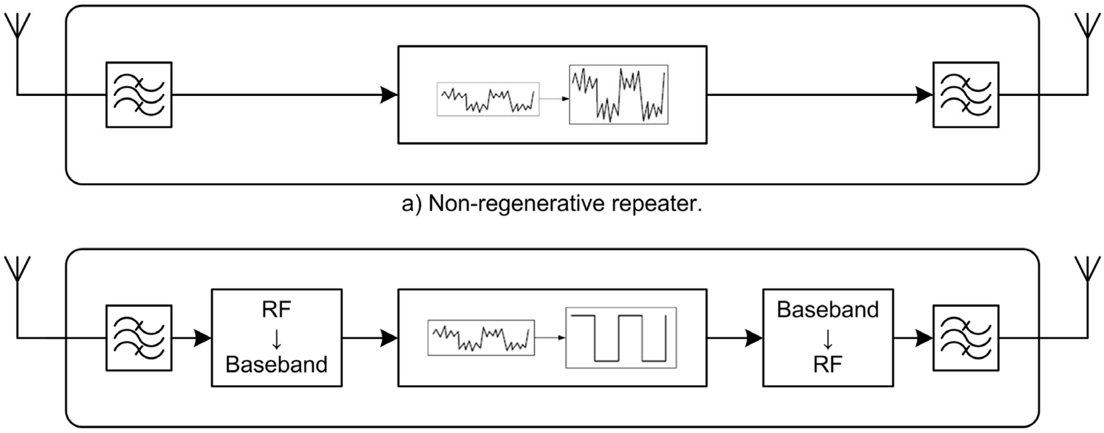


Figure 2.2 – Obstacle creating coverage hole (extracted from [Avit05]).

There are two types of repeaters: regenerative and non-regenerative. The former have the advantage of allowing the received signal to be cleaned before retransmission; the latter are simpler – hence cheaper – devices, as they simply amplify the received signal plus noise. Repeaters are generally connected to their donor cell via a directional radio link. In some cases, this connection may be made via an optical fibre, but this solution brings two disadvantages: it is more expensive, and it introduces extra delay (the problem of delay is discussed later on), as the speed of light in fibres is approximately 2/3 of that in the air. In this thesis, one only considers the connection via radio link. Repeaters are transparent to their donor BS, which is able to operate without needing to know whether or not a repeater is present. Inner-, outer- and open-loop power control algorithms are able to function transparently through the repeater [LaWN06].

A repeater is used to amplify a signal, being located between the target users of a cell and the corresponding donor BS. Figure 2.3 presents a simple model of both versions of repeaters (regenerative and non-regenerative).

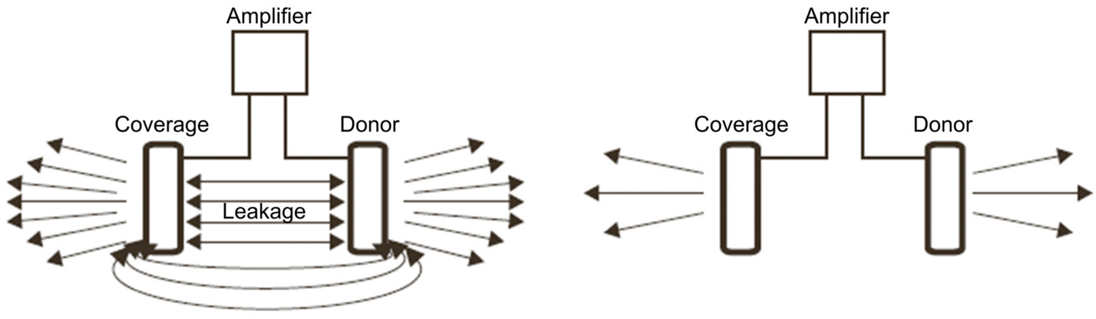


a) Non-regenerative repeater.

b) Regenerative repeater.

Figure 2.3 – Block diagram of a non-regenerative and a regenerative repeaters.

Repeaters have two antennas: the coverage (or service) antenna – which points to the repeater service area – and the donor antenna – that connects to the donor (or parent) BS. The donor antenna is normally an antenna with high directivity, in order to minimise the effects of multipath and inter-cell interference; the coverage antenna needs a beam wide enough to cover the desired area. Isolation between donor and coverage antennas is an essential issue for the performance of a repeater: it must be 15 dB higher than the repeater gain to guarantee an adequate protection against self-oscillation of the repeater [3GPP04], i.e., the repeater receiving and amplifying its own signal, in Figure 2.4.



a) Poor isolation

b) Good isolation

Figure 2.4 – Repeater self-oscillation (extracted from [Lähd06]).

Several factors have influence on the antenna isolation [3GPP04]:

- Antenna pattern: the optimum is a combination of donor and coverage antennas mounted in a way so that there is a null in the antenna pattern in the direction pointing towards the other antenna. In order to achieve that, antennas with a high front to back ratio are preferred.
- Vertical separation: in a typical configuration, when both antennas (that normally have a narrower aperture in the vertical antenna pattern) are mounted on a pole, there is a null in the antenna pattern pointing vertically up and down from the antenna's feeding point. If there is a horizontal separation between the antennas, additional lobes in the vertical antenna pattern have to be taken into account.
- Environment: this is a very important factor, as the reflection and attenuation properties of all materials near the antenna can influence isolation drastically. For example, if there is a

reflection from a building towards the pole with the mounted antennas, isolation can decrease over 10 dB. The material of the tower itself has also an effect on isolation (a concrete tower improves isolation). Shielding grids mounted near the antennas can improve isolation by approximately 5 dB.

The configuration of UL and DL repeater gains is an important factor to consider, which can usually be adjusted up to 90 dB [Lähd06]; this value varies according to the application (it is different for, e.g., macro- or pico-cells) and the manufacturer. The majority of repeaters allow configuring UL and DL gains independently. DL gain is typically configured relatively high, to maximise the DL coverage of the repeater. The UL gain should usually be about 10 dB less than the link loss between the repeater and the donor BS [LaWN06]. Repeaters may use Automatic Gain Control (AGC) to adjust the gain, so that self-oscillation is avoided; AGC is also important to ensure that the amplifier of the repeater is not driven into saturation (as a result of a high input signal, its characteristic no longer being linear). This has two effects in the signal spectrum [MuGo99]: it deforms and enlarges the spectrum within the bandwidth (which may lead to inter-symbol interference), and causes harmonics to appear at the multiples of the carrier frequency. AGC avoids this by lowering the repeater's gain if a high input signal is applied. If AGC is not present, attenuators may be placed at the repeater's input, to assure that a too high input signal is not applied.

Repeaters introduce a delay in both UL and DL of the order of 5 to 6 μs. This poses a problem, because the Rake receiver constructively combines only the paths within a certain time window, the others not being considered [GACR07].

2.4.2 Repeaters in UMTS Networks

Despite their use in GSM, repeaters are expected to play an even major role in UMTS. Some of the reasons are [GACR07]:

- Repeaters are a cost-effective way of increasing capacity in hotspots (small areas with high traffic volume) within the coverage area of a BS, by reducing the inter-cell interference. If properly adjusted, they can reduce the coupling loss between the BS and MTs that are close to the repeater. Therefore, in UL, MTs use a lower output power and the interference in neighbouring cells is reduced. [RaEr04] studies this case.
- The use of higher frequencies in UMTS implies higher propagation losses. Repeaters can be key devices to guarantee indoor coverage at low cost.
- During the last years, repeaters have improved in terms of operation and maintenance.

As mentioned earlier, regenerative repeaters have the advantage of cleaning the signal prior to the retransmission, but, in UMTS, the repeater cannot clean the bit stream, unless it first applies scrambling and channelisation codes, which makes this kind of repeater expensive to build.

UMTS BS and MTs can handle a 20 μs time delay between two paths [3GPP04]. This puts a practical upper limit on the number of repeaters that can be daisy-chained (which allows extending areas of coverage beyond the one feasible by using a single repeater).

The deployment of repeaters leads to some changes in the path of the signal between the BS and the MT: the link budget performance of the donor cell remains unchanged, but a second set of link budgets must be completed for the coverage area of the repeater. Due to the changes in some parameters, these link budgets are likely to be quite different from that of the donor cell. Table 2.6 describes which parameters are most likely to change and how. The combined effect of these parameters will probably result in a lower maximum allowed propagation loss for the repeater compared to the donor cell [LaWN06].

Table 2.6 – Differences between link budgets of donor cell and repeater (extracted from [LaWN06]).

Factor	Difference
Uplink SNR requirement	Repeater requires increased SNR, especially if it does not benefit from receive diversity.
Receiver noise figure	Depends on the receiver’s design.
Receiver antenna gain	Depends on scenario. Repeaters used to extend coverage along a road may use directional antennas.
Feeder loss	Depends on scenario.
Fast fading margin	Repeater requires increased margin, especially if it does not benefit from receive diversity.

Passing the WCDMA signal through two receiver sub-systems plus an additional transmitter degrades signal quality. This has a direct impact upon the receiver SNR requirement, and indirectly upon capacity and coverage performance. Regarding coverage, since the noise floor on the donor BS is raised, its effective coverage area is shrunk; however, this is clearly compensated by the new areas, covered by the repeaters. The impact of a repeater upon capacity depends on whether it is UL or DL limited: in the former, there is a loss of capacity by using a repeater, due to the increased UL SNR requirement for those users linking to the donor BS via the repeater; in the latter, both the DL load and link budgets need to be considered. The increased SNR requirement of the users linked to the donor BS via the repeater increases the DL loading of both the repeater and the donor cell. The increase in DL loading tends to decrease capacity. Furthermore, users located at the boundary area between the donor BS and the repeater are likely to incur in high levels of multipath and a corresponding loss of channelisation code orthogonality, which also tends to increase DL load and reduce capacity. However, users linked to the donor BS via the repeater require a relatively low share of BS power, as a result of the favourable link budget provided by the repeater gain and the directional radio link between donor BS and repeater [LaWN06].

Soft handover does not occur between the donor BS and the repeater, as they belong to the same logical cell and transmit the same DL signal and scrambling code, reducing signalling complexity.

2.5 State of the Art on Coverage and Capacity

In this section, the state of the art concerning this thesis' main objectives is presented.

The study of repeaters as coverage extenders, and how they modify interference in highway environments, is made in [LeLe00], where both UL and DL are analysed. The authors state that the installation of a repeater increases the noise level of the BS by 2.1 dB, which translates into a 13% shrinkage in UL coverage distance in a typical suburban environment (DL coverage is not affected). It is also noted that the cascade of repeaters introduces a significant increase in noise that is higher as the number of cascaded repeaters increases. Simulation results show that repeaters not only increase coverage, but also reduce the intra- to inter-cell interferences ratio from about 12% to 6%, which results in an increase of capacity in DL of 2 to 3 users. Findings also indicate that the noise floor in the BS only affects system performance when it exceeds -98 dBm. This work considers that MTs receive the signals from the repeater and from the BS, both contributions being perfectly combined in the MT. Maximum Ratio Combining (MRC) is applied. This work does not study repeaters in dead spots, and issues like pilot pollution and the influence of the repeater gain are not considered.

The use of broadband repeaters as a means to either improve signal quality in dead spots areas or to extend coverage areas is discussed in [AlGa04], with a focus on UL. This paper analyses the Bit Error Ratio (BER) performance in the presence of Additive White Gaussian Noise (AWGN) and multipath Rayleigh fading channels. Data transmission rates of 144 and 384 kbps are considered, as well as three different MT speeds (50, 120 and 250 km/h) and propagation delays (0.260, 2.60 and 4 μs). The authors conclude that repeaters are able to provide reliable and effective radio coverage in dead spot areas, regardless of the data rates. Regarding coverage extension, at 144 kbps, good results are obtained even at higher propagation delays on all MT speeds; however, at 384 kbps, additional repeater's transmission power is required to get a good response, particularly with a 4 μs propagation delay. This work assumes, among others, an MRC RAKE receiver, perfect isolation of repeater's antennas, and no power control.

In [Ali06], a study of repeaters used to cover dead spots and to extend coverage area is also made, but focusing on DL. BER is evaluated in the presence of AWGN and multipath Rayleigh fading channels. The MT speeds and data rates that are used in [AlGa04] are also used in this work. The results show that, regardless of speeds and data rates, repeaters are able to enhance the weak RF signals, although lower data rates do produce better performance. The users that receive both RF signals (from the repeater and the BS) with a different delay – meaning the repeater is being used to extend coverage – experience performance degradation. The author notes that the suitability of repeaters as a means to extend service coverage needs further study, especially for higher data rates; nonetheless, repeaters provide the best alternative to solve the coverage problem. The assumptions made in this paper are those made in [AlGa04].

The two previous works complement each other, as they make an identical analysis: one for UL, the other for DL. However, none of the two analyses the impact of repeaters on capacity, the pilot pollution problem or the repeater gain.

In order to minimise the noise rise that appears in the donor BS when repeaters are installed, [BCCC01] proposes Automatic On-off Switching (AOS) repeaters. This kind of repeaters detects the level of power received in UL, and switches off its transmission path automatically when there is no active user. This work analyses the UL of an AOS repeater used to cover dead spot areas. Results show that AOS repeaters can effectively reduce the noise enhancement, resulting in a UL capacity larger than the system with conventional repeaters. This improvement is inversely proportional to the average distance between repeater and donor BS. The following is assumed for the performance analysis: receivers get power only through the radio link with the donor BS or through one of the repeaters, perfect power control in UL and uniform distribution of MTs. [BCCC01] does not analyse DL, pilot pollution or the influence of the repeater gain.

Coverage inside buildings also needs to be considered. The study of the performance, in both UL and DL, of a repeater-based in-building solution in a scenario with speech traffic is the scope of [Hilt06]. The simulation results show that coverage is initially improved as a function of the repeater gain, up to 25 dB; from this value on, no additional gain in speech coverage is obtained. If the repeater gain is increased, UL coverage probability is reduced. However, this does not prevent the author from stating that repeater deployment provides full speech coverage throughout the building. Coverage improvement inside the building introduces additional UL interference into the system, reducing the donor cell UL coverage and capacity. This additional interference is harmful, in particular for the other indoor users within the donor cell that are not covered by the repeater. This paper also analyses capacity, and concludes that it is considerably increased compared to the scenario with general outdoor-to-indoor coverage. It is assumed that the MT experiences a radio channel that is a combination of the direct path signals and the delayed signals coming from the repeater; the cluster representing the direct path is assumed to be equal to the 3GPP Typical Urban channel profile [3GPP06], and the cluster for the repeater path is assumed to be equal to 3GPP Rural Area [3GPP06]. This paper considers only speech traffic and does not approach the pilot pollution problem.

In [BNIL06], the deployment of an indoor distributed antenna system is suggested. The deployment of this system ensures an increase in DL capacity and it also helps with the pilot pollution problem, as it makes the pilot of the donor BS the dominant one. Also, the interference produced to the neighbouring cells is significantly lowered. UL is not studied, as well as the gain of the repeater.

As mentioned earlier, repeaters are also used to increase capacity in hotspots. [RaEr04] studies this application of repeaters (in both UL and DL) in two traffic-distribution cases: hotspots located close to the cell border, and halfway between the donor BS and the cell border. Results show that repeaters are very effective in improving DL hotspot capacity: when considering hotspots located close to the cell border, the system tolerates approximately twice as high hotspot traffic load when the repeater is introduced; for hotspots located halfway between the donor BS and the cell border, there is an 80% increase in the tolerated hotspot traffic load. This work also considers the extent to which multipath destroys the orthogonality properties of the CDMA signal: repeaters are even more effective with improved orthogonality properties. As far as UL is concerned, the use of repeaters results, similarly to DL, in a reduction of outage, albeit in smaller extent. The authors note that it is very important to tune the repeater gain correctly, as an incorrectly tuned repeater may lead to a loss in capacity. It assumes: perfect power control in both UL and DL, negligible repeater noise, perfect isolation between repeater antennas, uniform distribution of users in the network, and a number of circular areas (hotspots) with increased traffic loads homogenously distributed within each circular area. [RaEr04] studies repeaters in hotspots only, and the issue of pilot pollution is not considered.

In [BoNL05], an assessment of the applicability of repeaters for DL capacity improvement in hotspots is made. Like [RaEr04], it states that repeaters are highly feasible solutions for extending the parent BS capacity in DL. This paper evaluates the throughput of a test MT within the hotspot with different repeater gains, showing that the highest throughput is achieved with a 70 dB repeater gain. The results also illustrate that a properly deployed repeater reduces soft handover probability, as the cell dominance area is improved and the pilot pollution problem is reduced. UL and application of repeaters in dead spots or coverage extension are not analysed.

All the studies mentioned until now assume that either receivers get power just through the radio link with the donor BS or through one of the repeaters – other contributions are not considered in any way –, or that all contributions are always perfectly combined in the MT – ideal MRC is applied. However, in real systems, none of the above happens, as only those paths within a certain time window are constructively combined, the others not being considered and causing a certain level of 'self-interference'. Since repeaters introduce a delay, this is an important issue to consider. In [GACR07], generic expressions for UL and DL are derived, so that transmission powers can be calculated without simplifications, for a general heterogeneous layout. This paper analyses a long road like scenario, with one BS and one repeater used as a coverage extender, and the behaviour of MTs is studied for different internal delays (from 5 to 11 μs). Results show that classical approximations lead to unrealistic, too optimistic, results. Considering transmitted powers, UL is the most affected link with differences up to 3 dB. The number of users that reach their E_b/N_0 target decreases from 96% to 85%. Important reductions on coverage are observed, especially when considering an internal delay of 11 μs and an orthogonality factor of 0.6, in which case a layout clearly inappropriate in a real situation could be considered good with the classical approximations. Admission regions have also been compared, showing reductions in the number of admitted users up to 8%.

There are other works that, despite not being completely within the scope of this thesis, deserve a brief reference. [NLBL05], although focusing on capacity improvement with repeaters, evaluates the repeater's optimum gain setting. The value obtained is between 68 and 72 dB, confirming the one from [BoNL05]. In [AKRL04], a novel adaptive filtering approach that allows repeaters to operate with gains equal to or greater than the existing isolation is introduced.

One can observe that, from the works presented in this section, some only analyse either UL or DL, or do not consider the influence of the repeater gain, or other limitations are noticed like considering perfect isolation of repeater's antennas, not analysing the impact on capacity, or considering only one service. The main novelty of this thesis is making an analysis that comprehends several aspects that are not consider as a whole in other works: it studies the impact of repeaters in coverage, capacity and QoS, in both urban and rural areas, it considers both Release 99 and HSPA (UL and DL) with multiple services, and it takes the feedback due to imperfect antenna isolation and the variation of the repeater gain into account.

Chapter 3

Model and Simulator Description

In this chapter, one starts by describing the link budget used for the connections between the BS and the repeater, and between the repeater and the MT. The single user radius model is then presented. This model intends to provide an overview of the network planning, for both rural and urban areas. Then, one analyses how delay affects the repeater and the BS's radii, and an approach to the BS transmission power as a capacity limiting factor is done. An overview of the multiple users simulator is then presented, describing its modules, the modifications done in order to implement the repeater and its main outputs. This chapter closes with the assessment of the simulator.

3.1 Link Budgets

Figure 3.1 depicts the radio link between BS and MT via a repeater. Based on it, one presents two sets of link budgets: the connections between the BS and the repeater – henceforth, designated as BS-Repeater (BS-R) link –, and between the repeater and the MT – Repeater-MT (R-MT) link. These link budgets are based on [Lope08], which adapted the Release 99 link budget described in [CoLa06] and [Sant04] to HSDPA and HSUPA. A third link budget, for the direct link between the BS and the MT – BS-MT link –, is also included.

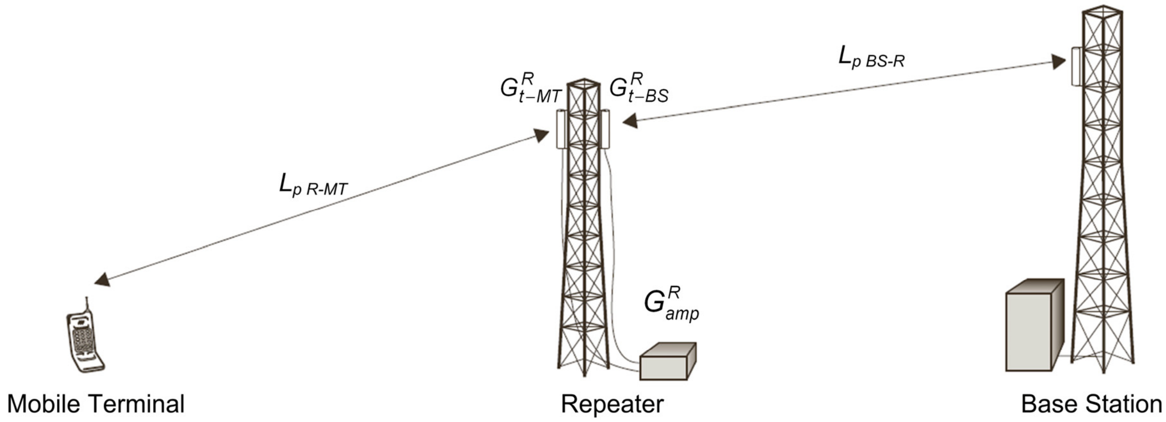


Figure 3.1 – Transmission path for a repeater installation (adapted from [Lähd06]).

As it is well known, the available received power at the antenna port can be calculated by:

$$P_{r\,[\mathrm{dBm}]} = P_{EIRP\,[\mathrm{dBm}]} - L_{p\,[\mathrm{dB}]} + G_{r\,[\mathrm{dBi}]} \tag{3.1}$$

where:

- P_{EIRP}: Equivalent Isotropic Radiated Power (EIRP)
- L_p: path loss
- G_r: receiving antenna gain

If diversity is used, G_r must account for the extra gain, being replaced in (3.1) by (3.2). It is only considered in UL, since there is no diversity neither in the repeater's donor antenna (as it is a highly directive antenna) nor in the MT (since there is no space for spatial diversity, and polarisation diversity requires doubling the equipment).

$$G_{rdiv\,[\mathrm{dB}]} = G_{r\,[\mathrm{dBi}]} + G_{div\,[\mathrm{dB}]} \tag{3.2}$$

where:

- G_{div}: diversity gain (typically, 3 dB for 2 antennas)

The EIRP for the BS-R link can be calculated by (3.3) for DL and (3.4) for UL. Equation (3.3) is also used to calculate the DL EIRP for the BS-MT link.

$$P^{BS}_{EIRP[\text{dBm}]} = P^{BS}_{Tx[\text{dBm}]} - L^{BS}_{c[\text{dB}]} + G^{BS}_{t[\text{dBi}]} \tag{3.3}$$

$$P^{R}_{EIRP-BS[\text{dBm}]} = P^{R}_{Tx-BS[\text{dBm}]} - L^{R}_{c[\text{dB}]} + G^{R}_{t-BS[\text{dBi}]} \tag{3.4}$$

where:

- P^{BS}_{EIRP} : EIRP from the BS
- L^{BS}_{c} : cable losses between BS's transmitter (Tx) and antenna
- G^{BS}_{t} : BS's transmitting antenna gain
- $P^{R}_{EIRP-BS}$: EIRP from the repeater to the BS
- P^{R}_{Tx-BS} : repeater transmission power to the BS allocated to the traffic channels
- L^{R}_{c} : cable losses between repeater's Tx and antenna
- G^{R}_{t-BS} : gain of the repeater's antenna transmitting to the BS (donor antenna)

The repeater transmission power to the BS, relative to the UL, is obtained by adding to the received power (from the MT) at the repeater's receiver input the repeater gain:

$$P^{R}_{Tx-BS[\text{dBm}]} = P^{R}_{Rx-MT[\text{dBm}]} + G^{R}_{amp[\text{dB}]} \tag{3.5}$$

where:

- P^{R}_{Rx-MT} : power from the MT at repeater's receiver (Rx) input
- G^{R}_{amp} : repeater's amplifier gain

As for the R-MT link, the EIRP is obtained by (3.6) for DL and (3.7) for UL (that is also used to obtain the EIRP for UL in the BS-MT link):

$$P^{R}_{EIRP-MT[\text{dBm}]} = P^{R}_{Tx-MT[\text{dBm}]} - L^{R}_{c[\text{dB}]} + G^{R}_{t-MT[\text{dBi}]} \tag{3.6}$$

$$P^{MT}_{EIRP[\text{dBm}]} = P^{MT}_{Tx[\text{dBm}]} - L_{u[\text{dB}]} + G^{MT}_{t[\text{dBi}]} \tag{3.7}$$

where:

- $P^{R}_{EIRP-MT}$: EIRP from the repeater to the MT
- P^{R}_{Tx-MT} : repeater transmission power to the MT allocated to the traffic channels
- P^{MT}_{EIRP} : EIRP from the MT
- G^{R}_{t-MT} : gain of the repeater's antenna transmitting to the MT (coverage antenna)

- P_{Tx}^{MT} : MT transmission power
- L_u: user body losses
- G_t^{MT} : MT's transmitting antenna gain

The repeater transmission power to the MT is obtained by:

$$P_{Tx-MT[\text{dBm}]}^{R} = P_{Rx-BS[\text{dBm}]}^{R} + G_{amp[\text{dB}]}^{R} \tag{3.8}$$

where:

- P_{Rx-BS}^{R} : received power from the BS at repeater's Rx input

Relatively to BS-R, the received power at Rx input can be calculated by (3.9) for DL and (3.10) for UL:

$$P_{Rx-BS[\text{dBm}]}^{R} = P_{r-BS[\text{dBm}]}^{R} - L_{c[\text{dB}]}^{R} \tag{3.9}$$

$$P_{Rx[\text{dBm}]}^{BS} = P_{r[\text{dBm}]}^{BS} - L_{c[\text{dB}]}^{BS} \tag{3.10}$$

where:

- P_{r-BS}^{R} : available receiving power, from the BS, at repeater's antenna port
- P_r^{BS} : available receiving power at BS's antenna port

Analogously, for the R-MT link:

$$P_{Rx[\text{dBm}]}^{MT} = P_{r[\text{dBm}]}^{MT} - L_{u[\text{dB}]} \tag{3.11}$$

$$P_{Rx-MT[\text{dBm}]}^{R} = P_{r-MT[\text{dBm}]}^{R} - L_{c[\text{dB}]}^{R} \tag{3.12}$$

where:

- P_{Rx}^{MT} : received power at MT's Rx input
- P_r^{MT} : available received power at MT's antenna port
- P_{r-MT}^{R} : available received power, from the MT, at repeater's antenna port

For the BS-MT link, the received power at Rx input can be obtained by (3.10) for UL and (3.11) for DL.

The Rx sensitivity can be approximated, for the three links, by:

$$P_{Rx\min[\text{dBm}]} = (N + I)_{[\text{dBm}]} + M_{I[\text{dB}]}^{UL/DL} - G_{P[\text{dB}]} + \rho_{N[\text{dB}]} \tag{3.13}$$

where:

- I: interference power, (3.16)

The Rx's total noise power is given by (3.15), while the processing gain and the SNR are obtained according to Table 3.1.

Table 3.1 – Processing gain and SNR/SINR definition for the various systems (adapted from [Bati08]).

System	Processing gain	SNR/SINR
Release 99 DL/UL	R_c/R_b	$E_b/N_0(R_b)$
HSDPA	Fixed and equal to SF_{16}	$\rho_{IN}(R_b)$
HSUPA	R_c/R_b	$E_b/N_0(R_b)$

The E_b/N_0, for Release 99 and HSUPA, is obtained from (2.10). The SINR for HSDPA is calculated by (2.9) or, rearranging (3.13), by:

$$\rho_{IN[\text{dB}]} = P_{Rx[\text{dBm}]} - (N + I)_{[\text{dBm}]} - M_{I[\text{dB}]}^{UL/DL} + G_{P[\text{dB}]} \quad (3.14)$$

where:

- P_{Rx}: power at receiver input

The Rx's total noise power is:

$$N_{[\text{dBm}]} = -174 + 10 \cdot \log(\Delta f_{[\text{Hz}]}) + F_{[\text{dB}]} \quad (3.15)$$

where:

- F: Rx's (repeater, MT or BS) noise figure
- Δf: signal bandwidth, in UMTS equal to R_c
- $M_I^{UL/DL}$: interference margin for DL and UL

The interference power is obtained by adding the power of the different sources of interference. When a repeater is used, there are two sources of interference: one resulting from the feedback due to imperfect antenna isolation and another from the possibility of the Rx getting the signal not only from the repeater but also directly from the Tx. In this thesis, the latter is not considered, as it is negligible compared to the former. So, the interference power is equal to the feedback power:

$$I_{[\text{dBm}]} = P_{FB[\text{dBm}]}^{R} \quad (3.16)$$

where:

- P_{FB}^{R} : repeater's feedback signal power, (3.17)

When considering the single user model, the interference margin is not taken into account, as this model leads to load factors near 0%. In the BS-MT link, the repeater's feedback signal power is, obviously, discarded.

Due to the imperfect isolation between the antennas of the repeater, there is some feedback that must be taken into account. The feedback signal causes additional interference in the system, but only when one is considering signals of identical frequency, i.e., the UL feedback signal interferes only with the UL signal, and analogously for the DL signal, as illustrated in Figure 3.2. Assuming that both antennas of the repeater are placed back-to-back, the feedback signal power is obtained by adding to the repeater's EIRP the front-to-back ratio of both antennas and subtracting the free space path loss between them, valid both for DL and UL:

$$P^R_{FB[\text{dBm}]} = P^R_{EIRP[\text{dBm}]} + \Omega^R_{t[\text{dB}]} + \Omega^R_{r[\text{dB}]} - L_{0[\text{dB}]} \tag{3.17}$$

where:

- Ω^R_t : repeater's transmitting antenna front-to-back ratio
- Ω^R_r : repeater's receiving antenna front-to-back ratio
- L_0: path loss in free space propagation

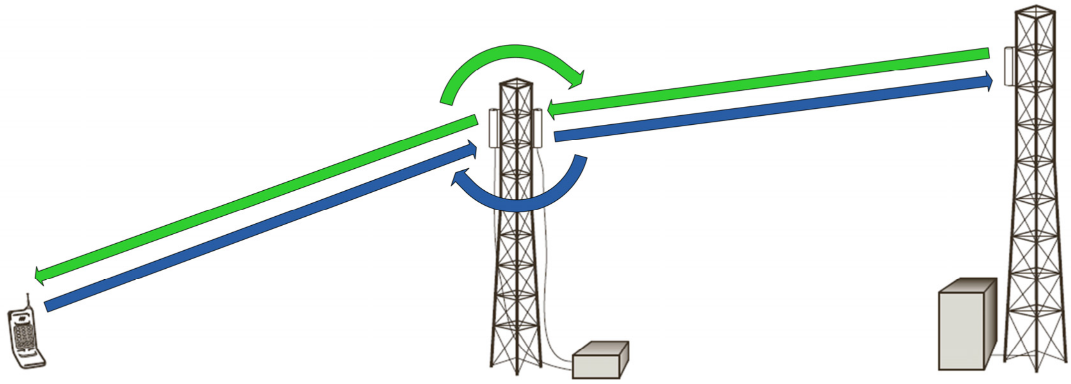


Figure 3.2 – Feedback related interference.

Some margins must be taken into account, to adjust additional losses due to radio propagation and others. So, the total margin due to additional losses is:

$$M_{[\text{dB}]} = M_{SF[\text{dB}]} + M_{FF[\text{dB}]} + L_{ind[\text{dB}]} - G_{SHO[\text{dB}]} \tag{3.18}$$

where:

- M_{SF} : slow fading margin
- M_{FF}: fast fading margin
- L_{ind}: indoor penetration losses
- G_{SHO}: soft handover gain (for HSUPA and Release 99 only)

Then, the maximum allowable path loss can be calculated by:

$$L_{p\max[\text{dB}]} = \underbrace{L_{p[\text{dB}]}}_{P_{Rx}=P_{Rx\min}} - M_{[\text{dB}]} \tag{3.19}$$

3.2 Single User Radius Model

The link budget presented in the previous section can be applied to two models: the single and the multiple users. The multiple users model considers a network with several users uniformly distributed and performing different services. The single user considers only one user, located at the edge of the cell in a network with no other load [Lope08], in order to calculate the maximum cell radius, i.e., the maximum distance that allows the user to be served with the desired throughput.

Several parameters, described in [CoLa06] and [Lope08], can be modified in the user interface, presented in Annex B. In this work, the new modifiable parameters are the ones concerning the repeater, namely:

- Donor and coverage antenna gains;
- Amplifier gain;
- DL and UL maximum Tx power;
- Distance between antennas and respective front-to-back ratio.

Other parameters, as noise factor and cable losses, can also be modified. The considered environments are pedestrian and vehicular, in both urban and rural areas.

The single user model obtains the cell radius using the total path loss as an input in one of the propagation models described in Annex C. When considering an urban area and the link between the repeater and the MT, the COST 231 Walfisch-Ikegami (W-I) model [DaCo99] is used, hence, the cell radius is given by [Lope08]:

$$R_{[\mathrm{km}]} = 10^{\frac{P_{EIRP[\mathrm{dBm}]} - P_{r[\mathrm{dBm}]} + G_{r[\mathrm{dBi}]} - M_{[dB]} - L'_{rt[\mathrm{dB}]} - L_{rm[\mathrm{dB}]} - L'_{0[\mathrm{dB}]}}{20+k_d}} \tag{3.20}$$

where:

$$L'_{rt[\mathrm{dB}]} = L_{rt[\mathrm{dB}]} - k_d \cdot \log(d_{[\mathrm{km}]}) \tag{3.21}$$

- L_{rt}: multiple screen diffraction loss
- k_d: dependence of the multi-screen diffraction loss versus distance
- d: distance
- L_{rm}: rooftop-to-street diffraction and scatter loss

$$L'_{0[\mathrm{dB}]} = L_{0[\mathrm{dB}]} - 20 \cdot \log(d_{[\mathrm{km}]}) \tag{3.22}$$

In the case of the BS-R link in an urban area, one considers free space attenuation and multiple screen diffraction loss (from COST 231 W-I). So, the cell radius in this case is:

$$R_{[\mathrm{km}]} = 10^{\frac{P_{EIRP[\mathrm{dBm}]} - P_{r[\mathrm{dBm}]} + G_{r[\mathrm{dBi}]} - M_{[dB]} - L'_{rt[\mathrm{dB}]} - L'_{0[\mathrm{dB}]}}{20+k_d}} \tag{3.23}$$

When considering a rural area, the COST 231 Okumura-Hata (O-H) model [DaCo99] is used, and the cell radius is given by:

$$R_{[\mathrm{km}]} = 10^{\frac{P_{EIRP[\mathrm{dBm}]} - P_{r[\mathrm{dBm}]} + G_{r[\mathrm{dBi}]} - M_{[dB]} - L'_{O-H[\mathrm{dB}]}}{44.90 - 6.55\log(h_{be[\mathrm{m}]})}} \tag{3.24}$$

where:

$$L'_{O-H[\mathrm{dB}]} = L_{O-H[\mathrm{dB}]} - [44.90 - 6.55\log(h_{be[\mathrm{m}]})]\log(d_{[\mathrm{km}]}) \tag{3.25}$$

- $L_{O\text{-}H}$: path loss obtained via the COST 231 O-H model, (C.11)

3.3 Delay

The two main paths from which the receiver gets the signal are: Tx-repeater-Rx and Tx-Rx (without passing through the repeater), as shown by Figure 3.3.

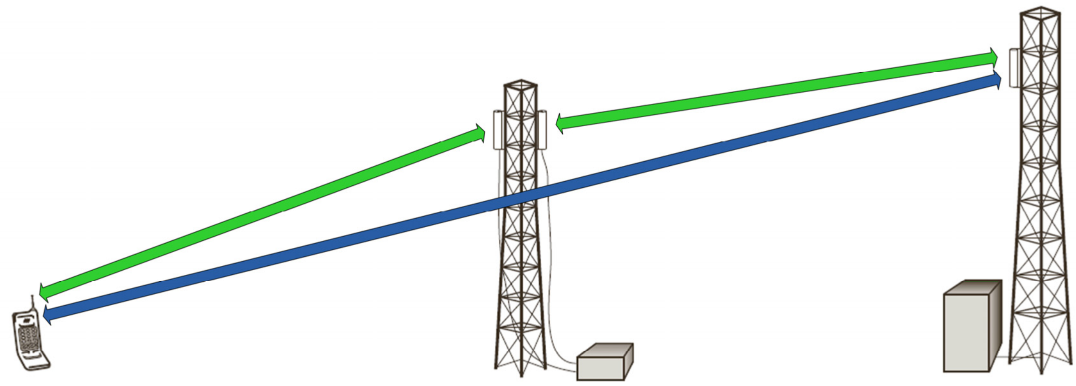


Figure 3.3 – The multipath issue between the BS and the MT.

As stated before, this multipath is not a problem if the time delay between the two paths is equal or lower than 20 μs [3GPP04], as in this case the Rake receiver will constructively combine the two signals [GACR07]. However, if a signal is not within this time window, its contribution will not be considered, but it will cause a certain level of 'self-interference'. The differential propagation delay between the two signals is given by:

$$\delta_\tau = \tau_{pBS-R} + \tau_R + \tau_{pR-MT} - \tau_{pBS-MT} \tag{3.26}$$

where:

- $\tau_{pBS\text{-}R}$: propagation delay between the BS and the repeater, defined as:

$$\tau_{pBS-R} = \frac{d_{BS-R}}{c} \quad (3.27)$$

- d_{BS-R}: distance between the BS and the repeater
- c: speed of light
- τ_R: repeater internal delay (usually between 5 and 6 μs)
- τ_{pR-MT}: propagation delay between the repeater and the MT, defined as:

$$\tau_{pR-MT} = \frac{d_{R-MT}}{c} \quad (3.28)$$

- d_{R-MT}: distance between the repeater and the MT
- τ_{pBS-MT}: propagation delay between the BS and the MT, defined as:

$$\tau_{pBS-MT} = \frac{d_{BS-MT}}{c} \quad (3.29)$$

- d_{BS-MT}: distance between the BS and the MT

Making the calculations, and assuming a repeater's internal delay of 5 μs, to avoid that 'self-interference' the difference between the distances travelled by the two signals cannot be greater than 4.5 km:

$$d_{BS-R} + d_{R-MT} - d_{BS-MT} \leq 4500 \quad (3.30)$$

This can limit either the BS or the repeater radius; hence, a more detailed analysis is required, for which purpose one considers three different situations, depicted in Figure 3.4, where each one is numbered according to the position of the user.

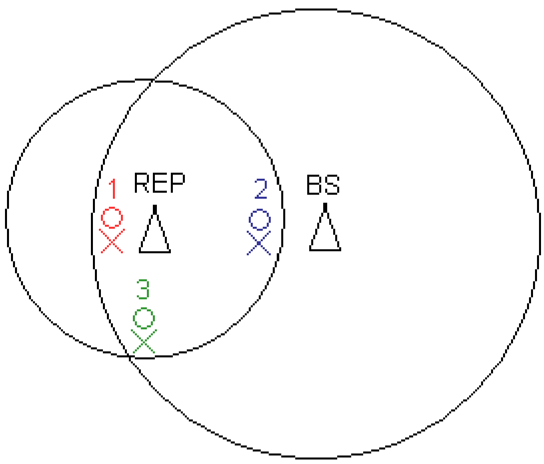


Figure 3.4 – Delay analysis schematic.

In Situation 1, the propagation delay between the two paths is exclusively due to the repeater's internal delay, so it does not limit any of the radii. In Situation 2, it is assumed that d_{BS-R} is equal to the BS radius and d_{R-MT} is equal to the repeater radius. Considering 4.5 km as the maximum difference between the two paths, one concludes that this situation limits the repeater radius to 2.25 km. As for Situation 3, assuming that d_{BS-R} = d_{BS-MT} is equal to the BS radius, it limits both radii to 4.5 km. So, to avoid the 'self-interference' due to the delay between the two paths in every situation, the BS and repeater radii are limited to 4.5 and 2.25 km, respectively.

The Rx gets the signal via many paths due to scattering, reflection or diffraction, which results in the signal experiencing time dispersion. The most common model used to represent the Power Delay Profile (PDP) of a time dispersive channel is the exponential decay model [Corr06]. When the receiver gets signals directly from the BS (or the MT) and via the repeater, the PDP of the overall received signal is the combination of the two individual profiles, as depicted in Figure 3.5 and expressed by [AlGa04]:

$$\mathcal{P}(\tau)_{[\mathrm{W/s}]} = \begin{cases} \frac{X_d}{\sigma_d} \cdot \exp\left\{-\frac{\tau}{\sigma_d}\right\}, & 0 < \tau < \delta \\ \frac{X_d}{\sigma_d} \cdot \exp\left\{-\frac{\tau}{\sigma_d}\right\} + \frac{X_r}{\sigma_r} \cdot \exp\left\{\frac{\tau-\delta}{\sigma_r}\right\}, & \delta \le \tau < \infty \end{cases} \quad (3.31)$$

where:

- $\mathcal{P}$: power delay
- τ: delay
- X_d: instantaneous signal level of the direct signal
- σ_d: delay spread of the direct path
- X_r: instantaneous signal level of the signal at the input of the repeater
- σ_r: delay spread of the path through the repeater

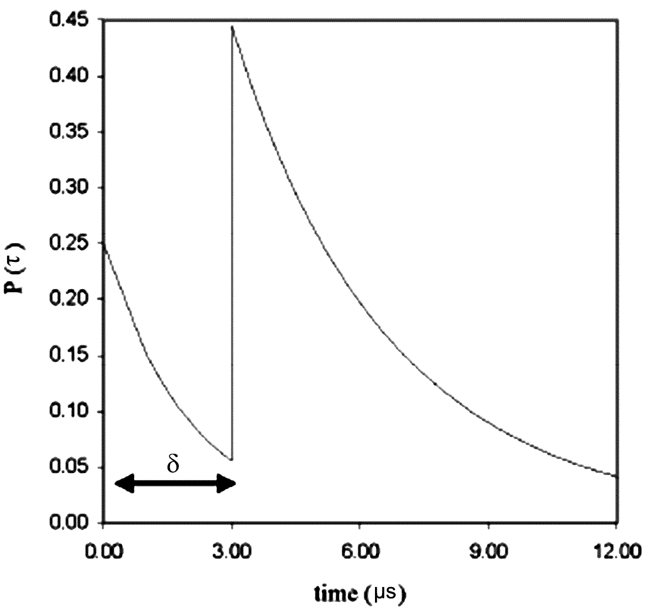


Figure 3.5 – Example of two signal power delay profile (extracted from [Ali06]).

3.4 Capacity

From the three fundamental parameters to analyse capacity (number of codes, load factor and the BS transmission power), the installation of a repeater affects only the last two.

The load factors can be obtained from (2.2) for UL and (2.3) for DL. A user connected to the BS via a repeater is, for a certain bit rate, likely to generate a higher load factor, since it probably requires a higher SNR. The equations to obtain the SNR from the bit rate (and vice-versa) are presented in Annex A.

The total BS transmission power is also a limiting factor when capacity is concerned, as it is shared among all users. For users connected directly to the BS, the total BS transmission power is obtained from (2.4). For users connected to the BS via the repeater, (2.4) is the total power that the repeater has to transmit to the MT. Hence, to calculate the transmitted power by the BS to a user within the repeater's coverage area, one has to take into consideration the link budget between the BS and the repeater. So, considering (2.4) and using (3.8), (3.9), (3.1) and (3.3), in this order – where applied, P_{Tx}^{R} and P_{Tx}^{BS} are replaced by P_{Tot}^{R} and P_{Tot}^{BS} –, one obtains:

$$P_{Tot[\text{dB}]}^{BS-R} = P_{Tot[\text{dB}]}^{R} - G_{amp[\text{dBi}]}^{R} + L_{c[\text{dB}]}^{R} - G_{r-BS[\text{dBi}]}^{R} + L_{p\ BS-R[\text{dB}]} - G_{t[\text{dBi}]}^{BS} + L_{c[\text{dB}]}^{BS} \tag{3.32}$$

where:

- $L_{p\ BS-R}$: path loss between the BS and the repeater
- G_{r-BS}^{R} : gain of the repeater's antenna receiving from the BS (donor antenna)
- P_{Tot}^{R} : total repeater transmission power, given by:

$$P_{Tot}^{R} = P_{Tx}^{R} + P_{C}^{R} \tag{3.33}$$

- P_{Tx}^{R} : repeater transmission power allocated to the traffic channels, given by (2.5)
- P_{C}^{R} : repeater transmission power allocated to the common channels

Equation (3.32) expresses the power that the BS has to transmit to a user (or group of users) connected via the repeater and requiring a certain bit rate and SNR.

3.5 Assessment Parameters

In this section, one presents the parameters that are analysed in the multiple users scenario.

- The blocking probability, P_b:

$$P_{b[\%]} = \frac{N_{ucov} - N_{userv}}{N_{ucov}} \cdot 100 \quad (3.34)$$

where:

- N_{ucov}: number of covered users
- N_{userv}: number of served users

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

$$\overline{R_{bj[\text{Mbps}]}} = \frac{R_{bserv[\text{Mbps}]}}{N_{userv}} \quad (3.35)$$

where:

- R_{bserv}: instantaneous served throughput, given by:

$$R_{bserv[\text{Mbps}]} = \sum_{j=1}^{N_{ucov}} R_{bj[\text{Mbps}]} \quad (3.36)$$

- The satisfaction grade, S_G:

$$S_G = \frac{\sum_{j=1}^{N_{ucov}} R_{bservj[\text{Mbps}]}}{\sum_{j=1}^{N_{ucov}} R_{breqj[\text{Mbps}]}} \quad (3.37)$$

where:

- R_{bservj}: served throughput of user j
- R_{breqj}: requested throughput of user j

3.6 Release 99/HSDPA/HSUPA with Repeater Simulator

In this section, the Release 99, HSDPA and HSUPA simulator developed is introduced. First, in Subsection 3.6.1, an overview of the simulator is presented, with the simulator's implementation being described in Subsection 3.6.2. In Subsection 3.6.3 the simulator input and output files are pointed out.

3.6.1 Simulator Overview

The simulator developed in this thesis, with the main structure being presented in Figure 3.6, was adapted from the ones developed in [CoLa06], for the Release 99 module, and [Lope08] and [Salv08], for the HSPA ones. While there were some changes introduced on the green modules, the main structure of the simulator was left unchanged. The presence of the repeater had to be programmed into the simulator, as well as the analysis of its impact.

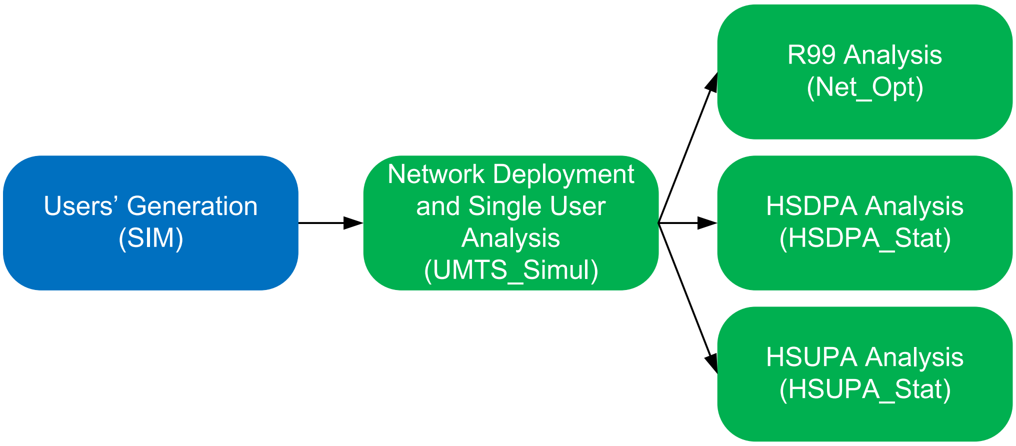


Figure 3.6 – Simulator overview.

This simulator has the primary objective of analysing repeaters in UMTS. It consists of five major modules:

- Users' Generation;
- Network Deployment without load;
- Release 99 analysis;
- HSDPA analysis;
- HSUPA analysis.

The Users' Generation module is described in detail in [CoLa06] and the version used is the one with the modifications introduced by [Lope08]. The input files for the traffic distribution are described in Annex D.

3.6.2 Repeater Implementation

In the remaining modules, changes were made in order to take the repeater into account.

The Network Deployment module is described in detail in [CoLa06]. This module places the users from the output file of the SIM program in the network, distributed throughout the most populated areas. After the users' placement, the network is deployed. In this thesis, only one BS is considered, but new routines had to be programmed so that the coverage area of the repeater is drawn, along with the BS's sectors. The user interface was modified in order to allow the modification of the repeater's amplifier gain and the BS-R distance, using default values for all the other repeater specific parameters. After the network deployment, a first network analysis is performed, BS and repeater's cell radii 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 Section 3.1. Again, the entire calculations specific to the repeater had to be programmed. Both the drawing of the coverage area and the calculation of the repeater's cell radius follow the same principles: the repeater is placed at a certain distance from the BS, after which the simulator can calculate the Rx power at the repeater; considering all gains and losses that occur at the repeater, its EIRP is computed, enabling the calculation of the radius and the drawing of the coverage area.

One of the main new features that had to be programmed is the interference caused by the repeater, as it has a direct impact on the calculations made every time a link budget is computed. The calculation of the interference comprehends obtaining the received and transmitted powers by the repeater, and taking the front-to-back ratio of both the repeater's antennas into account. Also, after the calculation of the interference power, the actual reduction in the repeater's sensitivity is obtained, then allowing the computation of the results with the interference considered.

All users within the coverage areas of the BS and of the repeater are the ones to be considered in the Release 99, HSDPA and HSUPA analysis modules. In Annex E, the user's manual for the UMTS_Simul is presented.

The Release 99 analysis module is described in detail in [CoLa06], and the HSPA ones in [Lope08]. The main objective of these modules is the analysis of network coverage and capacity, through a snapshot approach, calculating instantaneous network results. These modules were modified so that users covered by the repeater are taken into account. There are two important factors to consider when programming this new feature: as mentioned in Subsection 2.4.1, repeaters are transparent to their donor BS and, Subsection 2.4.2, there is no soft handover between the donor BS and the repeater. So, after the drawing of the coverage area of the repeater, the simulator has to consider the users covered by it. To do so, new routines had to be programmed so the simulator acknowledges this new area and considers users inside it as being covered, adding them to the total number of covered users, and then evaluating, from that total, the ones that are actually served.

The calculation of the coverage areas is done considering a reference scenario. It stands as an indicator for the number of users that are considered during simulations. A higher throughput considered for the reference scenario reduces the BS nominal radius, with fewer users being considered; the same happens if the vehicular environment is chosen instead of the pedestrian one. This analysis has the purpose of not considering users beyond the BS radius. The matter of the covered users has a slightly different approach in the Release 99 and HSPA analysis modules: while in the HSPA ones all users inside the coverage areas calculated considering the reference scenario are considered as covered, the Release 99 one recalculates the link budget for each user inside the coverage areas, taking that users' environment (pedestrian, vehicular or indoor) into account; so, the number of covered users returned is the number of effectively – meaning, with the respective environment considered – covered users.

There is one parameter that constitutes the main difference in the path loss calculation between single and multiple users models: the interference margin, used to emulate the load in the cell. Due to the interference margin, path loss decreases, leading to a lower cell radius when one compares the single user with the multiple users models.

The maximum instantaneous throughput at the BS is an important parameter in the analysis of system's capacity. In HSDPA, this value is associated to the number of HS-PDSCH codes. In this thesis, one only considers 10 codes for the multiple users analysis, for which the maximum application throughput is 6.0 Mbps; in HSUPA this value is 1.22 Mbps.

The Release 99 module considers up to four carriers, starting by serving the users with the requested throughput. This is done for each user within the coverage areas of the BS and of the repeater. A new Release 99 carrier is added if [CoLa06]:

- the number of used codes exceeds the number of available ones (16 codes from SF16 per carrier);
- the UL load factor is higher than 0.5;
- the DL load factor is higher than 0.7;
- the power used is higher than the available one.

The algorithm that implements the process described above is depicted in Figure 3.7.

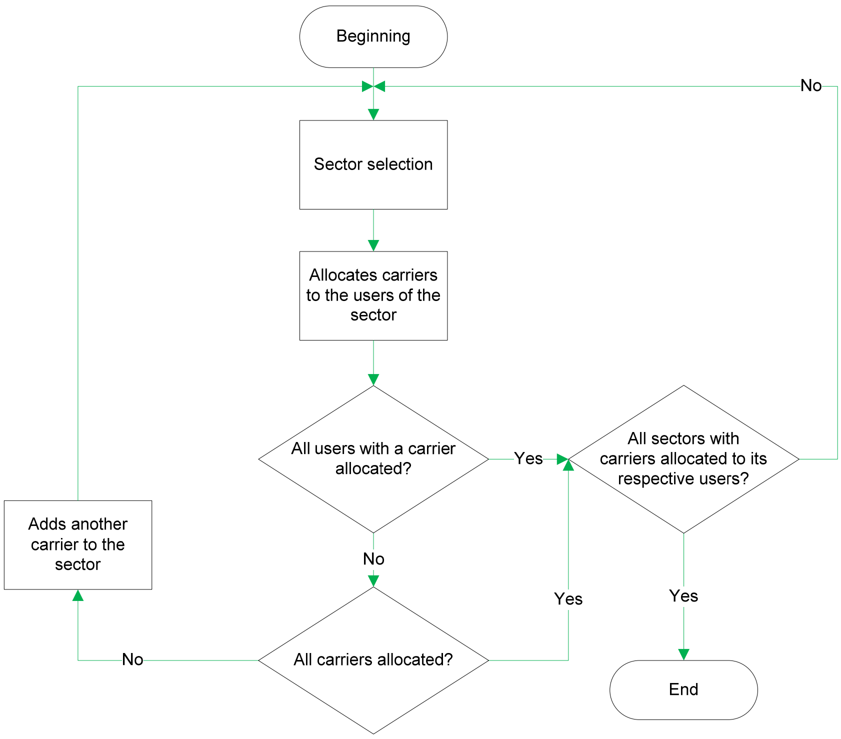


Figure 3.7 – Release 99's carrier allocation algorithm (adapted from [CoLa06]).

In HSPA, when considering the throughput that can be offered to the user, there are three different situations [Lope08]:

- the user is served with the requested throughput – the throughput associated to the path loss is higher than the service's throughput;

- the user is served with the throughput associated to the path loss – this throughput is higher than the minimum service and lower than the maximum service throughputs;
- otherwise, the user is delayed.

The procedure to calculate the user throughput for HSPA is shown in Figure 3.8.

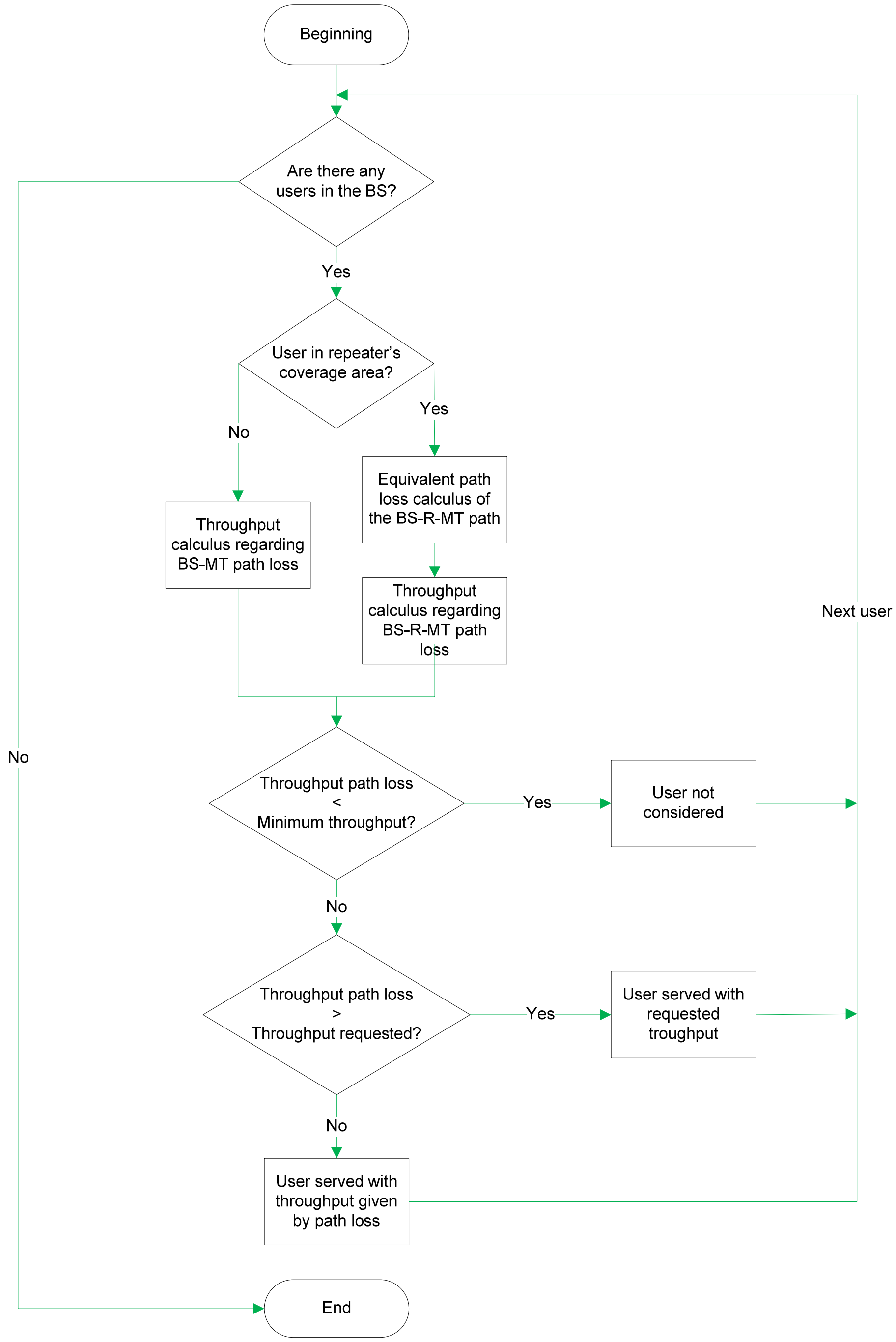


Figure 3.8 – HSPA user's throughput calculation algorithm (adapted from [Lope08]).

The analysis of system capacity is carried out at the BS level, by summing the throughput of all served users. Two possible cases can occur [Lope08]:

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

- otherwise, one of the reduction strategies, detailed in [Lope08], is applied.

This process is detailed in Figure 3.9.

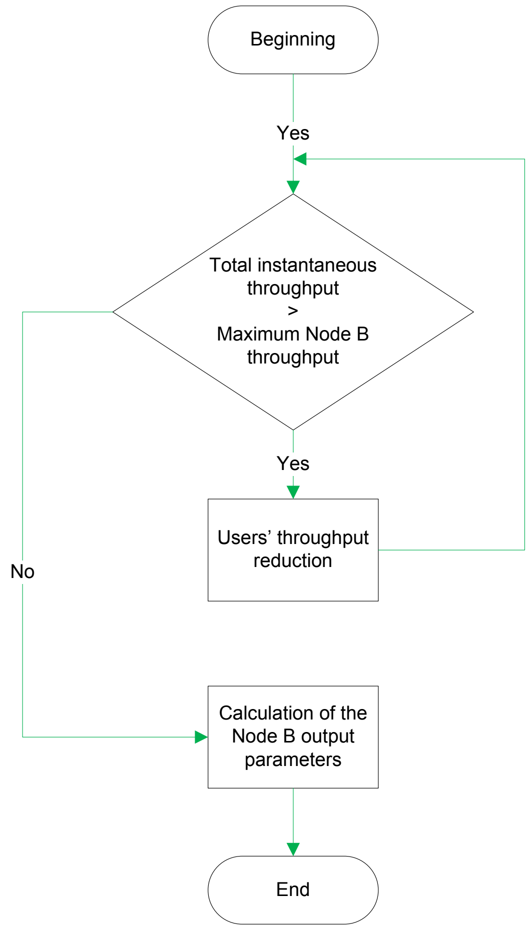


Figure 3.9 – HSPA algorithm to analyse the BS limitation (adapted from [Lope08]).

3.6.3 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;
- "Eb_N0.TAB", containing the E_b/N_0 values;
- "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;
- "EB.TAB", with the information of the location of the Node B.

The UMTS_Simul module creates 2 files that are going to be used by the Release 99, 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 Release 99, HSDPA and HSUPA modules execute the network analysis and produce several output files, which are used by the UMTS_Simul to present the results in MapInfo:

- “stats.out”, which includes all HSPA results for the instantaneous analysis, both for the network analysis and the statistics by service;
- “user.out”, with the information regarding the Release 99 users in the network, number of blocked, delayed and uncovered users;
- “data.out”, with the information about each sector and each Release 99 carrier.

3.7 Simulator Assessment

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

Regarding users’ insertion in the network and reduction strategies, the necessary validations have already been performed in [CoLa06] and [Lope08].

User’s geographical positions, as well as the requested throughputs, are random variables; hence, several simulations must be taken to ensure result validation. The default number of users considered per simulation is approximately 690 for Release 99 and 338 for HSPA (these results are justified in Section 4.1). Considering this value, 30 simulations were performed, executed in an Intel Core 2 Duo CPU at 2.4 GHz and 3 GB RAM, with an average simulation duration of 6 minutes for Release 99 and 2 minutes for HSPA. The parameter considered in this analysis is the number of served users.

The number of simulations is estimated based on the results presented in Figure 3.10, from which one can observe that there is almost no variation in the average, and that the standard deviation presents smooth variations. Also, Figure 3.11 presents the ratio of the standard deviation over the average value, where it is observed that there is no significant variation of this value when the number of simulation increases.

Taking those results into account, and in order to maintain the simulation time to a minimum, one has concluded that 5 is a suitable number of simulations, allowing a good accuracy and not requiring extended time of simulations. These results were obtained for HSDPA simulations. Although this is a different system from HSUPA and Release 99, with specific features, the simulation principle is essentially the same, and so, the same number of simulations is used for all systems.

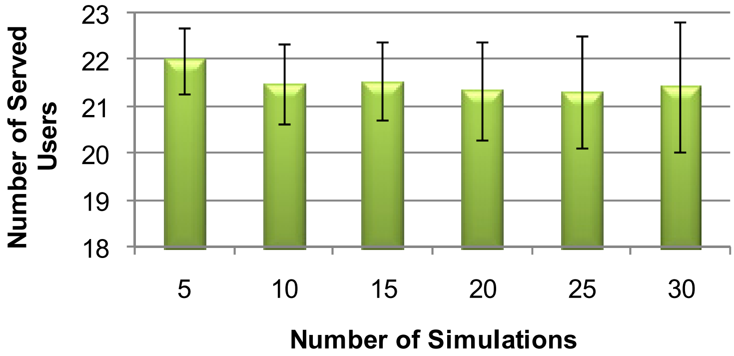


Figure 3.10 – Evolution of the number of served users for 30 simulations.

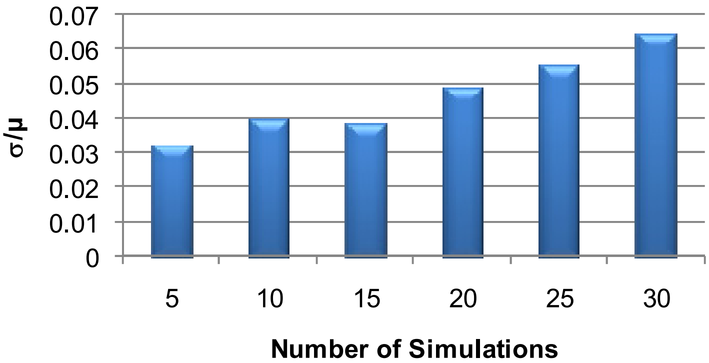


Figure 3.11 – Evolution of the standard deviation over average ratio for 30 simulations.

Chapter 4

Results Analysis

In this chapter, the results for both the single and multiple users simulator are presented. First, the single user radius model is analysed, for Release 99, HSDPA and HSUPA. Then, the results for the multiple users simulator presented in Chapter 3 are presented, considering several parameter variation, such as the repeater's amplifier gain or the BS-R distance, for the 3 systems analysed.

4.1 Scenarios Description

As mentioned earlier, two approaches are considered throughout this thesis: the single user and the multiple users ones. The environments considered for the single user analysis are pedestrian and vehicular (both for either urban or rural areas). For the multiple user analysis, one also considers the indoor environment and only the urban area is analysed, as it is considered that, since in a rural area the distribution of users is more scattered, the single user approach already gives a good approximation of the reality. 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 and fast fading margins is considered; the indoor environment characterises users performing services inside buildings. There are two kinds of indoor environment: the low and high losses, where the latter is used for users in deep indoor locations with high penetration attenuation. The percentages taken into account for the environments are [Lope08]:

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

In Table 4.1, one lists the attenuation margins associated with each type of environment.

Table 4.1 – Slow and fast fading and penetration margins values.

	Environment					
	Urban				**Rural**	
	Pedestrian	**Vehicular**	**Indoor low loss**	**Indoor high loss**	**Pedestrian**	**Vehicular**
M_{SF} [dB]	4.5	7.5	7.0	7.0	2.5	5
M_{FF} [dB]	0.3	1	0.3	0.3	0.1	1
L_{int} [dB]	0	11	11	21	0	5

The profile used for the services' penetration percentages, in HSPA, is depicted in Figure 4.1, [Lope08].

The parameters for link budget estimation, used for both scenarios, and the considered default values, are the ones listed in Table 4.2. For the single user scenario, the interference margin and the reduction strategy are not considered. The BS antenna gain is 17 dBi, with a 65º half power beam width radiation pattern detailed in [CoLa06]. For the single user scenario, the maximum BS antenna gain is used. Table 4.3 lists the default values assumed for the repeater.

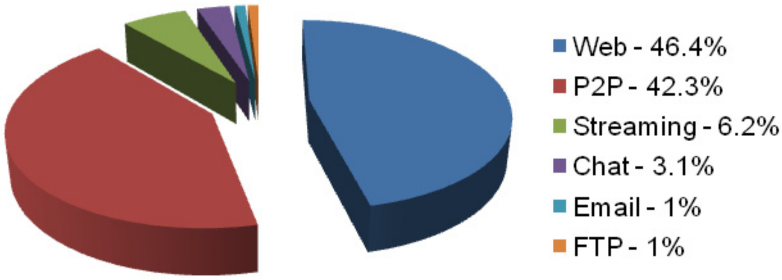


Figure 4.1 – Service profile.

Table 4.2 – Default values used in the link budget (based on [CoLa06] and [Lope08]).

Parameter	DL		UL	
	R99	R5	R99	R6
BS transmission power [dBm]	44.7		---	
MT transmission power [dBm]	---		24	
Frequency [MHz]	2112.5		1922.5	
Number of HS-PDSCH codes	---	10	---	
MT antenna gain [dBi]	0			
Maximum BS antenna gain [dBi]	17			
Cable losses between transmitter and antenna [dB]	2			
User losses (Voice) [dB]	3	---	3	---
User losses (Data) [dB]	---	1	---	1
Noise figure [dB]	9		5	
Diversity gain [dB]	---		3	
SHO gain [dB]	3	---	3	
Interference margin [dB] (multiple users)	5.2	6	3	6
Percentage of power for signalling and control [%]	25	10	---	
Throughput [kbps]	12.2	384	12.2	128
Environment	Pedestrian			
Reduction strategy	"QoS class reduction"			

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 and the traffic models characteristics detailed by service, are the ones presented in Table 2.5. In Release 99, one considers only the voice service and, in HSPA, only data services (which maintain their relative QoS priority values).

To determine the number of users in the default scenario, several simulations were performed to analyse the impact of the variation of the number of users in several parameters. The parameters analysed are different in Release 99 and HSPA. In Release 99, the objective is to find the number of users that leads to a blocking probability of approximately 1%. This approach leads to a default number of users of 690, which is the number of users in the area of the BS and repeater under analysis, all performing voice service. In HSPA, one analyses the number of users that are effectively served, Table 4.4. The number of users chosen is 338, as it is the one that resulted in a lower standard deviation. As mentioned before, in HSPA there is a certain service's penetration profile, hence, this 338 users are performing several different services.

Table 4.3 – Default values for repeater's parameters.

Parameter	
DL maximum transmission power [dBm]	32
UL maximum transmission power [dBm]	32
Amplifier gain [dB]	60
Donor antenna gain [dBi]	25
Coverage antenna gain [dBi]	17
Donor antenna front-to-back ratio [dB]	-40
Coverage antenna front-to-back ratio [dB]	-20
Cable losses [dB]	2
Noise figure [dB]	2.5
Distance between antennas [m]	2
BS-R distance [km]	1.5

Table 4.4 – Evaluation of the number of users.

	Approximate number of users							
	185		188		338		412	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
Number of served users	16.9	1.79	17.0	1.89	21.5	0.85	24.1	1.45

4.2 Single User Radius Model Analysis

In this section, Release 99, HSDPA and HSUPA results, considering the single user analysis, are presented. Two sets of results are considered: the cell radius between the BS and the repeater, and between the repeater and the MT, where each link is individually considered; both radii but considering the whole link (between the BS and the MT), where the power received by the repeater, its amplifier gain and interference are taken into account. In some cases, the obtained radii exceed the delay limited distances explained in Section 3.3 (4.5 km for the BS-R distance and 2.25 km for R-MT one), so, in such situations, the value presented is the delay limited one. In Annex F, one shows the tables with the main results regarding the single user analysis. When presenting the results in figures, in order to make them clearer, one uses “Ped” when referring to the pedestrian environment and “Veh” for the vehicular one.

4.2.1 Release 99 Evaluation

All the cell radius results in this subsection (and the following ones) were calculated using the single user model described in Section 3.2 and the values from Table 4.2 and Table 4.3. Release 99’s cell radii, considering voice service, for the environments introduced in Section 4.1, are presented in Figure 4.2.

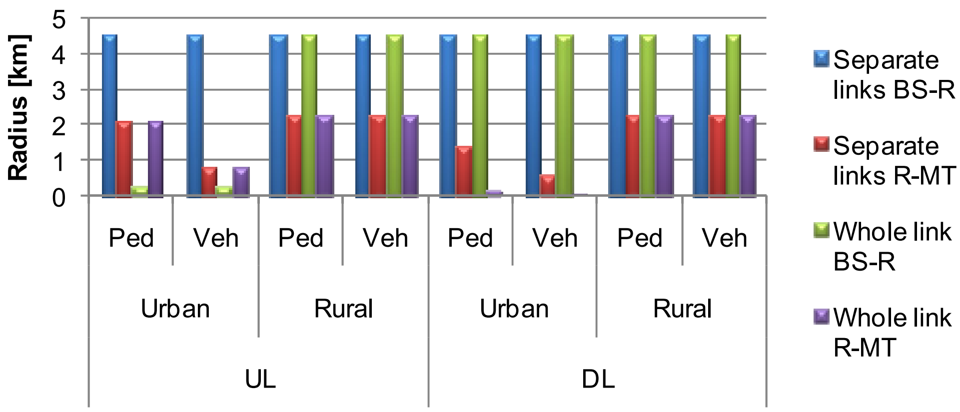


Figure 4.2 – Release 99 cell radii for the voice service with environment variation.

Some distances, when considering the whole link, obtained for urban areas are very limitative, as they restrict the placement of the repeater to a maximum distance of 0.24 km from the BS in UL and do not allow the MT to be farther than 0.06 km from the BS in DL. In these situations, one chooses to do a different approach: to obtain the R-MT distance as a function of the BS-R one, Figure 4.3. The results obtained for rural areas are always limited by the delay, hence, offer no other restrictions, and show that the placement of the repeater can be done with a good degree of flexibility. So, doing the same approach for rural areas is unnecessary and would lead, considering the same range of BS-R distances, to obtaining the maximum R-MT distance when separate links are considered. This is because the repeater is, for any considered amplifier gain, always transmitting its maximum power.

As expected, the cell radius is lower when considering a vehicular environment, both in urban and rural areas. This is due to the fact that the vehicular environment has higher attenuation margins and E_b/N_0.

For the installation of a repeater to be of interest, one considers that the R-MT distance has to be, at least, 0.1 km. This is not limitative in a pedestrian environment, as the R-MT distance is always higher than this value for BS-R distances up to 4.5 km (the limit imposed by the delay); as for the vehicular environment, it allows a BS-R distance of 2.5 km in DL and 2.0 km in UL. Figure 4.3 also highlights the fact that this link is UL limited. However, that is not always the case: when the gain is increased, the connection becomes DL limited, as depicted by Figure 4.4 (showing the R-MT distance as a function of the BS-R one, for a repeater's amplifier gain of 90 dB) and Figure 4.5 (depicting the R-MT distance as a function of the gain, for a repeater at 1 km from the BS).

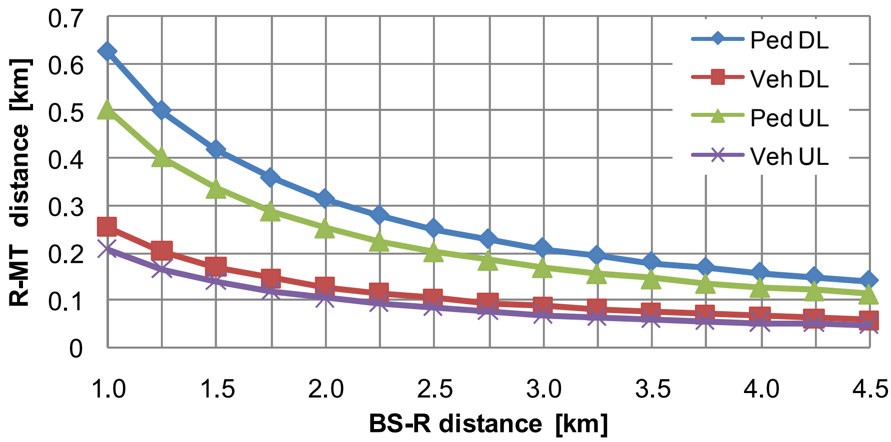


Figure 4.3 – Release 99 R-MT distance as a function of the BS-R one.

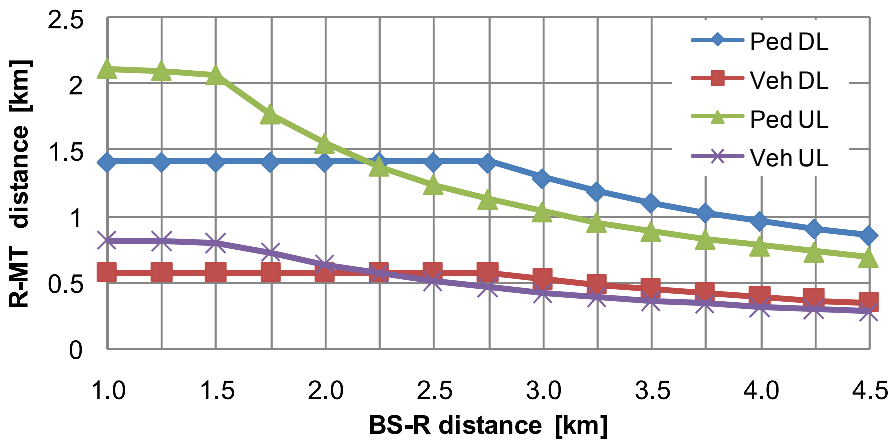


Figure 4.4 – Release 99 R-MT distance as a function of the BS-R one for 90 dB repeater's amplifier gain.

This change of the link that limits the connection is due to the fact that, in DL, there is an extra limiting factor: the maximum repeater transmission power (that in UL is never reached). This explains why, at a gain of 90 dB, the R-MT distance is the same for BS-R distances between 1.0 and 2.75 km (Figure 4.4), and why there is no change in the DL R-MT distance when the gain is increased to values past 75 dB (Figure 4.5). In UL, the obtained distances are only noise limited, this being the factor that explains why there is little or no difference when considering BS-R distances between 1.0 and 1.5 km, Figure 4.4, and why the R-MT distance remains constant, Figure 4.5, when increasing the gain from 85 to 90 dB. Note that, in Release 99, interference is never a limitation, as the reduction in the repeater's sensitivity is never sufficient to limit distance in either links.

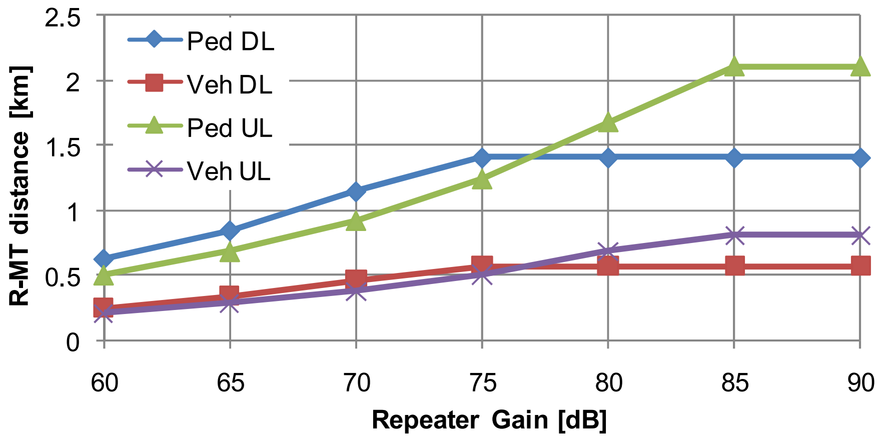


Figure 4.5 – Release 99 R-MT distance as a function of the repeater's amplifier gain.

Analysing the influence of the repeater's amplifier gain in the R-MT distance, one can conclude the following: in UL, the increase of the repeater's amplifier gain from 60 to 85 dB leads to an increase of the R-MT distance by a factor of 4.22, to 2.1 km, and 3.86, to 0.8 km, in pedestrian and vehicular environments, respectively; in DL, the R-MT distance increases 2.24 times, to 1.4 km, and 2.28 times, to 0.6 km, (respectively, for pedestrian and vehicular environments) when the repeater's amplifier gain is increased from 60 to 75 dB.

So, in Release 99, the R-MT distances obtained are always higher than 0.1 km for the pedestrian environment; the same can be said for the vehicular one, for BS-R distances up to 2.5 and 2.0 km (DL and UL, respectively). For the default conditions the link is UL limited, but, at higher repeater gains it may become DL limited due to the maximum repeater transmission power. For a BS-R distance of 1 km, at 75 dB the maximum transmission power is reached, and the connection becomes DL limited. Interference is never a limitation in Release 99.

4.2.2 HSDPA Evaluation

All the results presented in this section were obtained for a throughput, unless mentioned otherwise, of 3 Mbps. Figure 4.6 presents the HSDPA cell radii for the environments considered.

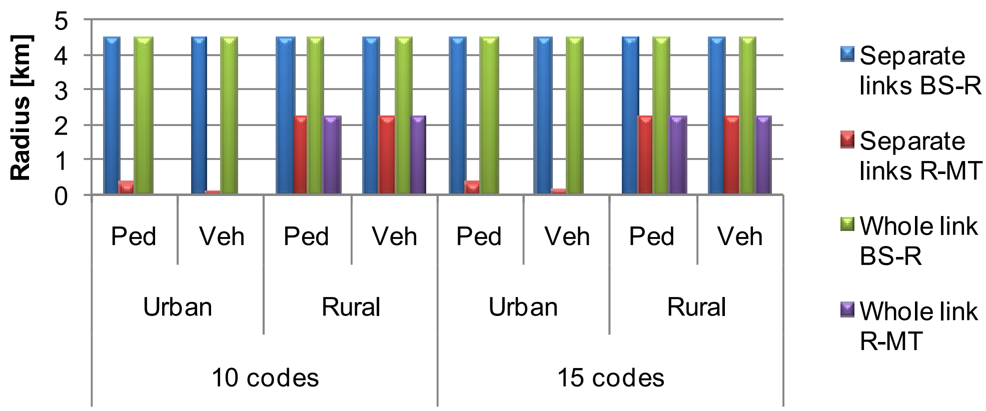


Figure 4.6 – HSDPA 10 and 15 codes cell radii for 3 Mbps with environment variation.

As for Release 99, some of the values obtained for urban areas are quite limitative, so the analysis of the R-MT distance as a function of the BS-R one in urban areas is also justified. Once again, and for similar reasons, the radii calculated for rural areas dismiss the need for an identical approach.

From that analysis, one concludes that the cell radius decreases when considering vehicular environment, in both urban and rural areas. In the HSDPA case, this is only due to the higher attenuation margins, since in this thesis one did not consider the SINR variation with the type of environment. Delay does not limit either distance, as the R-MT distance decreases below the minimum that is considered to be acceptable (0.1 km) before the BS-R one reaches the limit imposed by the delay, never even reaching it in the vehicular case. In fact, even in the pedestrian one, this distance is reached only for a BS-R distance of up to 1.25 km. Hence, as before, it is useful to observe the variation of the R-MT distance with the repeater's amplifier gain, for a certain BS-R distance (1 km), but now also considering different throughputs for 10, Figure 4.7, and 15 HS-PDSCH codes, Figure 4.8, where "Ped x" and "Veh x" represent pedestrian and vehicular environments at a throughput of x Mbps.

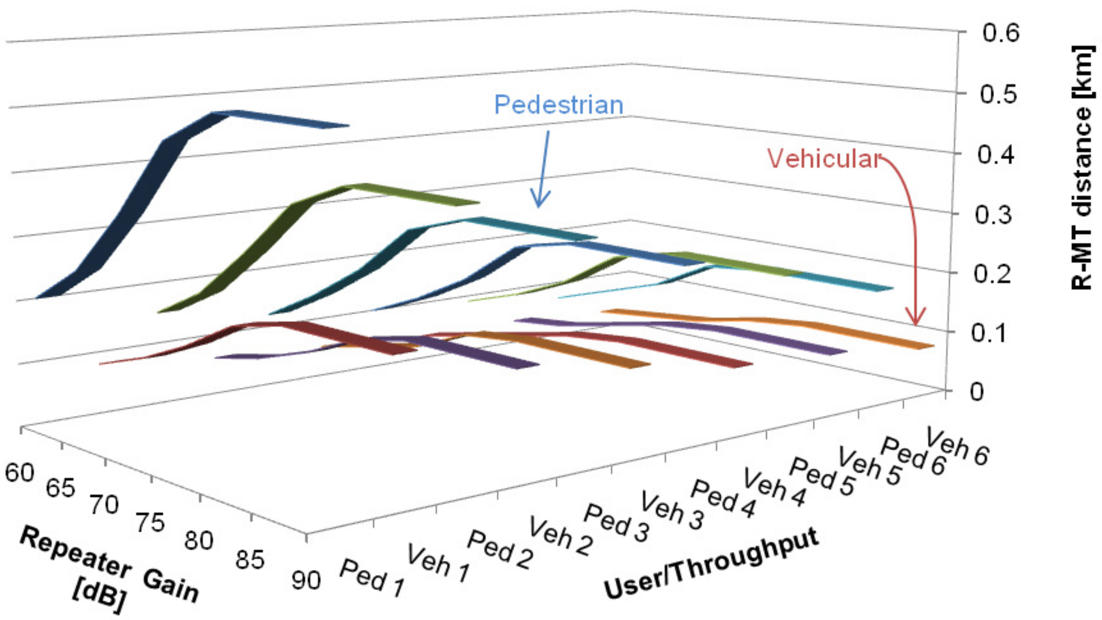


Figure 4.7 – HSDPA R-MT distance as a function of the repeater's amplifier gain for several throughputs.

As in Release 99 DL, the maximum repeater transmission power limits distances: at an amplifier gain of 80 dB that maximum is already achieved and no advantage is taken from further increasing the gain. Apart from that, only noise limits the distance between the repeater and the MT, since, in HSDPA, interference affects the BS-R link: at a gain of 60 dB it is not a limiting factor; however, at 90 dB and 10 HS-PDSCH codes, it restricts the BS-R distance to 1.5 km.

Considering the default values, increasing the gain from 60 to 80 dB leads to an increase in the R-MT distance by a factor of 2.83, to 0.3 km, in pedestrian and 2.8, to 0.1 km, in vehicular environment.

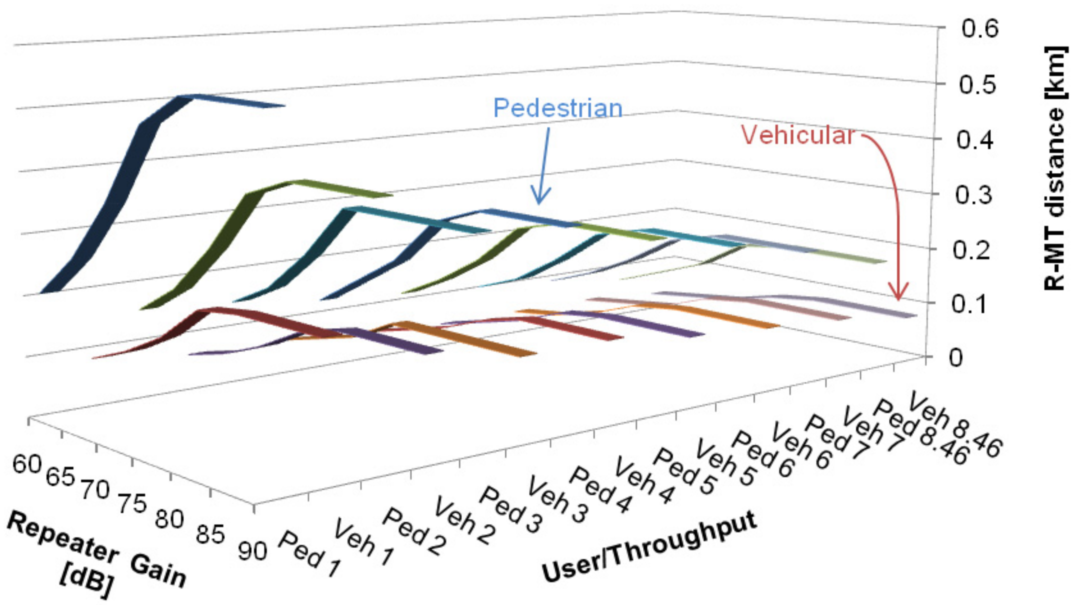


Figure 4.8 – HSDPA 15 codes R-MT distance as a function of the repeater's amplifier gain for several throughputs.

For all environments and number of codes, it is possible to observe that the R-MT distance decreases with the increase of the throughput. This is due to the fact that higher throughputs require higher SINR values, Figure A.1. One can also note that there is an increase in the R-MT distance when using 15 codes instead of 10. This is due to the curves presented in Figure A.1, where it is possible to observe that, for the same throughput, the use of 15 codes allows a higher cell radius than the use of 10 codes. Considering the pedestrian environment, a repeater's amplifier gain of 80 dB and 10 codes, one obtains an R-MT distance of 0.5 km for 1 Mbps and 0.2 km for 6 Mbps; for 15 codes the values are 0.6 and 0.3 km, respectively.

For HSDPA, the following concluding remarks can be made: the 0.1 km of distance between the BS and the repeater is never reached in a vehicular environment and, in a pedestrian one, it is only when the BS-R distance is lower than 1.25 km; for a BS-R distance of 1 km, the maximum R-MT one is reached at a gain of 80 dB, due to the maximum repeater transmission power; interference limits the BS-R distance, but only at higher gains; increasing the throughput leads to a decrease of the R-MT distance and the inverse happens when increasing the number of codes from 10 to 15.

4.2.3 HSUPA Evaluation

The cell radius results presented here were calculated for, unless mentioned otherwise, a throughput of 1.22 Mbps. Figure 4.9 presents the HSUPA radii for the environments considered.

As in the previous cases, the results for the urban areas are too limitative and an analysis of the R-MT distance as a function of the BS-R one is useful, Figure 4.10, and the ones for rural areas do not need a more detailed analysis.

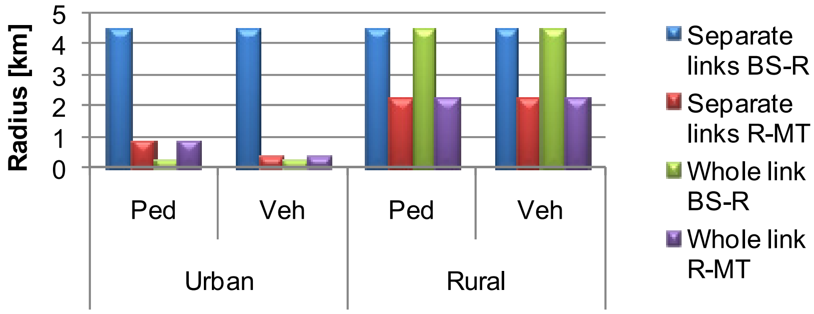


Figure 4.9 – HSUPA cell radii for 1.22 Mbps with environment variation.

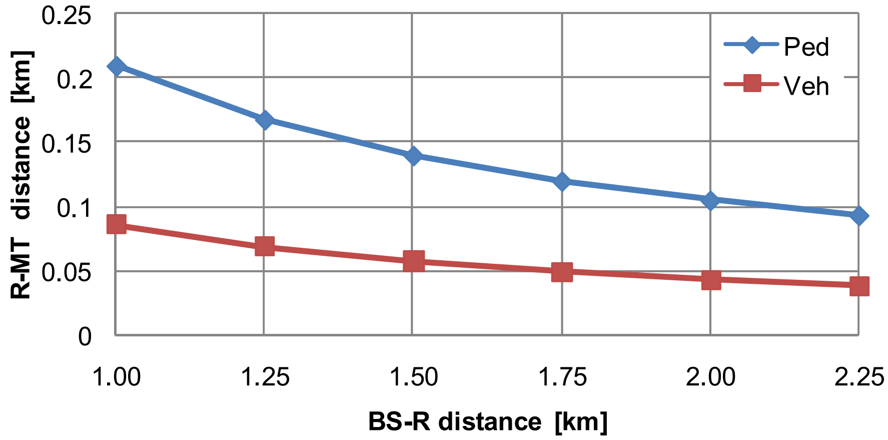


Figure 4.10 – HSUPA R-MT distance as a function of the BS-R one.

Once again, and for the same reasons of the HSDPA case, the pedestrian environment leads to a larger radius than the vehicular one, both in urban and rural areas. Figure 4.10 also shows that, at a BS-R distance of 2.25 km, the minimum distance between the repeater and the MT is not achieved in both environments (in the vehicular case it is never achieved) – which means that the delay does not pose a limitation –, indicating that one should use a higher amplifier gain.

In HSUPA, interference affects the R-MT link, by decreasing the repeater's sensitivity, and it has a considerable effect at amplifier gains higher than 80 dB. Figure 4.11 depicts the variation of the R-MT distance with that gain, for both environments, and interference and no interference cases, for a BS-R distance of 1 km. The increase of the repeater's amplifier gain from 85 to 90 dB does not influence the R-MT distance. That is due to the limitation introduced by noise: the MT cannot be farther away from the repeater, as the sensitivity from the latter does not allow it. Increasing the gain from 60 to 85 dB, leads to an increase in the repeater radius by a factor of 3.52, to 0.7 km, for the pedestrian environment and of 3.33, to 0.3 km, for the vehicular one. At 85 dB there is a reduction of 22% and 23% (respectively, for pedestrian and vehicular environments) on the R-MT distance due to interference.

Figure 4.12 shows the R-MT distance as a function of the repeater gain considering different throughputs, for a BS-R distance of 1 km.

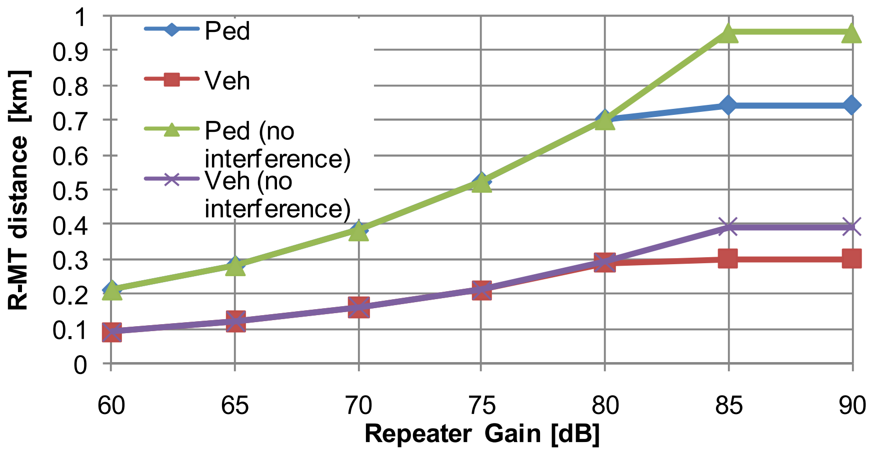


Figure 4.11 – HSUPA R-MT distance as a function of the repeater's amplifier gain.

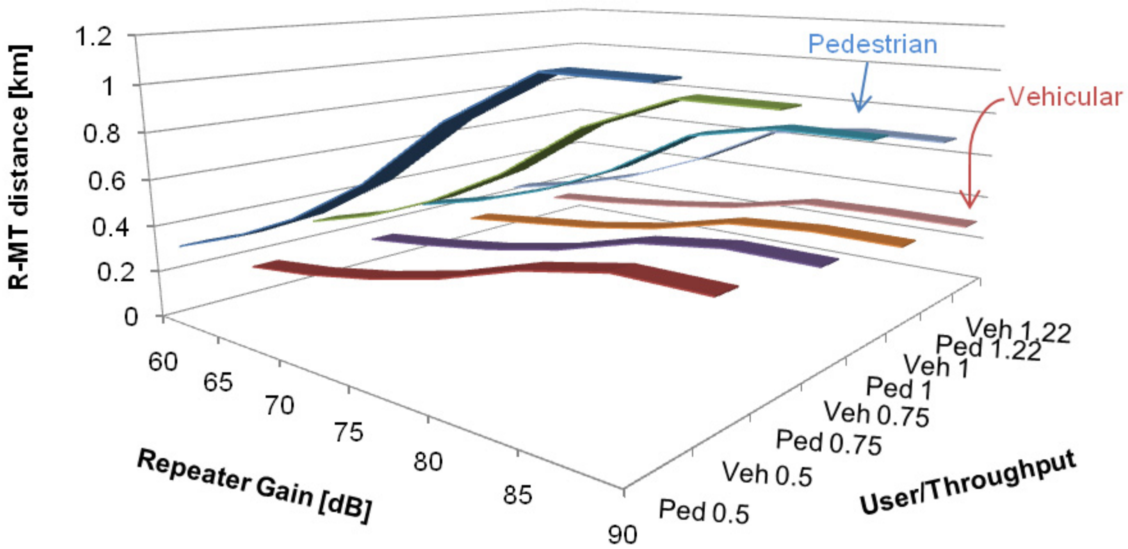


Figure 4.12 – HSUPA R-MT distance as a function of the repeater's amplifier gain for several throughputs.

The increase in the throughput leads to an expected decrease in the R-MT distance, explained by the increase in E_c/N_0 depicted by the curve in Figure A.3. Considering the pedestrian environment and for an amplifier gain of 85 dB, one has an R-MT distance of 1.2 km for 0.5 Mbps and of 0.7 km for 1.22 Mbps. For the vehicular environment the correspondent values are 0.5 and 0.3 km.

As a conclusion for the HSUPA analysis, one can highlight that the minimum R-MT distance (0.1 km) is never achieved in a vehicular environment, this requirement being fulfilled for the pedestrian one if the BS is not more than 2.0 km away from the repeater. Also, interference has a considerable effect in the R-MT link, limiting its maximum distance up to 23%. Due to the effect introduced by noise, for a BS-R distance of 1 km, the increase of the repeater gain beyond 85 dB does not lead to an increase in the R-MT distance. Finally, the increase in the throughput decreases the R-MT distance.

4.3 Release 99 Analysis in a Multiple Users Scenario

In this section, Release 99 simulation results are analysed. First, one examines the results of the default scenario, presented in Section 4.1, with variation of the repeater's amplifier gain. Afterwards, two more subsections introduce variations of two more parameters: BS-R distance and number of users. In Annex G additional results are shown. All the results presented in this section (and the following ones) were obtained using the multiple users simulator introduced in Section 3.6, and, for the default scenario, the system parameters presented in Table 4.2 and Table 4.3.

4.3.1 Default Scenario

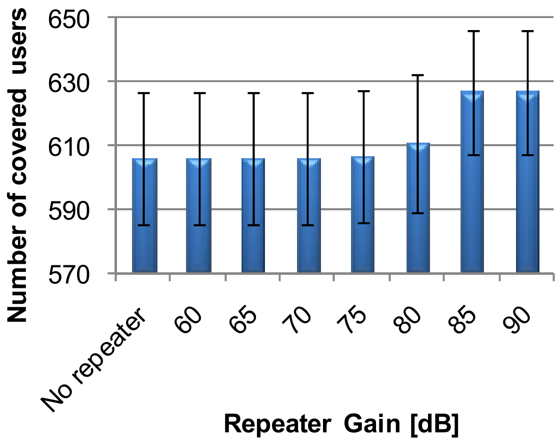
Figure 4.13 depicts the number of covered users, the covered area and the number of covered users per km^2 as a function of the repeater gain. As expected, with the increase of the repeater gain there is an expansion of the covered area (up to 7.81%), accompanied by an increase in the number of covered users (of 3.34%), until a gain of 85 dB. From that point on, there is no more increase, since the repeater reaches its maximum transmission power. For gains between 60 and 70 dB there is not an increase in the covered area because the repeater's coverage area is completely inside the BS one (the BS radius is 1.9 km, hence, as the BS-R distance is 1.5 km, the repeater radius has to be higher than 0.5 km – considering 0.1 km as the minimum – in order to increase the covered area). For 75 dB, there is an increase in the covered area, but not in the number of covered users. This can be explained by two facts: first, the increase in the covered area is not very significant – 0.28 km^2 –, which means that the new covered area may not reach any new users; then, because the Release 99 module reanalyses the covered users in light of their environment (Subsection 3.6.2) and only 10% of the users are pedestrian, may lead to some users that are reached by this new covered area to not be considered as covered. In Figure 4.13 b), a trend line is also represented. This line is, for values of the repeater gain between 65 and 85 dB, a polynomial of the second order with a correlation factor of 0.983; for that section, the trend line is given by (4.1). This is expected, since the covered area is a function of the square of the radius, which increases with the gain. From Figure 4.13 c), one can observe that, when the increase in the repeater gain actually represents an increase in the covered area, the number of covered users per km^2 decreases slightly, showing that the coverage area of the repeater is expanding to regions with lower user density.

$$A_{\mathrm{cov}[\mathrm{km}^2]} = 0.00177 \cdot {G^{R}_{amp[\mathrm{dB}]}}^2 - 0.21732 \cdot G^{R}_{amp[\mathrm{dB}]} + 17.975 \qquad (4.1)$$

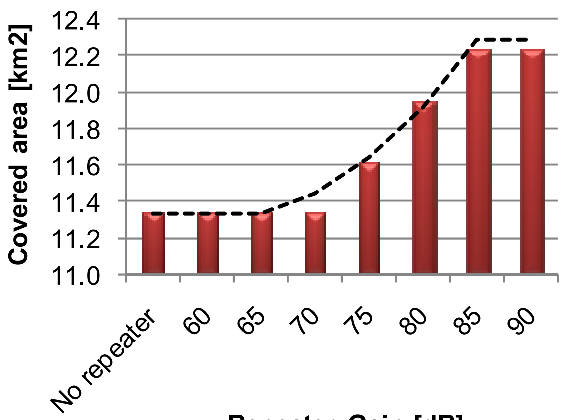
where:

- A_{cov}: covered area

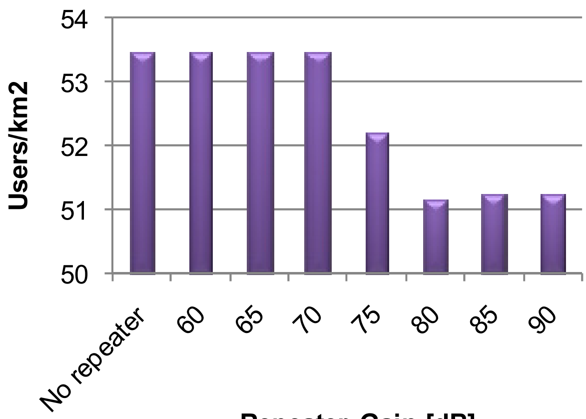
The blocking probability variation with the repeater's amplifier gain is shown in Figure 4.14. This parameter has a high standard deviation as it is very sensitive to the distribution of the users: a few more users covered are sufficient to increase the blocking probability significantly. The values obtained for this parameter are 3% to 4%, approximately. This is a high blocking probability, and it is due to the fact that several users are being covered by only one BS. One can observe a trend to an increase of the blocking probability with the repeater gain, although this is not very clear as the variations are always within the standard deviation limits.



a) Number of covered users.



b) Covered area.



c) Number of covered users per km^2.

Figure 4.13 – Release 99 coverage parameters as a function of the repeater's amplifier gain.

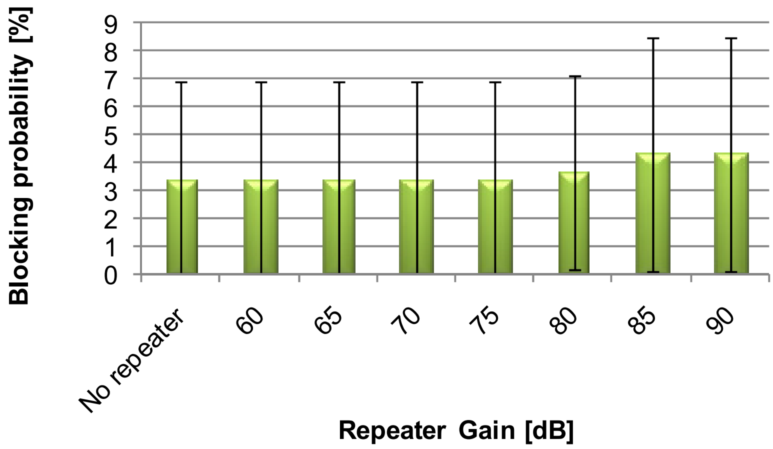
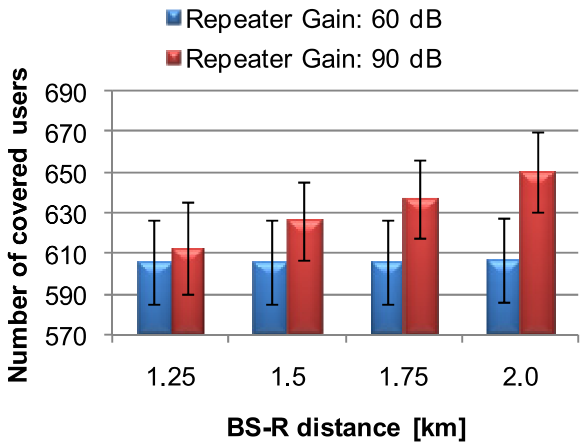


Figure 4.14 – Release 99 blocking probability as a function of the repeater's amplifier gain.

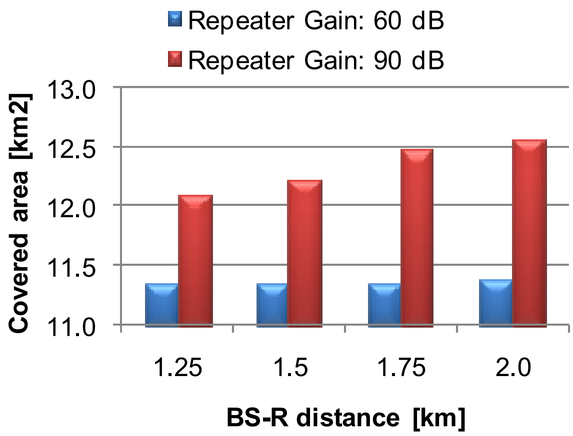
As a conclusion for the Release 99's default scenario analysis, one can note that the number of covered users increases 3.34% with the repeater gain for values between 75 and 85 dB, since the repeater reaches its maximum transmission power. The blocking probability shows a trend to increase with the repeater gain.

4.3.2 Distance between the BS and the Repeater

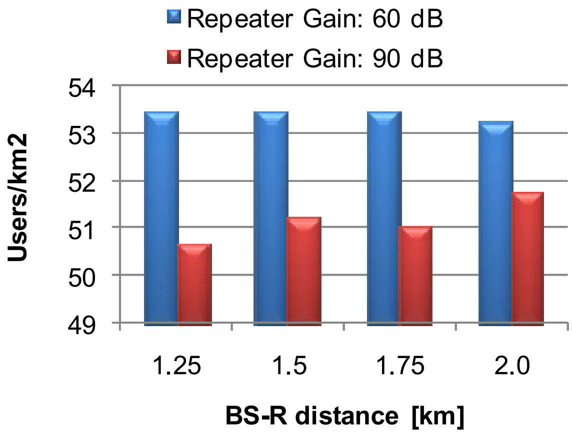
In this subsection, the variation of the BS-R distance is introduced. Figure 4.15 shows the number of covered users, the covered area and the number of covered users per km^2 as a function of the BS-R distance for repeater gains of 60 and 90 dB. For all the other values of the repeater gain, refer to Annex G.



a) Number of covered users



b) Covered area

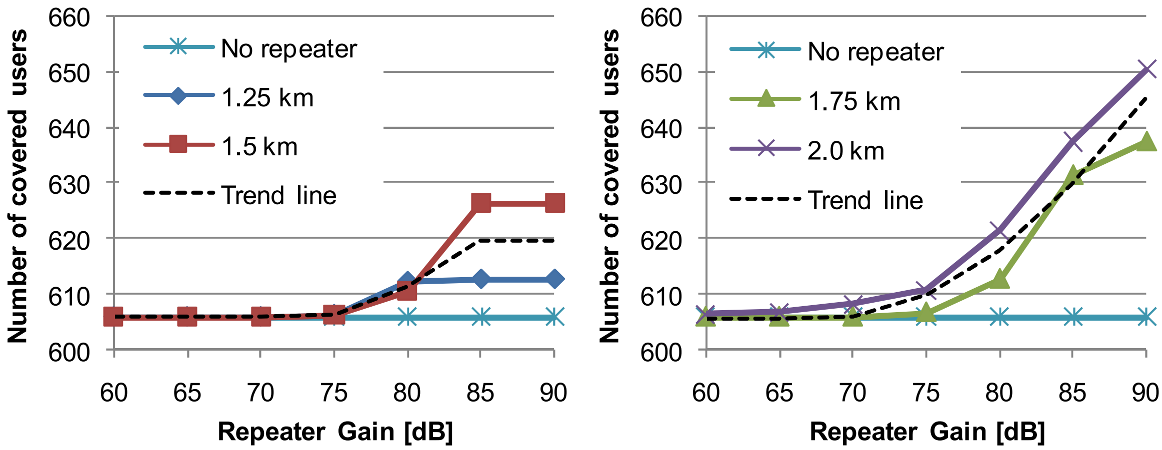


c) Number of covered users per km^2.

Figure 4.15 – Release 99 coverage parameters as a function of the BS-R distance for repeater's amplifier gains of 60 and 90 dB.

At a gain of 60 dB, regardless of the BS-R distance, there is no significant increase in the coverage area, event at a distance of 2 km, and hence the number of covered users remains constant. For the case of 90 dB, one can observe an increase in the number of covered users and in the covered area as the distance gets higher. This is due to the fact that, since at 90 dB the repeater is always radiating its maximum power, the repeater radius is always the highest possible, so the increase of the BS-R distance increases the covered area since the superposition of the coverage areas of the BS and the repeater is progressively reduced (being nonexistent at 2.0 km). The maximum increase in the covered area (relatively to the no repeater situation) is 10.82%, to which corresponds an increase of 7.33% in the number of covered users, obtained at 90 dB and 2.0 km. For every BS-R distance, the number of covered users per km^2 decreases with the increase of the repeater's amplifier gain, confirming what is observed in the default scenario, although that decrease is less noticeable at a BS-R distance of 2.0 km.

It is also useful to depict the evolution of the number of covered users with the repeater gain for all BS-R distances, Figure 4.16. In order to make the figure clearer, one chose not to represent the standard deviation: it remains approximately constant for all situations within an interval of 19 to 21 users.



a) BS-R distances of 1.25 and 1.5 km. b) BS-R distances of 1.75 and 2.0 km.

Figure 4.16 – Release 99 number of covered users as a function of the repeater's amplifier gain for different BS-R distances.

From Figure 4.16, it is possible to observe that the number of covered users starts to increase with the repeater gain only when this value is higher than 75 dB (70 dB for a BS-R distance of 2 km), for the same reasons that are explained in the default scenario subsection. For the BS-R distances of 1.25 and 1.5 km, Figure 4.16 a), the curve becomes constant at, respectively, 80 and 85 dB, points at which the repeater cannot further increase its transmission power. At the distances of 1.75 and 2.0 km, that point is only reached at 90 dB. However, one can notice that, at 1.75 km and 85 dB, the repeater is close to that maximum, that being the reason why the increase in the number of covered users when the repeater gain is increased to 90 dB is less pronounced. Comparing Figure 4.16 with the evolution of the covered area, Table G.1, one can observe that both follow the same trend. Nonetheless, there is a difference worth analysing: the BS-R distance of 2.0 km is the one that, consistently, covers the highest number of users, but that only has correspondence with the covered area at 90 dB. This is explained by the distribution of the users: the displacement of the repeater to 2.0 km away from the BS, allows its coverage area to reach a more populated area. Trend lines are also represented. These lines are polynomials of the second order – between repeater gains of 75 and

85 dB, in the case of Figure 4.16 a), and between 65 and 90 dB, for Figure 4.16 b) – with a correlation factor of 0.653 and 0.923, and given by (4.2) and (4.3), respectively for Figure 4.16 a) and b), indicating a good fit to the results of the simulation. The fact that a second order polynomial has a high correlation factor with the results of the simulation is expected, since the number of covered users depends of the covered area, which is a function of the square of the radius, and the radius increases with the gain. Higher orders were also analysed, but the slight increase in the correlation factor to 0.943, when using a sixth order, of the trend line in Figure 4.16 b) – the correlation of the trend line in Figure 4.16 a) does not improve – does not compensate for the increase in the complexity of the trend line.

$$N_{ucov} = 0.060 \cdot {G^{R}_{amp[\mathrm{dB}]}}^{2} - 8.280 \cdot G^{R}_{amp[\mathrm{dB}]} + 889.90 \tag{4.2}$$

$$N_{ucov} = 0.076 \cdot {G^{R}_{amp[\mathrm{dB}]}}^{2} - 10.197 \cdot G^{R}_{amp[\mathrm{dB}]} + 947.93 \tag{4.3}$$

Concerning the blocking probability, Figure 4.17, the conclusions are the same as the ones for the default scenario. There is a trend to an increase with the number of covered users, albeit this increase is within the limits of the standard deviation. As before, the values obtained for the blocking probability are high, its average value reaching 8.4% in the case of 90 dB and a BS-R distance of 2.0 km. This kind of values are unacceptable in a real network, but, as previously mentioned, are the result of considering only one BS.

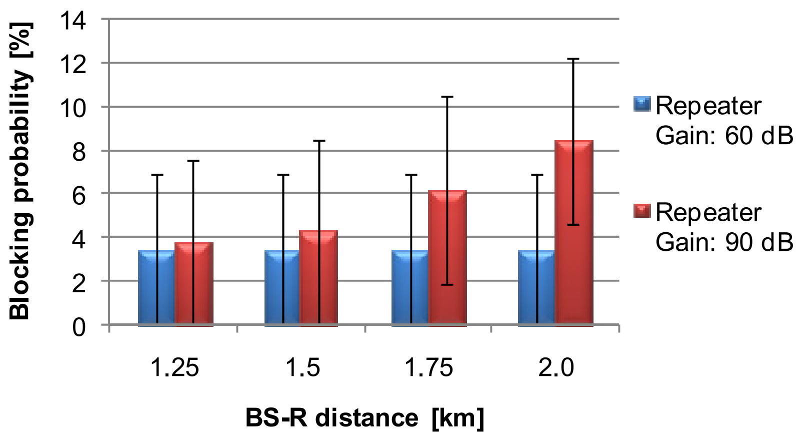
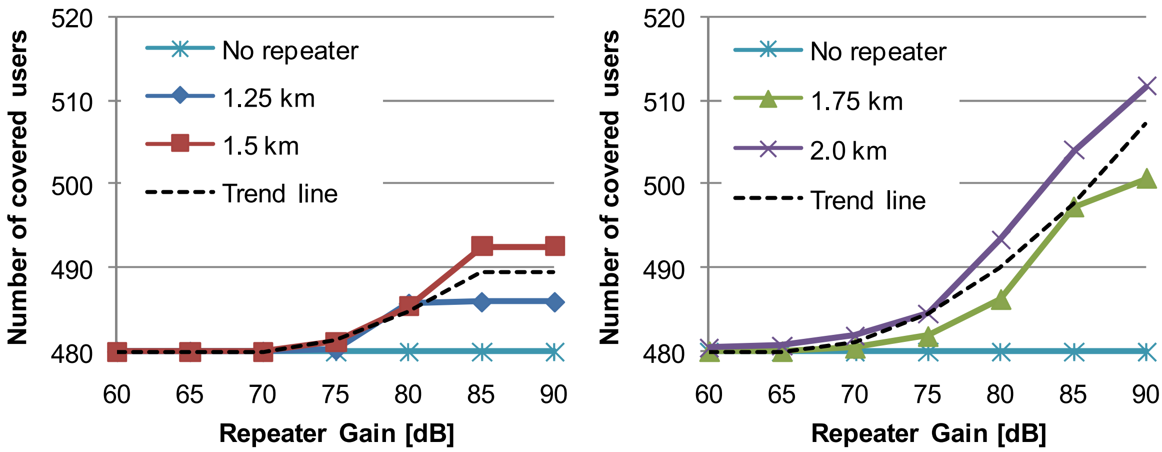


Figure 4.17 – Release 99 blocking probability as a function of the BS-R distance for repeater's amplifier gains of 60 and 90 dB.

So, analysing the variation of the BS-R distance, one observes that there is an increase in the number of covered users as the repeater is placed further away from the BS, for a repeater gain of 90 dB. The highest number of covered users is obtained at a BS-R distance of 2.0 km with an amplifier's gain of 90 dB, where the number of covered users increases 7.33%. As expected, the evolution of the number of covered users is well approximated by a polynomial of the second order. Regarding the blocking probability, one can notice an increase with the BS-R distance.

4.3.3 Number of Users

Two more numbers of users are analysed: 529 and 337. Figure 4.18 depicts the 529 users' case (the standard deviation is between 8 and 9 users), from which one can observe that the trend of growth of the number of covered users is very similar with the scenario with the default number of users. The trend lines – with correlation factors of 0.816 and 0.892, and given by (4.4) and (4.5), respectively for Figure 4.18 a) and b) – are, as previously, second order polynomials (between 70 and 85 dB in Figure 4.18 a), and starting at 65 dB in Figure 4.18 b)). The BS-R distance of 2.0 km is, once again, the one that provides the highest number of users with coverage.



a) BS-R distances of 1.25 and 1.5 km. b) BS-R distances of 1.75 and 2.0 km.

Figure 4.18 – Release 99 number of covered users as a function of the repeater's amplifier gain for different BS-R distances and for 529 users.

$$N_{ucov} = 0.0300 \cdot {G^{R}_{amp[dB]}}^{2} - 3.9940 \cdot G^{R}_{amp[dB]} + 612.31 \tag{4.4}$$

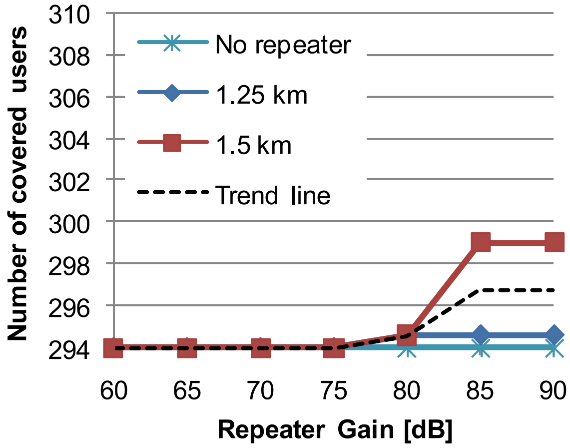
$$N_{ucov} = 0.0419 \cdot {G^{R}_{amp[dB]}}^{2} - 5.3944 \cdot G^{R}_{amp[dB]} + 653.39 \tag{4.5}$$

The same conclusions are valid for the 337 users scenario (for which the standard deviation is between 17 and 19 users), Figure 4.19. In this case, placing the repeater at a distance of 1.25 km from the BS is particularly inefficient, as the reduced increase in the covered area translates into virtually no new covered users. This also explains why the trend line for the BS-R distances of 1.25 and 1.5 km – given by (4.6) and also a second order polynomial between 75 and 85 dB – has a low correlation factor: 0.473. The one in Figure 4.19 b) – second order polynomial between 70 and 90 dB given by (4.7) – has a correlation factor of 0.876.

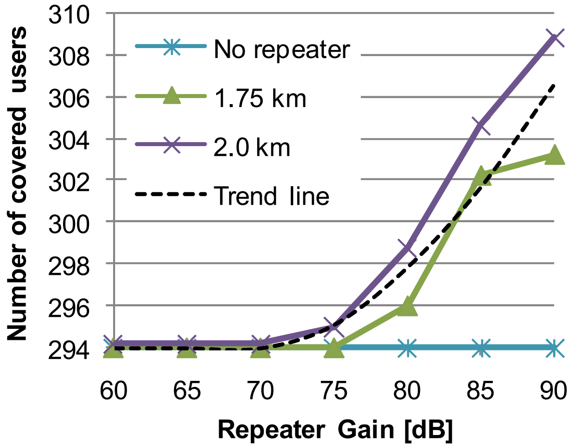
$$N_{ucov} = 0.0320 \cdot {G^{R}_{amp[dB]}}^{2} - 4.8400 \cdot G^{R}_{amp[dB]} + 477.00 \tag{4.6}$$

$$N_{ucov} = 0.0214 \cdot {G^{R}_{amp[dB]}}^{2} - 2.7746 \cdot G^{R}_{amp[dB]} + 382.83 \tag{4.7}$$

The relative increase in the number of covered users (comparing the no repeater case with the highest value obtained) is 5.03%, 6.58% and 7.33%, respectively for 337, 529 and 690 users, showing a slight increase when the number of users increases.



a) BS-R distances of 1.25 and 1.5 km.



b) BS-R distances of 1.75 and 2.0 km.

Figure 4.19 – Release 99 number of covered users as a function of the repeater's amplifier gain for different BS-R distances and for 337 users.

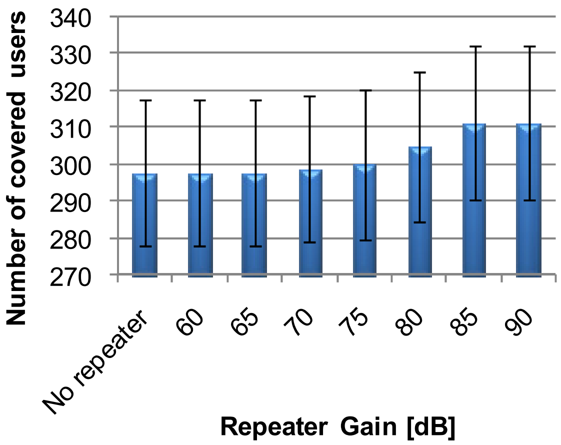
Hence, for the analysis of the variation of the number of users, the main conclusion is that the trend of growth of the number of covered users is similar for all the cases, also being the BS-R distance of 2.0 km that provides the highest number of covered users in every situation.

4.4 HSDPA Analysis in a Multiple Users Scenario

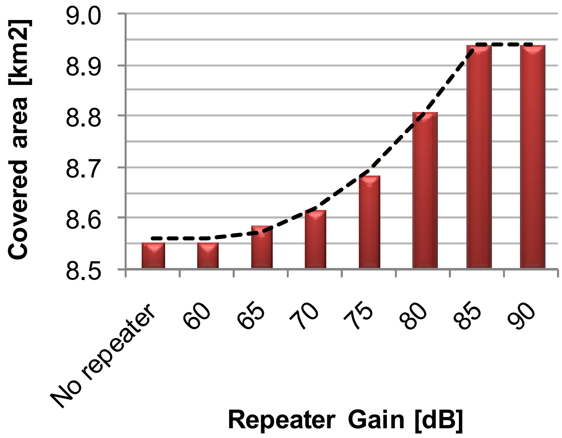
In this section, HSDPA main results are analysed. One only studies the case of 10 HS-PDSCH codes, since the 15 codes are not, yet, commonly used. First, the results of the default scenario, Section 4.1, with variation of the repeater's amplifier gain are presented. Afterwards, the influence of two more parameters is studied: BS-R distance and number of users. In Annex H additional results are shown.

4.4.1 Default Scenario

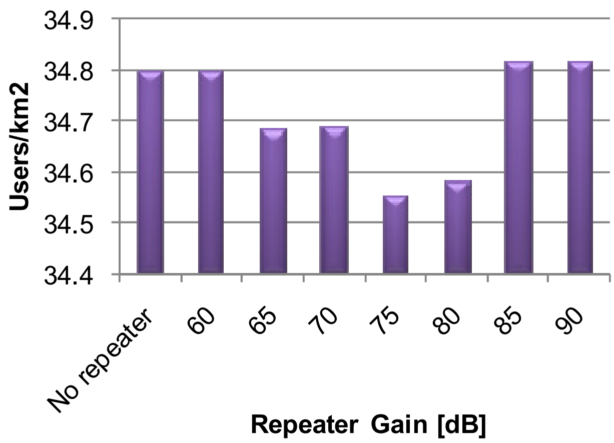
The evolution of the number of covered users, covered area and number of covered users per km^2 with the repeater's amplifier gain is presented in Figure 4.20. One can observe the expected increase in the covered area with the repeater gain, which, at 90 dB, is of 4.5%. However, this raise does not happen at 60 dB, as the entire area covered by the repeater is inside the one covered by the BS: the BS radius is 1.65 km, so the repeater one has to be at least 0.25 km in order to increase the covered area. Increasing the gain beyond 85 dB does not lead to an increase in the coverage area, since the repeater is already transmitting its maximum power. The results for the number of covered users have a high standard deviation (around 7%), due to the reduced number of simulations. Even so, one can observe that the increase in the coverage area leads to an increase in the number of covered users, except at 65 dB, where the new area is not sufficient to cover new users. At 90 dB that increase is of 4.57%. The trend line in Figure 4.20 b) is, similarly and for the same reasons of the Release 99 case, a second order polynomial – for values up to 85 dB – with a correlation factor of 0.997. This trend line is given by (4.8). The number of covered users per km^2 is practically insensitive to the repeater gain – the variations observed in Figure 4.20 c) are lower than 0.3 users/km^2 –, showing that the population density in the regions covered by the repeater is approximately constant.



a) Number of covered users.



b) Covered area.



c) Number of covered users per km^2.

Figure 4.20 – HSDPA coverage parameters as a function of the repeater's amplifier gain.

$$A_{\text{cov[km}^2]} = 0.00063 \cdot {G^R_{amp[\text{dB}]}}^2 - 0.07606 \cdot G^R_{amp[\text{dB}]} + 10.85379 \qquad (4.8)$$

The number of served users remains constant independently of the gain, Table H.2. This is because the maximum capacity of the BS is already achieved and is in accordance with the fact that the repeater does not improve the capacity of the BS.

The impact of the repeater in QoS can be analysed through the average throughput per user, Figure 4.21, and in the average satisfaction grade, Figure 4.22. The values obtained, around 0.27 Mbps for the average throughput per user and around 0.5 (for the best service) for the average satisfaction grade, are low. This is due to the fact that only one BS is being considered, and its capacity has to be shared among the highest possible number of users. Neither parameter is affected by the repeater: they both remain constant for any of the values of the repeater's amplifier gain. There are minor fluctuations, but all within the limits of the standard deviation. This indicates that the repeater gain does not degrade nor does it improve QoS.

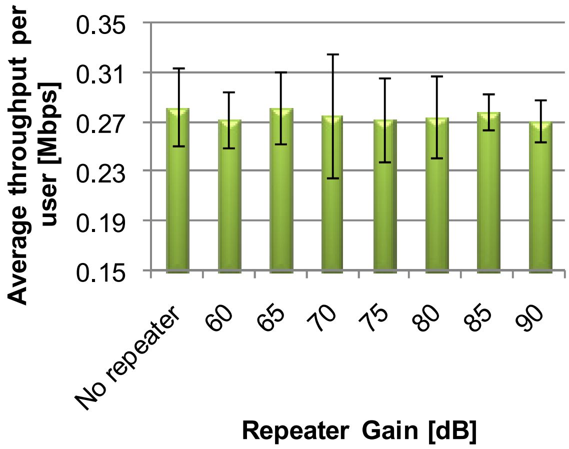


Figure 4.21 – HSDPA average throughput per user as a function of the repeater's amplifier gain.

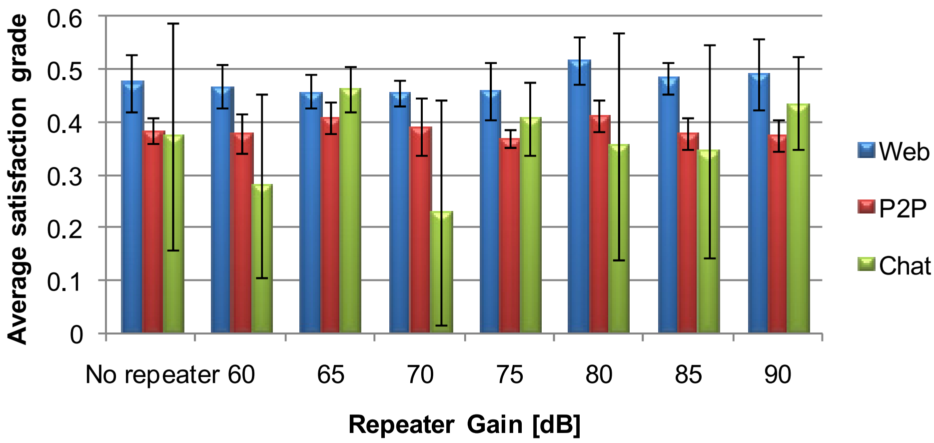


Figure 4.22 – HSDPA average satisfaction grade as a function of the repeater's amplifier gain.

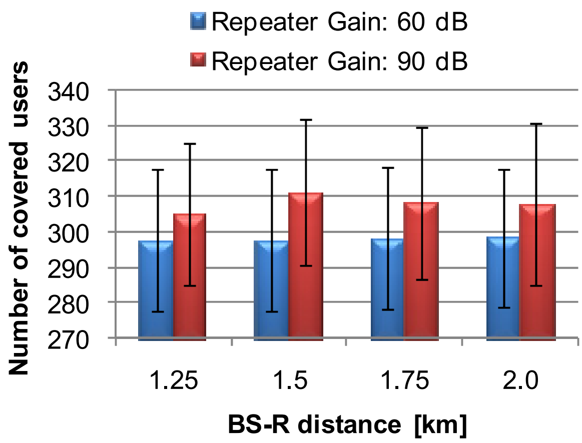
From Figure 4.22 it is also possible to observe that only three of the services are actually served: Web, P2P and Chat. Web is served because not only is the one with the highest QoS priority, but also because it is the service with highest percentage of users. Even though P2P is the service with the lowest QoS priority value, it is the service with the second highest percentage of users and it has a low minimum throughput, 0.128 Mbps, hence it is also served. Chat, which also has a low minimum throughput, is also served. No users are served with Streaming, as it has a high minimum throughput, 0.512 Mbps, although it is the second service on QoS priority list. The fact that there are no users served with Email or FTP can be explained by the low percentage of users requesting these services.

The value of the average satisfaction grade for Chat presents a standard deviation that, in some cases, goes up to 60% (for a gain of 70 dB it even reaches a value close to 100%). This is due to the fact that, in some of the simulations, there are actually no served users with Chat, in which situations the satisfaction grade is zero.

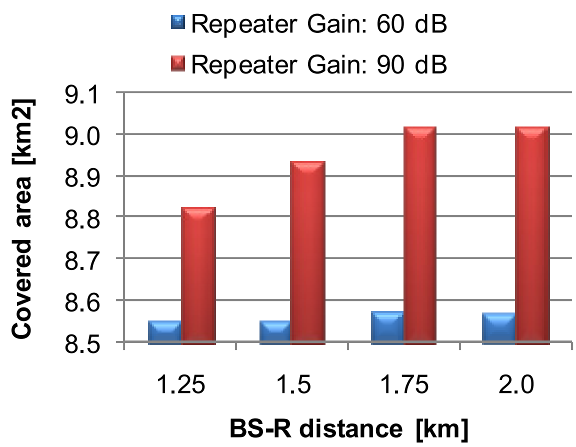
The following concluding remarks can be made: the number of covered users increases 4.57%, until a repeater's amplifier gain of 85 dB, at which gain the repeaters reaches its maximum transmission power; the number of served users is constant, independently of the gain, since the repeater does not improve the capacity of the BS; neither the average throughput per user nor the average satisfaction grade is affected by the repeater gain, indicating that the repeater does not influence QoS.

4.4.2 Distance between the BS and the Repeater

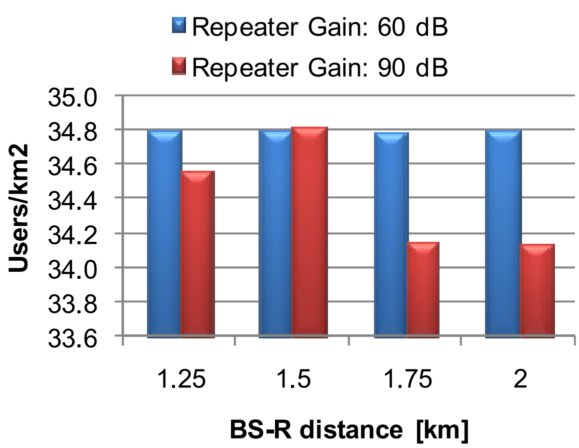
The evolution of the number of covered users, covered area and number of covered users per km^2 with the BS-R distance can be seen in Figure 4.23 (results for other repeater gains in Figure H.1 and Table H.1).



a) Number of covered users.



b) Covered area.

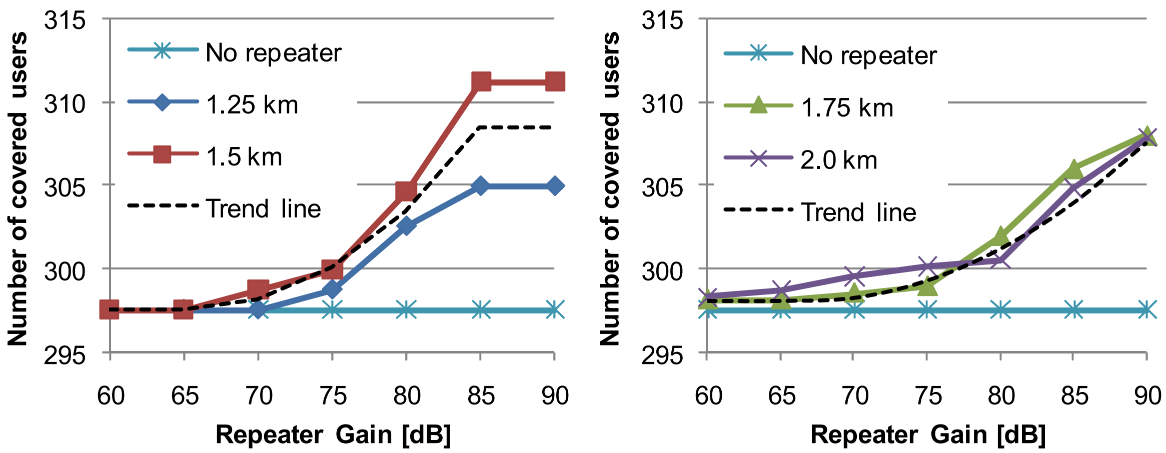


c) Number of covered users per km^2.

Figure 4.23 – HSDPA coverage parameters as a function of the BS-R distance for repeater's amplifier gains of 60 and 90 dB.

Regarding the number of covered users, one can notice a small increase, albeit within the limits of the standard deviation, when passing from a BS-R distance of 1.25 to 1.5 km. Placing the repeater farther away from the BS does not have a considerable effect in the number of covered users: the variations are minimum (no more than 3 users of difference). This in part explained by the distribution of the users in the area, as moving the repeater may be useful to cover new users, but may leave others with no coverage – as mentioned before the BS radius is 1.65 km, so at a BS-R distance of 1.75 km, the two coverage areas are completely disjoint, leaving some users without coverage in the area between them. So, the distribution of the users explains the difference to the behaviour of the increase in the covered area, Figure 4.23 b), which shows a maximum increase of 3.15% and 5.44%, respectively for a BS-R distance of 1.25 and both 1.75 and 2.0 km (as mentioned before, for the 1.5 km case is 4.5%), Table H.1. This small increase also explains why there is no more noticeable growth in the number of covered users. At 60 dB, there is no difference between the distances of 1.25 and 1.5 km, since the repeater coverage area is still completely superimposed with the BS one, which also explains the increase when the repeater is at 1.75 km from the BS (there is no more superimposition); at 2.0 km there is a slight decrease, as a result of the fact that the repeater is radiating less power (the gain of the amplifier is the same and the received power from the BS is obviously lower). Analysing the 90 dB case – at which gain the repeater is always radiating its maximum power –, it can be observed that there is a steady increase in the covered area when increasing the BS-R distance from 1.25 to 1.75 km, resulting from the progressive decrease in the superimposition of the two coverage areas (the BS and the repeater's). At 2.0 km there is no change in the covered area, which is explained by the fact that the repeater is still radiating its maximum power and, at 1.75 km, there is no more superimposition of the coverage areas. As before, one observes that the number of covered users per km^2 is not greatly affected by the repeater gain, or by the BS-R distance.

Figure 4.24 depicts the evolution of the number of covered users with the repeater's amplifier gain, for the BS-R distances studied, where the standard deviation is not represented as, being approximately constant in every situation (between 19 and 22 users), would only make the figure more confusing.



a) BS-R distances of 1.25 and 1.5 km. b) BS-R distances of 1.75 and 2.0 km.

Figure 4.24 – HSDPA number of covered users as a function of the repeater's amplifier gain for different BS-R distances.

As it can be seen, there is an expected increase in the number of covered users with the repeater's gain. At the distances of 1.25 and 1.5 km, Figure 4.24 a), the curve levels at the gains of 85 and 90 dB: this happens because the repeater reaches its maximum transmission power. There is not an immediate raise in the number of covered users when the gain is increased for the same reasons explained above. A trend line was computed for those two distances: it has a correlation factor of 0.870 and it is, between 65 and 85 dB, a second order polynomial, (4.9), which, as explained before, is coherent with the fact that the number of covered users depends of the area, which varies with the square of the radius. For the BS-R distances of 1.75 and 2.0 km, Figure 4.24 b), the number of covered users grows constantly, from 60 to 90 dB. This is due to two facts: first, the repeater only reaches its maximum transmission power at 90 dB, then, even at 60 dB, the repeater already covers a few users, since, at these distances, its coverage area is not superimposed with the BS one. Also, one can notice that the number of covered users increases slowly until a certain point (75 dB at 1.75 km and 80 dB at 2.0 km), and then starts to increase at a higher pace. This is related with the users' distribution in the area, since the behaviour of the function of the covered area with the repeater does not reflect those two different paces, Table H.1. Also, at 1.75 km, the increase between the gains of 85 and 90 dB is not as pronounced, which is also due to the fact that, at 85 dB, the repeater is almost at its maximum transmission power, meaning that the increase in the covered area when the gain increases to 90 dB is smaller. A trend line is also represented: again, and for the same reasons, it is a second order polynomial (starting at 65 dB), with a correlation factor of 0.963 and it is given by (4.10).

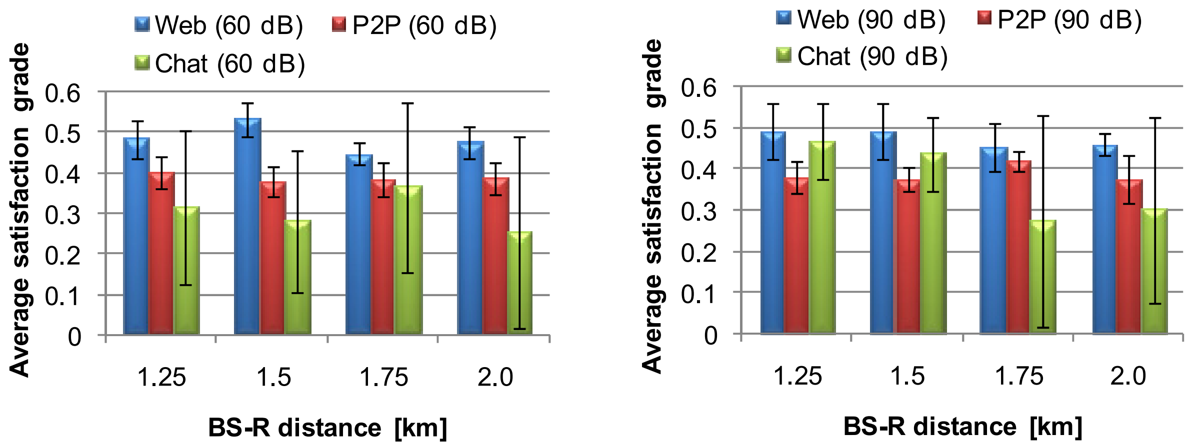
$$N_{ucov} = 0.0309 \cdot {G^{R}_{amp[\text{dB}]}}^{2} - 4.1006 \cdot G^{R}_{amp[\text{dB}]} + 433.81 \tag{4.9}$$

$$N_{ucov} = 0.0170 \cdot {G^{R}_{amp[\text{dB}]}}^{2} - 2.260 \cdot G^{R}_{amp[\text{dB}]} + 373.32 \tag{4.10}$$

As before, the number of served users does not vary with the repeater's amplifier gain or with the BS-R distance.

Concerning QoS parameters, as with the default scenario, the repeater does not cause any impact, neither in the average throughput per user, Figure H.2, nor in the average satisfaction grade, Figure 4.25. The values obtained are similar to the ones obtained in the default scenario, hence, and for the same reasons, equally unsatisfactory. The differences that one can observe, either with the variation of the distance or with both the distance and the repeater gain, are within the standard deviation. Hence, one can confirm that the repeater does not affect QoS.

As a conclusion, one observes that increasing the distance leads to an increase in the covered area, most noticeably at a repeater's amplifier gain of 90 dB, of up to 5.44%. The number of covered users does not have exactly the same behaviour: there is a slight increase between 1.25 and 1.5 km, but the same is not verified for the two remaining distances, which is explained by the distribution of the users in the area. The BS-R distances of 1.25 and 1.5 km exhibit a growth of the number of covered users that follows a second order polynomial trend until a gain of 85 dB, at which it levels due to the maximum repeater's transmission power, while the distances of 1.75 and 2.0 km increase continuously up to 90 dB, also with a trend line that is a second order polynomial. The average throughput per user and average satisfaction grade are constant, as well as the number of served users.

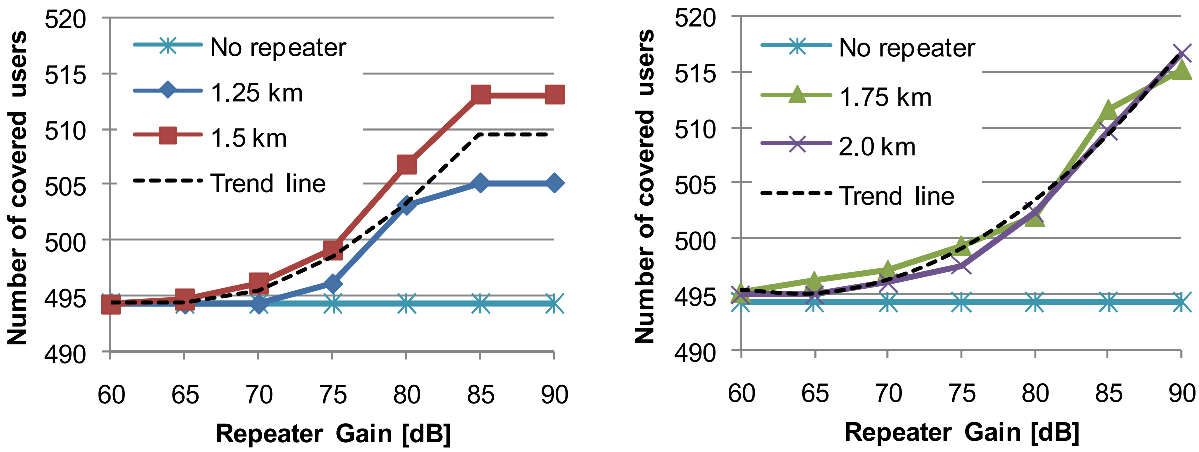


a) Repeater's amplifier gain of 60 dB. b) Repeater's amplifier gain of 90 dB.

Figure 4.25 – HSDPA average satisfaction grade as a function of the BS-R distance for repeater's amplifier gains of 60 and 90 dB.

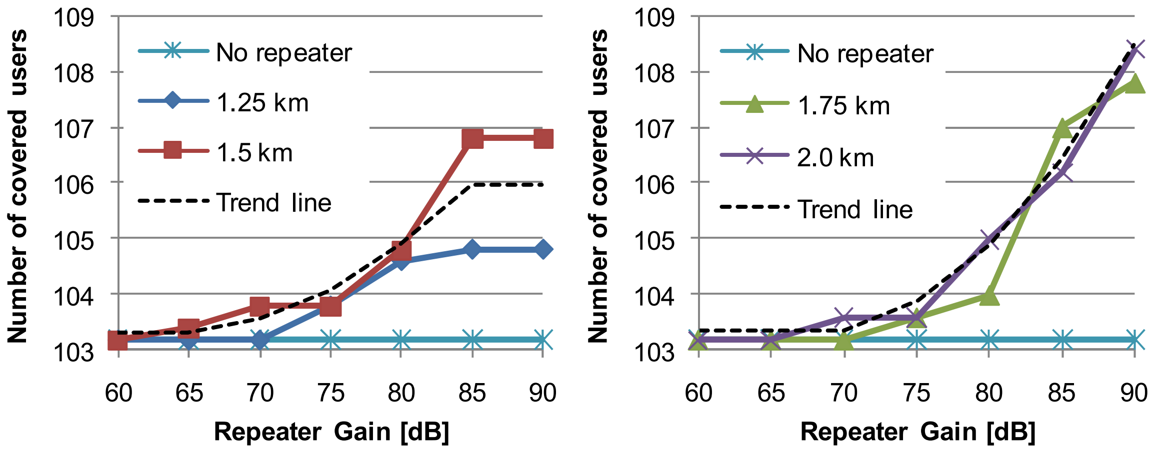
4.4.3 Number of Users

Two more numbers of users are studied: 532 and 125 users. Obviously, the number of covered users is higher with 532 users and is lower with 125. What is interesting to analyse is if the trend of the increase in the number of covered users with the repeater's amplifier gain is the same. Figure 4.26 and Figure 4.27 allow, when compared between them and with Figure 4.24, this analysis. The standard deviation is between 16 and 19 users for the 532 users scenario, and between 14 and 16 users for the 125 users one.



a) BS-R distances of 1.25 and 1.5 km. b) BS-R distances of 1.75 and 2.0 km.

Figure 4.26 – HSDPA number of covered users as a function of the repeater's amplifier gain for different BS-R distances and for 532 users.



a) BS-R distances of 1.25 and 1.5 km. b) BS-R distances of 1.75 and 2.0 km.

Figure 4.27 – HSDPA number of covered users as a function of the repeater's amplifier gain for different BS-R distances and for 125 users.

The trend of growth of the number of covered users with the repeater's amplifier gain is identical independently of the number of users. The trend lines – which have a correlation factor of 0.861, 0.981, 0.817 and 0.962, and are given by (4.11), (4.12), (4.13) and (4.14), respectively for Figure 4.26 a) and b), and Figure 4.27 a) and b) – are, as previously, second order polynomials (between repeater gains of 65 and 85 dB in the case of BS-R distances of 1.25 and 1.5 km, and between 65 and 90 dB in Figure 4.27 b)). One can also observe that, for 125 users, the increase in the number of covered users is not as smooth. This is due to the more scattered distribution of the users: there are more areas with no users placed, which means that an increase in the covered area does not translate into an increase in the covered users is some situations (observe the 70 to 75 dB interval for the distances of 1.5 and 2.0 km).

$$N_{ucov} = 0.0334 \cdot {G^{R}_{amp[dB]}}^{2} - 4.2403 \cdot G^{R}_{amp[dB]} + 628.65 \quad (4.11)$$

$$N_{ucov} = 0.0308 \cdot {G^{R}_{amp[dB]}}^{2} - 3.9143 \cdot G^{R}_{amp[dB]} + 619.53 \quad (4.12)$$

$$N_{ucov} = 0.0056 \cdot {G^{R}_{amp[dB]}}^{2} - 0.7079 \cdot G^{R}_{amp[dB]} + 125.68 \quad (4.13)$$

$$N_{ucov} = 0.0101 \cdot {G^{R}_{amp[dB]}}^{2} - 1.3611 \cdot G^{R}_{amp[dB]} + 149.16 \quad (4.14)$$

The highest increase obtained in the number of covered users, relatively to the situation without the repeater, is 5.04%, 4.57% and 4.49%, respectively for 125, 338 and 532 users, showing that there are no considerable differences in the increase of the number of covered users.

Concerning the number of served users, it increases when one switches to a scenario with a higher number of users; however this is independent of the repeater, as the number of served users is constant within each number of users, Table H.3 and Table H.4. This is due to the fact that, when there is a significant increase in the number of users, the number of served users is increased by reducing the average throughput per user. To better illustrate this situation, one more situation with less users, 52, is analysed, Table H.5, where the number of served users is the lowest. The repeater is not sufficient to increase the number of served users as it does not cover a high enough number of new users.

So, the trend of growth of the number of covered users is identical independently of the number of users in the scenario. The number of served users increases when changing to a scenario with a higher number of users, but this is independent of the repeater.

4.5 HSUPA Analysis in a Multiple Users Scenario

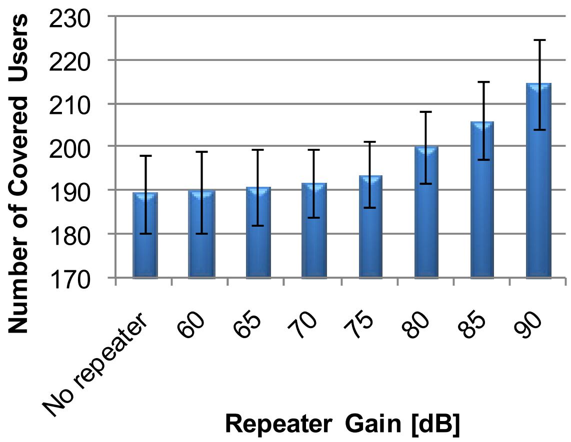
In this section, HSUPA main results are analysed. First, the results of the default scenario, introduced in Section 4.1, with variation of the repeater's amplifier gain are presented. Then, the influence of two more parameters is studied: BS-R distance and number of users. In Annex I one presents additional results.

4.5.1 Default Scenario

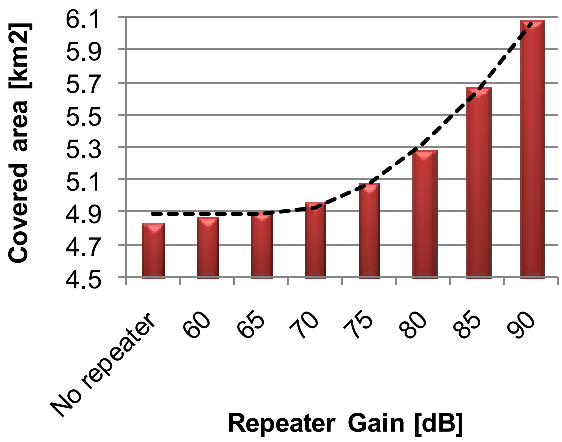
The evolution of the number of covered users, covered area and number of users covered per km^2 with the repeater's amplifier gain is presented in Figure 4.28. The increase in the covered area reaches, at a repeater gain of 90 dB, 25.8%. It is the highest increase so far, due to the fact that the repeater does not reach its maximum transmission power, and because the covered area with no repeater is the smallest of the three systems, as the BS radius is 1.24 km. This value of the BS radius also shows that there is no superposition of the BS's and repeater's coverage areas. As expected, the number of covered users also increases, reaching a growth of 13.3% at 90 dB. At 60 dB this increase is barely noticeable (on average, only 1 more user covered) because the repeater coverage area is still reduced. The trend line for the covered area, as a function of the repeater gain, (4.15), is, as in the previous situations, a second order polynomial, with a correlation factor of 0.997. The number of covered users per km^2 decreases with the gain. This is due to the distribution of the users: the growth of the repeater coverage area makes it cover regions that have a lower number of users.

$$A_{\text{cov[km}^2]} = 0.00176 \cdot {G^R_{amp[\text{dB}]}}^2 - 0.22527 \cdot G^R_{amp[\text{dB}]} + 12.071 \qquad (4.15)$$

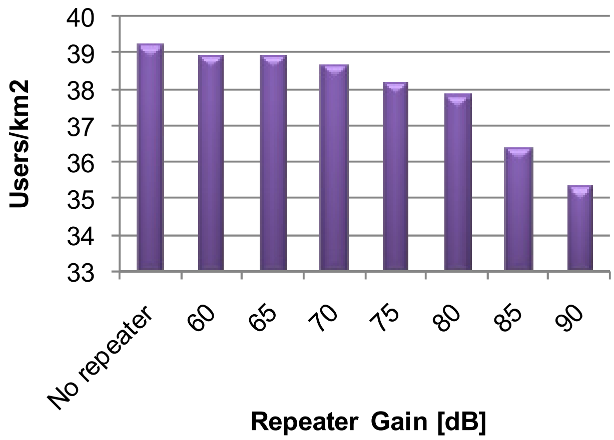
As in HSDPA, and for the same reasons, the number of served users remains constant with the increase of the repeater gain, Table I.2. This number is lower than in HSDPA, but this is expected, considering the lower capacity of HSUPA.



a) Number of covered users.



b) Covered area.



c) Number of covered users per km^2.

Figure 4.28 – HSUPA coverage parameters as a function of the repeater's amplifier gain.

The impact of the repeater in QoS can be analysed by the average user throughput, Figure 4.29, and by the average satisfaction grade, Figure 4.30. The values obtained are around 0.13 Mbps, for the average throughput per user, and 0.45, for the average satisfaction grade. Similarly to HSDPA, these are low values, but are the result of considering only one BS. As can be observed, those parameters are not affected by the repeater, all the variations being within the standard deviation's limits. Hence, as in HSDPA, QoS is not influenced by the repeater.

Similarly to the HSDPA case, there are services that are not actually offered. The reasons are the same, but now Chat service is also reduced: although it is higher in the QoS priority, it is the least representative of the services in terms of number of users.

Concluding, there is an increase, which reaches 13.3% at 90 dB, in the number of covered users as the repeater's amplifier gain gets higher. Also, the number of served users and the QoS parameters do not vary with the repeater gain.

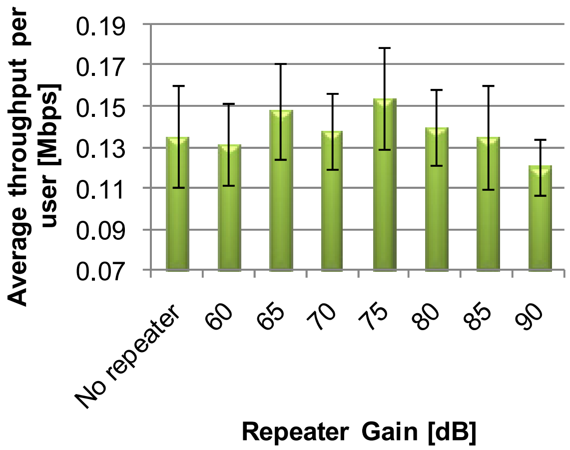


Figure 4.29 – HSUPA average throughput per user as a function of the repeater's amplifier gain.

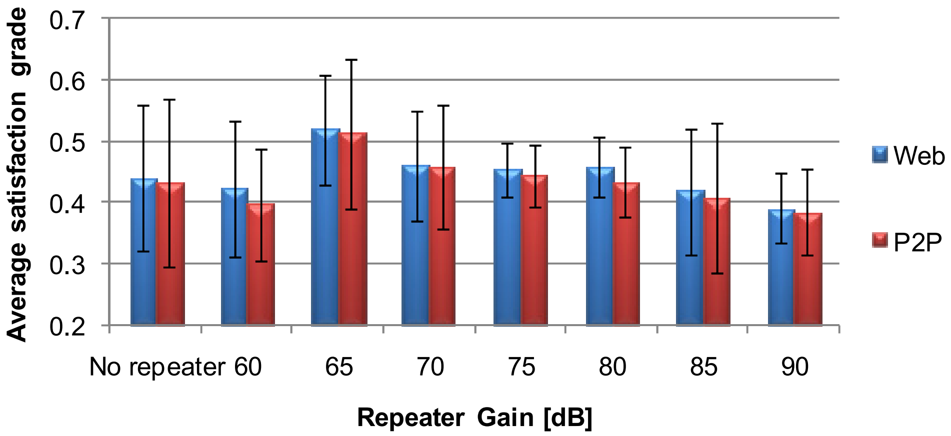
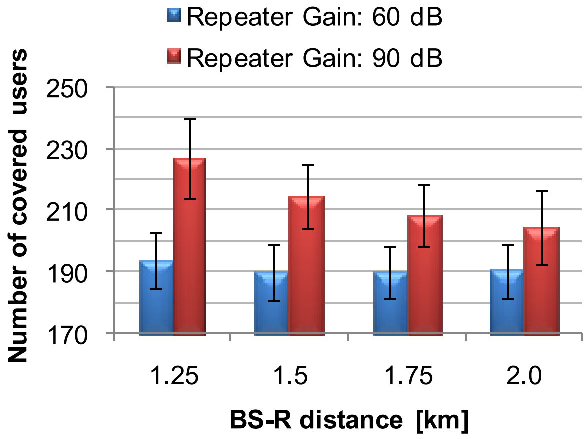


Figure 4.30 – HSUPA average satisfaction grade as a function of the repeater's amplifier gain.

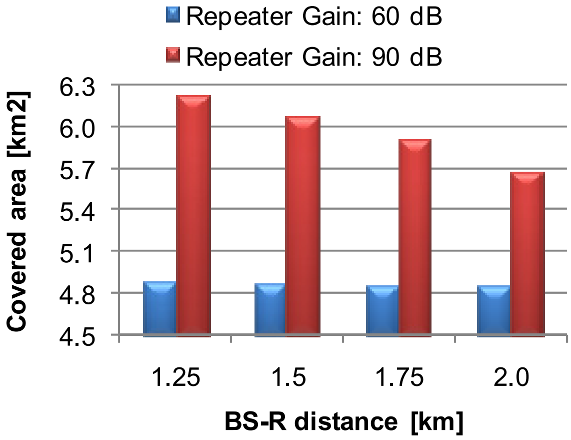
4.5.2 Distance between the BS and the Repeater

From Figure 4.31, it can be observed that the covered area decreases with the BS-R distance. Since, in HSUPA, the coverage areas of the BS and of the repeater are always disjoint, the biggest covered area (that corresponds to a 28.8% increase relatively to the situation without repeater) is obtained when the repeater is closer to the BS, starting to decrease as the repeater is placed farther away from the BS as a result of the increase of the path loss, Table I.1. This is more noticeable for a repeater gain of 90 dB but it also happens at 60 dB. The number of covered users follows the same trend, especially at a gain of 90 dB, where the increase goes up to 19.7%; at 60 dB it is practically constant, as the shrinking of the coverage area is marginal. For every BS-R distance, the behaviour of the number of covered users per km^2 confirms the one observed in the default scenario: a decrease with the increase of the repeater gain. Also, the differences between distances are negligible.

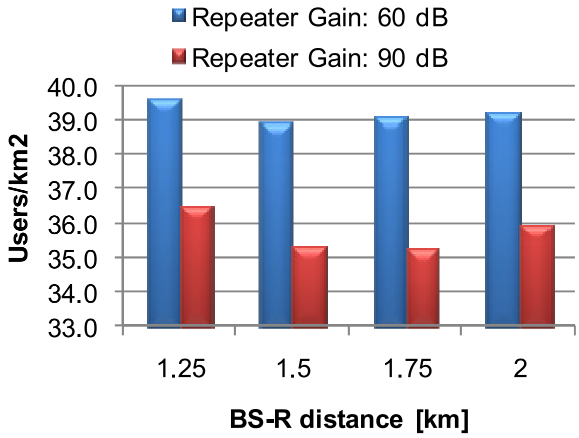
Figure 4.32, where the standard deviation, which is always between 8 and 10 users, is omitted in order to make the figure clearer, depicts the number of covered users as a function of the repeater's amplifier gain for the several BS-R distances, from which one can observe the increase in the number of covered users with the repeater gain.



a) Number of covered users.



b) Covered area.



c) Number of covered users per km^2.

Figure 4.31 – HSDPA coverage parameters as a function of the BS-R distance for repeater's amplifier gains of 60 and 90 dB.

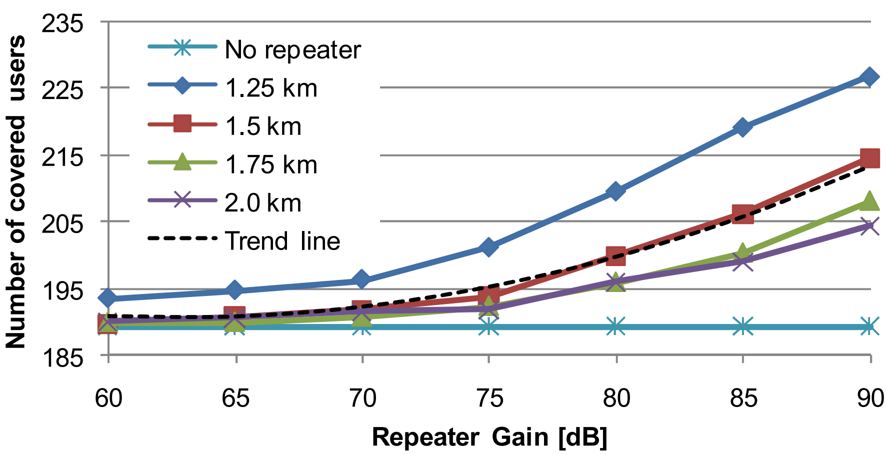


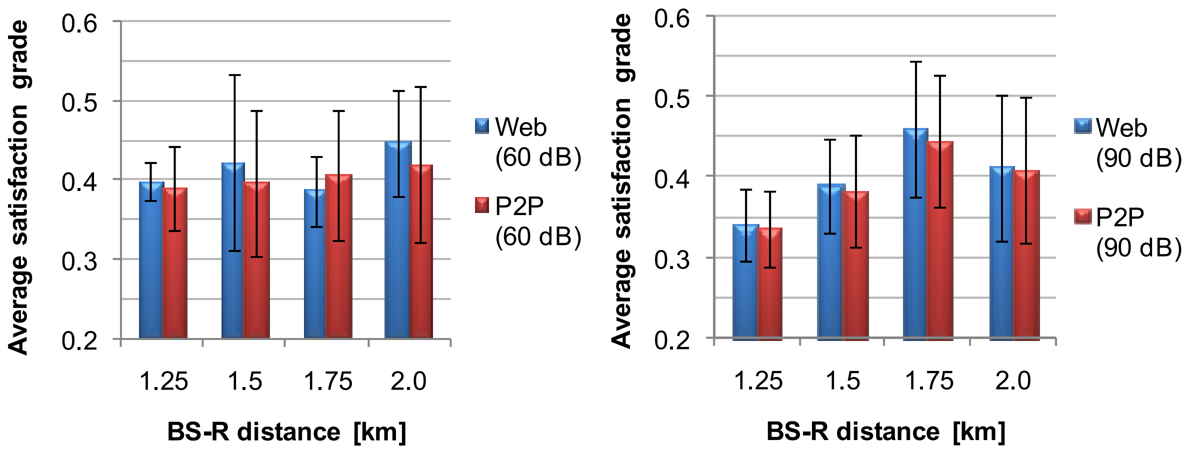
Figure 4.32 – HSUPA number of covered users as a function of the repeater's amplifier gain for different BS-R distances.

The BS-R distance of 1.25 km is the one that provides coverage to a largest amount of users, in conformity with the previously seen fact that it is the distance that has the biggest covered area. Following it are the distances of 1.5, 1.75 and 2.0 km, in this order, also coherent with the amount of covered area provided by each one of those situations. The lines of 1.75 and 2.0 km are superimposed until a gain of 85 dB; however this is explained by the distribution of the users, since the covered area for a BS-R distance of 1.75 km if, for the same gain, always larger than for 2.0 km, Table I.1. The trend line, (4.16), – with a correlation factor of 0.696 – is a second order polynomial, for the reasons explained before.

$$N_{ucov} = 0.0301 \cdot {G^{R}_{amp[dB]}}^{2} - 3.7729 \cdot G^{R}_{amp[dB]} + 308.99 \tag{4.16}$$

As expected, and similarly to the previous cases, the number of served users is constant independently of the repeater gain and of the BS-R distance, Table I.2.

The QoS parameters – average throughput per user, Figure I.2, and average satisfaction grade, Figure 4.33 – are approximately constant, confirming that the repeater does not have an impact on QoS. Similarly to the default scenario, and for the same reasons, the values obtained are considerably low.



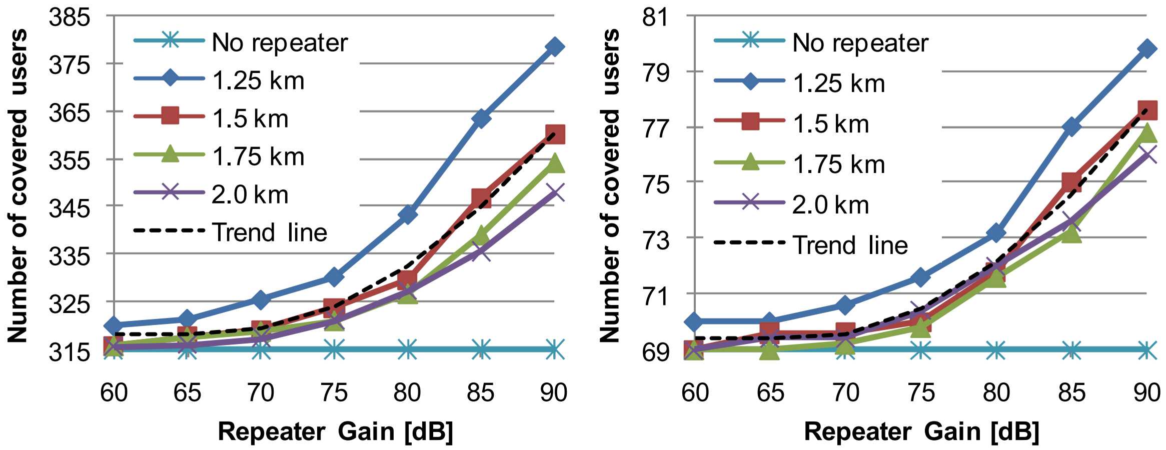
a) Repeater's amplifier gain of 60 dB. b) Repeater's amplifier gain of 90 dB.

Figure 4.33 – HSDPA average satisfaction grade as a function of the BS-R distance for repeater's amplifier gains of 60 and 90 dB.

The following concluding remarks can be made: the number of covered users and the covered area decrease as the repeater gets farther away from the BS, the largest number of covered users being obtained at a BS-R distance of 1.25 km and a repeater's amplifier gain of 90 dB, representing an increase of 19.7%; for all the repeater gain values, the BS-R distance of 1.25 km is the one that covers the highest number of users; the evolution of the values of the number of covered users is, for all the BS-R distances, well approximated by a second order polynomial; the number of served users is constant and the QoS parameters are also not affected either by the BS-R distance, or by the repeater gain.

4.5.3 Number of Users

From Figure 4.34, and comparing it with Figure 4.32, one can observe that the trend of the growth of the number of covered users is similar for all the number of users. The trend lines, as before, second order polynomials (starting at a repeater gain of 65 dB), have correlation factors of 0.812 and 0.902, and are given by (4.17) and (4.18), respectively for Figure 4.34 a) and Figure 4.34 b).



a) 532 users. b) 125 users.

Figure 4.34 – HSDPA number of covered users as a function of the repeater's amplifier gain for different BS-R distances.

$$N_{ucov} = 0.0726 \cdot {G^{R}_{amp[dB]}}^{2} - 9.5802 \cdot G^{R}_{amp[dB]} + 634.31 \quad (4.17)$$

$$N_{ucov} = 0.0146 \cdot {G^{R}_{amp[dB]}}^{2} - 1.9387 \cdot G^{R}_{amp[dB]} + 133.79 \quad (4.18)$$

The relative increase in the number of covered users (comparing the no repeater case with the highest value obtained) is 15.7%, 19.7% and 20.0%, respectively for 125, 338 and 532 users. This increase is higher than the one observed in HSDPA, which is not surprising considering that the covered area also has a more pronounced increase.

With reference to the number of served users, the situation is the same that in HSDPA, where one can observe, for the same reasons, an increase in the number of served users when changing from a scenario with less users to one with a largest amount, Table I.3 to Table I.5. The difference between the scenarios with 532 and 338 users is not very noticeable, however, it is clear that a lower number of users is served when analysing the 125 and 52 users scenarios.

So, the analysis of this two other scenarios with different numbers of users allow us to conclude that the trend of growth of the number of covered users is similar, independently of the scenarios, and that the number of served users is higher when one considers a scenario with more users, although it is independent of the repeater.

Chapter 5

Conclusions

In this chapter, the main conclusions of this thesis are drawn and some aspects to be developed in future work are pointed out.

The main objectives of this thesis were to study and analyse radio repeaters in UMTS and their impact in coverage, capacity and QoS. These goals were accomplished through the development and implementation of two models: the single user and the multiple users. First, a single user model was developed and implemented in C++, with the purpose of calculating the maximum distances between the BS and the repeater, and the repeater and the MT for Release 99, 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 analysed. The multiple users simulator was implemented in MapBasic and C++, which allowed the analysis of several results considering the variation of some parameters.

A single user model for Release 99, HSDPA and HSUPA, all with a repeater, was developed with the main purpose of calculating the maximum distances between the BS and the repeater, and the repeater and the MT, in order to have a first idea regarding the repeater's placement. Several parameters were considered, namely, for the repeater, amplifier gain, donor and coverage antennas gain and front-to-back ratio, and, for the non repeater parameters, frequency, BS and MT antenna gains, margins for indoor attenuation and both slow and fast fading, among others.

For the multiple users analysis, pre-existent simulators were modified in order to take the repeater into account. The multiple users model main goal is to assess the impact of the repeater in a more realistic scenario, with several users performing different services, through the individual analysis of Release 99, HSDPA and HSUPA. This simulator considers only one BS with a repeater. The main modifications made to the existent simulators had to do with taking the interference caused by the repeater into account, and considering the repeater's coverage area. The influence of the variation of three parameters was studied: repeater's amplifier gain, distance between the BS and the repeater, and number of users.

The default scenario considered is the one presented in Section 4.1, for the multiple users analysis. The single user default scenario has some minor differences: there is no interference margin, the throughput is different in HSDPA and HSUPA (3 and 1.22 Mbps, respectively), and the BS-R distance is variable.

For the default single user Release 99 scenario in rural areas, the placement of the repeater can be done with a good degree of flexibility, as the distances obtained are only limited by the interference caused by the delay. For urban areas, and considering 0.1 km as the minimum R-MT distance, the repeater can be up to 4.5 km away from the BS (the limit imposed by the delay) in a pedestrian environment and, in the vehicular one, up to 2.5 and 2.0 km, respectively in DL and UL. In this system, the connection becomes DL limited at repeater gains higher than 75 dB, since, in DL, the R-MT distance is limited by the repeater's maximum transmission power. In UL, the only limitation is noise, hence, interference is never a limitation in Release 99. For a fixed BS-R distance of 1.0 km, increasing the repeater gain up to 75 dB allows the DL R-MT distance to grow by a factor of 2.24 – to 1.4 km – and 2.28 – to 0.6 km –, respectively for the pedestrian and vehicular environments.

Considering now the HSDPA default scenario, with a throughput of 3 Mbps and 10 HS-PDSCH codes, the conclusions for rural areas are the same. For urban areas, the minimum R-MT distance of 0.1 km is only achieved in a pedestrian environment and provided that the repeater is not more than 1.25 km away from the BS. For a BS-R distance of 1.0 km, the maximum repeater transmission power is reached at a repeater gain of 80 dB. Interference affects the BS-R link, although it only poses a problem at higher repeater gains, limiting the BS-R distance to 1.5 km when considering a repeater gain of 90 dB. Increasing the repeater gain up to 80 dB translates in an increase in the R-MT distance of 2.83 and 2.8 times in pedestrian and vehicular environments, respectively. Varying the user's throughput, one can observe that, in a pedestrian environment, the MT can be up to 0.5 km away from the repeater, for 1 Mbps, and up to 0.2 km, for 6 Mbps.

Concerning the HSUPA default scenario analysis, and for a throughput of 1.22 Mbps, once again the results for rural areas are only limited by the delay. In respect to urban areas, in a vehicular environment, one never reaches the minimum R-MT distance of 0.1 km; in a pedestrian environment it is achieved if the BS-R distance is not higher than 2.0 km, hence the interference caused by the delay is not a limitation. Considering now a fixed BS-R distance of 1.0 km, noise limits the increase in the R-MT distance to a repeater's amplifier gain of 85 dB, at which the repeater radius is already 3.52 and 3.33 times larger than it was at 60 dB (respectively, for pedestrian and vehicular environments). Under these conditions, interference decreases the R-MT distance by 22% in a pedestrian environment, and by 23% in a vehicular one. Analysing the variation of the user's throughput, one obtains a maximum R-MT distance of 1.2 km for 0.5 Mbps and of 0.7 km for 1.22 Mbps, for a pedestrian environment. For a vehicular one, those values are 0.5 and 0.3 km.

In the multiple users simulator, for the Release 99 default scenario, as the repeater's amplifier gain increases, there is an increase of the covered area of up to 7.81% with a correspondent increase of 3.34% in the number of covered users. This increase happens until a repeater gain of 85 dB, at which the maximum transmission power of the repeater is achieved. Concerning the blocking probability, the values obtained present a high standard deviation, but one can still notice a trend to an increase with the gain.

The variation of the distance between the BS and the repeater is also analysed. There is an increase in the covered area (and in the number of covered users) as the repeater is placed further away from the BS, since the superimposition of the coverage areas of the BS and the repeater is progressively reduced. At a repeater gain of 60 dB that increase is barely noticeable, but at 90 dB it is already clear and it is also translated into a noticeable growth in the number of covered users. The closer the repeater is to the BS, the earlier (in terms of the evolution of the repeater's amplifier gain) the maximum transmission power is achieved, hence, the more limited the growth of the coverage area is. Only at the distances of 1.75 and 2.0 km is this point achieved just at 90 dB. The highest number of covered users is obtained at a BS-R distance of 2.0 km with an amplifier's gain of 90 dB, which results in a 10.82% increase in the covered area and 7.33% in the number of covered users. The evolution of the number of covered users is well approximated by a polynomial of the second order, which is expected as the number of covered users is related to the coverage area that is a function of the square of the radius. In what concerns the blocking probability, one can notice an increase with the BS-R distance, although it presents a high standard deviation.

Two scenarios with different number of users (529 and 337) are also studied. One can observe that the trend of growth of the number of covered users is similar for all the number of users, also being the BS-R distance of 2.0 km that provides the highest number of covered users in every situation. For the scenarios of 529 and 337 users, the growth in the number of covered users is of 5.03% and 6.58%, respectively.

Concerning the HSDPA multiple users default scenario, the covered area and the number of covered users increase 4.5% and 4.57%, respectively, until a repeater's amplifier gain of 85 dB, at which gain the maximum transmission power of the repeater stops the repeater radius to grow any further. The number of served users is constant, independently of the gain, since the repeater does not improve the capacity of the BS. Regarding the QoS parameters, neither the average throughput per user nor the average satisfaction grade is affected by the repeater gain, indicating that the repeater does not influence QoS.

The influence of the BS-R distance is also studied. Increasing the distance leads to an increase in the covered area, most noticeably at a repeater's amplifier gain of 90 dB, of up to 5.44%. For this gain, at the distances of 1.75 and 2.0 km the covered area is the same as the BS's and the repeater's coverage areas are totally disjoint and the repeater is radiating its maximum power. The number of covered users does not have exactly the same behaviour: there is a slight increase between 1.25 and 1.5 km, but the same is not verified for the two remaining distances, which is explained by the distribution of the users in the area. Analysing the number of covered users as a function of the repeater's amplifier gain, one can observe two different situations: one for the BS-R distances of 1.25 and 1.5 km, and another for the 1.75 and 2.0 km ones. The former case exhibits a growth that follows a second order polynomial trend until a gain of 85 dB, at which it levels due to the maximum repeater's transmission power; the latter increases continuously up to 90 dB, also with a trend line that is a second order polynomial. As in the previous situations, both the number of served users and the QoS parameters – average throughput per user and average satisfaction grade – are constant independently of not only the repeater gain, but also of the BS-R distance.

Two more scenarios with 125 and 532 users are also analysed. The trend of growth is identical to the one observed in the 338 users scenario. The growth in the number of covered users goes up to 5.04%, 4.57% and 4.49%, respectively for 125, 338 and 532 users. The number of served users increases when changing to a scenario with a higher number of users, although this is independent of the repeater, as it does not cover a large enough number of new users.

Finally, an analysis is also done for HSUPA multiple users. Considering the default scenario, there is an increase in both the covered area and the number of covered users as the repeater's amplifier gain gets higher. This increases reaches, at 90 dB, 25.8% for the covered area, and 13.3% for the number of covered users. The number of served users does not vary with the repeater gain, and the same is valid for the average throughput per user and for the average satisfaction grade, hence, the repeater does not affect QoS.

Regarding the variation of the BS-R distance, the number of covered users and the covered area decrease as the repeater gets farther away from the BS, since the path loss increases and, in HSUPA, for the distances studied, there is never superposition of the covered areas of the BS and of the repeater. So the largest covered area is obtained at a BS-R distance of 1.25 km and a repeater's amplifier gain of 90 dB, representing an increase of 28.8% and of 19.7% in the number of covered users. An analysis of the number of covered users as a function of the repeater gain shows that, for all the repeater gain values, the BS-R distance of 1.25 km is the one that covers the highest number of users. The evolution of the values of the number of covered users is, for all the BS-R distances, well approximated by a second order polynomial. As in the previous cases, the number of served users is constant. The QoS parameters are also not affected either by the BS-R distance, or by the repeater gain.

From the analysis of two other scenarios with different number of users (125 and 532), one concludes that the trend of growth of the number of covered users is similar, independently of the scenarios, and, hence, well approximated by a second order polynomial. For the scenario with 125 users, the highest increase in the number of covered users is of 15.7%; for the 532 users case, that increase is of 20.0%. As in HSDPA, the number of served users is higher when one considers a scenario with more users, although it is independent of the repeater.

Single user results show that it is in Release 99 that the radius of the repeater is larger, followed by HSUPA and, finally, HSDPA, but the largest increase in the number of covered users is, as the multiple users analysis showed, in HSUPA, which is also due to the fact that it is the system that, without repeater, has the smallest covered area; the smallest gain, in number of covered users, obtained with the installation of the repeater is in HSDPA. In Release 99, the blocking probability shows a trend to increase as the repeater covers more new users. In HSPA, the QoS parameters are not affected by the repeater gain or by the BS-R distance.

The installation of a repeater provides increases in the number of covered users that varies with the system and, obviously, with the distribution of users in a given area. Being less expensive equipments than BSs, repeaters can be an interesting solution to cover dead spots, provided that the capacity of the BS to which the repeater is connected is not exhausted. If the installation of a repeater is advantageous or not, depends on the specific case and must always be the subject of a cost-benefit analysis from the operator.

For future work, one suggests: study of a repeater placed in a network with more than one BS, in order to evaluate the behaviour of the repeater when receiving signal from several BSs; the use of a repeater to increase capacity in hotspots; introduce services' variation; different types of repeater's antennas; repeaters in HSPA+ and LTE networks.

Annex A – Systems Throughput

For HSDPA, the values of SINR as a function of the bit rate for 5, 10 and 15 HS-PDSCH codes, i.e., ρ_{IN5}, ρ_{IN10} and ρ_{IN15}, are calculated, based on [Lope08], Figure A.1:

$$\rho_{IN5}(R_{b[\mathrm{Mbps}]})_{[\mathrm{dB}]} = 0.1856 \cdot R_b^5 - 1.6176 \cdot R_b^4 + 6.7608 \cdot R_b^3 - 16.7997 \cdot R_b^2 + 27.3903 \cdot R_b - 4.9847 \quad \text{(A.1)}$$

$$\rho_{IN10}(R_{b[\mathrm{Mbps}]})_{[\mathrm{dB}]} = 0.0382 \cdot R_b^5 - 0.6722 \cdot R_b^4 + 4.4891 \cdot R_b^3 - 14.2023 \cdot R_b^2 + 24.3795 \cdot R_b - 4.6875 \quad \text{(A.2)}$$

$$\rho_{IN15}(R_{b[\mathrm{Mbps}]})_{[\mathrm{dB}]} = \begin{cases} 0.0061 \cdot R_b^5 - 0.1633 \cdot R_b^4 + 1.6581 \cdot R_b^3 - 7.8530 \cdot R_b^2 + 18.9881 \cdot R_b - 3.9237, & R_b \leq 5.4 \\ 0.0952 \cdot R_b^4 - 2.7432 \cdot R_b^3 + 29.4923 \cdot R_b^2 - 138.1340 \cdot R_b + 257.0166, & 5.4 < R_b \leq 8.46 \end{cases} \quad \text{(A.3)}$$

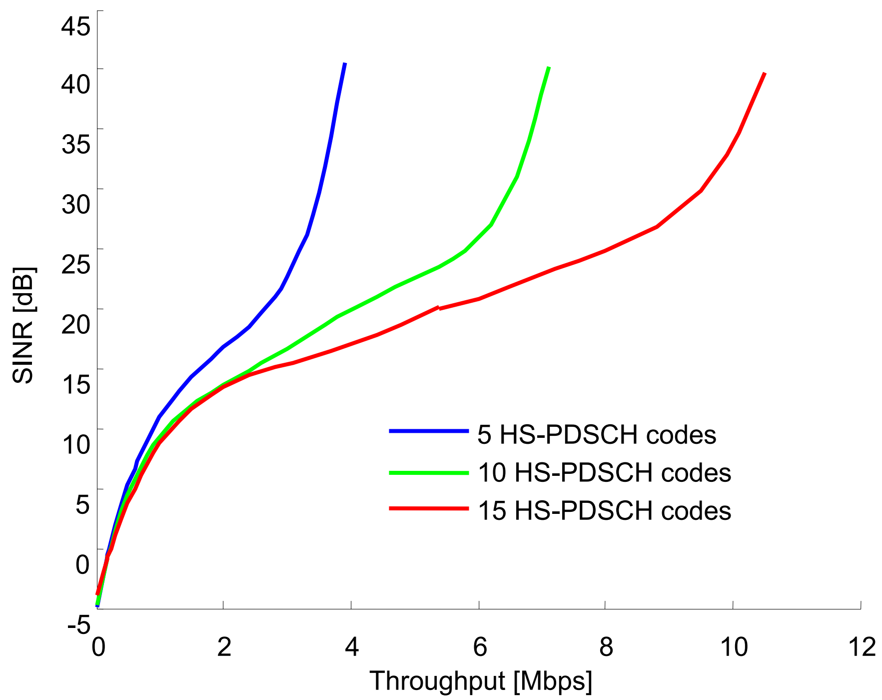


Figure A.1 – SINR as a function of the throughput (extracted from [Lope08]).

The throughput as a function of the SINR is given by (A.4), (A.5) and (A.6) for 5, 10 and 15 HS-PDSCH codes, respectively [Lope08], Figure A.2.

$$R_{b5}(\rho_{IN[\mathrm{dB}]})_{[\mathrm{Mbps}]} = \begin{cases} 0, & \rho_{IN} < -4 \\ 0.095 \cdot \rho_{IN} + 0.38, & -4 < \rho_{IN} \le 2 \\ 0.0464 \cdot \rho_{IN} + 0.2828, & -2 < \rho_{IN} \le 9 \\ 0.15 \cdot \rho_{IN} - 0.65, & 9 < \rho_{IN} \le 15 \\ 0.2 \cdot \rho_{IN} - 1.4, & 15 < \rho_{IN} \le 22 \\ 3.0, & \rho_{IN} > 22 \end{cases} \tag{A.4}$$

$$R_{b10}(\rho_{IN[\mathrm{dB}]})_{[\mathrm{Mbps}]} = \begin{cases} 0, & \rho_{IN} < -4 \\ 0.085 \cdot \rho_{IN} + 0.34, & -4 < \rho_{IN} \le 2 \\ 0.0167 \cdot \rho_{IN} + 0.2034, & -2 < \rho_{IN} \le 1 \\ 0.076 \cdot \rho_{IN} + 0.65, & 1 < \rho_{IN} \le 6 \\ 0.0085 \cdot \rho_{IN}^{2} + 0.0271 \cdot \rho_{IN} + 0.1141, & 6 < \rho_{IN} \le 24 \\ 0.1667 \cdot \rho_{IN} + 1.599, & 24 < \rho_{IN} \le 26.4 \\ 6.0, & \rho_{IN} > 26.4 \end{cases} \tag{A.5}$$

$$R_{b15}(\rho_{IN[\mathrm{dB}]})_{[\mathrm{Mbps}]} = \begin{cases} 0, & \rho_{IN} < -5 \\ 0.0367 \cdot \rho_{IN} + 0.183, & -5 < \rho_{IN} \le 1 \\ 0.09 \cdot \rho_{IN} + 0.13, & 1 < \rho_{IN} \le 3 \\ 0.1296 \cdot \rho_{IN} + 0.014, & 3 < \rho_{IN} \le 10 \\ 0.3 \cdot \rho_{IN} - 1.7, & 10 < \rho_{IN} \le 16 \\ 0.54 \cdot \rho_{IN} - 5.5, & 16 < \rho_{IN} \le 25 \\ 0.3 \cdot \rho_{IN} + 0.5, & 25 < \rho_{IN} \le 26.5 \\ 8.46, & \rho_{IN} > 26.5 \end{cases} \tag{A.6}$$

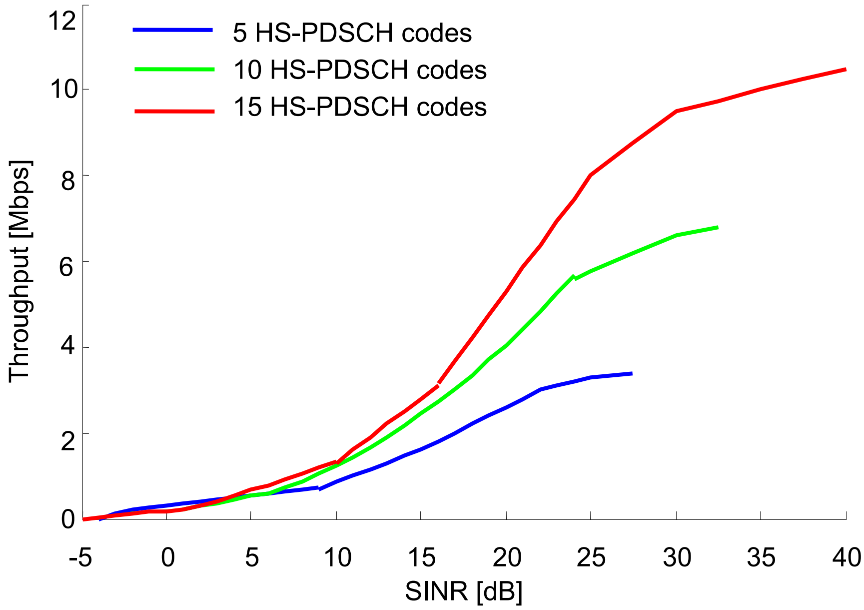


Figure A.2 – Throughput as a function of SINR (extracted from [Lope08]).

For HSUPA the performance metric used is the E_c/N_0, which is expressed as a function of the bit rate by [Lope08], Figure A.3:

$$E_c / N_0 (R_{b[\text{Mbps}]})_{[\text{dB}]} = \begin{cases} 10 \cdot R_b - 12.5, & 0 \le R_b \le 0.1 \\ 4.2 \cdot R_b - 11.9334, & 0.1 < R_b \le 0.45 \\ 5.187 \cdot R_b^2 + 0.659 \cdot R_b - 11.3473, & 0.45 < R_b \le 1.0 \\ 6.8 \cdot R_b - 12.3, & 1.0 < R_b \le 1.22 \end{cases} \quad \text{(A.7)}$$

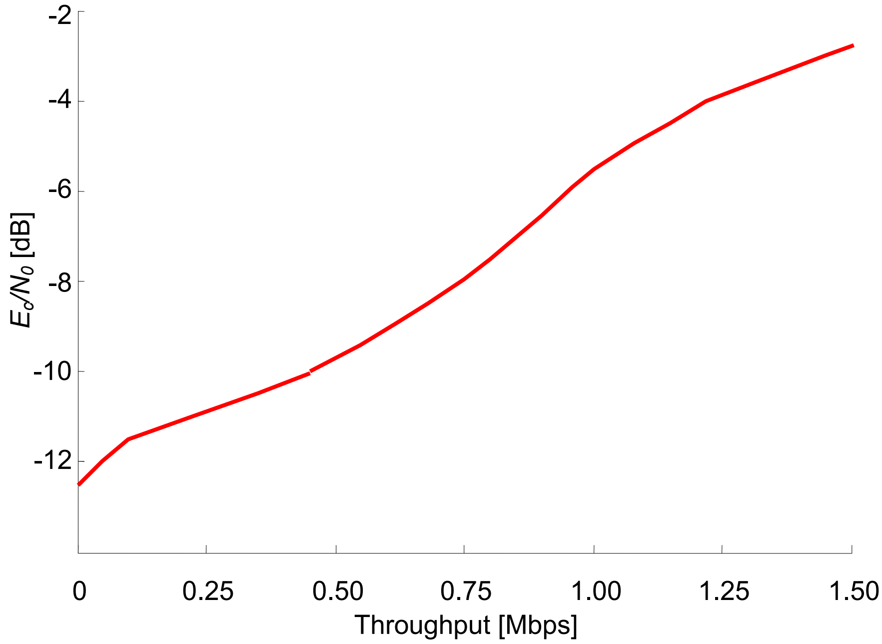


Figure A.3 – E_c/N_0 as a function of throughput (extracted from [Lope08]).

The bit rate value as a function of E_c/N_0 is [Lope08], Figure A.4:

$$R_b(E_c/N_{0[dB]})_{[Mbps]} = \begin{cases} 0, & E_c/N_0 < -12.5 \\ 0.1 \cdot E_c/N_0 + 1.25, & -12.5 < E_c/N_0 \leq -11.5 \\ 0.225 \cdot E_c/N_0 + 2.6875, & -11.5 < E_c/N_0 \leq -9.5 \\ 0.1333 \cdot E_c/N_0 + 1.8167, & -9.5 < E_c/N_0 \leq -8 \\ 0.1 \cdot E_c/N_0 + 1.55, & -8 < E_c/N_0 \leq -5.5 \\ 0.1467 \cdot E_c/N_0 + 1.8067, & -5.5 < E_c/N_0 \leq -4.02 \\ 1.22, & E_c/N_0 > -4.02 \end{cases} \quad \text{(A.8)}$$

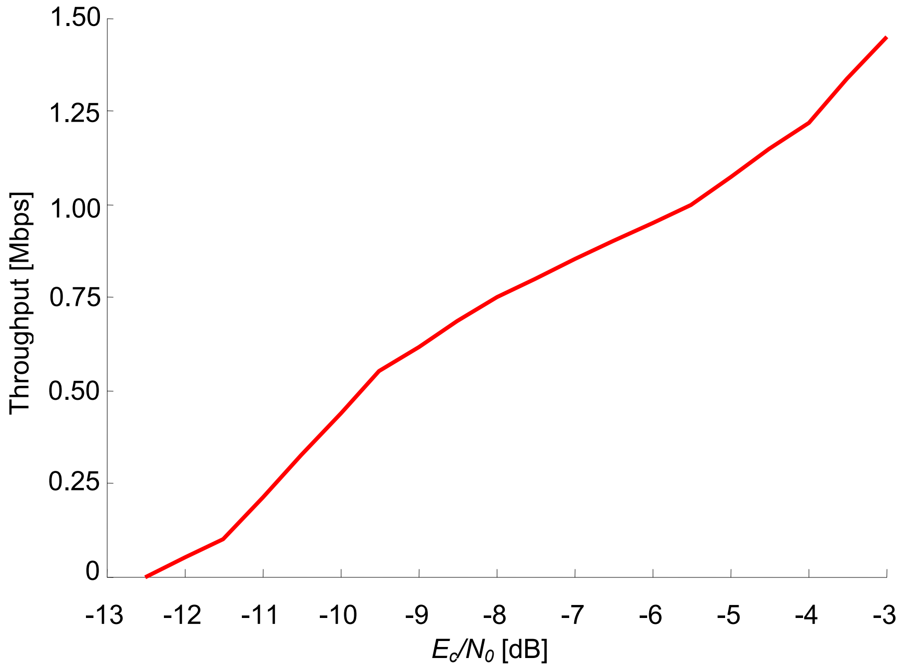


Figure A.4 – Throughput as a function of E_c/N_0 (extracted from [Lope08]).

For Release 99, E_b/N_0 values are presented in Table A.1.

Table A.1 – E_b/N_0 values (based on [CoLa06]).

Bit rate [kbps]	Environment	E_b/N_0 [dB]	
		UL	DL
12.2 (CS)	Pedestrian	5.8	7.7
12.2 (CS)	Vehicular	6.9	8.0

Annex B – Single User Model Interface

In this annex, the single user model interface for Release 99, Figure B.1, HSDPA, Figure B.2, and HSUPA, Figure B.3, are shown.

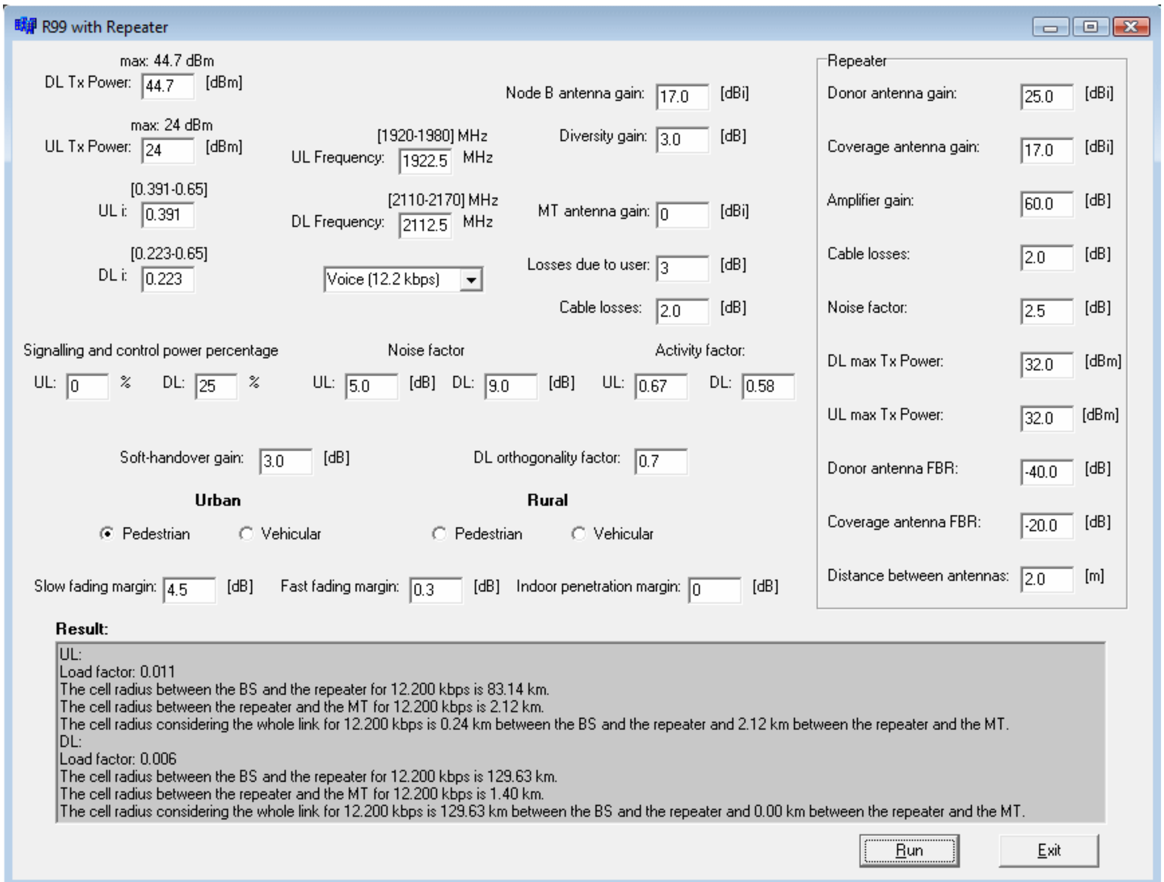


Figure B.1 – Release 99 single user model interface.

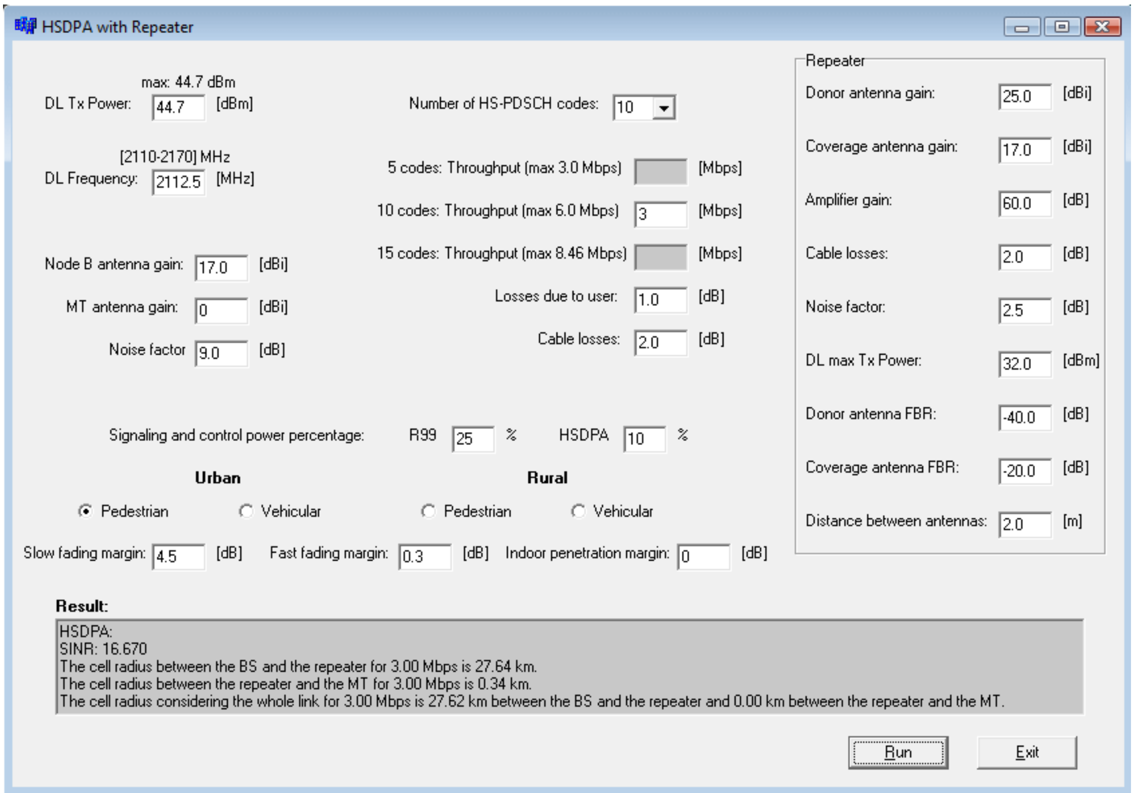


Figure B.2 – HSDPA single user model interface.

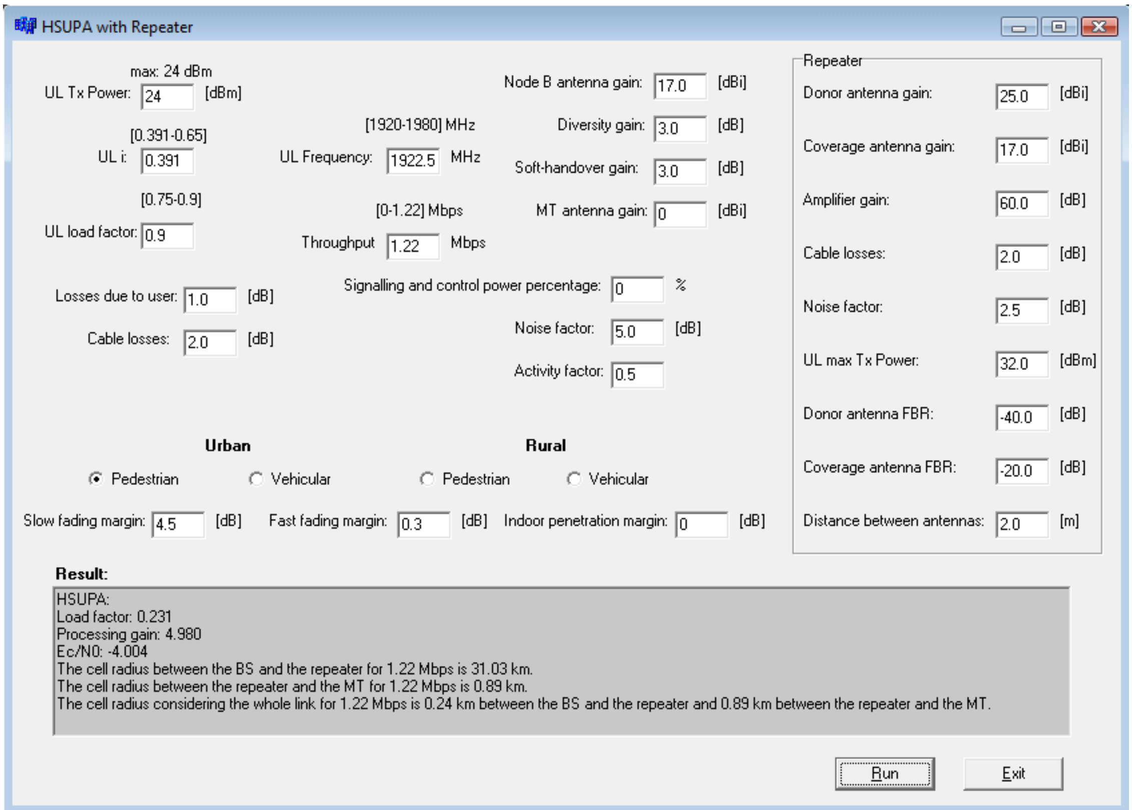


Figure B.3 – HSUPA single user model interface.

Annex C – Propagation Models

C.1 COST 231 Walfisch-Ikegami

In this section, the COST 231 W-I, [DaCo99], propagation model is presented.

The path loss for the LoS situation (when the street orientation angle, φ=0) is:

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

In all other cases, one has

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

where:

- L_0: path loss in free space propagation, given by:

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

- L_{rt}: multiple screen diffraction loss:

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

- L_{bsh}: losses due to the fact that BS antennas are above or below the rooftop level:

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

- h_b: BS height
- H_B: building height
- k_a: increase of the path loss for BS antennas below the rooftops of the adjacent buildings:

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

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

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

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

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

- w_B: distance between middle points of adjacent buildings
- L_{rm}: rooftop-to-street diffraction and scatter loss:

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

- w_s: street width
- L_{ori}: street orientation loss:

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

- φ: road orientation with respect to the direct radio path
- h_m: MT height

This model is restricted to the range of parameters shown in Table C.1. As it can be seen, UMTS frequencies are not fully covered.

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

In the absence of specific values, the following are recommended [Corr06]:

- $w_B \in [20, \; 50]$ m
- $w_s = w_B / 2$

- $\varphi = 90^{o}$
- $H_{B[\mathrm{m}]} = 3 \times (\#\,\mathrm{floors}) + H_{roof\,[\mathrm{m}]}$
- $H_{roof\,[\mathrm{m}]} = \begin{cases} 3, \mathrm{pitched} \\ 0, \mathrm{flat} \end{cases}$

Table C.1 – Restrictions of the COST 231 W-I propagation model (extracted from [DaCo99]).

Parameter	
Frequency [MHz]	[800, 2000]
BS height [m]	[4, 50]
MT height [m]	[1, 3]
Distance between BS and repeater or repeater and MT [km]	[0.02, 5]

The Release 99 DL and HSDPA frequencies values used, [2110, 2170] MHz, exceed the frequency validation values and some of the calculated cell radius are below the distance validation values. Nevertheless, the model is used, since it is adjusted to urban non-line of sight propagation.

Table C.2 lists the values of the propagation model's parameters. For the parameter that represents the dependence of the multi-screen diffraction loss versus frequency, k_f, only the dense urban case was considered.

Table C.2 – Values used in the COST 231 W-I propagation model (extracted from [Lope08]).

Parameter	Value
Street width [m]	24
Building separation [m]	48
BS height [m]	26
Building height [m]	24
MT height [m]	1.8
Orientation angle [º]	90

C.2 COST 231 Okumura-Hata

The COST 231 O-H propagation model is based on field measurements by Okumura et al., [OOKF80], that were fit into equations by Hata, [Hata80]. Later, this formulation was extended, [DaCo99], to cover higher frequencies.

The path loss median value is given by:

$$L_{p[\text{dB}]} = 46.30 + 33.90\log(f_{[\text{MHz}]}) - 13.82\log(h_{be[\text{m}]}) + [44.90 - 6.55\log(h_{be[\text{m}]})]\log(d_{[\text{km}]}) \\ -H_{mu[\text{dB}]}(h_m, f) + C_{m[\text{dB}]} - \sum \text{correction factors} \tag{C.11}$$

where:

- h_{be}: BS effective height

- $$H_{mu[\text{dB}]} = \begin{cases} [1.10\log(f_{[\text{MHz}]}) - 0.70]h_{m[\text{m}]} - [1.56\log(f_{[\text{MHz}]}) - 0.80], & \text{small city} \\ 8.29\log^2(1.54h_{m[\text{m}]}) - 1.10, \quad f \le 200 \text{ MHz}, & \text{urban centers} \\ 3.20\log^2(11.75h_{m[\text{m}]}) - 4.97, \quad f \ge 400 \text{ MHz}, & \text{urban centers} \end{cases} \tag{C.12}$$

- $$C_{m[\text{dB}]} = \begin{cases} 0, & \text{small city} \\ 3, & \text{urban centres} \end{cases}$$

The correction factors used in this thesis are:

- K_{th}: terrain undulation:

$$K_{th}(\Delta h)_{[\text{dB}]} = -3\log^2(\Delta h_{[\text{m}]}) - 0.5\log(\Delta h_{[\text{m}]}) + 4.5 \tag{C.13}$$

  where:
  - Δh: terrain undulation height

- K_{hp}: position in terrain undulation:

$$K_{hp}(\Delta h)_{[\text{dB}]} = -2\log^2(\Delta h_{[\text{m}]}) + 16\log(\Delta h_{[\text{m}]}) - 12 \tag{C.14}$$

- K_{mp}: mixed paths:

$$K_{mp}(\beta)_{[\text{dB}]} = \begin{cases} \begin{cases} -12.4\beta^2 + 27.2\beta, & d > 60 \text{ km} \\ -8.0\beta^2 + 19.0\beta, & d < 30 \text{ km} \end{cases} & \text{A} \\ \begin{cases} 11.9\beta^2 + 4.7\beta, & d > 60 \text{ km} \\ 7.8\beta^2 + 5.6\beta, & d < 30 \text{ km} \end{cases} & \text{B}(\beta < 0.8) \end{cases} \tag{C.15}$$

  where:
  - β: distance ratio

- K_{oa}: open areas:

$$K_{oa}(f)_{[\text{dB}]} = 4.78\log^2(f_{[\text{MHz}]}) - 18.33\log(f_{[\text{MHz}]}) + 40.9 \tag{C.16}$$

- K_{qo}: quasi open areas:

$$K_{qo}(f)_{[\text{dB}]} = K_{oa}(f)_{[\text{dB}]} - 5 \tag{C.17}$$

- K_{su}: suburban areas:

$$K_{su}(f)_{[\text{dB}]} = 2.00\log^2\left(\frac{f_{[\text{MHz}]}}{28}\right) + 5.40 \tag{C.18}$$

This model is restricted to the range of parameters shown in Table C.3. Like in the COST 231 W-I model, UMTS frequencies are not completely covered.

Table C.3 – Restrictions of the COST 231 O-H model (extracted from [DaCo99]).

Parameter	COST 231 O-H
Frequency [MHz]	[1500, 2000]
BS effective height [m]	[30, 200]
MT height [m]	[1, 10]
Distance between BS and repeater or repeater and MT [km]	[1, 20]

The Release 99 DL and HSDPA frequencies used, [2110, 2170] MHz, exceed the frequency validation values and some of the calculated cell radius are above the distance validation values. Nevertheless, as this is the model that best fits the scenario, it is the one that is used.

The standard deviation for urban, σ_u, and suburban, σ_s, environments is approximated by:

$$\sigma_u(f)_{[\text{dB}]} = 0.70\log^2(f_{[\text{MHz}]}) - 2.50\log(f_{[\text{MHz}]}) + 11.10 \tag{C.19}$$

$$\sigma_s(f)_{[\text{dB}]} = 0.98\log^2(f_{[\text{MHz}]}) - 3.40\log(f_{[\text{MHz}]}) + 11.88 \tag{C.20}$$

In Table C.4, the values for the propagation model's parameters, as well as the correction factors used by default on the simulator, are listed. For the C_m parameter, only the urban centres case was considered.

Table C.4 – Values and correction factors used in the COST 231 O-H propagation model.

Parameter	Value
Node B height [m]	26
MT height [m]	1.8
Correction factors	Open areas

Annex D – Service's Characterisation

The users' generator program is based on parameters provided by the MOMENTUM project, [MOME04], with the adaptations from [Lope08]. There is a correspondence between the services' traffic distribution files used and the ones from MOMENTUM, with similar service percentages, Table D.1.

Table D.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.srt	Email
	FTP.rst	FTP

Annex E – User's Manual

In this annex, one presents the simulator’s user manual. Release 99 and HSPA are two different simulators, but, as they are very similar, one presents this manual as if it was the same simulator, highlighting the differences when necessary. 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 E.1.

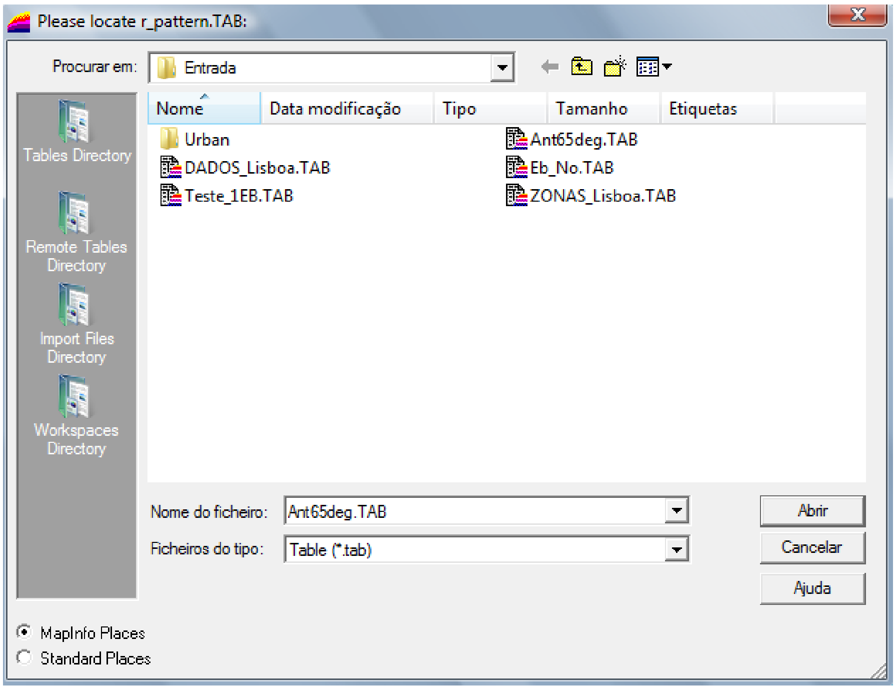


Figure E.1 – Window for the introduction of the initial 3 input files.

After the introduction of the geographical information, a new options bar is displayed in MapInfo, where it is possible to choose between Release 99 (‘UMTS’ menu), HSDPA and HSUPA, Figure E.2, and define the simulation’s characteristics.

Among the several options that are available for Release 99, HSDPA and HSUPA, the windows for the propagation model and services’ colours are common for the three systems, Figure E.3 and Figure E.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 E.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 E.5, not being possible to define a minimum service throughput lower than the ones presented. For Release 99, as one only uses the voice service, which has a fixed throughput, this window does not apply.

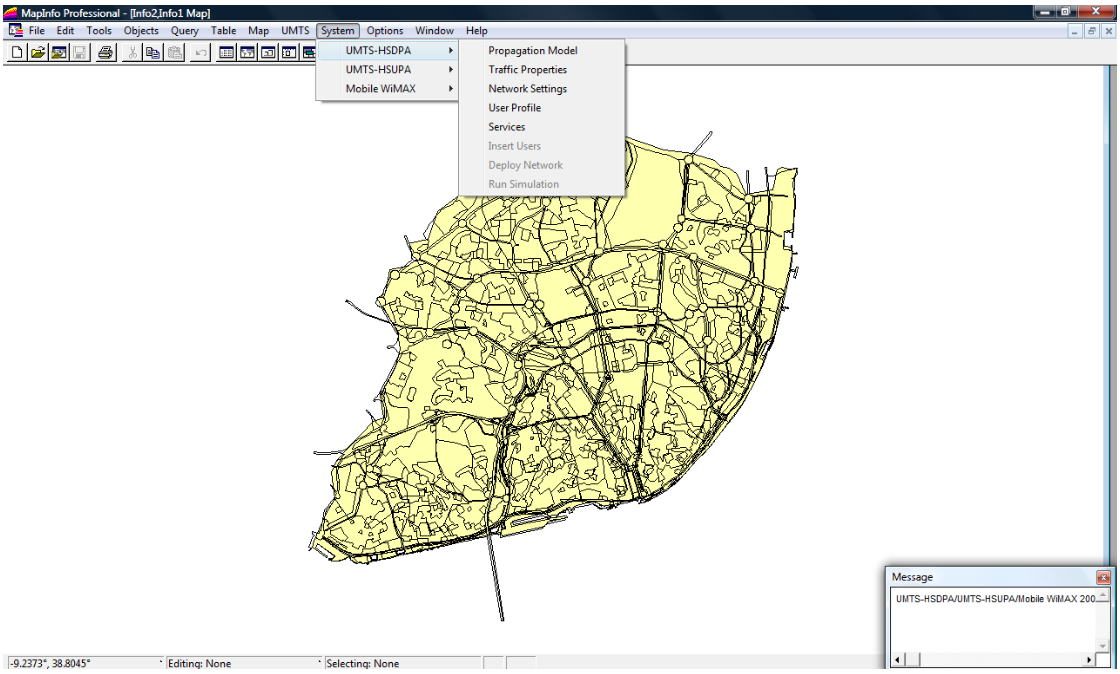


Figure E.2 – View of the simulator menu bar with the several options for each one of the systems.

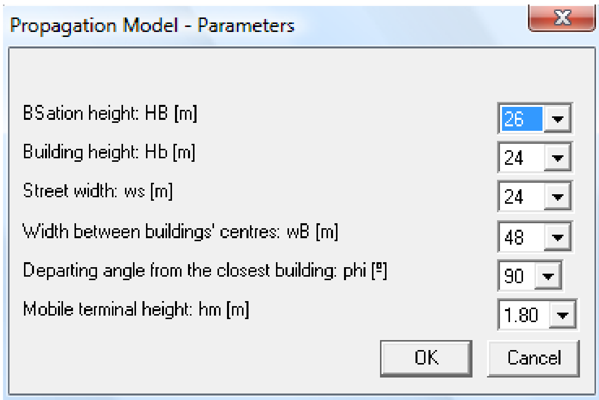


Figure E.3 – Propagation model parameters.

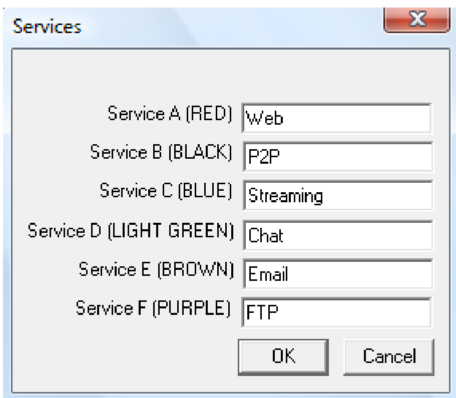
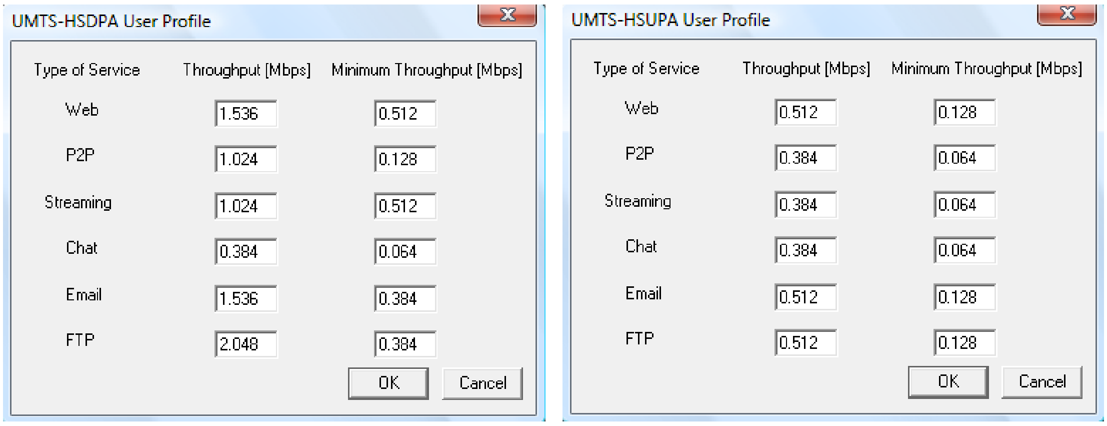


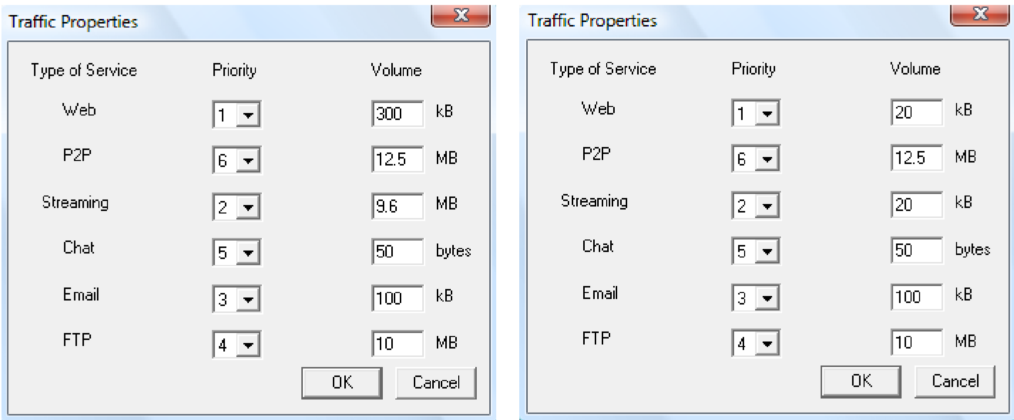
Figure E.4 – Services' colour assignment.



a) HSDPA. b) HSUPA.

Figure E.5 – HSDPA and HSUPA maximum and minimum service throughput.

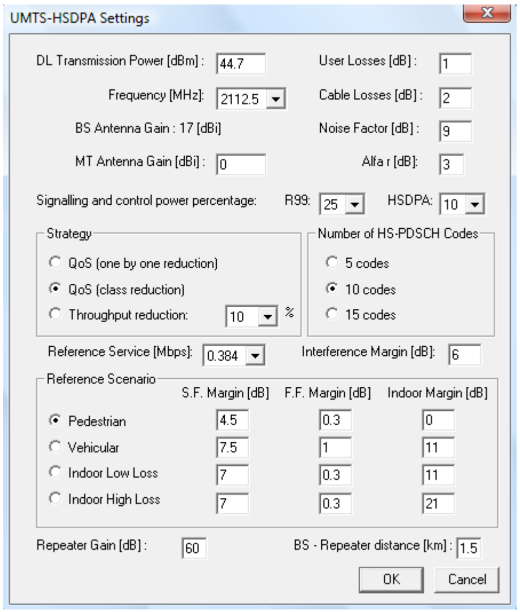
Traffic properties, like the volume and service QoS priorities, can be modified, Figure E.6. Again, one only presents the HSPA windows, since Release 99 only deals with the voice service.



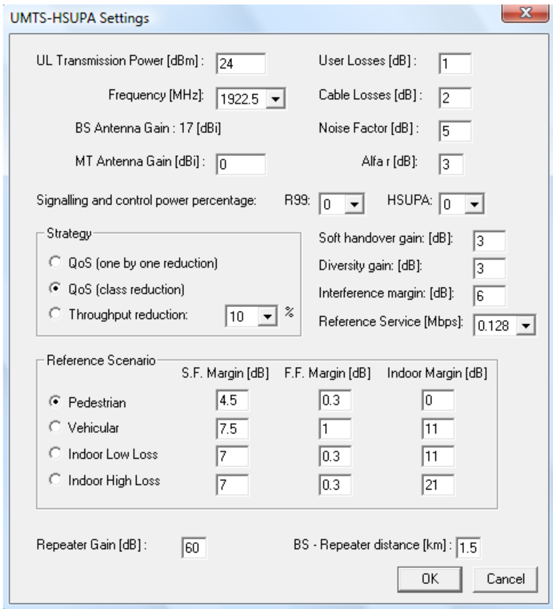
a) HSDPA. b) HSUPA.

Figure E.6 – HSDPA and HSUPA traffic properties window.

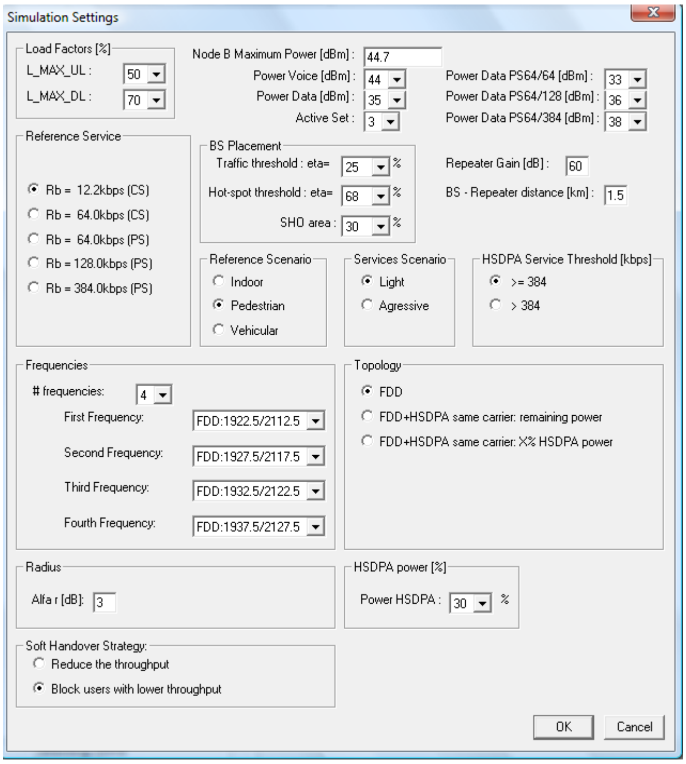
It is possible to modify the different radio parameters of the three systems, along with the reference scenario, reference service and reduction strategy (if applied), Figure E.7. The default values are presented in Section 4.1.



a) HSDPA.



b) HSUPA.



c) Release 99.

Figure E.7 – HSDPA, HSUPA and Release 99 simulations' parameters.

After pressing the "OK" button, in the "Message" window, the results regarding the cell radius for the reference service and the different services considered are displayed. The window in Figure E.8 presents HSDPA results. From now on, unless there are significant differences, only HSDPA windows are presented, since the procedures are identical to the three systems.

Later, in the network setting window, the functionality "Insert Users" is activated, to introduce 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 BS location, so that it can be placed in the city area, Figure E.9.

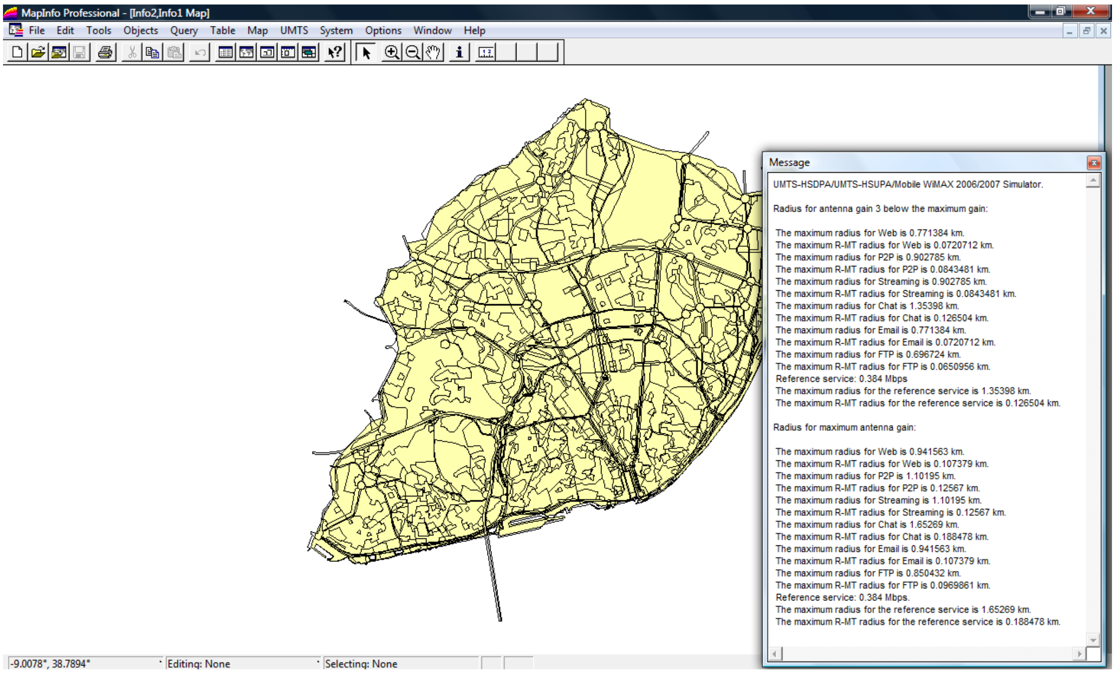


Figure E.8 – Visual aspect of the application after running the HSDPA settings window.

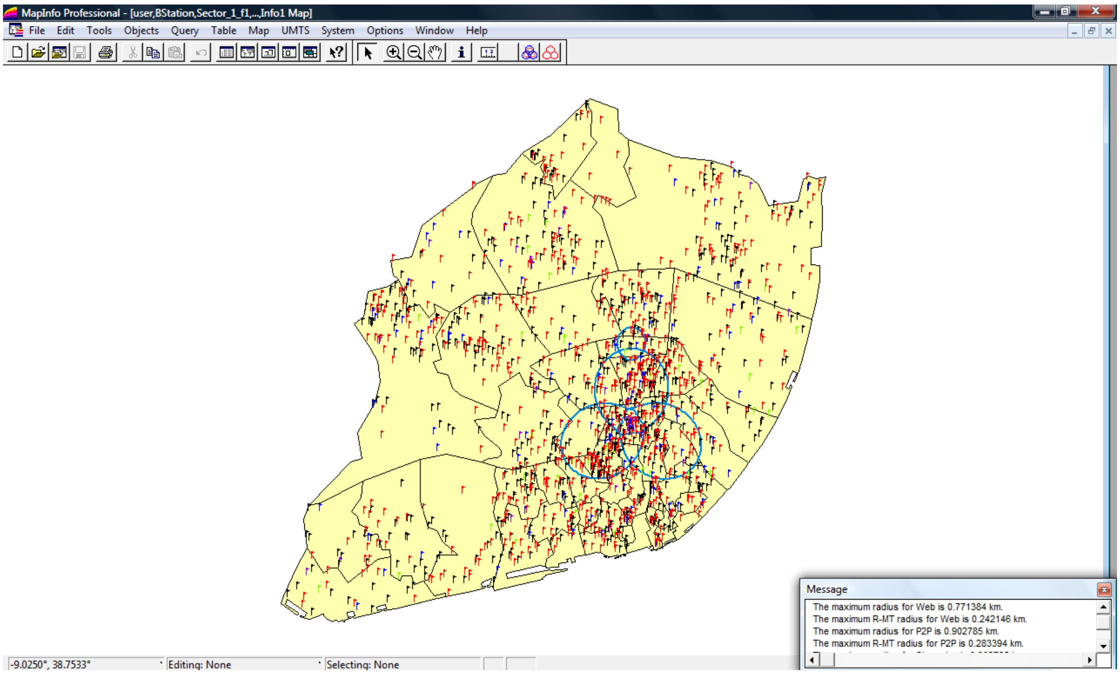
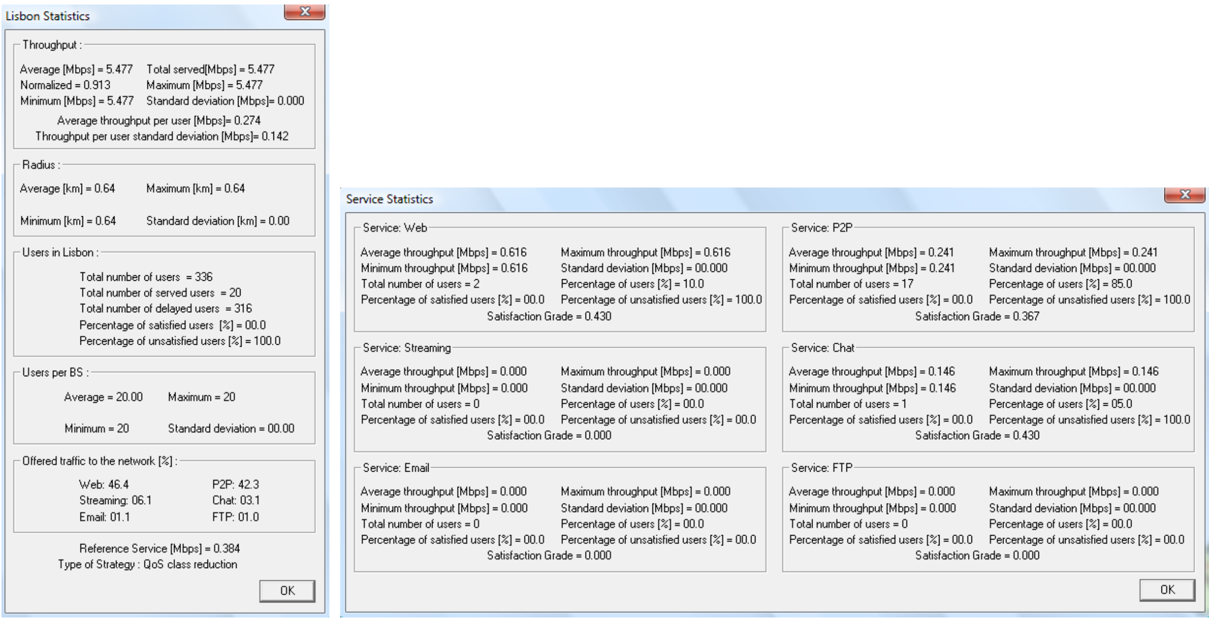


Figure E.9 – Result of the “Network Deployment” with the BS and the repeater.

After showing Figure E.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. Figure E.10 shows an example of those results for HSDPA, which also displays some results by service, and Figure E.11 for Release 99.



a) Instantaneous results. b) Instantaneous results detailed by services.

Figure E.10 – HSDPA results for the city of Lisbon.

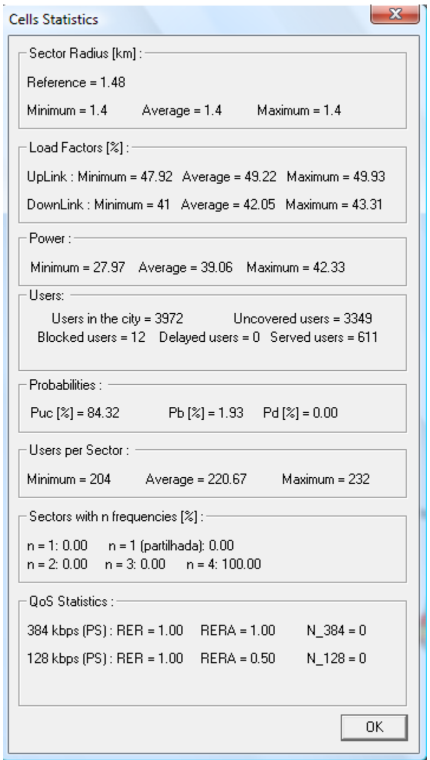


Figure E.11 – Release 99 instantaneous results for the city of Lisbon.

Annex F – Single User Results

In this annex, the Release 99, Table F.1 to Table F.4, HSDPA, Table F.5 to Table F.8, and HSUPA, Table F.9 to Table F.12, single user radius results are detailed. In Table F.1, Table F.5 and Table F.9, for the whole link values, the path loss limited distances are highlighted in yellow and the delay limited ones in red.

Table F.1 – Release 99 cell radii for the voice service with environment variation.

Release 99			Radius [km]			
			Separate links		Whole link	
			BS-R	R-MT	BS-R	R-MT
UL	Urban	Pedestrian	4.50	2.12	0.24	2.12
		Vehicular	4.50	0.81	0.25	0.81
	Rural	Pedestrian	4.50	2.25	4.50	2.25
		Vehicular	4.50	2.25	4.50	2.25
DL	Urban	Pedestrian	4.50	1.40	4.50	0.14
		Vehicular	4.50	0.57	4.50	0.06
	Rural	Pedestrian	4.50	2.25	4.50	2.25
		Vehicular	4.50	2.25	4.50	2.25

Table F.2 – Release 99 R-MT distance for different BS-R ones and 60 dB repeater's amplifier gain.

BS-R distance [km]	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50
DL R-MT distance (pedestrian) [km]	0.63	0.50	0.42	0.36	0.31	0.28	0.25	0.23	0.21	0.19	0.18	0.17	0.16	0.15	0.14
DL R-MT distance (vehicular) [km]	0.25	0.20	0.17	0.14	0.13	0.11	0.10	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.06
UL R-MT distance (pedestrian) [km]	0.50	0.40	0.33	0.29	0.25	0.22	0.20	0.18	0.17	0.15	0.14	0.13	0.13	0.12	0.11
UL R-MT distance (vehicular) [km]	0.21	0.16	0.14	0.12	0.10	0.09	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.05

Table F.3 – Release 99 R-MT distance for different BS-R ones and 90 dB repeater's amplifier gain.

BS-R distance [km]	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**	**2.25**	**2.50**	**2.75**	**3.00**	**3.25**	**3.50**	**3.75**	**4.00**	**4.25**	**4.50**
DL R-MT distance (pedestrian) [km]	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.40	1.28	1.19	1.10	1.03	0.96	0.91	0.86
DL R-MT distance (vehicular) [km]	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.56	0.52	0.48	0.44	0.41	0.39	0.37	0.35
UL R-MT distance (pedestrian) [km]	0.50	0.40	0.33	0.29	0.25	0.22	0.20	0.18	0.17	0.15	0.14	0.13	0.13	0.12	0.11
UL R-MT distance (vehicular) [km]	0.21	0.16	0.14	0.12	0.10	0.09	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.05

Table F.4 – Release 99 R-MT distance for different repeater's amplifier gains.

Repeater gain [dB]	**60**	**65**	**70**	**75**	**80**	**85**	**90**
DL R-MT distance (pedestrian) [km]	0.63	0.85	1.15	1.41	1.41	1.41	1.41
DL R-MT distance (vehicular) [km]	0.25	0.34	0.46	0.57	0.57	0.57	0.57
UL R-MT distance (pedestrian) [km]	0.50	0.68	0.92	1.24	1.68	2.11	2.11
UL R-MT distance (vehicular) [km]	0.21	0.28	0.38	0.51	0.69	0.81	0.81

Table F.5 – HSDPA 10 and 15 codes cell radii for 3 Mbps with environment variation.

HSDPA			**Radius [km]**			
			Separate links		**Whole link**	
			BS-R	**R-MT**	**BS-R**	**R-MT**
10 codes	Urban	Pedestrian	4.50	0.34	4.50	0.03
10 codes	Urban	Vehicular	4.50	0.14	4.50	0.01
10 codes	Rural	Pedestrian	4.50	2.25	4.50	2.25
10 codes	Rural	Vehicular	4.50	2.25	4.50	2.25
15 codes	Urban	Pedestrian	4.50	0.36	4.50	0.03
15 codes	Urban	Vehicular	4.50	0.15	4.50	0.01
15 codes	Rural	Pedestrian	4.50	2.25	4.50	2.25
15 codes	Rural	Vehicular	4.50	2.25	4.50	2.25

Table F.6 – HSDPA R-MT distance for different BS-R ones and 60 dB repeater's amplifier gain.

BS-R distance [km]	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
R-MT distance (pedestrian) [km]	0.14	0.11	0.09	0.08	0.07	0.06	0.05	0.05	0.05
R-MT distance (vehicular) [km]	0.06	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.02

Table F.7 – HSDPA 10 codes R-MT distance for different throughputs and repeater's amplifier gains.

Repeater gain [dB]	R-MT distance [km]											
	Throughput [Mbps]											
	1		2		3		4		5		6	
	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh
60	0.20	0.08	0.15	0.06	0.12	0.05	0.10	0.04	0.09	0.04	0.07	0.03
65	0.26	0.11	0.20	0.08	0.17	0.07	0.14	0.06	0.12	0.05	0.10	0.04
70	0.36	0.15	0.28	0.11	0.23	0.09	0.19	0.08	0.16	0.07	0.13	0.05
75	0.48	0.20	0.37	0.15	0.31	0.13	0.26	0.10	0.22	0.09	0.18	0.07
80	0.53	0.22	0.41	0.17	0.34	0.14	0.28	0.11	0.24	0.10	0.19	0.08
85	0.53	0.22	0.41	0.17	0.34	0.14	0.28	0.11	0.24	0.10	0.19	0.08
90	0.53	0.22	0.41	0.17	0.34	0.14	0.28	0.11	0.24	0.10	0.19	0.08

Table F.8 – HSDPA 15 codes R-MT distance for different throughputs and repeater's amplifier gains.

Repeater gain [dB]	R-MT distance [km]															
	Throughput [Mbps]															
	1		2		3		4		5		6		7		8.46	
	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh
60	0.20	0.08	0.15	0.06	0.14	0.06	0.12	0.05	0.11	0.04	0.10	0.04	0.09	0.04	0.07	0.03
65	0.27	0.11	0.20	0.08	0.18	0.08	0.17	0.07	0.15	0.06	0.13	0.05	0.12	0.05	0.10	0.04
70	0.37	0.15	0.28	0.11	0.25	0.10	0.22	0.09	0.20	0.08	0.18	0.07	0.16	0.06	0.13	0.05
75	0.50	0.21	0.38	0.15	0.34	0.14	0.30	0.12	0.27	0.11	0.24	0.10	0.21	0.09	0.18	0.07
80	0.55	0.22	0.41	0.17	0.34	0.14	0.33	0.14	0.29	0.12	0.26	0.11	0.23	0.10	0.19	0.08
85	0.55	0.22	0.41	0.17	0.34	0.14	0.33	0.14	0.29	0.12	0.26	0.11	0.23	0.10	0.19	0.08
90	0.55	0.22	0.41	0.17	0.34	0.14	0.33	0.14	0.29	0.12	0.26	0.11	0.23	0.10	0.19	0.08

Table F.9 – HSUPA cell radii for 1.22 Mbps with environment variation.

HSUPA		Radius [km]			
		Separate links		Whole link	
		BS-R	R-MT	BS-R	R-MT
Urban	Pedestrian	4.50	0.89	0.24	0.89
	Vehicular	4.50	0.37	0.24	0.37
Rural	Pedestrian	4.50	2.25	4.50	2.25
	Vehicular	4.50	2.25	4.50	2.25

Table F.10 – HSUPA R-MT distance for different BS-R ones and 60 dB repeater's amplifier gain.

BS-R distance [km]	1.00	1.25	1.50	1.75	2.00	2.25
R-MT distance (pedestrian) [km]	0.21	0.17	0.14	0.12	0.10	0.09
R-MT distance (vehicular) [km]	0.09	0.07	0.06	0.05	0.04	0.04

Table F.11 – HSUPA R-MT distance for different repeater's amplifier gains.

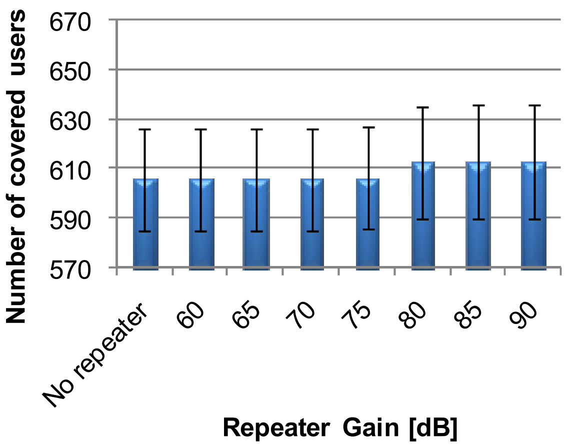
Repeater Gain [dB]	60	65	70	75	80	85	90
R-MT distance (pedestrian) [km]	0.21	0.28	0.38	0.52	0.7	0.74	0.74
R-MT distance (vehicular) [km]	0.09	0.12	0.16	0.21	0.29	0.30	0.30
R-MT distance without interference (pedestrian) [km]	0.21	0.28	0.38	0.52	0.70	0.95	0.95
R-MT distance without interference (vehicular) [km]	0.09	0.12	0.16	0.21	0.29	0.39	0.39

Table F.12 – HSUPA R-MT distance for different throughputs and repeater's amplifier gains.

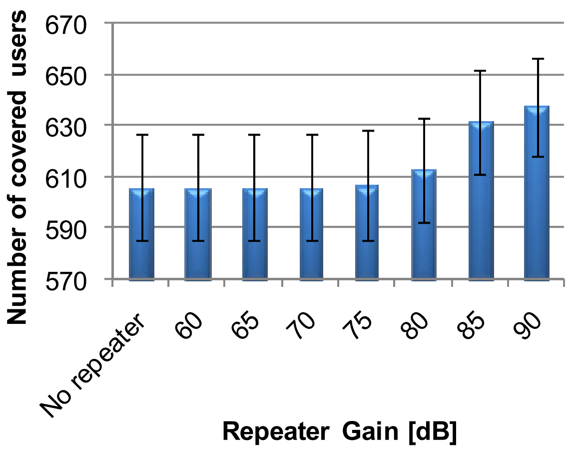
Repeater gain [dB]	R-MT distance [km]							
	Throughput [Mbps]							
	0.5		0.75		1		1.22	
	Ped	Veh	Ped	Veh	Ped	Veh	Ped	Veh
60	0.29	0.12	0.27	0.11	0.23	0.09	0.21	0.09
65	0.4	0.16	0.36	0.15	0.31	0.13	0.28	0.12
70	0.54	0.22	0.49	0.20	0.42	0.17	0.38	0.16
75	0.73	0.30	0.66	0.27	0.57	0.23	0.52	0.21
80	0.99	0.41	0.89	0.37	0.77	0.32	0.70	0.29
85	1.18	0.48	1.03	0.42	0.84	0.35	0.74	0.30
90	1.18	0.48	1.03	0.42	0.84	0.35	0.74	0.30

Annex G – Release 99 Additional Results

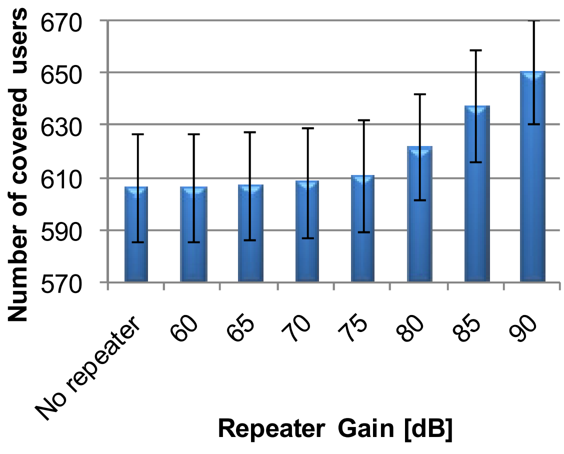
In this annex, supplementary results regarding the Release 99 analysis for the multiple users scenario are presented. Concerning repeater gain variation, the number of covered users is presented in Figure G.1, for several BS-R distances.



a) BS-R distance of 1.25 km.



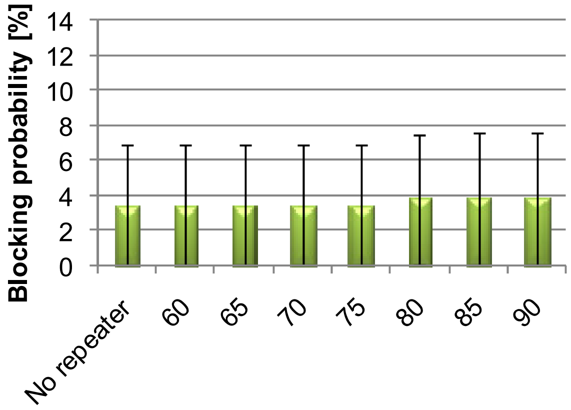
b) BS-R distance of 1.75 km.



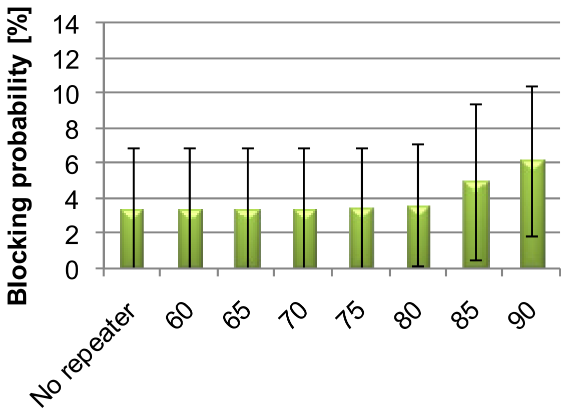
c) BS-R distance of 2.0 km.

Figure G.1 – Release 99 number of covered users as a function of the repeater's amplifier gain.

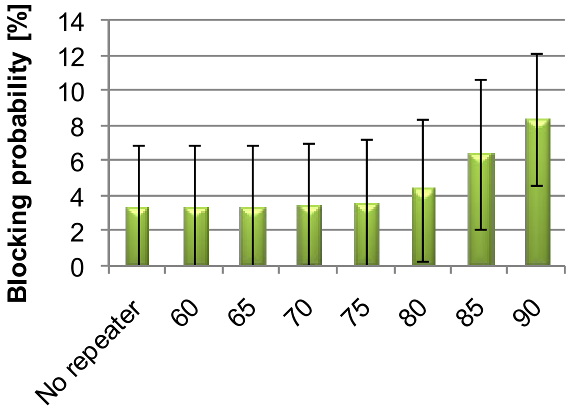
The blocking probability as a function of the repeater's amplifier gain is shown in Figure G.2.



a) BS-R distance of 1.25 km.



b) BS-R distance of 1.75 km.



c) BS-R distance of 2.0 km.

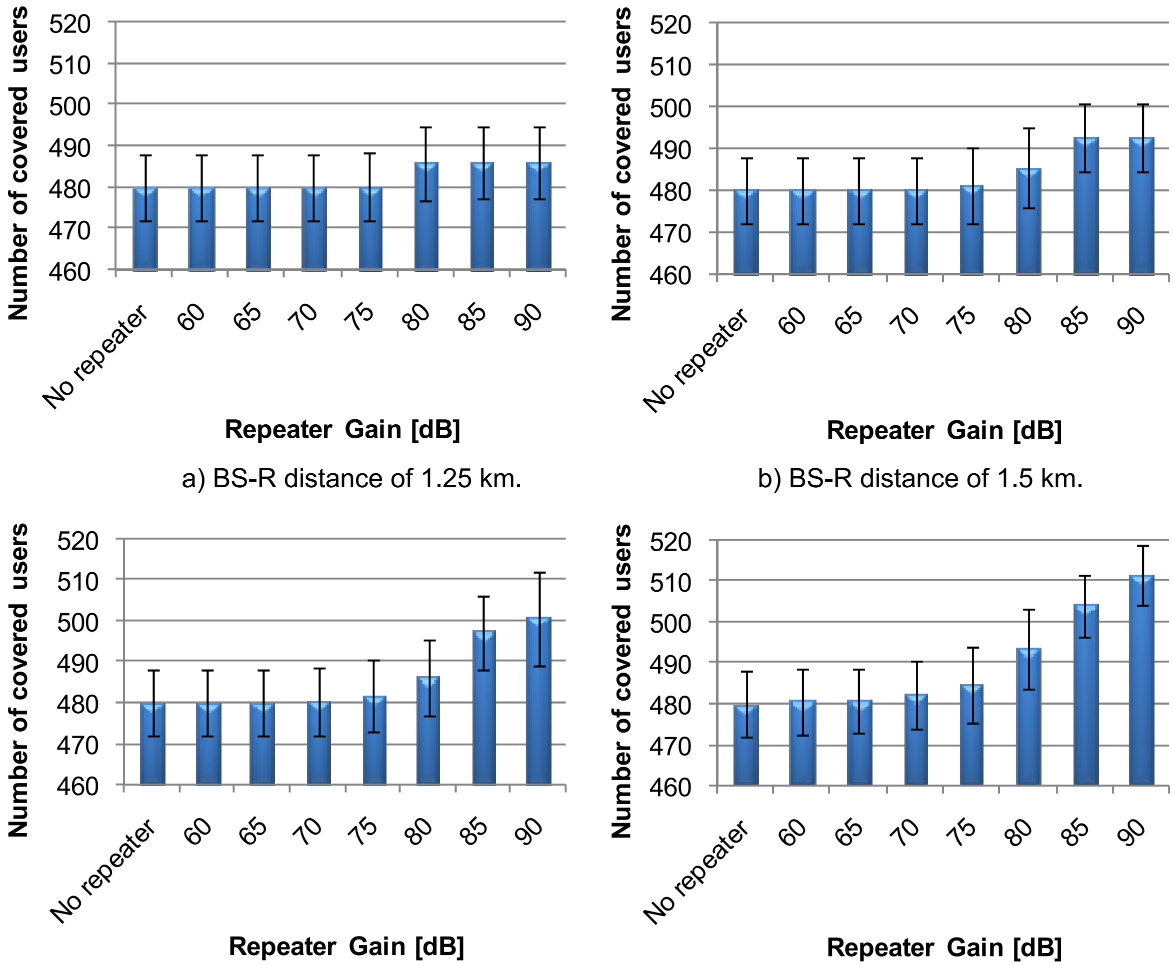
Figure G.2 – Release 99 blocking probability as a function of the repeater's amplifier gain.

The covered area and the increase provided by the repeater are presented in Table G.1.

Table G.1 – Release 99 covered area and respective increase provided by the repeater.

Repeater gain [dB]	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]
No rep.	11.34	0.00	11.34	0.00	11.34	0.00	11.34	0.00
60	11.34	0.00	11.34	0.00	11.34	0.00	11.38	0.37
65	11.34	0.00	11.34	0.00	11.34	0.00	11.42	0.66
70	11.34	0.00	11.34	0.00	11.48	1.24	11.48	1.22
75	11.67	2.86	11.62	2.44	11.62	2.50	11.60	2.25
80	12.08	6.47	11.94	5.30	11.89	4.84	11.81	4.10
85	12.09	6.64	12.23	7.81	12.40	9.36	12.21	7.63
90	12.09	6.64	12.23	7.81	12.49	10.09	12.57	10.82

The number of covered users as a function of the repeater's amplifier gain for the scenarios with 529 and 337 users is depicted in Figure G.3 and Figure G.4, respectively.



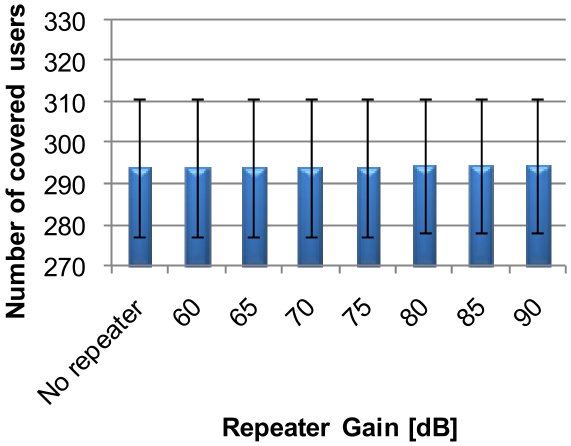
a) BS-R distance of 1.25 km.

b) BS-R distance of 1.5 km.

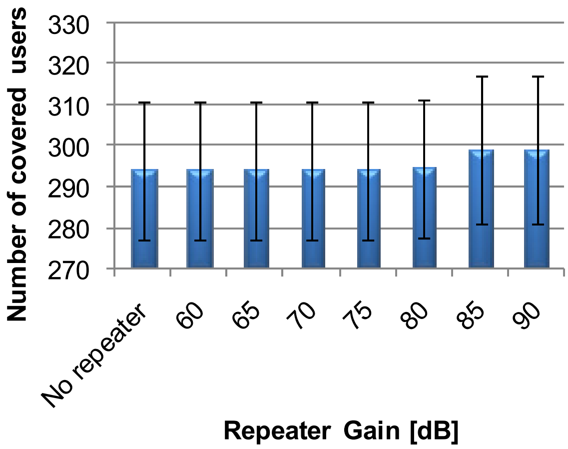
c) BS-R distance of 1.75 km.

d) BS-R distance of 2.0 km.

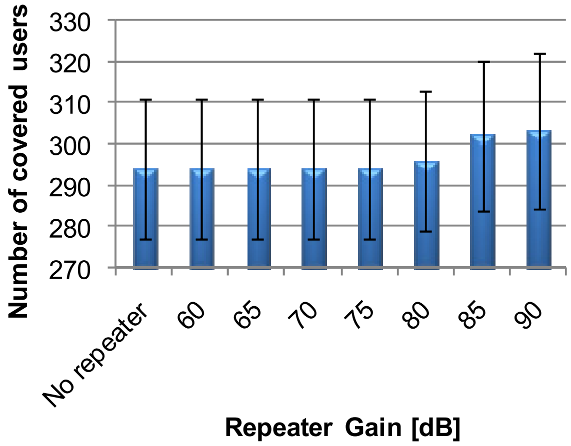
Figure G.3 – Release 99 number of covered users as a function of the repeater's amplifier gain, for 529 users.



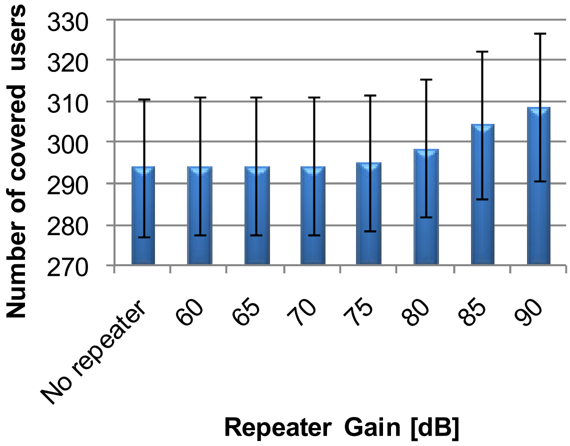
a) BS-R distance of 1.25 km.



b) BS-R distance of 1.5 km.



c) BS-R distance of 1.75 km.

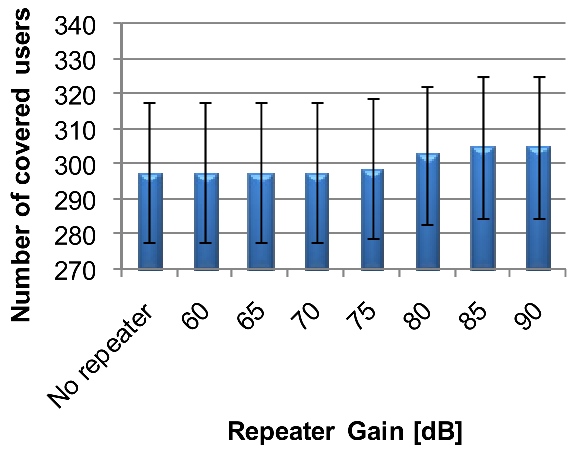


d) BS-R distance of 2.0 km.

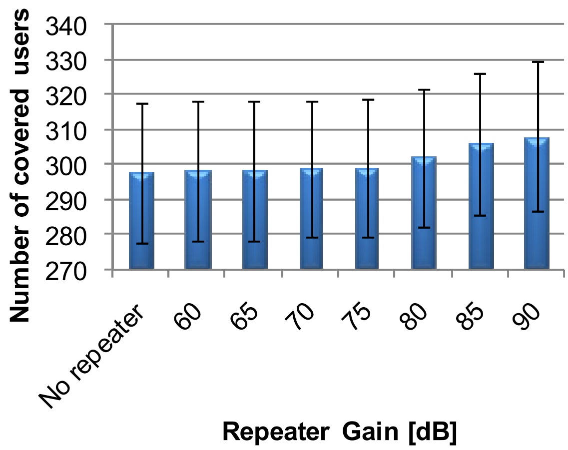
Figure G.4 – Release 99 number of covered users as a function of the repeater's amplifier gain, for 337 users.

Annex H – HSDPA Additional Results

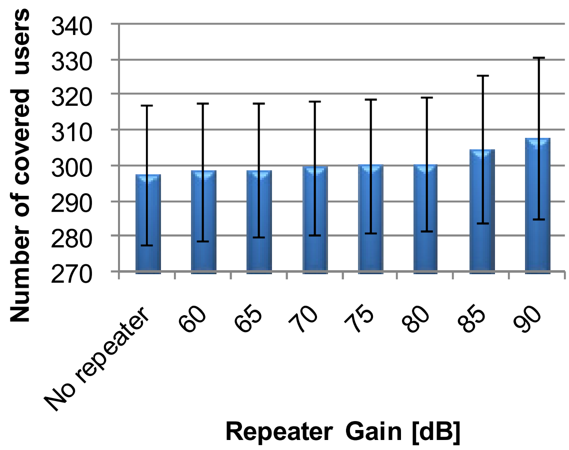
Extra results regarding the HSDPA analysis for the multiple users scenario are presented in this annex. Concerning repeater's amplifier gain variation, the number of covered users is presented in Figure H.1, for several BS-R distances.



a) BS-R distance of 1.25 km.



b) BS-R distance of 1.75 km.



c) BS-R distance of 2.0 km.

Figure H.1 – HSDPA number of covered users as a function of the repeater's amplifier gain.

The covered area and the increase provided by the repeater are presented in Table H.1.

Table H.1 – HSDPA covered area and respective increase provided by the repeater.

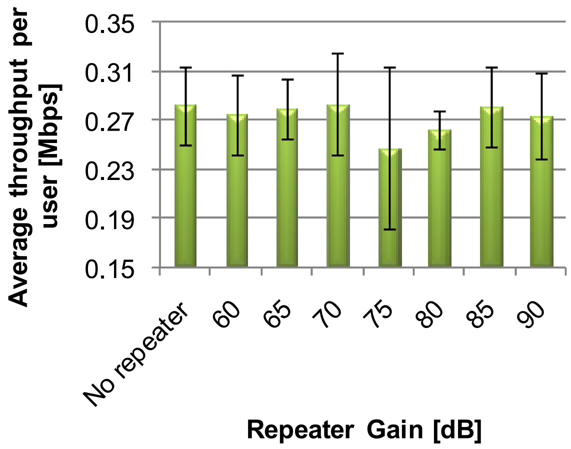
Repeater gain [dB]	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]
No rep.	8.55	0.00	8.55	0.00	8.55	0.00	8.55	0.00
60	8.55	0.00	8.55	0.00	8.57	0.24	8.57	0.18
65	8.55	0.00	8.58	0.33	8.59	0.44	8.58	0.33
70	8.55	0.00	8.61	0.71	8.62	0.83	8.61	0.62
75	8.68	1.45	8.68	1.50	8.68	1.47	8.65	1.12
80	8.82	3.09	8.81	2.98	8.78	2.68	8.73	2.03
85	8.82	3.15	8.94	4.50	8.97	4.89	8.88	3.76
90	8.82	3.15	8.94	4.50	9.02	5.44	9.02	5.44

The number of served users as a function of the repeater's amplifier gain and BS-R distance, for the default number of users, is presented in Table H.2.

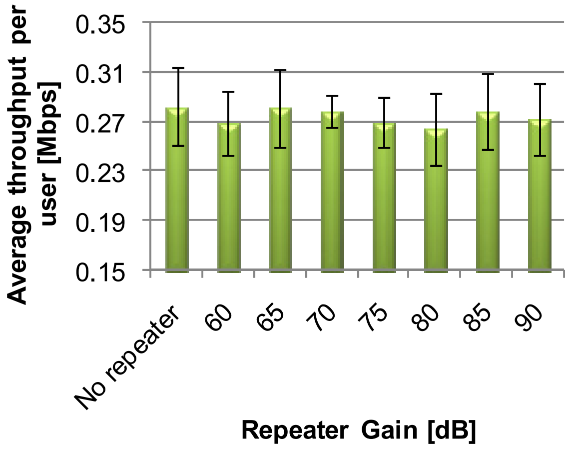
Table H.2 – HSDPA number of served users considering repeater's amplifier gain and BS-R distance.

	Number of served users							
Repeater gain [dB]	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
No rep.	19.6	2.07	19.6	2.07	19.6	2.07	19.6	2.07
60	20.4	1.82	21.0	1.22	20.6	1.82	20.0	2.34
65	20.2	1.64	20.4	1.52	20.2	1.48	19.8	2.95
70	20.0	3.16	20.6	3.21	19.8	0.84	19.6	1.82
75	21.0	1.87	20.4	2.70	20.4	1.67	21.0	2.24
80	20.6	2.51	21.2	3.56	22.0	2.12	19.4	2.30
85	19.0	2.45	20.2	1.48	20.0	1.87	19.6	0.89
90	20.6	1.82	21.0	1.58	21.0	2.64	20.4	1.82

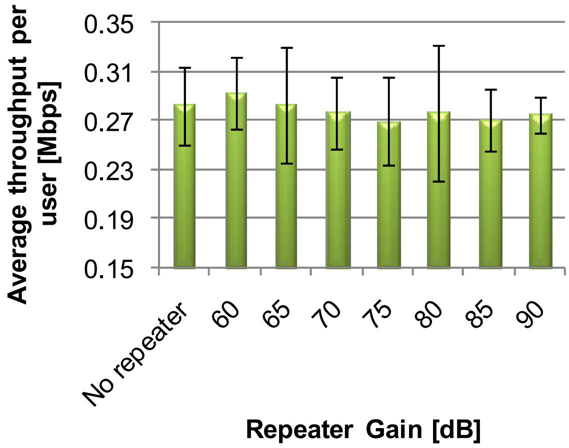
The average throughput per user as a function of the repeater's amplifier gain is depicted in Figure H.2.



a) BS-R distance of 1.25 km.



b) BS-R distance of 1.75 km.



c) BS-R distance of 2.0 km.

Figure H.2 – HSDPA average throughput per user as a function of the repeater's amplifier gain.

The average satisfaction grade for the repeater's amplifier gain variation is represented in Figure H.3, Figure H.4 and Figure H.5, respectively for BS-R distances of 1.25, 1.75 and 2.0 km.

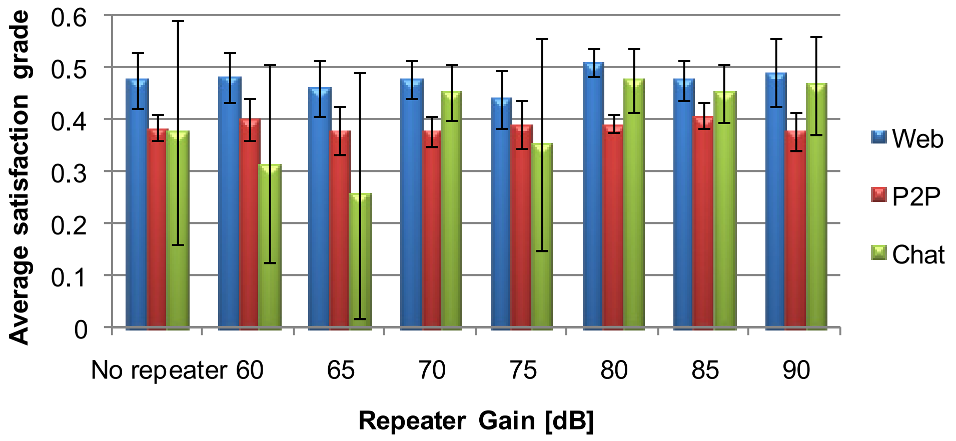


Figure H.3 – HSDPA average satisfaction grade as a function of the repeater's amplifier gain, for a BS-R distance of 1.25 km.

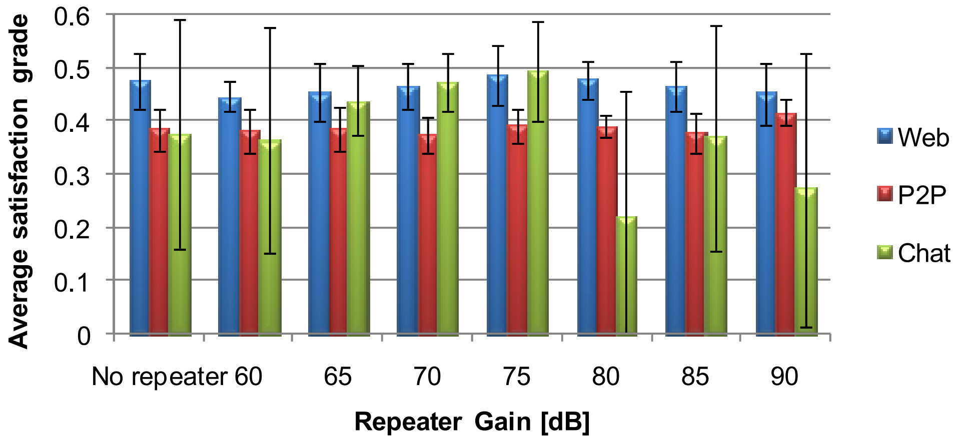


Figure H.4 – HSDPA average satisfaction grade as a function of the repeater's amplifier gain, for a BS-R distance of 1.75 km.

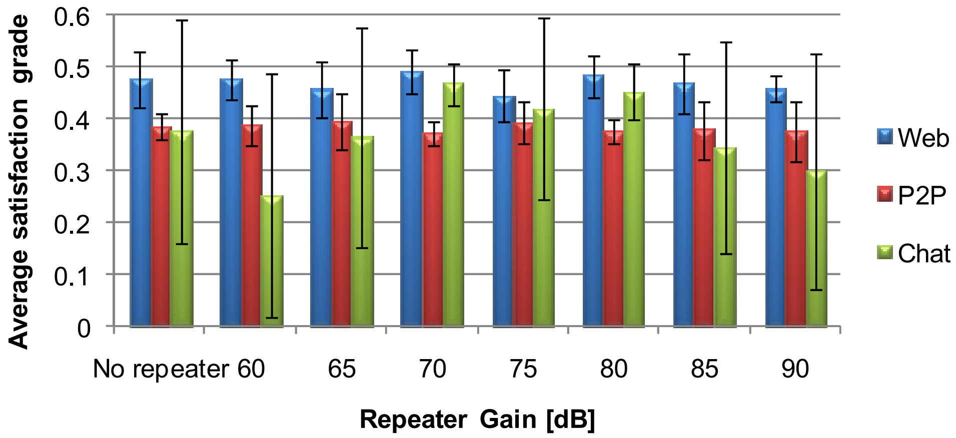
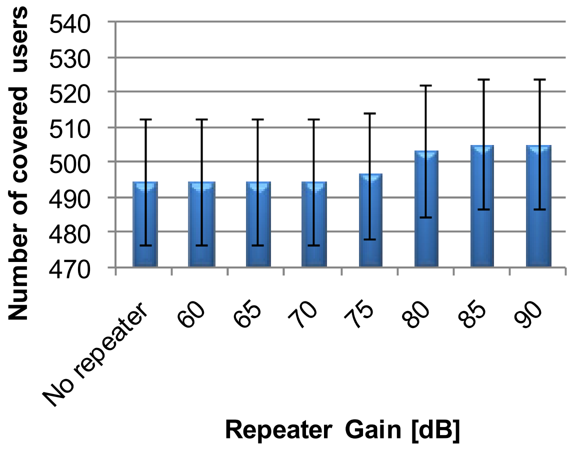
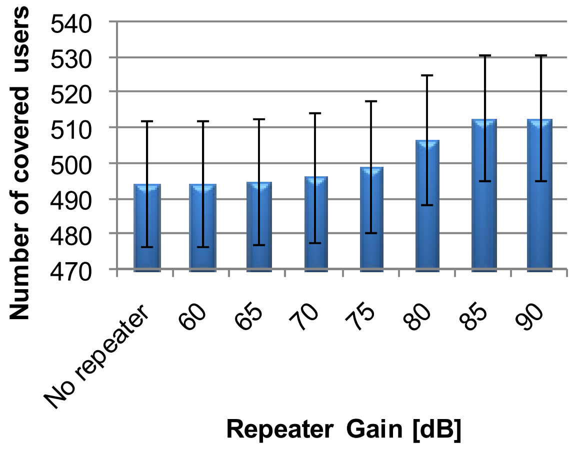


Figure H.5 – HSDPA average satisfaction grade as a function of the repeater's amplifier gain, for a BS-R distance of 2.0 km.

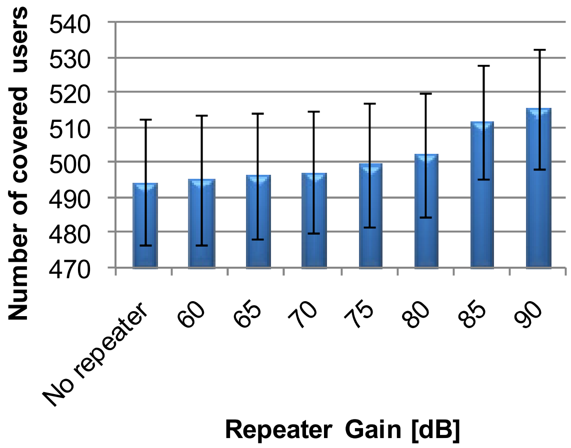
The number of covered users as a function of the repeater's amplifier gain for the scenarios with 532 and 125 users is depicted in Figure H.6 and Figure H.7, respectively.



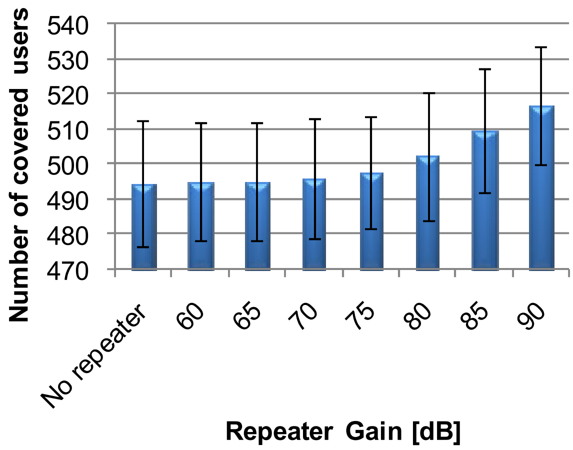
a) BS-R distance of 1.25 km.



b) BS-R distance of 1.5 km.

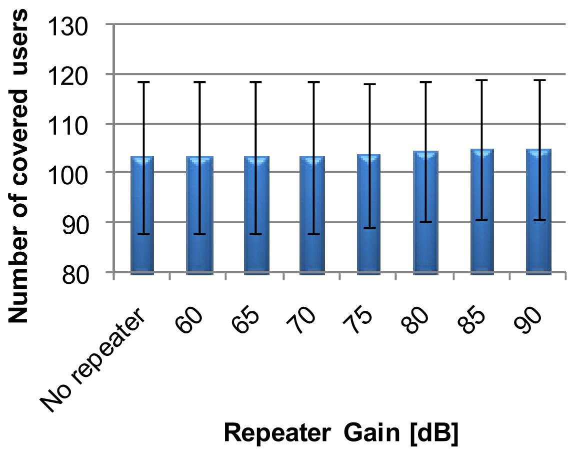


c) BS-R distance of 1.75 km.

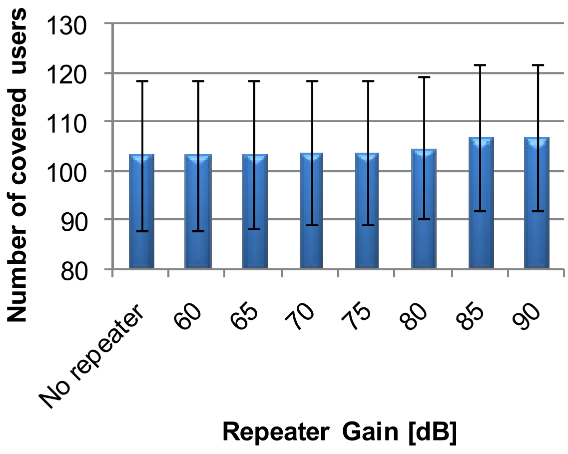


d) BS-R distance of 2.0 km.

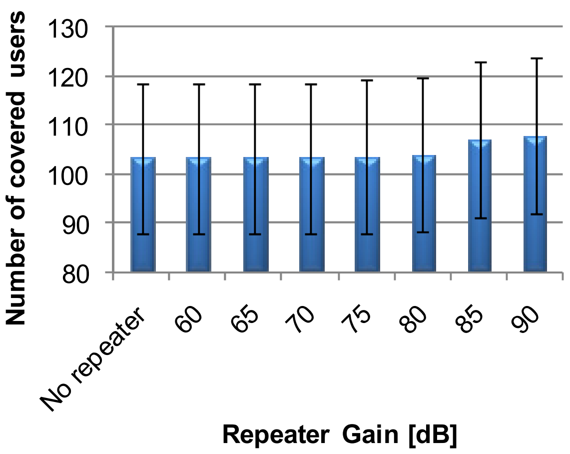
Figure H.6 – HSDPA number of covered users as a function of the repeater's amplifier gain, for 532 users.



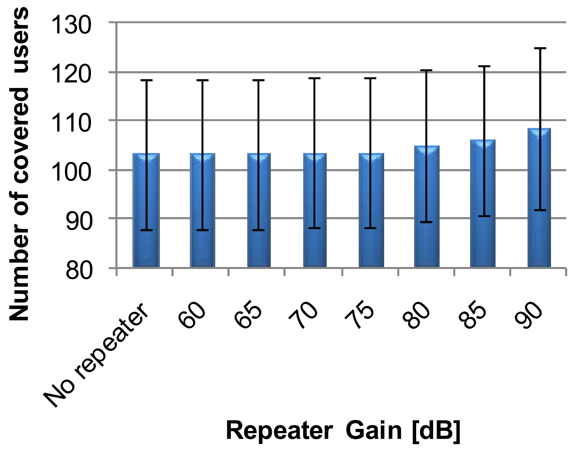
a) BS-R distance of 1.25 km.



b) BS-R distance of 1.5 km.



c) BS-R distance of 1.75 km.



d) BS-R distance of 2.0 km.

Figure H.7 – HSDPA number of covered users as a function of the repeater's amplifier gain, for 125 users.

The number of served users as a function of the repeater's amplifier gain and BS-R distance, for 532, 125 and 52 users, is presented in Table H.3, Table H.4 and Table H.5, respectively. For the 52 users scenario, one only performed simulations to the BS-R distance of 2.0 km, as it is enough to demonstrate the desired viewpoint.

Table H.3 – HSDPA number of served users considering repeater's amplifier gain and BS-R distance, for 532 users.

Repeater gain [dB]	Number of served users							
	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
No rep.	23.8	1.64	23.8	1.64	23.8	1.64	23.8	1.64
60	24.6	1.67	24.6	1.52	23.6	1.95	25.4	2.07
65	24.2	1.09	24.0	2.55	24.6	3.29	24.0	1.73
70	25.0	3.39	25.8	3.27	23.6	1.67	24.6	2.70
75	25.0	2.34	23.8	3.03	23.8	3.11	23.6	2.61
80	24.8	2.77	23.8	2.17	24.4	2.51	23.4	2.51
85	22.6	1.52	23.2	1.09	23.8	2.77	23.8	2.28
90	23.4	0.89	23.8	2.28	24.8	1.92	24.0	1.58

Table H.4 – HSDPA number of served users considering repeater's amplifier gain and BS-R distance, for 125 users.

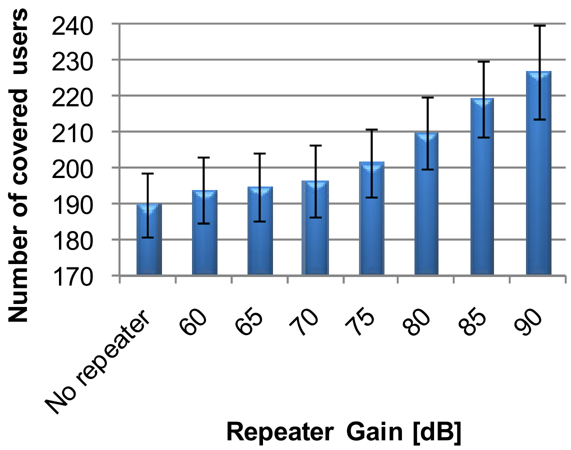
Repeater gain [dB]	Number of served users							
	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
No rep.	13.6	2.70	13.6	2.70	13.6	2.70	13.6	2.70
60	13.4	2.97	13.6	2.19	14.8	3.35	14.4	2.88
65	13.4	2.70	13.4	3.58	14.0	2.91	13.8	4.09
70	13.8	3.11	14.6	2.30	14.6	3.13	14.0	2.12
75	13.8	3.19	13.0	2.24	13.8	2.49	15.0	2.83
80	13.8	2.77	14.0	2.45	14.4	2.88	14.4	3.58
85	13.8	2.39	14.6	2.41	14.6	2.61	14.8	2.95
90	14.4	2.70	13.6	2.61	14.4	2.70	14.8	2.17

Table H.5 – HSDPA number of served users considering repeater's amplifier gain and BS-R distance, for 52 users.

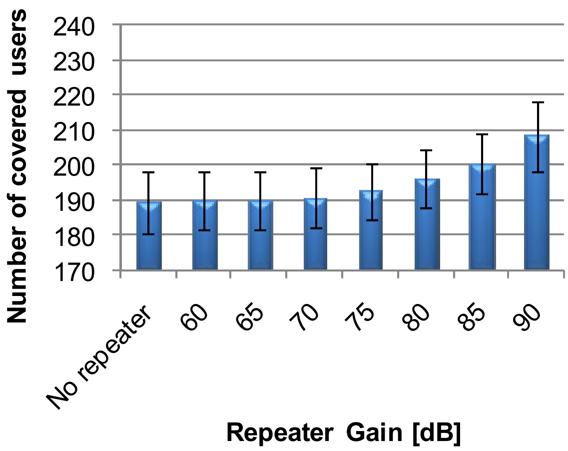
Repeater gain [dB]	Number of served users	
	BS-R distance [km]	
	2.0	
	Average	Std. dev.
No rep.	8.4	3.21
60	8.4	3.21
65	8.4	3.21
70	8.4	3.21
75	8.4	3.21
80	8.4	3.21
85	8.4	3.21
90	8.6	2.88

Annex I – HSUPA Additional Results

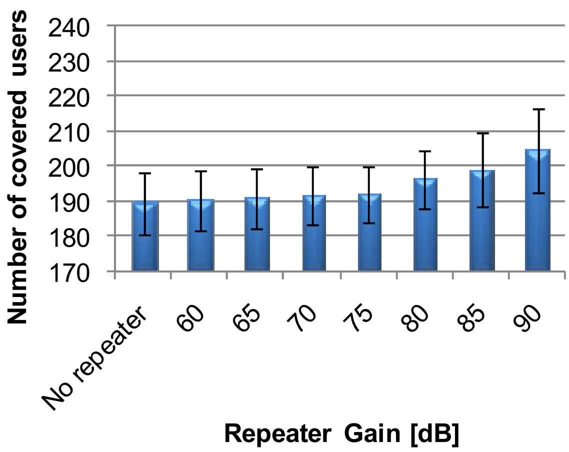
In this annex, extra results with reference to the HSUPA multiple users scenario are presented. The number of covered users with repeater's amplifier gain variation, for several BS-R distances, is presented in Figure I.1.



a) BS-R distance of 1.25 km.



b) BS-R distance of 1.75 km.



c) BS-R distance of 2.0 km.

Figure I.1 – HSUPA number of covered users as a function of the repeater's amplifier gain.

The covered area and the increase provided by the repeater are presented in Table I.1.

Table I.1 – HSUPA covered area and respective increase provided by the repeater.

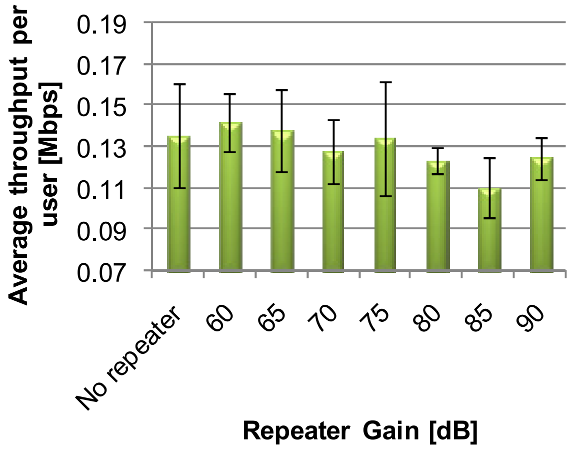
Repeater gain [dB]	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]	Covered area [km^2]	Increase [%]
No rep.	4.83	0.00	4.83	0.00	4.83	0.00	4.83	0.00
60	4.89	1.18	4.87	0.86	4.86	0.59	4.85	0.47
65	4.94	2.22	4.90	1.46	4.88	1.10	4.87	0.86
70	5.03	4.06	4.96	2.73	4.93	1.99	4.91	1.56
75	5.18	7.30	5.08	5.10	5.01	3.75	4.97	2.87
80	5.48	13.46	5.28	9.39	5.16	6.87	5.09	5.28
85	6.02	24.60	5.66	17.25	5.44	12.59	5.30	9.64
90	6.22	28.76	6.08	25.81	5.91	22.26	5.68	17.58

The number of served users as a function of the repeater's amplifier gain and BS-R distance, for the default number of users, is presented in Table I.2.

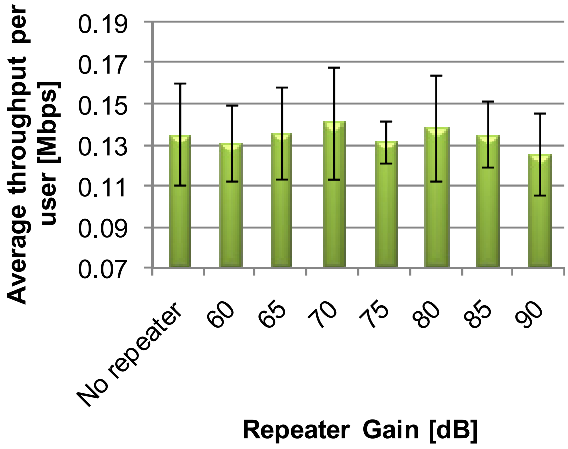
Table I.2 – HSUPA number of served users considering repeater's amplifier gain and BS-R distance.

	Number of served users							
Repeater gain [dB]	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
No rep.	8.6	1.14	8.6	1.14	8.6	1.14	8.6	1.14
60	8.2	0.84	8.6	0.89	8.0	1.00	9.0	1.22
65	8.6	1.52	7.6	1.67	8.8	1.30	8.2	2.05
70	8.8	1.48	8.2	1.09	8.4	0.89	8.4	1.34
75	9.0	1.58	7.4	1.34	8.2	1.09	8.6	0.89
80	9.4	0.55	8.2	0.84	8.2	1.64	8.6	1.52
85	9.6	1.14	8.8	1.79	9.4	0.89	8.2	1.30
90	9.0	0.71	9.6	1.52	8.8	1.79	8.6	0.55

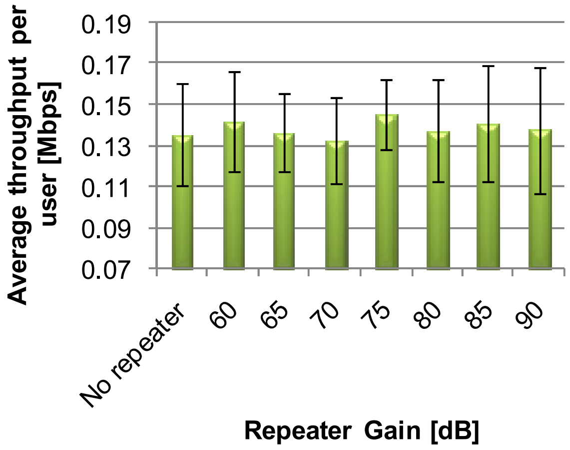
The average throughput per user as a function of the repeater's amplifier gain is depicted in Figure I.2.



a) BS-R distance of 1.25 km.



b) BS-R distance of 1.75 km.



c) BS-R distance of 2.0 km.

Figure I.2 – HSUPA average throughput per user as a function of the repeater's amplifier gain.

The average satisfaction grade for the repeater's amplifier gain variation is represented in Figure I.3, Figure I.4 and Figure I.5, respectively for BS-R distances of 1.25, 1.75 and 2.0 km.

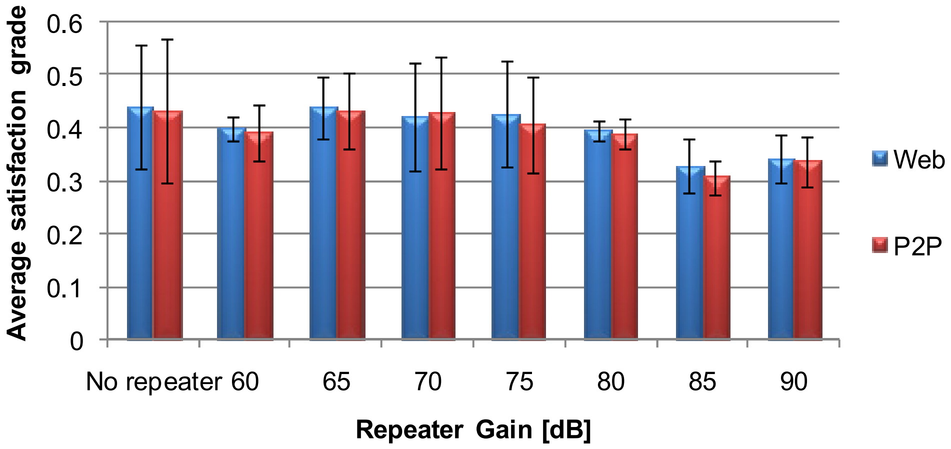


Figure I.3 – HSUPA average satisfaction grade as a function of the repeater's amplifier gain, for a BS-R distance of 1.25 km.

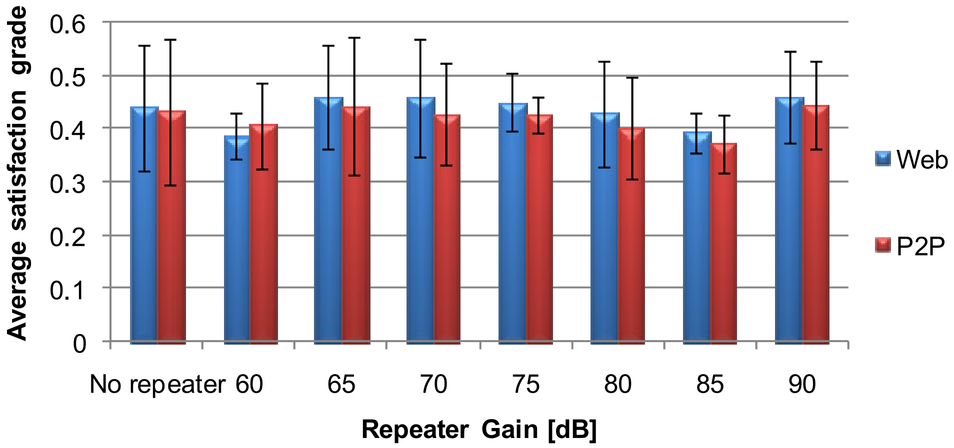


Figure I.4 – HSUPA average satisfaction grade as a function of the repeater's amplifier gain, for a BS-R distance of 1.75 km.

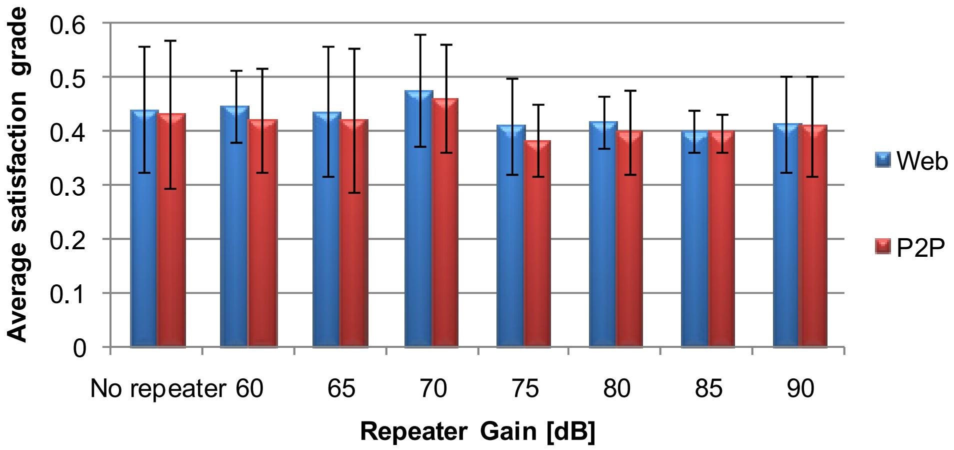
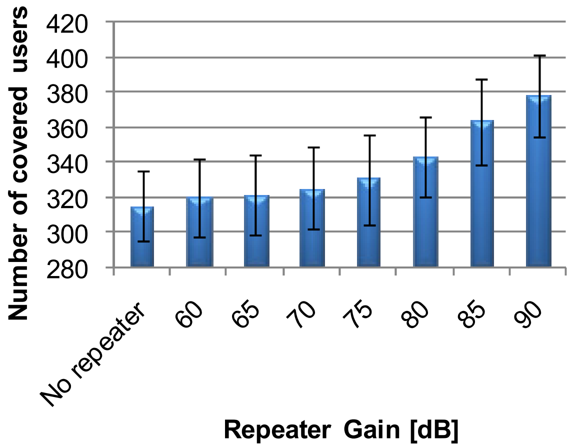
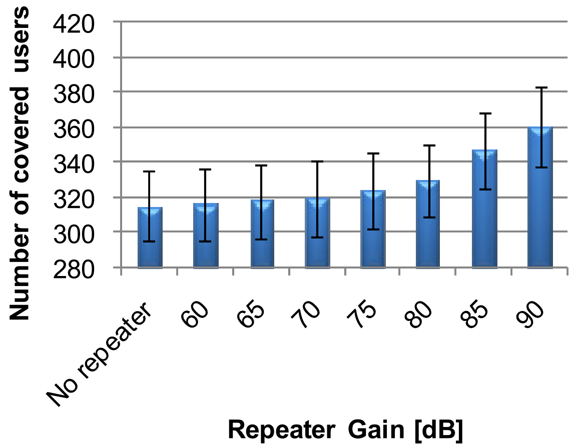


Figure I.5 – HSUPA average satisfaction grade as a function of the repeater's amplifier gain, for a BS-R distance of 2.0 km.

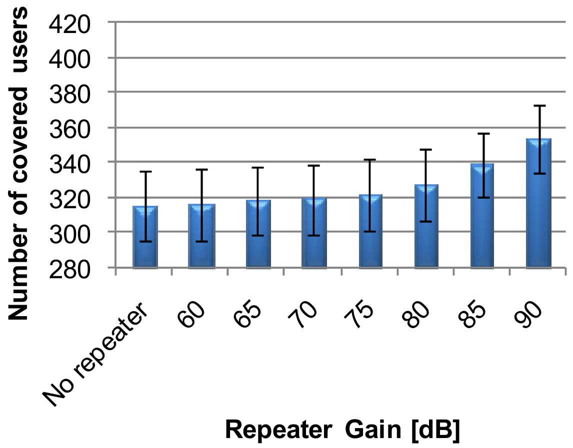
The number of covered users as a function of the repeater's amplifier gain for the scenarios with 532 and 125 users is depicted in Figure I.6 and Figure I.7, respectively.



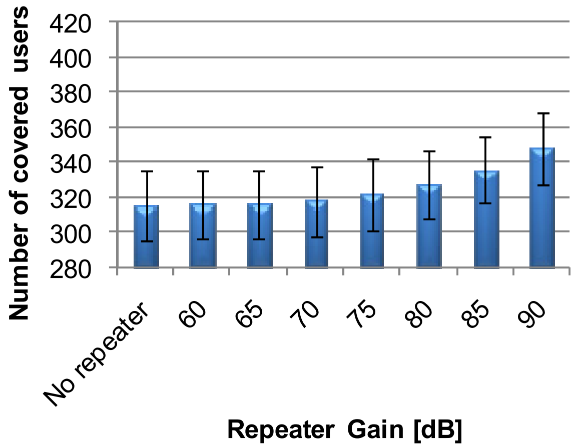
a) BS-R distance of 1.25 km.



b) BS-R distance of 1.5 km.

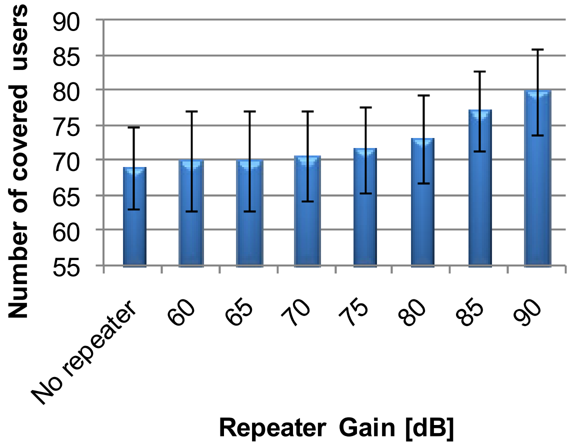


c) BS-R distance of 1.75 km.

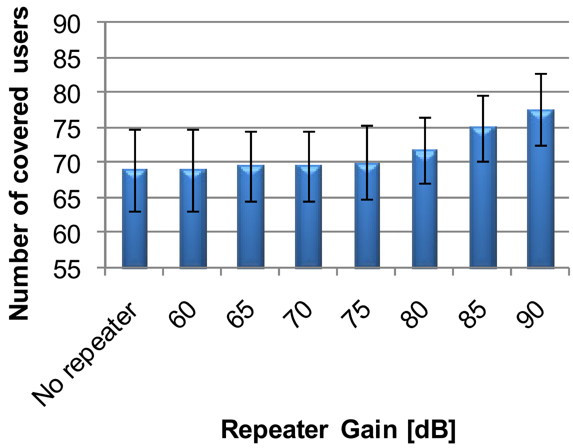


d) BS-R distance of 2.0 km.

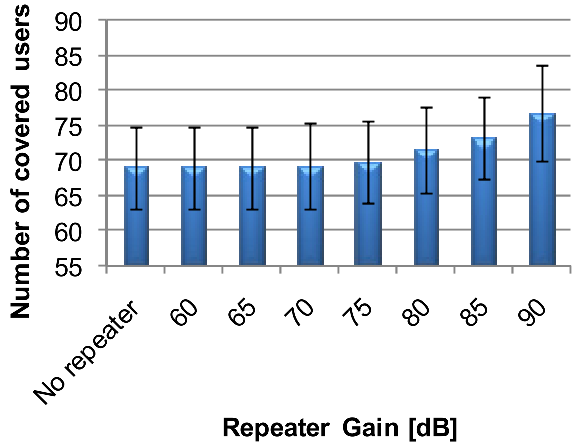
Figure I.6 – HSUPA number of covered users as a function of the repeater's amplifier gain, for 532 users.



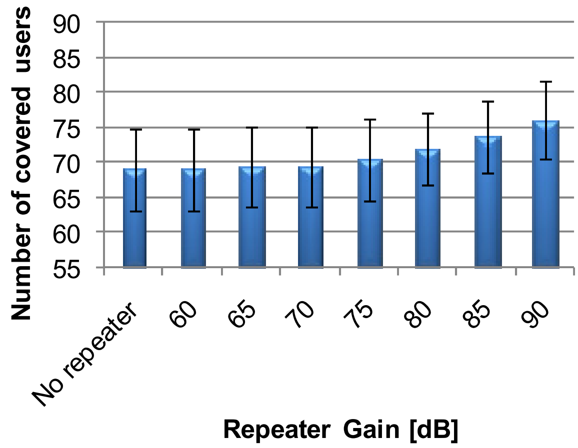
a) BS-R distance of 1.25 km.



b) BS-R distance of 1.5 km.



c) BS-R distance of 1.75 km.



d) BS-R distance of 2.0 km.

Figure I.7 – HSUPA number of covered users as a function of the repeater's amplifier gain, for 125 users.

The number of served users as a function of the repeater's amplifier gain and BS-R distance, for 532, 125 and 52 users, is presented in Table I.3, Table I.4 and Table I.5, respectively. For the 52 users scenario, one only performed simulations to the BS-R distance of 2.0 km, as it is enough to demonstrate the desired viewpoint.

Table I.3 – HSUPA number of served users considering repeater's amplifier gain and BS-R distance, for 532 users.

Repeater gain [dB]	Number of served users							
	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
No rep.	9.8	1.30	9.8	1.30	9.8	1.30	9.8	1.30
60	10.2	0.84	9.2	1.30	9.0	0.71	10.0	1.22
65	8.8	1.48	8.2	1.92	9.0	1.41	9.4	0.89
70	9.0	1.58	9.6	1.14	9.0	0.71	8.8	1.48
75	8.6	0.89	9.8	1.30	10.4	1.67	8.4	1.52
80	9.6	1.52	8.8	1.79	9.6	1.95	8.2	2.28
85	10.6	1.52	8.8	1.79	9.4	1.14	8.8	0.45
90	10.4	1.14	9.4	0.89	9.8	0.84	8.6	0.89

Table I.4 – HSUPA number of served users considering repeater's amplifier gain and BS-R distance, for 125 users.

Repeater gain [dB]	Number of served users							
	BS-R distance [km]							
	1.25		1.5		1.75		2.0	
	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.	Average	Std. dev.
No rep.	5.2	1.09	5.2	1.09	5.2	1.09	5.2	1.09
60	5.2	1.09	5.2	0.84	5.4	0.89	5.8	1.09
65	5.6	0.89	5.6	0.89	5.6	0.89	5.4	1.14
70	5.2	1.09	5.8	1.48	5.4	1.34	5.6	0.89
75	5.4	0.89	5.4	0.89	5.0	1.00	5.8	1.09
80	5.4	1.52	5.2	0.84	5.6	0.89	6.2	1.48
85	6.6	0.89	6.0	1.22	5.2	1.09	5.8	1.30
90	6.0	1.22	5.8	0.45	5.6	0.89	6.4	1.14

Table I.5 – HSUPA number of served users considering repeater's amplifier gain and BS-R distance, for 52 users.

Repeater gain [dB]	Number of served users	
	BS-R distance [km]	
	2.0	
	Average	Std. dev.
No rep.	4.0	2.34
60	4.0	2.34
65	3.6	2.07
70	3.6	2.07
75	3.8	2.28
80	3.4	1.82
85	4.2	2.49
90	4.2	2.49

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