UNIVERSIDADE TÉCNICA DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Optimisation of UMTS-TDD Base Stations Location for Non-Uniform Traffic Distributions

Luís Miguel Rego Pires
(*Licenciado*)

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

Supervisor: Professor Luís Manuel de Jesus Sousa Correia

Jury

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To my wife Susana and my son Tiago

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Abstract

This work deals with the optimisation UMTS TDD base stations location for non-uniform traffic distributions for a given service area, the main objective being to co-locate TDD base stations with FDD ones in high bit rate traffic areas. A simulator for UMTS TDD was developed and implemented, together with an optimisation algorithm to transfer high bit rate users to TDD network based on a given threshold, low bit rate ones staying in FDD network. A radio resources management algorithm was developed and implemented, having a crucial importance in dealing with codes and timeslot. Six scenarios are analysed in the city (Lisbon), including network dependency on the parameters given above. As expected, the system behaves worse when the number of high bit rate users increases, caused by the increase of traffic in TDD base stations, leading to bit rate reductions for each user. It is verified that the better bit rate threshold is 128 kbps, the load one is 30%, and timeslot asymmetry one is 9:3. In general, by applying good radio resources management approaches, implying bit rate reductions, high bit rate users can be supported, and using co-location of TDD base stations, with a remarkable improvement on the overall system performance, can optimise the FDD network.

Keywords

UMTS. TDD. Co-located Base Stations. Radio network dimensioning. System performance. Network optimisation.

Resumo

Este trabalho tem como objectivo, a optimização da localização de estações base UMTS-TDD para uma dada área, usando uma distribuição de tráfego não uniforme, sendo o principal objectivo co-localizar estações base TDD em áreas de elevado débito binário. Foi desenvolvido e implementado: um simulador para UMTS-TDD; um algoritmo de optimização para separar utilizadores de alto débito, colocando-os na rede TDD baseado num limiar predefinido, ficando os de baixo na rede FDD e um algoritmo de gestão de recursos rádio (códigos e timeslots). Seis cenários na cidade de Lisboa foram analisados, incluindo a dependência da rede em relação aos parâmetros supra-referidos. Tal como esperado, o sistema comporta-se pior quando o número de utilizadores de alto débito cresce, dado que as estações base TDD tendem a ficar com mais tráfego, iniciando um processo de reduções do débito para cada utilizador. Verificou-se que o limiar de débito mais adequado é 128 kbps, sendo a carga de 30% e a assimetria mais adequada de 9:3. Em geral, aplicando uma boa gestão de recursos rádio, implicando reduções no débito, consegue-se suportar utilizadores de alto débito e optimizar uma rede FDD, utilizando co-localização de estações base TDD e com uma notável melhoria nos parâmetros que medem o desempenho do sistema.

Palavras chave

UMTS. TDD. Co-localização de Estações Base. Dimensionamento de redes rádio. Desempenho do sistema. Optimização de rede.

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List of Acronyms

2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	3^{rd} Generation Partnership Project
4G	4^{th} Generation
ACLR	Adjacent Channel Leakage power Ratio
ACS	Adjacent Channel Selectivity
AMC	Adaptive Modulation and Coding
BCH	Broadcast CHannel
BER	Bit Error Rate
BHCA	Busy Hour Call Attempt
BoD	Bandwidth-on-Demand
BPSK	Binary Phase Shift Keying
BS	Base Station
CAC	Call Admission Control
CDMA	Code Division Multiple Access
CN	Core Network
CR	Code Rate
CS	Circuit Switched
DCH	Dedicated CHannel
DECT	Digital Enhanced Cordless Telephone
DL	Downlink
DRER	Delayed Relative Effective Rate
DS-CDMA	Direct Sequence CDMA

EDGE	Enhanced Data for Global Evolution
EIRP	Equivalent Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
FBI	Feedback Information
FCFS	First-Come First-Served
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FTP	File Transfer Protocol
GGSN	Gateway GPRS Support Node
GIS	Geographic Information System
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GPS	Global Positioning System
GP	Guard Period
HARQ	Hybrid Automatic Request
HBR	High Bit Rate
HCR	High Chip Rate
HDR	High Data Rate
HLR	Home Location Register
HO	HandOver
HHO	Hard HO
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
HTTP	Hyper Text Transfer Protocol
IMT-2000	International Mobile Telecommunications – 2000
IP	Internet Protocol
IS-95	Interim Standard 95
ISDN	Integrated Services Digital Network
ITU	International Telecommunications Union
ITU-T	ITU – Telecommunication standardisation sector
JD	Joint Detection
LBR	Low Bit Rate

LCR	Low Chip Rate
LoS	Line of Sight
MAI	Multiple Access Interference
ME	Mobile Equipment
MIMO	Multiple Input Multiple Output
MMS	Multimedia Message Service
MT	Mobile Terminal
MSC	Mobile Switching Centre
MSS	Mobile Satellite System
NLoS	Non Line of Sight
OMC	Operations and Maintenance Centre
OVSF	Orthogonal Variable Spreading Factor
PC	Power Control
PCS	Personal Communications Systems
PHS	Personal Handy/phone System
PLMN	Public Land Mobile Network
PS	Packet Switched
PSTN	Public Switched Telephone Network
QoS	Quality of Service
QPSK	Quaternary Phase Shift Keying
RAB	Radio Access Bearer
RER	Relative Effective Rate
RF	Radio Frequency
RNS	Radio Network Subsystems
RRC	Radio Resource Control
RRM	Radio Resource Management
RT	Real Time
Rx	Receive
SF	Spreading Factor
SGSN	Serving GPRS Support Node
SHO	Soft HO
SIM	Subscriber Identity Module
SIR	Signal to Interference Ratio
SMS	Short-Message Service

SNR	Signal-to-Noise Ratio
SOHO	Small Offices /Home Office
SOM	Self Organising Maps
SSHO	Softer HO
TCP	Transmission Control Protocol
TD-CDMA	Time Division CDMA
TD-SCDMA	Time Division Synchronous CDMA
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TFCI	Transport-Format Combination Indicator
TPC	Transmit Power Control
TS	Timeslot
Tx	Transmitter
UDP	User Datagram Protocol
UE	User Equipment
UL	UpLink
UMTS	Universal Mobile Telecommunications System
USIM	UMTS SIM
UTRA	Universal Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VoIP	Voice over IP
VLR	Visitor Location Register
WCDMA	Wideband CDMA
WWW	World Wide Web

List of Symbols

α	DL orthogonality factor
$\overline{\alpha}$	Average orthogonality factor in the cell
λ_i	Mean calls in a busy hour
η	Cell load
η_{DL}^{FDD}	FDD DL load factor
η_{DL}^{TDD}	TDD DL load factor
$\overline{\eta_{DL}}$	Average load factor across the cell
η_{UL}^{FDD}	FDD UL load factor
η_{UL}^{TDD}	TDD UL load factor
A_{cov}	Coverage area of the square for an ideal network
$A_{n\mathrm{cov}}$	Square area, without coverage
A_{sqr}	Total area of the square
$A_{sqr\_n\mathrm{cov}}$	Non covered area of the square
B_i	Information bandwidth
B_t	Transmitted bandwidth
C_{Cap}	Cell capacity
C_{free}	Number of free codes for TDD mode
CR	Code rate
C_{used}	Number of used codes for TDD mode
$DRER_{1920}$	DRER for 1920 kbps bit rate

$DRER_{384}$	DRER for 384 kbps bit rate
$DRER_{128}$	DRER for 128 kbps bit rate
E_b	Bit energy
F_{FM}	Fast fading margin
F_M	Fading margin
F_N	Noise figure
F_{SM}	Slow fading margin
GP	Length of the guard period
G_p	Processing gain
G_r	Receiver antenna gain
G_{SH}	SHO gain
G_t	Transmitter antenna gain
i	Inter-to-intra-cell interferences ratio
I_{Intra}	Intra-cell interference
I_{Inter}	Inter-cell interference
L_C	Cable losses
L_{Other}	Others loss
L_P	Path loss
$\overline{L_p}$	Average propagation loss between BS and MT
L_{Pmax}	Maximum propagation loss
L_{UB}	User body loss
L_x	Additional attenuations in a link
M	Size of the symbol set
N	Total effective noise plus interference power
N_0	Noise power density
N_b	Number of users blocked
$N_{ChipsSlot}$	Number of chips in a slot
N_{cov}	Number of covered users
N_d	Number of delayed users
$N_{GuardPeriod}$	Number of chips for the guard period
N_{ncov}	Number of non covered users
$N_{pole_{DLj}}$	DL pole capacity for the j^{th} RAB

$N_{pole_{ULj}}$	UL pole capacity for the j^{th} RAB
N_{red_BS}	Number of TDD BS with reduction of the bit rate
N_{rf}	Noise spectral density of the MT receiver front-end
N_{serv}	Number of served users
N_{serv_DL}	Number of served users in DL for TDD mode
N_{serv_UL}	Number of served users in UL for TDD mode
N_{TDD_BS}	Number of TDD BS co-located in the FDD network
N_{TDD_USERS}	Number of TDD users
N_{TS}^{DL}	Number of timeslots for DL
N_{TS}^{UL}	Number of timeslots for UL
N_{user}	Total number of users
N_U	Number of users associated/connected to a BS
$N_{U\_TDD\_BS}$	Number of users reduced per TDD BS
N_{USERS_1920}	Number of users with a bit rate 1920 kbps
N_{USERS_384}	Number of users with a bit rate 384 kbps
N_{USERS_128}	Number of users with a bit rate 128 kbps
$N_{USERS\_1920-384}$	Number of users suffering a bit rate reduction from 1920 kbps to 384 kbps
$N_{USERS\_384-128}$	Number of users suffering a bit rate reduction from 384 kbps to 128 kbps
N_{USERS_128-64}	Number of users suffering a bit rate reduction from 128 kbps to 64 kbps
N_{Users_DL}	Number of users in DL for TDD mode
N_{Users_UL}	Number of users in UL for TDD mode
P_b	Blocking probability
P_d	Delay probability
P_{ncov}	Non covered users
P_r	Antenna received power
P_{Rx}	Receiver input power
P_{Rxmin}	Receiver sensitivity for a given service bearer
P_t	Transmitted power (delivered to the antenna)
P_{Tx}	Transmitter output power
P_{Tx}^{BS}	BS transmitted power
R	Cell radius

$R_{-3\text{dB}}$	Nominal radius for -3dB gain
$\overline{R_b}$	Average bit rate
R_b	Service bit rate
R_{b_DL}	Bit rate in DL for TDD mode
R_{b_UL}	Bit rate in UL for TDD mode
R_{bj}	Service bit rate of user j
R_C	WCDMA chip rate
RER_{1920}	RER for 1920 kbps bit rate
RER_{384}	RER for 384 kbps bit rate
RER_{128}	RER for 128 kbps bit rate
R_I	Receiver interference power
R_N	Receiver noise power
R_{N0}	Receiver noise density
R_{TDD_BS}	Bit rate reduction per TDD BS
$R_{U\_service}$	Bit rate reduced per user (service)
SIR_{DL}	SIR for DL
SIR_{UL}	SIR for UL
T_f	Frame duration
T_S	Total timeslots in a frame
v_j	Activity factor of user j

Chapter 1

Introduction

This chapter gives a brief overview of the work. Before establishing the work's targets and original contributions, the scope and motivations are brought up. The current State-of-the-Art on the scope of the work is also presented. At the end of the chapter, the work structure is provided.

1.1 Overview

A long way has been left behind, since it was first heard about the 3rd Generation (3G) of mobile systems, namely IMT-2000 or even Universal Mobile Telecommunications System (UMTS). Many thoughts were put ahead inside standardisation bodies, leading to the presentation of several standards and a variety of multiple radio access techniques. 3G is characterised by [LaWa02]:

- allowing both voice and high speed data;
- using the available spectrum in a more efficient way;
- simplifying international roaming;
- attaining economies of scale in equipment production.

3G extensively introduced the Wideband Code Division Multiple Access (WCDMA) approach. Despite of the huge investment already done in 2nd Generation (2G) Time Division Multiple Access (TDMA) systems in Europe, and in other parts of the world, with Global System for Mobile communications (GSM) [Rapp96], this new access method was the one approved for UMTS. Operators working with TDMA systems needed to change a considerable amount of network elements in order to get on track with CDMA. An intermediate step between 2G and 3G, namely the 2.5G (based on upgrading the GSM network to provide faster data services), was envisaged to fit in to the timeframe within which 3G was still under development, and where 2G could no longer satisfy users requirements and needs. High Speed Circuit Switched Data (HSCSD), with up to 57.6 kbps, by using several traffic channels, General Packet Radio Service (GPRS), with up to 115 kbps, by using additional network elements that allow the Mobile Terminal (MT) to form a packet switched connection to an external packet data network, or even the Enhanced Data for Global Evolution (EDGE), with up to 384 kbps, by implementing a new air interface modulation (8-PSK) and sophisticated channel coding techniques, were the strongest predecessors of 3G systems.

As UMTS penetration increases, it allows the network to carry a larger share of data traffic. WCDMA technology provides a few advantages, since it enables the operator to provide more interesting data services, including web browsing, person-to-person video calls, sports and news video clips, and mobile-TV. UMTS enables simultaneous voice and data, which allows, for example, browsing or emailing during voice conferencing, or real time video sharing during voice calls. Operators also offer laptop connectivity to the Internet and corporate Intranet with the maximum bit rate of 384 kbps in Downlink (DL) and 64 kbps in Uplink (UL) in UMTS Release 99. The number of UMTS subscribers globally was 70 million at the end of 2006 [HoTo06]. Mobile business is driven by the availability of attractive terminals. In order to reach a major market share, terminal offering for all market segments is required. There are currently available over 200 different UMTS terminal models from more than 30 suppliers, launched since 2005. It is expected that soon all new terminals will support UMTS.

The radio interface of the UMTS Terrestrial Radio Access (UTRA) covers both a Frequency Division Duplex (FDD) part for the paired bands and a Time Division Duplex (TDD) [HoTo00] one for the unpaired bands of the spectrum. FDD can be used for asymmetric traffic, however, in order to be spectrally efficient, DL and UL channel bandwidths should be matched to the asymmetry. Since Internet traffic is bursty by nature, and the asymmetry is always changing, the channel bandwidth cannot be precisely set in FDD so, in this respect, TDD is more efficient. Furthermore, channel bandwidths are typically set by the constraints of the available equipment, hence, FDD systems operators do not have the option to vary channel bandwidths dynamically in UL and DL. Since TDD operates by switching transmission between UL and DL over a very rapidly time interval, it can support voice and other symmetrical services as well as asymmetric ones. TDD can also handle a dynamic mix of both traffic types. The relative capacity of DL and UL can be changed in favour of one link over the other, by giving a greater time allocation, through time slots. Typically, there is more traffic in DL than in UL, accordingly, the operator should be able to allocate more time to DL transmission than to UL, which is not possible with the paired spectrum required for FDD systems, where it is not possible to re-allocate the use of the different bands. As a result, in TDD, it is possible to make a very efficient use of the available spectrum, and the original intent of UMTS was that the TDD spectrum would be used to provide high data rates in selected areas. TDD attracted a great deal of attention for its capability of flexible and efficient usage of frequency resources in transferring highly asymmetric and bursty data traffic based on Internet Protocol (IP).

There are a few characteristics that are typical of TDD systems, differentiating them from FDD ones:

- *Possible interference between UL and DL:* since both UL and DL share the same frequency in TDD, the signals of the two transmission links can interfere with each other, which is not the case in FDD.
- *Flexible capacity allocation between UL and DL:* in TDD, UL and DL are divided in the time domain, being possible to change the duplex switching point and to move capacity from UL to DL, or vice versa, given the requirements for asymmetry between UL and DL.
- *Interference:* TDD allows interference mitigation via proper frequency planning. TDD requires only one interference-free channel compared with FDD, which requires two interference-free channels.
- *Discontinuous transmission:* MT and Base Station (BS) transmissions are discontinuous in TDD, which puts requirements on the implementation. Switching between transmission links requires time, and switching transients must be controlled, so, in order to avoid the overlapping between UL and DL, a guard period is used at the end of each slot.
- *Reciprocal channel:* fast fading depends on frequency, therefore, in FDD, fast fading is uncorrelated between UL and DL. As the same frequency is used for both UL and DL in TDD, fast fading characteristics are the same in UL and DL. Based on the received signal, the TDD transceiver can estimate the fast fading that will affect its transmission, and this knowledge can be used in power control and in adaptive antenna techniques.

With the extraordinary success of 3G mobile communication services, service providers have been affording huge investments on network infrastructures. Due to the high costs and the scarcity of radio resources, an accurate and efficient mobile network planning is of outmost importance. With the rapid growth of the network size and number of users, efficient quantitative methods to support decisions for BS location have become essential. This need is even more acute now, with the advent of 3.5G systems, such as High Speed Downlink/Uplink Packet Access (HSDPA/HSUPA) [HoTo06], due to the increased complexity of the system and the number of parameters that must be considered.

In UMTS Release 99, WCDMA supports 2 Mbps of bit rate for DL (it is 1920 kbps, realistically), this bit rate being very distant from actual needs of users, from the concept always on and from all services over IP. TDD over FDD is a good start to High Bit Rate (HBR) for cellular networks. Release 99 is technologically (modulation – QPSK, capacity, coverage, and others addressed in this thesis) closed to 2 Mbps for TDD and 384 kbps for FDD in DL, so it is not possible to guarantee higher bit rates for either of them. HSDPA (modulation 16-QAM or 64-QAM) is a packet-based data service in WCDMA DL with data transmission up to 8-10 Mbps (and 20 Mbps for Multiple Input Multiple Output (MIMO) systems) over a 4.4 MHz bandwidth in WCDMA DL. HSDPA includes Adaptive Modulation and Coding (AMC), MIMO, Hybrid Automatic Request (HARQ), fast cell search, and advanced receiver design. In 3rd Generation Partnership Project (3GPP) [3GPP06] standards, Release 4 specifications provide efficient IP support, enabling provision of services through an all-IP core network, and Release 5 specifications focus on HSDPA to provide data rates up to approximately 10 Mbps to support packet-based multimedia services. HSDPA and HSUPA offer asymmetric links over FDD. MIMO systems are the work item in Release 6 specifications, which will support even higher data transmission rates, up to 20 Mbps. HSDPA is evolved from and backward compatible with Release 99 WCDMA systems, and is part of the High Speed Packet Access (HSPA) family, which provides a roadmap for UMTS-based networks to increase their data transfer speeds and capacity. Current HSDPA deployments now support 1.8 Mbps, 3.6 Mbps and 7.2 Mbps in DL.

1.2 Motivation and Contents

Current mobile users live in a multi-dimensional world, moving among indoor, outdoor urban, and outdoor rural environments, with a degree of mobility ranging from essentially stationary, through pedestrian, up to very high vehicular speeds. The increasing number of users of mobile radio networks, and their data services, require tools for planning the optimal configuration of these networks. Especially in urban areas, radio network planning dealing with the positioning of BSs, as well as the optimum setting of antenna patterns, is a very demanding task. The state of the art still requires some manual planning of BS location and a non fully automatic optimisation process, which requires an experienced person, and is very time consuming. The expected high traffic demand in mobile radio networks requires fast and automatic planning and optimisation tools, in order to fully exploit the limited resources. Interference is a key element, together with capacity and coverage. TDD means that all signals share the same timeslots (TS), codes and power, among others. As a consequence, capacity, codes, TS and BS to co-locate, are fundamental in planning and optimisation of TDD over FDD.

Several research projects and groups already tackled this very challenging subject, providing some valuable contributions in this area. The IST-MOMENTUM European project [MOME01], for example, developed a considerable amount of work and documentation on the analysis of UMTS system-behaviour and the optimisation of radio network design, through the deployment of new planning methods, with the support of system manufacturers, network operators, service providers, and university research teams.

In this thesis, an optimisation of UMTS TDD BSs location for non-uniform traffic distributions is proposed, based on an existing FDD network, leading to a placement of BSs for hot spot areas. Naturally, for this type of work, the study of new cellular networks or of commercial ones, like UMTS FDD, is needed. UMTS TDD has been discontinued (due to its limitations), being implemented only in some countries in the world (UK, China, Denmark and Japan). Apparently, one could say that the theme of this work is outdated, since it deals with the dimensioning of a TDD network (network implementation in simulator and using TDD for optimisation of a FDD network). Naturally, when this work started, the vision was UMTS TDD would be implemented over UMTS FDD in the near future. The focus was the use of TDD as a cellular network over FDD, hence, the development of algorithms to optimise UMTS FDD via TDD BSs in hot spot places was of great value. Nevertheless, the results presented in this thesis are general for TDD, without depending on the specified UMTS network.

BS placement is the most important problem to achieve a high cell planning efficiency. 3G systems provide a great variety of services, and today this kind of systems is in commercial use, so it is important solve the problem: how to place a BS, which depends on the traffic density, channel condition, interference scenario, the number of BSs, and other network planning parameters; at the end, it becomes a hard problem. The location of BS is a parameter optimisation problem. Network optimisation implies a great reduction in investment by cellular operators in placement of BSs, and when a optimisation method is implemented over an existing network, the main objective is to give a better bit rate where it is needed (hot spot areas).

The development of an optimisation algorithm for FDD and TDD modes, TDD over UMTS FDD, is the novelty of this work, leading to a fundamental performance parameter: the number of TDD BSs to co-locate with FDD ones. The algorithm gives the number of TDD BSs according to three input parameters (bit rate threshold, load decision and TS asymmetry) needed to control the process of optimisation, as a function of scenarios, users profile and service area (terrain characteristics and users non-uniform distributions).

Six chapters, including the current one, compose the present work; in addition, eleven Annexes are appended to this document. In Chapter 2, a brief overview of UMTS is given, mainly focusing on the FDD and TDD modes. In the end, an overview of services and applications is presented. Chapter 3 describes specific issues regarding network planning in UMTS. It covers capacity, coverage, interference, and link budget for the two modes of operation (FDD and TDD). It also addresses several optimisation algorithms from literature. In the end, one provides a description of conceptual optimisation algorithm developed. Chapter 4 is devoted to a functional description of the simulator platform. A detailed description of the development and implemented optimisation algorithm is performed, including input and outputs parameters. At the end, a validation of the simulator platform and optimisation algorithm is provided. Chapter 5 provides an analysis of simulation results for all tested scenarios. After the introduction to the scenarios characterisation (demographics, geography and users profile), details about services considerations (bit rate and service penetration) are given, and then the reasons for the choice of the reference scenario and reference configurations are presented. Finally, simulations results on the variation of bit rate, load and timeslot asymmetry are also present. Chapter 6 presents the final conclusions and further suggestions of work to be done in the future.

Annex A provides a presentation of the COST-231 Walfish-Ikegami propagation model; Annex B provides presentations of the link budget used in the simulator developed; Annex C presents the flowcharts of the most important parts of the simulator platform, focussing on the FDD mode; Annex D presents the flowcharts of the most important parts of the simulator, namely the new algorithms developed for TDD and all the modified flowcharts to adapt both modes; Annex E provides a simple validation of TDD; Annex F presents minimum and average radius in TDD mode; Annex G describes the software Manual – UMTS – Simul FDD/TDD; Annexes H, I, J and K present all the performance parameters (FDD and TDD mode) resulted from simulations.

Chapter 2

UMTS Overview

This chapter provides an overview of UMTS, focusing on network architecture and radio interface aspects. Afterwards, a description of FDD and TDD modes is provided. At the end, an overview of services and applications is presented.

2.1 Network Architecture

UMTS consists of a number of logical network elements, each having a defined functionality. In the standards, network elements are defined at the logical level, but this quite often results in a similar physical implementation, especially since there are a number of standard open interfaces [HoTo00], [3GPP00d]. Network elements are grouped into UMTS Terrestrial Radio Access Network (UTRAN), which handles all radio related functionalities, and the Core Network (CN), which is responsible for switching and routing calls and data connections to external networks. One has also the User Equipment (UE) that interfaces the user to the network via the radio interface. Figure 2.1 shows the elements in UMTS Public Land Mobile Network (PLMN).

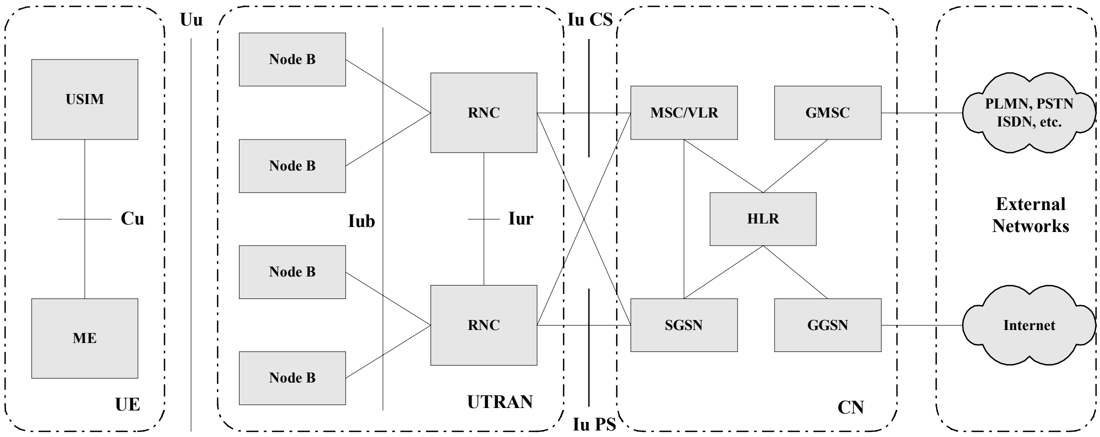


Figure 2.1. Network Elements in UMTS PLMN (adapted from [HoTo00]).

Both the UE and the UTRAN include protocols that are specific of the needs of the WCDMA radio technology. On the contrary, the definition of the CN was adopted from the existing GSM/GPRS one. This enabled the system, with a new radio technology but with a known CN one, to be deployed in an easier way, allowing for competitive advantages such as global roaming. In the next paragraphs each of these elements is described in more detail.

In UMTS, the MT is called Mobile Equipment (ME). The protocol stacks of the radio interface as well as the operating elements for the user interface are incorporated in the MT, which includes the UMTS Subscriber Identity Module (USIM). The UTRAN consists of one or more Radio Network Subsystems (RNSs), which is a sub-network within UTRAN, and contains one Radio Network Controller (RNC), and one or more BSs, called Node Bs. RNCs may be connected to each other via an Iur interface, while RNCs and Node Bs are connected with an Iub interface; Iu, Iur and Iub are logical interfaces, which may be provided via any suitable transport network. The CN contains a multitude of switching systems, as well as gateways to others networks, and also databases that are used for, e.g., mobility management, user management, and billing.

The CN is divided into two domains: Packet Switched (PS) and Circuit Switched (CS). The main elements of the CN are the Home Location Register (HLR), Mobile Switching Centre (MSC) / Visitor Location Register (VLR), Gateway MSC (GMSC), Serving GPRS Support Node (SGSN), and Gateway GPRS Support Node (GGSN).

The RNC is the network element responsible for the management of the radio resources of the UTRAN. It interfaces with the CN (normally to one MSC and one SGSN), and also terminates the Radio Resource Control (RRC) protocol that defines the messages and procedures between the UE and the UTRAN (the RNC is the service access point for all services that UTRAN provides in the CN). The RNC is essentially responsible for the following:

- Call Admission Control (CAC);
- Radio Resource Management (RRM);
- Code allocation;
- Power Control (PC);
- Packet scheduling;
- Handover (HO);
- Encryption.

The main function of the Node B is to perform the radio interface to the UE (processing channel coding, rate adaptation, spreading, etc.), but it also performs some basic RRM operations, such as the inner loop PC and it can manage one or several calls. The way radio resources are used is an RRM task of extreme importance, which has a strong impact in the fulfilment of QoS requirements. There are three basic aspects that need to be considered: PC, CAC and HO. PC mechanisms and HO are dealt with in Section 2.2. CAC (restriction of access to voice/data calls) and congestion control (either by lowering bit rates of services, or by carrying out intra-frequency HO, or even disconnecting calls) need to be performed in order to avoid overload and the increase of interference. Users located on the edge of the cell require more power from the BS, consequently, their are pushed out of the cell effective coverage area in the first place. While powering off the major interferers, an immediate interference decrease is achieved, the transmitted power from the BS may consequently be reduced, and the system becomes more stable – more users will be further allowed to enter the cell. This is known as the cell breathing phenomenon, i.e., a reduction/increase on the size of the cell due to interference control.

HLR is a database located in the user home network that stores the master copy of the user service profile. It is created when a new user subscribes to the network, and remains stored as long as the subscription is active. MSC/VLR is the switch (MSC) and the database (VLR) that serves the UE in its current location: the MSC is used to switch CS transactions, and the VLR holds a copy of the visiting user service profile, as well as more precise information on the UEs location within the service network (CS domain); GMSC is the switch at the point where UMTS PLMN is connected to external CS networks. The SGSN functionality is similar to that of MSC, but it is used for PS services, whole the GGSN functionality is similar to the GMSC, relative to PS services, acting as a router.

All UTRAN elements are the same for both modes (TDD and FDD).

2.2 Radio Interface Aspects

The International Mobile Telecommunications–2000 (IMT-2000) spectrum allocation in Europe, Japan, Korea and USA is shown in Figure 2.2 [HoTo00]. In Europe and in most of Asia, the IMT-2000 bands of 2×60 MHz (1920-1980 MHz plus 2110-2170 MHz) are available for UMTS FDD. The availability of the TDD spectrum varies: in Europe 25 MHz is available for licensed use in 1900-1920 MHz and 2020-2025 MHz, the rest of the unpaired spectrum being for unlicensed applications in the 2010-2020 MHz band.

One of the most important characteristics of WCDMA is the fact that power is the common shared resource among users. In DL, the total Radio Frequency (RF) transmitted power is shared among users, while in UL there is a maximum tolerable interference level at the BS; this interference power is shared among transmitting MTs in the cell, in the sense that each one contributes to it. Power being the common resource makes WCDMA very flexible in handling mixed services, as well as services with variable bit rate demands [3GPP00a]. RRM is done by allocating power to each user (connection) to ensure that the maximum interference is not exceeded. Reallocation of codes or timeslots is normally not needed as the bit rate demand changes, which means that the physical channel allocation remains unchanged even if the bit rate changes. Furthermore, WCDMA requires no frequency planning, since a cell reuse factor of one is applied.

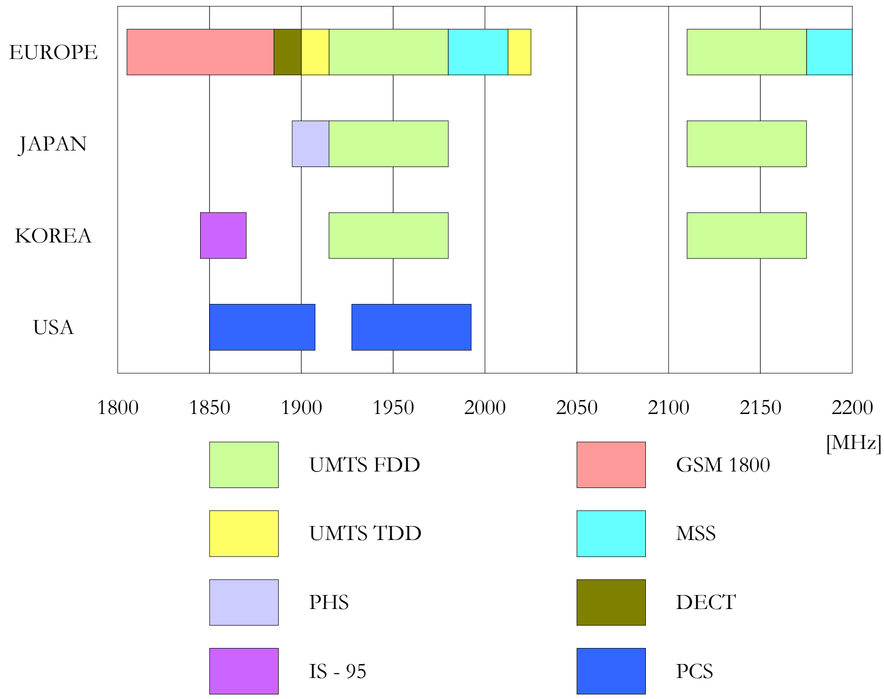


Figure 2.2. IMT-2000 spectrum allocation in Europe, Japan, Korea and USA (based on [HoTo00]).

In order to support high bit rates (2 Mbps), the use of a variable Spreading Factor (SF) and multicode connections is supported. The chip rate of 3.84 Mcps – High Chip Rate (HCR) leads to a carrier bandwidth of approximately 4.4 MHz. The Bandwidth-on-Demand (BoD) concept is guaranteed, because WCDMA supports highly variable user data rates. A frame of 10 ms duration is allocated to each user, during which the user data rate is kept constant; however, capacity among users can change from frame to frame. Table 2.1 summarises the main parameters related to the WCDMA radio interface.

In UMTS, there are mainly three different types of HO: Hard HO (HHO), similar to GSM, used in both modes, Soft HO (SHO), only in the FDD mode, and Softer HO (SSHO), also only in the FDD mode. With HHO, a connection is switched from a BS to another, or between carries, without simultaneous connections, while SHO occurs when an MT communicates simultaneously with up to three BSs (controlled by the RNC), and the SSHO occurs over different sectors of the same BS.

Table 2.1. Main WCDMA parameters (extracted from [HoTo00]).

Multiple access method	DS-CDMA (FDD) TD-CDMA (TDD)
Duplexing method	FDD/TDD
BS synchronisation	Asynchronous operation.
Chip rate [Mcps]	3.84
Carrier spacing [MHz]	4.4
Frame length [ms]	10
Service multiplexing	Multiple services with different QoS requirements multiplexed on one connection.
Multirate concept	Variable spreading factor and multicode.
Detection	Coherent using pilot symbols or common pilot.
Multiuser detection, smart antennas	Supported by the standard. Optional in the implementation.

The FDD and TDD modes differ not only in the duplex techniques, but also in their multiple-access ones. FDD uses direct sequence WCDMA (multiple-access based on CDMA/Frequency Division Multiple Access (FDMA)), while TDD uses TD-CDMA (multiple-access based on CDMA/FDMA/TDMA). It can generally be said that the only place where UMTS FDD and UMTS TDD differ is in the physical layer of the UTRAN protocol stack. All others protocols and system components are nearly the same. Multiple access of both modes is based on the same time scheme. Besides the time division into frames of 10 ms, in TDD, each frame is divided into 15 timeslots, each corresponding to the duration of 2 560 chips. The chip duration is around 0.2604 μs. Optionally, the TDD mode can be operated at a Lower Chip Rate (LCR) of 1.28 Mcps.

The transmission of the physical channels consists of two processes [3GPP00f]: spreading and modulation. Spreading consists of channelisation and scrambling, the former transforms each symbol into a number of chips, given by SF, thus, increasing the signal bandwidth, while in the latter, scrambling codes allow the signals from different sources to be further separable (not changing the signal bandwidth). The modulation process is Quaternary Phase Shift Keying (QPSK) for DL and Binary Phase Shift Keying (BPSK) for UL. The same SF produces different bit rates in UL and DL, which is directly related to the modulation. Channelisation codes are based on the Orthogonal Variable Spreading Factor (OVSF) technique [HoTo00], have the characteristic of maintaining DL orthogonality among users (or different services allocated to one user) in an ideal scenario, even if they operate at different bit rates, therefore, one physical resource can carry multiple services with variable bit rates. As the bit rate demand changes, the power allocated to this physical resource is adjusted, so that Quality of Service (QoS) is guaranteed at any instant of the connection [3GPP00b]. The transmission from different sources is separated by the scrambling codes.

In the FDD mode, open and closed loop PC can be distinguished. Open loop PC is used if no direct feedback loop exists between UE and Node B. The closed loop consists of two loops, outer and inner ones: the inner-loop controls on the basis of the timeslot, being performed between UE and Node B, and can be transmitted to each timeslot, i.e., 1 500 commands are transmitted per second; the outer loop works on the basis of frame lengths, i.e., 10 ms intervals, being implemented in the RNC, and being responsible for establishing the target value for the inner loop. PC on the DL in the TDD mode follows the same principle as in the FDD one, with two closed loops interleaved in one another, being considerably slower than on the UL with a period of 10 ms. On TDD UL, the inner loop is open, and the MT calculates the transmitter power on the basis of measured and received parameters. The DL uses what is referred to as mobile controlled closed loop PC, the same as in the FDD mode. The control interval varies, depending on the division of timeslots on UL and DL.

The PC used in TDD HCR mode is slower compared to the one in FDD, as referred. Although such a PC is basically less specific, it makes sense because of the TDMA components in the multiple access technique of TDD HCR. It should be noted that fast PC is difficult to implement in TDD HCR, the reason being that the MT only transmits for a fraction of the duration of the time frame, and the channel state can change significantly when an MT moves to the next transmission point. Depending on the switching points selected within a time frame between UL and DL, the transmitter power can be changed once or even several times in a time frame, i.e., within 10 ms. TDD LCR gives a faster PC functionality. This is advantageous, because the LCR has less frequency diversity, which can be compensated with faster control algorithms. PC for TDD is performed on a frame basic, i.e., one PC update per 10 ms.

2.3 FDD and TDD Modes

In UTRA, the different services needs are supported in a spectrum efficient way by a supported combination of TDD and FDD. The FDD mode is intended for applications in public macro– and micro–cell environments, with data rates of up to 384 kbps and high mobility. The TDD mode, on the other hand, is advantageous for public micro– and pico - cell environments (hot spot areas with low mobility), supporting data rates up to 2 Mbps. Therefore, the TDD mode is particularly well suited for environments with high traffic density and indoor coverage, where applications require high data rates and tend to create highly asymmetric traffic, i.e., Internet access. Individual user signals or physical channels are separated through the use of different spreading codes. Table 2.2 summarises the main differences between FDD and TDD (HCR and LCR) modes.

Table 2.2. Main parameters related to FDD and TDD modes.

Duplexing method	FDD	TDD	
Chip rate type	-	HCR	LCR
Multiple access method	CDMA/FDMA	CDMA/FDMA /TDMA	CDMA/FDMA /TDMA
Spreading factor UL	4-256	1-16	1-16
Spreading factor DL	4-512	1-16	1-16
FDMA channel spacing [MHz]	4.4	4.4	1.6
TDMA frame duration [ms]	10	10	10 (divided in 2 sub-frames)
Slots/Frame UL	-	15	15 (7 timeslots/sub-frame)
Slots/Frame DL	-	15	15 (7 timeslots/sub-frame)
Chip rate [Mcps]	3.84	3.84	1.28
Modulation	QPSK	QPSK	QPSK or 8PSK

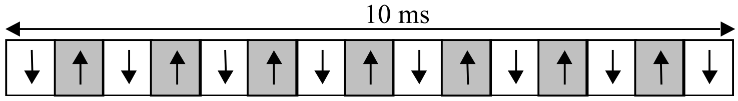
In the TDD mode, each time frame contains a minimum of one timeslot for each link. In contrast to the FDD mode, in TDD a physical channel is not only characterised by the spreading code, but also by the timeslot; because of the CDMA component, several physical channels can be implemented simultaneously, through the use of suitable spreading codes in a timeslot.

Whereas in FDD the entire duration of one or more time frames is available to a physical channel for data transmission, a physical channel in TDD only receives the duration of one timeslot per time frame. Since the bit rate drops as the SF increases, in TDD only SFs between 1 to 16 are used, so that about the same transmission rates can be achieved for a physical channel as with the FDD mode (SF in UL between 4 to 256, and in DL from 4 up to 512). In FDD, the distribution of traffic capacity to UL and DL cannot be changed, because of the fixed frequency channel bandwidths, while in TDD, the portion of the time frame available to UL and DL can be varied. This occurs through the selection of a switching point within a time frame.

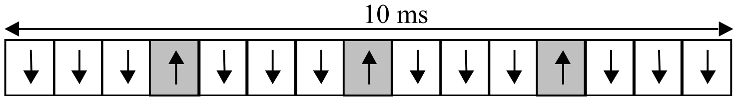
In FDD, the Dedicated CHannel (DCH) is mapped onto two physical channels. The Dedicated Physical Data CHannel (DPDCH) carries higher layer information including user data, while the Dedicated Physical Control CHannel (DPCCH) carries the necessary physical layer control information. The DPDCH and DPCCH are spread by a specific code, chosen from an OVSF code pool, which preserves the orthogonality among users in different channels.

In TDD, physical channels are defined by spreading code, frequency channel and timeslot within a time frame. A physical channel can occupy a timeslot in each time frame, or only in a subset of all frames. In addition to a dedicated physical channel, six common physical channels also exist in TDD. Examples for multiple and single switching point configurations as well for symmetric and asymmetric UL/DL allocations are given in Figure 2.3. A distinction is essentially made among four different types of configurations.

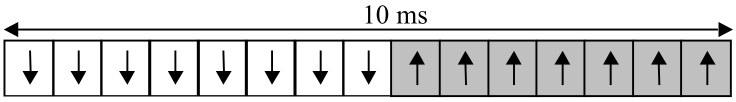
In scenarios with low inter-cell interference, the operation with a single channelisation code with SF 1 is also possible for the DL physical channels to transmit high data rates. For UL physical channels, transmission with a single code and different SF in the range of 16 down to 1 is favourable, because this leads to a smaller peak-to-average transmission power ratio. To support higher data rates, different channelisation codes may be used in parallel, which is called the multicode operation.

(a) 

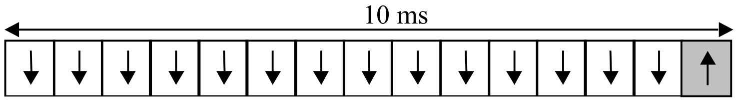
Multiple-switching-point configuration (symmetric DL/UL allocation).

(b) 

Multiple-switching-point configuration (asymmetric DL/UL allocation).

(c) 

Single-switching-point configuration (symmetric DL/UL allocation).

(d) 

Single-switching-point configuration (asymmetric DL/UL allocation).

Figure 2.3. TDD HCR frame structure examples (adapted from [3GPP00e]).

2.4 Services and Applications

The classification of four service classes in UMTS (conversational, streaming, interactive and background) [3GPP00a] by 3GPP has the main purpose of defining the quality requirements of different applications, taking the limitations of the radio interface into account, in particular the connection delay:

- *The Conversational class* is related to voice transmission. The traditional voice application, as well as Internet and multimedia ones, like Voice over IP (VoIP) and video conferencing tools, are conversational applications. It is characterised by symmetric and real-time conversational pattern services, with low emphasis on signal quality.
- *The Streaming class* characterises real time video transmission. The human perception to the delay variation is the main requirement. It is characterised by real-time almost unidirectional data flow applications with low delay variation, which can be processed as a steady continuous stream.

- *The Interactive class* is manly used in interactive applications like web browsing, data base retrieval and server access. It is characterised by 'request-response' pattern services, highly asymmetric, with low round trip delay and high signal quality.
- *The Background class* is characterised by a destination that is not expecting data within a certain time. Examples are e-mails, SMS, download of databases, and reception of measured records. It is characterised by non real-time asymmetric services, with high signal quality.

3GPP defined the most relevant parameters that classify the several services and applications in UMTS, and their relevance for each class; the main quality requirements for each service class can be seen in Table 2.3.

Within the traffic classes previously described, eight services were identified in [FeSC02] as follows:

- *Speech-telephony* - Traditional speech-telephony.
- *Video-telephony* - Communication for the transfer of voice and video between two locations.
- *Streaming Multimedia* - Service that allows the visualisation of multimedia documents on a streaming basis, e.g., video, music, or slide show.
- *Web Browsing* - This is an interactive exchange of data between a user and a web server, allowing the access to web pages. This information may contain text, extensive graphics, video and audio sequences.
- *Location Based Service* – A service that enables users to use location-based information, such as the location of the nearest gas stations, hotels, restaurants, and so on.
- *Multimedia Messaging Service (MMS)* - A messaging service that allows the transfer of text, image and video.
- *E-mail* - A process of sending messages in electronic format, usually in text form, but can also include images and video clips.
- *File Download* - Download of a file from a database.

The four 3GPP service classes previously described group services according to specific characteristics and performance requirements. From the Conversational class, *Speech-*

telephony and *Video-telephony* services are chosen; from the Streaming class, *Streaming Multimedia* is chosen, which service covers both audio and video streaming; from the Interactive class *Web Browsing* and *Location Based* services are chosen, the average DL session volume differentiating these two services; from the Background class *File Download*, *E-Mail* and *MMS* services are chosen, *File Download* is a bidirectional service but highly asymmetric, most of the traffic being DL, the remaining services being differentiated by their average bit rate and DL session volume.

Table 2.3. Main characteristics of the different service classes (based on [3GPP00a], [3GPP00b] and [3GPP00c]).

Class	Conversational	Streaming	Interactive	Background
Fundamental characteristics	Preserve time relation (variation) between information entities of the stream. Conversational pattern (stringent and low delay).	Preserve time relation (variation) between information entities of the stream.	Request response pattern within a certain-time. Preserve data integrity (packets must be transparently transferred with low BER).	The destination is not expecting the data within a certain time. Preserve data integrity.
Transfer delay	Minimum and fixed	Minimum and variable	Moderate and variable	Large and variable
Traffic priority	Low	Low	High	Low
Buffering	No	Allowed	Allowed	Allowed
Nature of traffic	Symmetric	Asymmetric	Asymmetric	Asymmetric
Bandwidth	Guaranteed bit rate	Guaranteed bit rate	No guaranteed bit rate	No guaranteed bit rate
Applications	Videophone, interactive games, VoIP, conversational voice and video.	High quality streaming audio, still image, telemetry (monitoring).	Voice messaging, FTP, web-browsing, transaction services e-commerce.	Email, SMS, MMS, FAX.

Chapter 3

Radio Network Planning and Optimisation

This chapter describes specific issues regarding network planning in UMTS. It covers capacity, coverage, interference, and link budget for the two modes of operation (FDD and TDD). It also addresses the several performance parameters of the system. Several optimisation algorithms from literature are evaluated. At the end, one provides a description of the conceptual optimisation algorithm and its input and output parameters.

3.1 Capacity

The planning of a radio network in UMTS is a process in which the possible configurations and the quantity of network equipment are estimated based on the operator requirements in terms of:

- Coverage:
  - coverage regions;
  - information of the type of regions;
  - propagations conditions;
  - link budget.
- Capacity:
  - available spectrum;
  - forecasts on user growth;
  - traffic volume forecast.
- QoS:
  - coverage probability;
  - blocking probability;
  - access and transmission delays;
  - average throughput.

Network dimensioning is a process through which an initial estimation of the amount of network equipment and possible configurations is determined. Key parameters of this dimensioning phase are coverage and capacity planning.

With respect to coverage planning, there are four basic aspects that require analysis: coverage regions, area type information, propagation conditions, and link budget (see Section 3.3). The coverage region is either a licence obligation or an operator strategic decision. The area type information results from both geographic and demographic information. The propagation conditions need to be completely identified, in order to avoid unexpected propagation behaviours and results. By knowing these, the related parameters (link budget) may be adjusted in the planning tools and the path loss model used with its validation limits.

In terms of capacity planning, three main aspects need to be analysed: available spectrum, subscriber growth forecast, and traffic density information. The spectrum available in Portugal corresponds to 4 paired carriers (FDD) and 1 unpaired carrier (TDD) per operator. FDD carriers may be used on a hierarchical cell structure, covering umbrella, macro–, micro- or pico-cells, while TDD spectrum is mainly planned to cover hot spot areas, where capacity for asymmetric traffic with HBR is required. Subscriber growth forecasts result from marketing projections. Traffic density information for UMTS networks is still non-existing, the currently required figures being estimated.

As in WCDMA all users share the same interference resources in the air interface, they cannot be analysed independently: each user influences the others and causes other transmission powers to change; therefore, the whole prediction process required for completing the UMTS radio network planning has to be done iteratively until transmission powers stabilise. The frequency reuse in WCDMA system is 1, and only one carrier is considered here. The system is proven to be typically interference-limited by the air interface, thus, the amount of interference/capacity per cell must be obtained. Capacity evolution is a key issue in cellular systems, it being important to estimate the number of users per cell and per MHz.

As shown in [HoTo00], capacity depends more on the load in DL than in UL. The reason is that in DL the maximum transmission power is the same, being shared among users, regardless of the number of users, while in UL each additional user has its own power amplifier. Therefore, even with low load in DL, coverage decreases as a function of the number of users. So one may conclude that coverage is limited by the UL, while capacity is DL limited. Capacity in both UL and DL is addressed hereafter, aiming at identifying if any of the connections is more restrictive than the other. The capacity per cell is therefore dependent on UL and DL load factors. The UL load factor as defined for the FDD mode as [HoTo00]:

$$\eta_{UL}^{FDD} = (1+i)\cdot\sum_{j=1}^{N_U}\frac{1}{1+\dfrac{R_C/R_{bj}}{\left(E_b/N_0\right)_j}\cdot\dfrac{1}{v_j}}, \tag{3.1}$$

where:

- E_b/N_0 Energy per bit over noise spectral density;
- i Inter-to intra-cell interferences ratio, seen by the BS (typically 65%);
- N_U Number of users per cell;
- R_{bj} Service bit rate of user j (depends on the service) based on Table 2.4;
- v_j Activity factor of user j at physical level (varies between 0 and 1, typically being 0.67 for speech and 1 for data);
- R_C WCDMA chip rate (3.84 Mcps).

There are many possibilities of configurations for the TDD frame structure, as shows in Figure 2.3. The maximum DL asymmetry for a TDD HCR frame is 14:1 (number of timeslots in DL, N_{TS}^{DL}=14 and N_{TS}^{UL}=1, number of timeslots in UL) [HoTo00], which means that, theoretically, the maximum number of users in terms of codes in DL is 14×16=224; for UL it is 1×16=16. This reflects the particular situation when, for DL, all MTs are making use of a unique service at a time, no mixture of service being considered. So, this case does not reflect the reality of UMTS. Another aspect is allocated timeslots on demand. The concept of timeslots not allocated in a fixed pre-determined manner, but rather on demand is derived from GPRS, and applied to UMTS TDD, meaning that all timeslots can be shared by active users, allocated in DL and UL separately. The allocation of the timeslots depends on the environment radio conditions. The UL load factor per timeslot, for the TDD mode, is given by:

$$\eta_{UL}^{TDD} = \left(1+i\right)\cdot\frac{1}{1+\dfrac{R_C/R_b}{E_b/N_0}\cdot\dfrac{1}{v}}. \tag{3.2}$$

The DL load factor for the FDD mode is obtained through [HoTo00]:

$$\eta_{DL}^{FDD} = \sum_{j=1}^{N_U} v_j\cdot\frac{\left(E_b/N_0\right)_j}{R_C/R_{bj}}\cdot\left[\left(1-\overline{\alpha}\right)+i\right], \tag{3.3}$$

where:

- $\overline{\alpha}$ Average orthogonality factor in the cell (depends on multipath propagation, range from 1, fully orthogonal, up to 0; the values considered hereafter are 60% for vehicular and 90% for pedestrian).

The DL load factor per timeslot for the TDD mode is given by:

$$\eta_{DL}^{TDD} = v \cdot \frac{E_b / N_0}{R_C / R_b} \cdot \left[\left(1 - \overline{\alpha}\right) + i \right]. \tag{3.4}$$

The air interface capacity in DL is directly determined by the required transmission power. As the BS transmission power increases, more interference is generated in the system and less capacity is available for MTs. In order to overcome this limitation, it is necessary to reduce to the maximum possible extend the BS transmitted power per link, leading to a constraint in system capacity. The BS power for FDD mode may be expressed by [HoTo00]:

$$P_{Tx}^{\ BS} = \frac{N_{rf} \cdot R_C \cdot \sum_{j=1}^{N_U} v_j \cdot \frac{\left(E_b / N_0 \right)_j}{R_C / R_{bj}} \cdot \overline{L_{p_j}}}{1 - \overline{\eta_{DL}}}, \tag{3.5}$$

where:

- $\overline{L_{p_j}}$ Average propagation loss between BS and MT_j;
- $\overline{\eta_{DL}}$ DL load factor (average value across the cell);
- N_{rf} Noise spectral density of the MT receiver front-end.

$$N_{rf[\text{dBm}]} = -174_{[\text{dBm}]} + F_{N[\text{dBm}]}, \tag{3.6}$$

where:

- F_N Noise figure.

For the TDD mode, the evaluation is done per timeslot, so the sum of N_U users in (3.5) disappears. By knowing the users locations, it is possible to check the amount of power that a given scenario is requesting to each BS, and if there is enough power to deliver to all users (based on the value set up by the operators).

Many times, the processing gain, G_p (for FDD), is also expressed in terms of the information bit rate, R_b, and the code chip rate R_C,

$$G_p = \frac{R_C}{R_b} \tag{3.7}$$

G_p is calculated differently for FDD and TDD modes. In TDD, it is required to take the slotted structure and the midamble into account, however, the frame is divided into 15 slots and the information is transmitted in one or several slots using one or more codes. If the G_p is calculated for data rates that can be supported by transmission in one or more slots, the following expression can be used:

$$G_p = \frac{R_c}{R_b} \cdot \frac{k}{15} \cdot \frac{N_{ChipsSlot} - Midamble - N_{GuardPeriod}}{N_{ChipsSlot}}, \tag{3.8}$$

where:

- $N_{ChipsSlot}$ is the number of chips in slot;
- $N_{GuardPeriod}$ is the number of chips for guard period;
- k is the number of slots used for the service considered (i.e., voice service k=1, see Table 3.1).

In the context of this thesis, (3.8) is simplified and implemented in the TDD simulator as:

$$G_p = \frac{R_c}{R_b} \cdot \frac{k}{15}. \tag{3.9}$$

In TDD, R_b is given by

$$R_b = \frac{\log_2\left(M\right) \cdot CR \cdot \left(T_s \cdot R_c - GP\right)}{SF \cdot T_f}, \tag{3.10}$$

where:

- M is the size of the symbol set (QPSK type, i.e., 4);
- T_s is the slot duration (666.7 μs);
- T_f is the frame duration (10 ms);
- CR is the code rate (1/3);
- GP is the length of the guard period (96 chips);
- SF is the spreading factor (from 1 to 16 in powers of 2).

Examples of the processing gain for some services and the E_b/N_0 values considered in the TDD link budget are given in [LaWa02]. The required E_b/N_0 values are substantially higher for the DL than for the UL. This stems mainly from the fact that no diversity scheme is included in the DL calculation. If that had been the case, link performance would improve and balancing of the two links would be easier. However, since transmit diversity is not as efficient as receive diversity, there are higher requirements on DL E_b/N_0 values. Due to the wish to balance the links and to get good capacity and coverage performance, it is anticipated that transmit diversity will be implemented in commercial BS products, at least in those aimed at outdoor deployment.

Three resources potentially limit FDD and TDD modes: BS power, load in DL and number of codes. In FDD, BS power and load in DL limit the system while, in TDD, only the number of codes does.

Each timeslot supports 16 users (maximum), because the maximum SF per timeslot is 16. The maximum bit rate for a user with 1 code in use as 13.8 kbps, so for 16 users in one timeslot, the maximum bit rate is 221 kbps for 16 codes. According to this, Table 3.1 presents the bit rate, respective codes and timeslots.

Table 3.1. Codes and timeslots variation according to bit rate [3GPP00e].

Bit rate [kbps]	Codes	Number of timeslots
13.8	1	1
32	3	1
64	5	1
128	10	1
384	28	2
1920	140	9

Analysing Table 3.1, in the last row, a HBR service (1920 kbps) requires 140 codes and 9 timeslots, actually 144 codes resulting from $9 \times 16 = 144$; nevertheless, there are 4 more codes in the last DL timeslot to use. To guarantee HBR, it is essential to have 9 timeslots in DL, so there are only 6 timeslots in UL. However, it is still required a maximum of 3 timeslots for signalling/control, and a minimum of 1 timeslot. In conclusion, for HBR services the optimal frame asymmetry is 9/3, with 3 timeslots for signalling/control, and a symmetric frame structure is not supported. Theoretically, TDD can use all 16 codes and all timeslots, because it applies Joint Detection (JD) to eliminate Multiple Access Interference (MAI) that intra-cell interference causes by CDMA operation. JD supports higher channel load factors by minimising multiple access interference caused by CDMA multipoint access. It further increases the dynamic range of multi signal detection to enable TDD transmission. Furthermore, Smart Antennas are applied to minimise inter-cell interference. However, since 16 codes represent the blocking point per timeslot, 12 to 14 codes per timeslot are used for signalling/control of 1 to 2 %. In this way, TDD can use 75 to 85 % of the 16 codes.

3.2 Interference

When both TDD and FDD coexist in the same system, there is the need for a careful network planning, due to adjacent channel interference. In a building or outdoor environments, where an FDD system is already deployed, there is the possibility to increase the capacity by deploying a TDD system in conjunction with the existing FDD one, which leads to a complex interference environment that must be analysed. Also, users cause interference on each other, depending on the location and the type of service.

Signal to Interference Ratio (SIR) can be calculated as follows for UL [3GPP00g]:

$$SIR_{UL} = \frac{G_p \cdot P_r}{(1-\beta) \cdot I_{Intra} + I_{Inter} + N_0}, \tag{3.11}$$

where:

- G_p Processing gain;
- P_r Received signal;

- I_{Intra} Intra-cell interference;
- I_{Inter} Inter-cell interference;
- N_0 Thermal noise, which usually may be neglected compared to interference.

A rough estimation for I_{Intra} is to make it equal to $P_S \times N_U$, N_U being the number of users that are associated or connected to a given BS. The fraction F of the intra-cell interference to the total one is obviously given by:

$$F = \frac{I_{Intra}}{I_{Intra} + I_{Inter}}. \tag{3.12}$$

SIR in DL can be expressed as follows [3GPP00g]:

$$SIR_{DL} = \frac{G_p \cdot S_P}{\overline{\alpha} \cdot I_{Intra} + I_{Inter} + N_0}. \tag{3.13}$$

Parameter I_{Intra} includes interference caused by traffic and common channels. In the multi-operator case, I_{Inter} may include the interference coming from the adjacent operator. The orthogonality factor $\overline{\alpha}$ (average) takes into account the fact that the DL is not perfectly orthogonal due to multipath propagation. Compared to a micro-cellular environment, a signal in a macro-cellular one follows a more complex path, which is translated into a more complex multipath; because of these higher distances (more reflection and refraction points), the orthogonality factor in a macro-cellular environment is expected to be higher than in a micro-cellular one. Within the FDD system, interference can occur only between the MT and the BS, due to the fact that there is a small guard band between adjacent UL and DL channels. DL channels interfere with other DL ones, and UL channels interfere with other UL ones, but UL and DL do not affect each other. A limit situation occurs when an MT from operator A is transmitting on full power very close to a BS from operator B that is receiving on the adjacent carrier.

In the TDD mode, interference analysis is more complicated, because there are TDD-specific interference scenarios. Within a TDD system, the same carrier is used for both UL and DL, therefore, MTs and BSs may cause interference to each other, leading to TDD-to-TDD interference for both UL and DL, creating possible BS-to-BS, BS-to-MT and MT-to-MT interference scenarios. A brief description of these scenarios follows:

1. If all cells are timeslot synchronised and the same slot asymmetry is applied, i.e., the same slots are used for UL and DL transmission in the cells, and all MTs in the system transmit and receive at the same time, hence, not interfering with each other. The same applies to BSs. However, interference still exists because one BS in one cell will interfere with the MTs in surrounding cells, and MTs in one cell will interfere with BSs in other cells. This leads to MT-to-BS and BS-to-MT interference.
2. If all cells are timeslot unsynchronised and a different slot asymmetry is applied, when UL and DL are applied in the same timeslot in different cells, the MT in one cell is transmitting at the same time an MT in another cell is receiving, the same situation occurring for the two BSs, leading to MT-to-MT and BS-to-BS interference.

Another scenario comprises interference between FDD and TDD modes, due to adjacent spectrum allocations. Although the TDD and FDD coexistence is a good solution for global coverage, interference problems can occur as a result of the proximity between the frequency bands. Figure 3.1, shows the possible interference scenario in TDD mode.

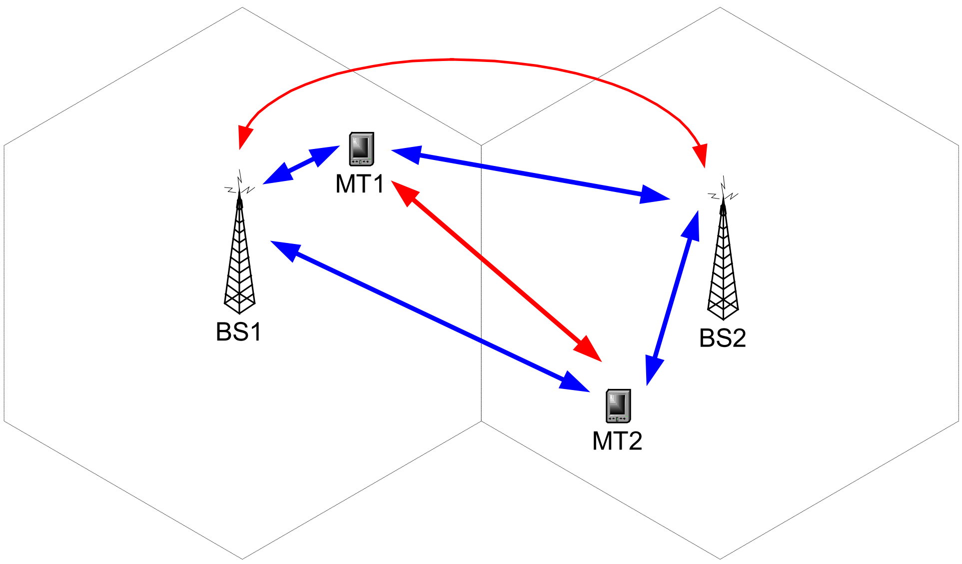


Figure 3.1. Possible interference scenarios in TDD (adapted from [QiWD00]).

3.3 Link Budget

A link budget is required to be implement in the simulator in order to estimate the TDD cells radius. Input parameters include propagation loss (information about city, widths of roads, heights of buildings, building separation and others) on the coverage, as well as several other main network planning parameters, like average MT received power, cell coverage, interference, and load factor.

The well-know semi-empirical Walfisch, Bertoni and Ikegami propagation models, were adapted by COST 231 based on measurements performed in Europe [DaCo99], producing acceptable estimations for urban environments. Like any kind of propagation model, this one also has some constrains, e.g., on frequency band, BS height and distance. For example, the validity range of this model in frequency is [800, 2000] MHz, while UMTS works in [1900, 2170] MHz, hence, for the upper band of UMTS, one is using the model outside its range; nevertheless, this does not imply a large error, since the difference in frequency is not large. This model has also distance limitations between BS and MT, being applicable for Non Line of Sight (NLoS) in [0.2, 5] km, and in [0.02, 0.2] km for Line of Sight (LoS), which satisfy most of UMTS micro-cell radii, mainly in urban areas. Therefore, this model may be used for estimation of signal propagation loss in UMTS and consequently estimation of the cell radius (more details in Annex A).

In this work, the main goal is to achieve optimal network values for micro-cells, therefore, the COST 231-Walfisch-Ikegami propagation model was selected and implemented in this thesis, Annex A.

In order to perform radio network planning, one needs to establish the link budget for coverage, capacity and optimisation reasons. The maximum path loss is obtained from

$$L_{Pmax[\mathrm{dB}]} = P_{t[\mathrm{dBm}]} + G_{t[\mathrm{dBi}]} + G_{r[\mathrm{dBi}]} + G_{SH[\mathrm{dB}]} - P_{Smin[\mathrm{dBm}]} - \sum L_{x[\mathrm{dB}]} - \sum F_{M[\mathrm{dB}]}, \tag{3.14}$$

where:

- L_{Pmax} is the maximum propagation loss allowed for a given service;
- P_t is the transmitted power (delivered to the antenna);
- G_t is the transmitter antenna gain;
- G_r is the receiver antenna gain;
- G_{SH} is the soft handover gain, only for the FDD mode;
- P_{rmin} is the receiver sensitivity for a given service bearer;

- L_x represents additional attenuations in a link, which may be user body loss L_{UB}, cable loss L_C, and others (car loss) L_{Other};
- F_M represents fading margins, i.e., fast fading margin F_{FM}, and slow fading margin F_{SM}.

A major parameter in radio network planning is P_{rmin}, because it depends on the service type, therefore, different L_{Pmax} and cell radius are expected for each service. P_{rmin}, is defined as follows:

$$P_{rmin[\mathrm{dBm}]} = \frac{E_b}{N_0}_{[\mathrm{dB}]} - G_{p[\mathrm{dB}]} + N_{[\mathrm{dBm}]}, \tag{3.15}$$

where:

- E_b/N_0 is the ratio between energy of bit and noise density, which depends of the service, mobile speed, receiver algorithms, and BS antenna structure;
- G_p is the processing gain obtained from (3.7), for the FDD mode and (3.9) for the TDD mode;
- N is the total effective noise plus interference power, see Annex B.

The full link budget calculation is presented in Annex B. There are some differences in the link budget between FDD and the TDD mode, which are described in the following paragraphs.

When UL and DL are applied in the same timeslots in different cells, interference occurs. In this situation, an MT in one cell is transmitting at the same time as an MT in another cell is receiving, and the same situation occurs for the two BSs. These situations occur when slots are not synchronised, the severity of the ‘asynchronism’ heavily depending on the specific UL/DL slot allocation and on the related switching points. The acceptable amount of out-of-band emission is specified by an emission mask and Adjacent Channel Leakage power Ratio (ACLR), on the receiver side, the Adjacent Channel Selectivity (ACS) defines the impact of the adjacent channel power that results from imperfection of the receiver filters.

As it has been noted already, synchronisation of cells, i.e., ensuring that frames and timeslots of different cells do not overlap, but rather start and end at the same point in time, is important, especially for TDD UL capacity. If the load in interfering cells is high and cells within the system are not synchronised – causing the considered UL and DL slots to overlap – the UL capacity in a slot may be significantly reduced, potentially to almost zero. Consider an UL/DL slip of the slots. A synchronisation error causes overlap in DL and UL slots at every switching point, resulting in large capacity losses. However, if the number of switching points is reduced, the result may not be as bad for the whole system, even though the slots bordering the switching points would still have a great problem.

TDD radio performance is characterised by synchronisation needs, asymmetry, and low cell breathing [LaWa02]. Pole capacity and load factor methodology are not of particular interest in the TDD planning procedure, since power-based load control is not needed to ensure system stability and coverage, code limitation in each slot will strike before coverage is badly affected. Also, pole capacity can be used only on a slot-by-slot basis in TDD, so its accuracy is poor, due for example to low SF and few users per slot.

In the link budget (for the TDD mode), there are two parameters with some importance, the BS noise figure and fast fading margin. In the first, BS receiver in pico-cells has been proposed as one way of counteracting the possibly of severe interference problems that may arise from time to time in TDD (and partly also in FDD). The idea is to make the receiver less sensitive to interfering signals coming from TDD and FDD MTs, and other TDD BSs located close to the BS. However, this approach does not completely solve the problems, and it also has the negative effect of increasing the overall interference level in the own system, since then the desired MTs must increase their respective output powers to compensate for the poorer UL Rx performance. The second parameter is similar to the transmit PC headroom in FDD. It ensures that the Transmit Power Control (TPC) scheme has enough room to vary the power to compensate for fading effects. If TPC is not used, this parameter is set to zero.

In conclusion, absolute values of the maximum allowed propagation loss are lower for TDD than for FDD, due to the slotted property of TDD. However, another effect of this property is that coverage is also much more stable when load increases, i.e., cell breathing is much lower. Without DL transmit diversity, there is quite a large unbalance between UL and DL in terms of maximum allowed propagation loss. Low rate services seem to be close to be code limited in many cases, while high rate services are most often interference limited. A timeslot reuse factor of 1 may be possible for speech services, but probably not for data services with a speed of 64 kbps or more. However, the reuse factor may not have to be decided on a permanent basis, but could potentially result from an 'average utilisation effect' from channel allocation decisions made by a dynamic channel allocation scheme. Delay requirements impact heavily upon the throughput obtainable. Non-delay sensitive services can reach a much higher throughput than delay sensitive ones. TDD capacity is degraded by an FDD system deployed in the same area and operating on adjacent carriers, especially if the FDD system is highly loaded. Some coordination of TDD and FDD network planning is highly recommended. Also, some degree of coordination regarding parameter setting, e.g., for HO and load control purposes, is beneficial. The spectral efficiencies of TDD and FDD do not differ significantly from each other.

3.4 Optimisation Algorithms for Mobile Communications

This section provides a presentation of some selected optimisation algorithms for mobile communications system, from the literature. The selection criterion was based on the algorithms that present analytical tractability, adapted to mobile communications, like UMTS, and adapted to the objective of this thesis: optimisation of UMTS TDD BS location for non-uniform traffic distributions, supporting FDD coverage in hot spot areas; it is necessary to identify this areas and to provide an optimal (near optimal) location and optimisation of the BSs, because network optimisation is one of the biggest challenges that a mobile operator has. This is not a problem of dimensioning and optimising a new network (without coverage and with a certain traffic/users distribution), but rather problem of a adapting existing networks for a constant increase of traffic/users. For the case of creating a new UMTS network based on an existent GSM one, the problem of coverage in UMTS exist, since it is lower compared to GSM, i.e., UMTS frequency is high compared to GSM one, so there are several gaps in the coverage, creating a new problem: optimisation the new BSs locations.

In [KoFN02], a solution based on the simulated annealing algorithm for 3G BS position is presented. This algorithm is a heuristic procedure of optimisation, which is based on some results of statistical physics. This article uses two different methods. In the first, the simulated annealing is a series of homogenous Markov chains, also called homogenous annealing. The main concern in this case is the chain length. With the properties of Markov chains by, presuming *a priori* Gaussian distribution and evaluating the chain length until the stationary state of the chain is reached by using this assumption, it can be proven that at several different cooling schedules the algorithm finds an optimal solution in the discrete solution space in infinite time with a probability of 1. In the second, is the classical Boltzmann annealing are used, as comparison, which is one of the so-called inhomogeneous simulated annealing algorithms. After each successful neighbour selection follows a cooling and then a new neighbour search. One must be careful here with the choice of the cooling schedule, once the probability density function used to find neighbours in the state space is defined. This paper is developed for a new UMTS FDD network, naturally for multi-service, but not based on an existing network.

In [BiLa01], a fast planning algorithm with neural networks for the optimal location of the BS and their antenna characteristics in a WCDMA system is developed. The predictions of the coverage in an urban area as well as the optimisation process itself are based on neural networks. Coverage is predicted with the help of sophisticated back propagation networks, whereas for the optimisation of the positions of the BS and of the antenna patterns Self Organising Maps (SOMs) are applied. SOMs consist of the artificial neurons organised on a regular grid of dimension. Each neuron is represented by an n-dimensional weight vector (called codebook vector), where n is equal to the dimension of the input vectors. Neighbourhood relations link adjacent neurons to each other, so that the neurons build a topology. Due to neighbourhood relations, the weight vectors are arranged during the training process in such a way that they represent the input vectors in space. The algorithm selects the best matching unit of the SOM and moves it towards the presented input vector, which means that the weight vector of the neuron is adapted to the input vector. The Euclidean distance determines the best matching unit. For the optimisation of the BS sites, a two-dimensional SOM is applied where the BSs are represented by the neurons and their location by the respective weight vector, locations in the coverage area are presented to the net, which means that for each location the best matching unit, which is mostly equivalent to the best server, is calculated and adapted. This work is developed for a new UMTS FDD network, but not based on an existing network.

In [PaYP02], BS automatical placement by using genetic approach is proposed for inhomogeneous traffic density environments, where offered traffic loads may limit BS coverage. The objective is to set the various parameters, like traffic density, channel condition, interference scenario, number of BSs and other network planning parameters, so as to optimise BS placement and transmit power. The proposed algorithm is often described as a global search method, and is performed as an optimisation tool. This method is a computational model inspired by evolution. It represents a potential solution as a simple chromosome like data structure called an individual, and determines which individuals can survive in a certain criterion formulated to maximise or minimise a given objective function. Binary string representation, a classical representation method of genetic algorithm, is applied and a hierarchical approach is considered. It divides the service area into several pixels, which are taken as potential BSs. Since the above approaches represent BS positions as discrete points, it is not possible to consider all of the potential BSs. The genetic algorithm presented is only for one service (voice – 8 kbps) and for a GSM network.

In [AmCM01], a mathematical programming model aimed at supporting the decisions in the process of planning is proposed addressing, where to locate the new BSs and which configuration to select from a given set of possibilities. Computational results are obtained with greedy randomised algorithm. This algorithm is a simple heuristic in which a randomised greedy procedure is applied a predefined number of times and the best solution found is returned. In each run of greedy randomised algorithm, one starts from an empty set of active BSs and at each iteration one randomly selects an available candidate site (in which to install an additional BS) from a set of available candidate site, which yields the best improvements in the objective function. This paper is developed for a new UMTS FDD network, but not based on an existing network.

In [AmCM02], an enhanced model that aims at optimising BS locations as well as their configurations, such as antenna height, tilt and sector orientation, is presented. In this paper, a Tabu Search algorithm is developing that takes traffic coverage and installation costs into account. This algorithm is a meta-strategy for guiding local search procedures through the solution space of an optimisation problem towards good approximate solutions. In Tabu Search algorithms, the following ‘moves’ are considered to explore the solution space: removing a BS, installing a new BS, removing an existing BS and installing a new one (swap). At each step, a new current solution is obtained by carrying out the best available move, even though it may worsen the objective function value. To prevent cycles and to try to escape from local optima, some moves are forbidden for a certain number of iterations (they are added to a Tabu list). The best solution found during iterations is stored, and returned after a predefined maximum number of steps. As initial solution of the Tabu Search algorithm the solution (i.e., the set of active BSs and the assignment of test points to active BSs) obtained with a greedy randomised algorithm is considered. This paper is developed also for a new UMTS FDD network, naturally for multi-service, but not based on an existing network.

In [AmCM03], three heuristics algorithms are present: randomised greedy, reverse greedy procedures, and Tabu Search. In the first randomised greedy algorithm (add), BSs are added iteratively to a set of active BSs. At each iteration there is a current set of sites (possibly empty) in which BSs have already been installed. For each remaining candidate site, the above assignment procedure is then applied to obtain a corresponding vector. At each iteration, the fraction of traffic that is currently covered is randomly selected among the fraction of those that yield the largest value. The procedure stops when the addition of the new BS worsens the current solution value, according to an utility function defined in the paper. In the second algorithm, randomised reverse greedy (remove), BSs are removed iteratively starting from a set of active BSs. Given the current active set, for each candidate site, the above procedure is applied, so as to obtain corresponding vectors. The remove procedure stops when the removal of another BS worsens the current solution value according to the utility function defined in the paper. The last algorithm is the one presented in [AmCM02].

In [SeCa04], a study of planning, dimensioning and optimising cellular UMTS FDD networks is presented. For such, a simulator was developed that, based on an existing UMTS network, makes its dimensioning and optimisation. An application called *UMTS_Simul* was developed in MapBasic, which works on a Geographic Information System (GIS) software – MapInfo [MAPI04]. The developed application works together with another software, called *Net_opt* developed in the C++ language, which makes the calculations of the network dimensioning. Another application called *SIM* was developed to create lists of users in the network. These lists, together with the data from the network being simulated, are the input parameters to the *UMTS_Simul* application. The tool user can define the reference scenario, being able to vary some of the network parameters. Then, it is possible to make the network dimensioning, the main results of the simulation being presented at the end. It is also possible, before or after the dimensioning, to execute the algorithm to place new BSs to optimise the network. In this document, some simulations were made, with the UMTS network provided by Vodafone [Voda02], in order to analyse the effect of the variation of the different network parameters.

Varying the number of users, the reference service, the usage scenario, the different network parameters, the distribution of traffic and the number of frequencies yields a performance analysis of the network. Different scenarios with different services were used together with a non-uniform geographic traffic distribution. The simulations were made using the UMTS FDD mode. A scenario with 9 000 generated users, pedestrian environment and a 64 kbps service was used as reference. In this scenario, the average blocking and delaying probabilities obtained were around 1 %, using all the 4 available frequencies. An optimisation algorithm for an FDD network was also present (adding FDD BSs), repeating the simulations and comparing its results with the ones of the initial network. With the new network the obtained results improved, increasing the number of covered users and decreasing the number of users without service. However, this optimisation algorithm covers all open spaces areas, and this is not the best approach, because not all open spaces areas needed to be covered. This document contemplates an optimisation algorithm, spatial distribution of users and non-uniform traffic, but all of these considerations are valid only for the FDD mode.

As referred in the beginning of this section, network optimisation is one of the biggest challenges that a mobile operator faces. The problem of this thesis is not one of dimensioning and optimising a new network, but rather a problem of adapting to existing networks, answering to a constant increase of traffic/users in hot spot areas, High Data Rate (HDR) areas with asymmetric traffic. All of the analysed papers present strategies to implement and optimise new networks but not to adapt and optimise existing networks. All papers, except one, deal with UMTS FDD networks, naturally for multi-service, which is a good start. There are three other important considerations: the spatial distribution of users, the non-uniform distribution of the traffic, and the TDD mode. In the next section, an optimisation algorithm developed for UMTS TDD BS location for non-uniform traffic distribution co-located with existing networks (in this case, the FDD mode one) is present.

3.5 Conceptual Optimisation Algorithm Developed

In the previous sections, seven articles are analysed, five – [KoFN02], [BiLa01], [AmCM01], [AmCM02] and [AmCM03] – provide solutions for a new UMTS FDD network, naturally for multi-service, but non-based on an existent network to optimise. In [PaYP02], the genetic algorithm presented is only for one service (voice – 8 kbps) and for a GSM network, inadequate to a UMTS FDD/TDD network. The last article, [SeCa04], was chosen to adapt the simulator, with the coexistence of the two modes and automatically optimisation BS location for non-uniform traffic distributions to hot spot areas, HDR areas with asymmetric traffic, applying the TDD mode. This adaptation implied the development of a new part in the simulator.

Figure 3.2 shows the optimisation algorithm (included in the dimensioning of the FDD network). It begins by analysing the instantaneous load present in the FDD network. Depending on the load target (based on the comparison of cumulative load and load target, measuring the impact of one user) users are transferred (routing) to the FDD (LBR users) or the TDD (HBR users) network. A reduction bit rate process is called for LBR users (FDD network), the objective being to reduce for each user the service bit rate, only if it is greater than 1920 kbps (these users are reduced to 384kbps), 384 kbps (to 128kbps) and 128 kbps (to 64kbps). Service bit rates for HBR users are analysed according to the bit rate target. The resource management algorithm begins when the service bit rate is greater than the bit rate target. The main objective of this algorithm is to provide a good resource management (codes and TS management) for the TDD network. Finally, when the HBR user is transferred to the TDD mode, he is contributing to the addition of a new TDD BS in the network co-located with the FDD one.

The specific input parameters for the optimisation algorithm presented in the next chapter are:

- Bit rate threshold;
- HBR users, not supported in FDD network;
- Locations of FDD BS overloaded;
- Number of FDD BS overloaded;
- Load threshold.

The specific output parameters of the optimisation algorithm are:

- Number of TDD BS co-located in the FDD network, N_{TDD_BS};
- Cell capacity [GB/h], C_{Cap}, results from cumulative bit rate in network in one hour.
- RER and DRER;
- Number of TDD BS with reduction of the bit rate, N_{red_BS};
- Bit rate reduction per TDD BS, R_{TDD_BS};

- Number of users reduced per TDD BS, $N_{U\_TDD\_BS}$;
- Bit rate reduced per user (service), $R_{U\_service}$;

N_{red_BS}, R_{TDD_BS}, $N_{U\_TDD\_BS}$ and $R_{U\_service}$ are output parameters of the management resources algorithm presented in Chapter 4. All the output parameters given by FDD and TDD simulator are also present.

For CS connections, one of the factors is the blocking probability, P_b, calculated by,

$$P_b = {N_b}/{N_{\mathrm{cov}}}. \tag{3.16}$$

where,

- N_b is the number of users blocked;
- N_{cov} is the number of users covered.

In a PS connection the delay probability can be calculated via,

$$P_d = {N_d}/{N_{\mathrm{cov}}}. \tag{3.17}$$

where,

- N_d is the number of users delayed.

The probability of a user remaining without coverage, P_{ncov}, is given by,

$$P_{n\mathrm{cov}} = {N_{n\mathrm{cov}}}/{N_{user}}. \tag{3.18}$$

where,

- N_{user} is the total number of users;
- N_{ncov} is the number of users not covered.

The number of users served, N_{serv}, is given by,

$$N_{serv} = N_{users} - N_{n\mathrm{cov}} - N_d - N_b. \tag{3.19}$$

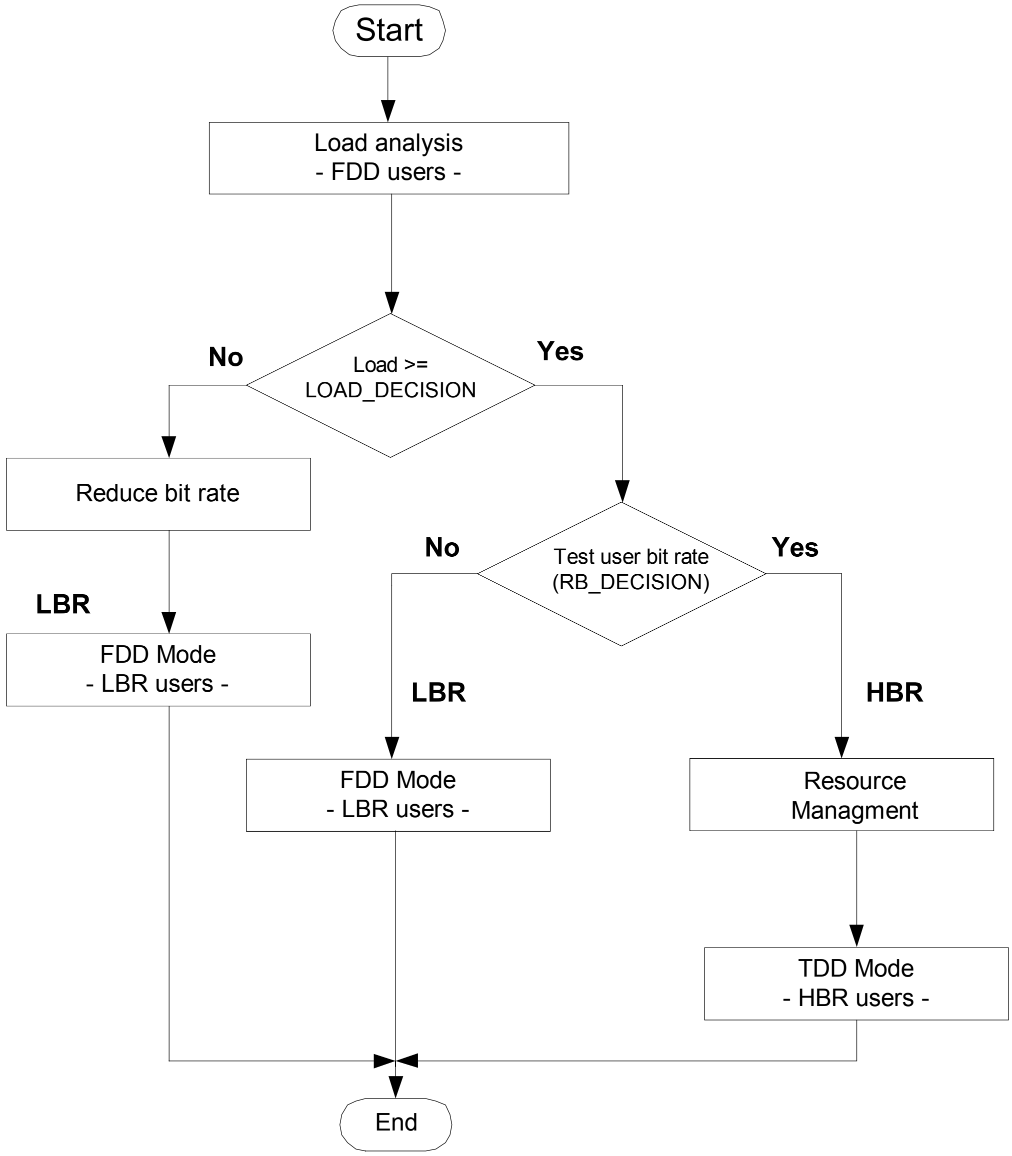


Figure 3.2. Optimisation algorithm.

Others parameters are considered in the FDD simulator and optimisation algorithm: Relative Effective Rate (RER) and Delayed Relative Effective Rate (DRER). These parameters are calculated for HBR users (1920 kbps, 384 kbps, 128 kbps):

$$RER_{1920} = \frac{N_{USERS\_1920-384}}{N_{USERS\_1920}}, \qquad (3.20)$$

$$DRER_{1920} = \frac{N_{USERS\_1920-384}}{\left(N_{USERS\_1920} + N_{USERS\_384} + N_{USERS\_128} + N_{TDD\_USERS}\right)}, \qquad (3.21)$$

$$RER_{384} = \frac{N_{USERS\_384-128}}{N_{USERS\_384}}, \tag{3.22}$$

$$DRER_{384} = \frac{N_{USERS\_384-128}}{\left(N_{USERS\_1920} + N_{USERS\_384} + N_{USERS\_128} + N_{TDD\_USERS}\right)}, \tag{3.23}$$

$$RER_{128} = \frac{N_{USERS\_128-64}}{N_{USERS\_128}}, \tag{3.24}$$

$$DRER_{128} = \frac{N_{USERS\_128-64}}{\left(N_{USERS\_1920} + N_{USERS\_384} + N_{USERS\_128} + N_{TDD\_USERS}\right)}. \tag{3.25}$$

where:

- N_{TDD_USERS} is the number of TDD users;
- N_{USERS_1920} is the number of users with a bit rate 1920 kbps;
- N_{USERS_384} is the number of users with a bit rate 384 kbps;
- N_{USERS_128} is the number of users with a bit rate 128 kbps;
- $N_{USERS\_1920-384}$ is the number of users suffering a bit rate reduction from 1920 kbps to 384 kbps;
- $N_{USERS\_384-128}$ is the number of users suffering a bit rate reduction from 384 kbps to 128 kbps;
- N_{USERS_128-64} is the number of users suffering a bit rate reduction from 128 kbps to 64 kbps.

RER gives a notion of the quantity of users that had the bit rate was reduced by the network (1920 kbps to 384 kbps, 384 kbps to 128 kbps and 128 kbps to 64 kbps), while DRER gives the average value of users that had the bit rate reduced.

In the next chapter, the development of the TDD simulator and of the optimisation algorithm for UMTS TDD BS location for non-uniform traffic distributions is described in detail.

Chapter 4

Simulator Description

The present chapter provides a functional description of the simulator platform developed within the scope of this thesis, with the main objective of allowing the convergence benefits of the UMTS FDD/TDD system from the optimisation of UMTS TDD BS location for non-uniform traffic distributions point of view. A detail description of the development and implementation of the optimisation algorithm is performed, including input and outputs parameters. At the end, a validation of the simulator platform and optimisation algorithm is provided.

4.1 General Simulator Structure

The objective of this thesis was to develop an algorithm for the optimisation of an FDD network by adding TDD BSs and separating users according to high and low bit rates (FDD and TDD networks are run in parallel). For this, it was necessary to develop a simulator platform with the TDD mode based on a developed simulator for the FDD mode, with coexistence of the two modes. As mentioned in the previous chapter, the development of this simulator is based on an existing one [SeCa04].

As described in previous chapters, radio network planning is mainly based on three items: traffic, propagation, and services. In order to build a tool, capable of performing radio planning and optimisation, some major functional blocks are needed:

- traffic/service forecast tables;
- non-uniform traffic distributions;
- propagation model fiting the environment requirements;
- description of services and radio interface characteristics, for both UMTS modes.

A simulator platform and optimisation algorithm was designed, and all major parameters were identified. This tool begins by the optimisation of the FDD network, by the reduction of users bit rate, if needed and routing HBR users to the TDD mode (creating a new TDD network in parallel with the FDD one) and finishes with optimised FDD and TDD networks.

In order to achieve this optimum configuration, sets of simulations are performed, some major network quality indicators being analysed for each set; in this way, it is possible to implement an algorithm that changes, from set to set, some parameters in the network that directly or indirectly influence system capacity. The optimisation algorithm stops when the required quality network goals are achieved.

The simulator platform is a snapshot in time, means that some major network quality indicators (blocking, delay, load factor in DL direction, cell capacity and HBR users) are analysed by the optimisation algorithm, and a decision on a proper measure is taken in order that the simulation converges to the nearly optimum network. The realisation of sets of runs ensures that one gets the desired statistical relevance. The first step at the FDD network is to reduce users bit rate when the load is lower than a given target. The second step occurs when the load is higher, and starts the TDD simulator, decreasing the load in the FDD network, by putting HBR users to the TDD mode. If cell capacity is larger than the target, the third step starts by reducing users bit rate served by TDD BSs. Figure 4.1 presents the simulator platform structure.

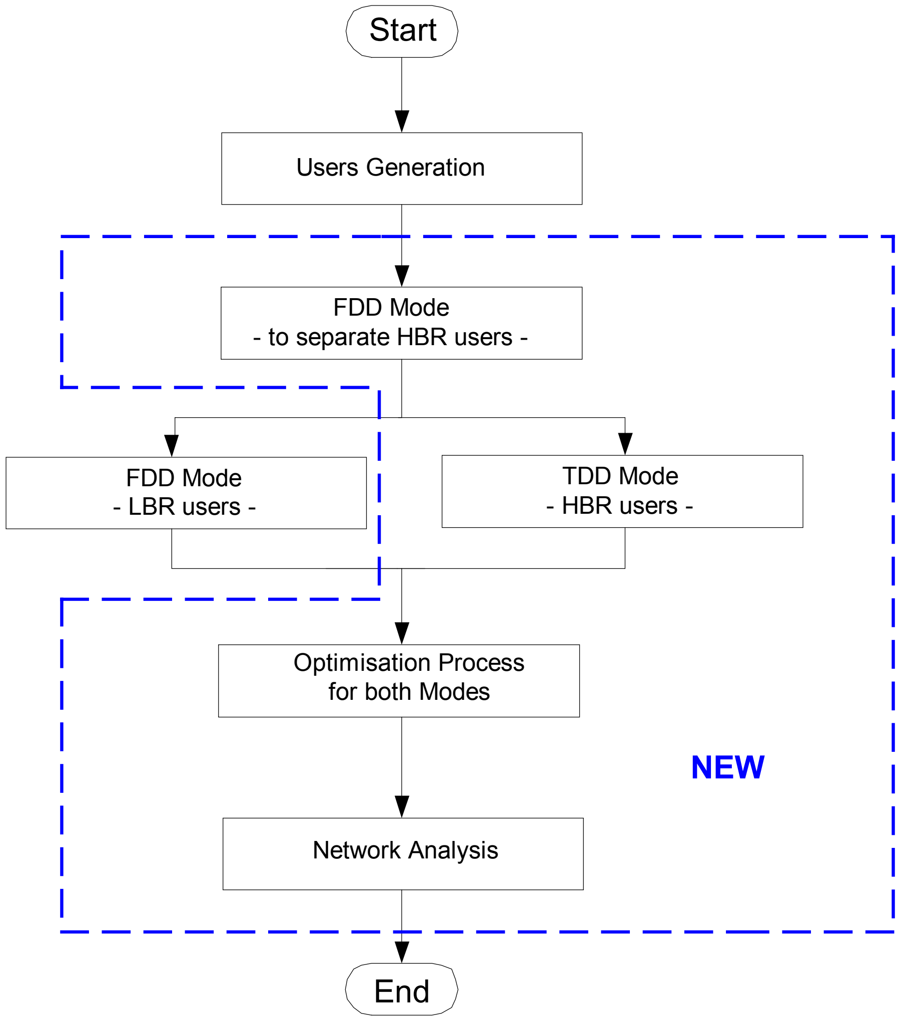


Figure 4.1. Simulator platform structure.

In Figure 4.1, within the dot line (in blue), the functional blocks developed within the scope of this thesis are high lighted. The users generation process provides users generation based on realistic information about city in study (described in Section 4.2). Separate HBR users process, is responsible for the comparison based on service bit rate and bit rate target (described in Section 4.4). This process is executed during the optimisation algorithm and the output is LBR and HBR users. Optimisation process is responsible for: reducing service bit rate (both modes), resource management (only in the TDD network), adding new TDD BSs in the existing FDD network. At last, is provided network analysis witch consists in: testing the optimisation algorithm repeating the simulations and comparing its results with the ones of the initial network – reference scenario – (verifying the standard specifications), in search of a nearly optimum FDD/TDD network.

4.2 Users Generation

In order to obtain realistic data for evaluation, the simulator [SeCa04] takes several inputs based on actual scenarios, namely, non-uniform traffic distributions. The generation of a user consists of the specification of two characteristics:

- mobility type used;
- service the user generates.

Busy Hour Call Attempt (BHCA) grids specify, for each pixel of the scenario, the service usage. Nevertheless, due to the mobility characteristics of some operational environments, several services are not available in these environments. The available services per operational environment are presented in [FCXV03]. For simplification, BHCA grids take these restrictions into consideration by setting to zero the BHCA value of unavailable services in specific operational environment pixels. This allows using the BHCA grids directly for services generation in each pixel.

The number of users to be generated in a certain pixel is given by a Poisson arrival process for the specific BHCA value of that pixel, using data from MOMENTUM [MOME04]. Arrival rate values are used for new calls generation with an arrival Poisson process. Knowing the number of users for each service, the algorithm generates of users per service, with the specifics characteristics, i.e., position, path loss (dependent on the scenario), service, and mobility. The position is computed by verifying which is the pixel where the user is located, according to [FCXV03].

The algorithm for users generation developed in [SeCa04], *SIM* did not generate users for high bit rate services hence this feature was added within the scope of this thesis. The first step of the algorithm, presented in Annex C – Figure C.1, is to compute the number of users with a defined service. The spatial distribution of users is computed next. This algorithm was validated in [SeCa04]. After the algorithm end, it is possible to save the information at an output file, specified by the user.

The supplementary link loss between user and BS is computed according to the scenario where the user is inserted. The *SIM* application creates a list of users, the algorithm being present in Figure C.2, Annex C. In order to obtain realistic data for this evaluation, the simulator takes several inputs based on actual scenarios. Some of these inputs are given by a GIS application, (GIS is a methodology to visualise, manipulate, analyse and display spatial data, combining layers of information about a region, which maps linked to databases).

4.3 FDD Simulator

In [SeCa04], an application, *UMTS_Simul* was developed, in MapBasic, which uses the tool GIS MapInfo [MAPI04], to obtain coverage and path losses, which is then passed to another module developed in C++, *Net_opt*. In Figure 4.2, the basics of the *Net_opt* algorithm for the FDD mode are presented.

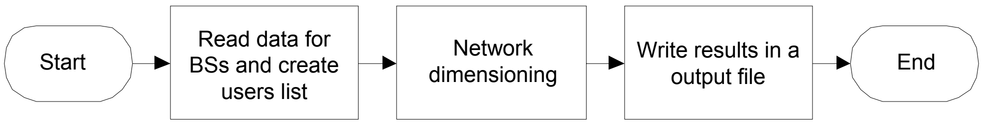


Figure 4.2. *Net_opt* algorithm for FDD mode (adapted from [SeCa04]).

The traffic information goes to the network dimensioning block (see Figure C.3, in Annex C), jointly with other data network. The optimisation network block is used for determining the best performance of the network, in a defined scenario. This block adds new FDD BSs in specified zones (not covered areas), determined by an optimisation algorithm.

The *UMTS_Simul* application performs allocation and other calculations, e.g.: emission power, load factor, users without service, and soft and softer HO. This application requires some data input parameters like:

- antenna gain for BSs;
- E_b/N_0 per service and scenario;
- detailed information (on widths of roads, heights of buildings, building separation and others) the study area;
- location of each BS.

UMTS_Simul calculates the nominal radius of each sector for the reference scenario, UL and DL, for a received power equal to the receiver sensibility. The more restrict radius corresponds to the nominal radius of the sector. COST-231 Walfish-Ikegami is the propagation model used, Annex A, and the link budget is given according to (3.14), Annex B. Then, the nominal areas for a bit rate (covered areas) are created and represented in the map for a reference scenario. Note that the BS sectors have a predefined orientation: 0º, 120º, or 240º.

The *Net_opt* algorithm begins by reading data files provided by the GIS application, which stores information about sectors, users covered, users connected to the sector, and blocked, delayed and users in hard HO.

Finally, the parameters from all sectors are computed and writen in an output file.

4.4 TDD Simulator

The first step in the development of the TDD simulator was adding HBR users (1920 kbps users) in *SIM* the application. The consequences of this addition include some changes in the *UMTS_Simul* application, like new coverage radius and service throughput. In this application, an initial choice of the UMTS mode (TDD or FDD) is required. All the procedures executed in *UMTS_Simul* application for FDD are maintained. For the TDD mode, it is necessary to choose the channel asymmetry, which includes the number of UL, DL and signalling/control timeslots (by default 9 timeslots in DL, 3 timeslots in UL, and 3 timeslots for signalling/control), the BS maximum supported throughput and the BS frequency (only one frequency is provided – by default 1900 MHz). The following statistics are provided: user per timeslot; free codes per timeslot; load per timeslot; bit rate per timeslot and DL power per timeslot. Other statistics are: users in the city, uncovered users, delayed users, served users; uncovered and delay probability of the system; BS throughput (maximum, average and minimum) of the system; BS power (maximum, average and minimum) of the system and sector radius (maximum, reference and minimum) of the system.

As previously described, the TDD simulator was developed maintaining the FDD simulator structure. For each BS, five arrays with 15 positions representing 15 timeslots, were added. Their arrays correspond to DL/UL powers, DL/UL codes, DL/UL number of users, DL/UL loads and DL/UL bit rates per timeslot. Algorithms were developed (described in the next paragraphs, and presented in Annex D) for timeslots allocation and to calculate network quality indicators.

The TDD simulator (see Annex F) begins by optimising the FDD network, requiring the following input parameters:

- demographic data about the city (files: *Dados.dat* and *Zonas.dat*);
- scenarios: vehicular, pedestrian and indoor (file: *Users.txt*);
- BS location (file: *Network.dat*);
- BS antenna gain (file: *R_pattern.dat*);
- users spatial traffic distribution (file: *Users.txt*);
- service configuration (controlled by the tool user);
- E_b/N_0 for each service and scenario (file: *Eb_No.dat*);
- propagation model parameters (controlled by the tool user);
- link budget parameters (controlled by the tool user);
- MT and BS configuration (controlled by the tool user);
- slot symmetry (UL/DL), configured by the tool user (default: 9/3);
- number of control slots in a TDD frame, configured by the tool user (default: 3);
- TDD frequency, configured by the tool user (default: 1900 MHz);
- operation mode (FDD or TDD), configured by the tool user (default: TDD);
- BS maximum throughput, configured by the tool user (default: 1920 kbps).

The outputs are the following:

- covered users;
- number of users;
- uncovered users;
- served users, see (3.19);
- uncovered probability, see (3.18);
- delay probability, see (3.17);
- delay connections;

- free codes (based on Table 3.1), number of users, load factors (see (3.2) and (3.4), for UL and DL, respectively), bit rate and power, per timeslot and per BS in both UL and DL;
- sector radius: maximum, reference and minimum;
- BS throughput: maximum, reference and minimum;
- BS power: maximum, reference and minimum.

The TDD module maintains the structure of the FDD one, Figure 4.3.

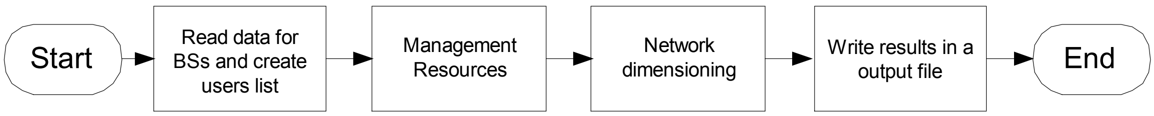


Figure 4.3. *Net_opt* algorithm for TDD mode.

The *Net_opt* application is the most important part of the TDD simulator. This new *Net_opt* begins by reading all data coming from *UMTS_Simul*, according to the description in Section 4.3, creating users lists. Then, follows an algorithm to manage the most important resources in TDD, timeslots and codes, network dimensioning being next algorithm, before writing all results in outputs files.

Several variables and constants are used in the flowcharts presented next, Table 4.1.

Table 4.1. Description of the several flowcharts variables and constants.

Flowchart Variable/Constant	Description
LOAD_MAX_UL, LOAD_MAX_UL	Maximum Allowed Load in UL and DL.
Load DL, Load UL	Cumulative Load in UL and DL.
MAX_POWER	Maximum Allowed BS TX Power.
Users (Sector), Users (TSlot)	Number of users per Sector and per TS.
Num_BSs	Number of BSs in the system.
BS Codes	Number of BS codes

Figure 4.4 presents the resources management algorithm. This algorithm begins by calculating the needed codes, for all HBR users (TDD users) in all TDD BSs. The procedure

begins by 1920 kbps users down to 128 kbps ones, and verifies if there are enough free codes for all users covered by TDD BSs. If there are not enough codes in the BS, the bit rate user is reduced, users with the higher bit rate, like 1920 kbps, are reduced two times (maximum) to 512 kbps and to 384 kbps; 384 kbps users are reduced two times to 128 kbps and to 64 kbps; finally, 128 kbps users are reduced once to 64 kbps. When there are no more free codes in a BS, users go on an outage state, starting from 1920 kbps to 128 kbps. This procedure is applied for all TDD users and for all TDD BSs.

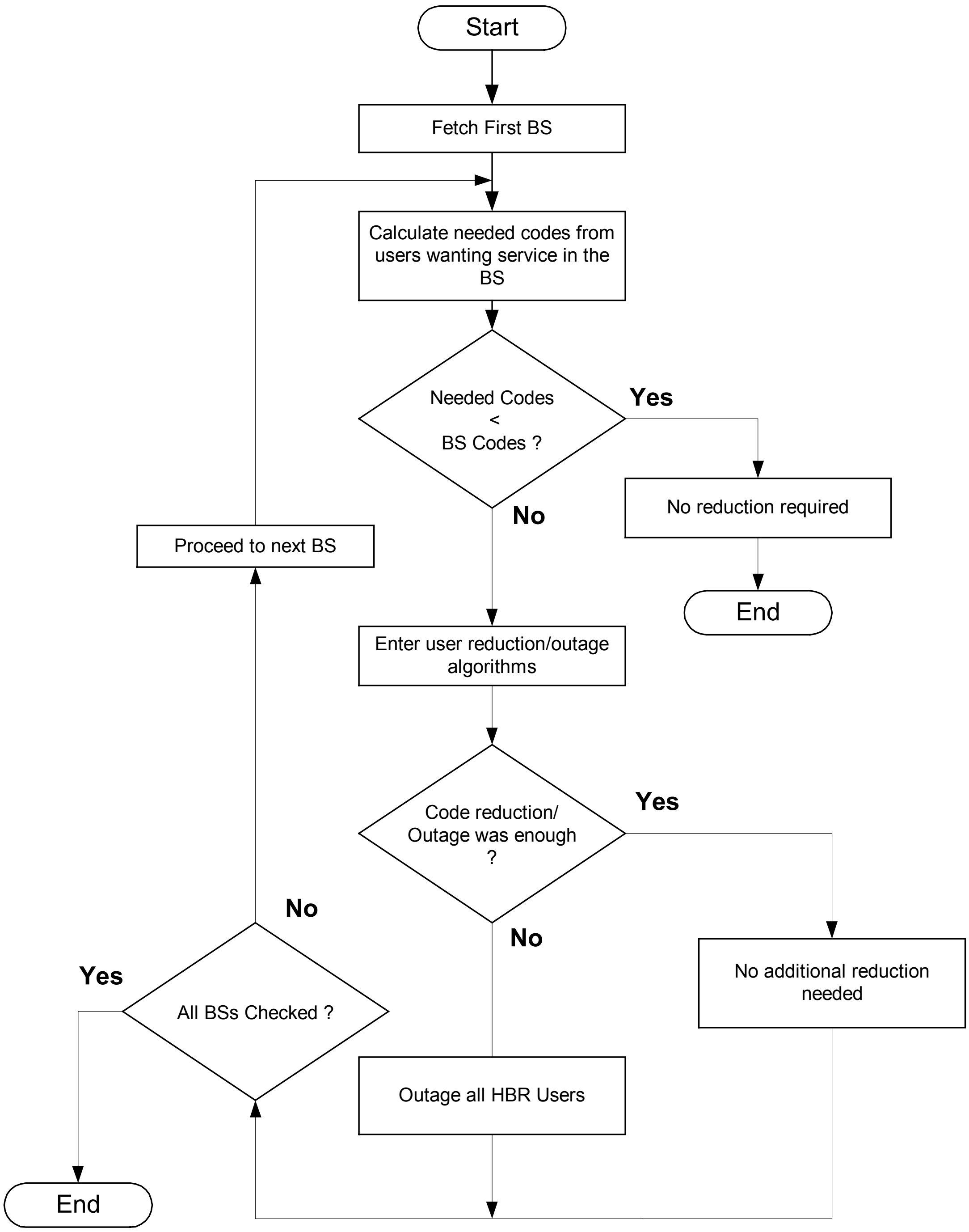


Figure 4.4. Resources management algorithm for the TDD mode.

Network dimensioning is presented in Figure 4.5, others algorithms being presented in Annex D:

- Load per TS in UL, calculates load per TS in UL;
- Load per TS in DL, calculates load per TS in DL;
- Codes allocation per TS in UL, calculates needed codes per TS in UL;
- Codes allocation per TS in DL, calculates needed codes per TS in UL;
- Power per BS, calculates power per BS in DL;
- BS power per TS, calculates BS power per TS in DL;
- Users allocation TS in UL, allocates TS in UL;
- Users allocation TS in DL, allocates TS in DL;
- Bit rate allocation TS in UL, calculates bit rate per TS in UL;
- Bit rate allocation TS in DL, calculates load per TS in DL.

Network dimensioning begins by calculating the load per timeslot in both links (UL, Figure D.1 and DL, Figure D.2), for the first user covered by the first BS in the first sector. Afterwards, it compares the cumulative load in UL and DL of the current BS with the maximum one, 50% in UL and 70% in DL (both can be changed in the simulator). After this, the algorithm calculates the power needed for users per timeslot (Figure D.5 and Figure D.6), and then verifies the current power in the BS (the default value is 38 dBm, but this can be changed in the simulator). If there are not enough resources (DL power, load UL and DL), users are delayed. The algorithm is applied for all users covered by network, finishes if no more BSs are present in the network.

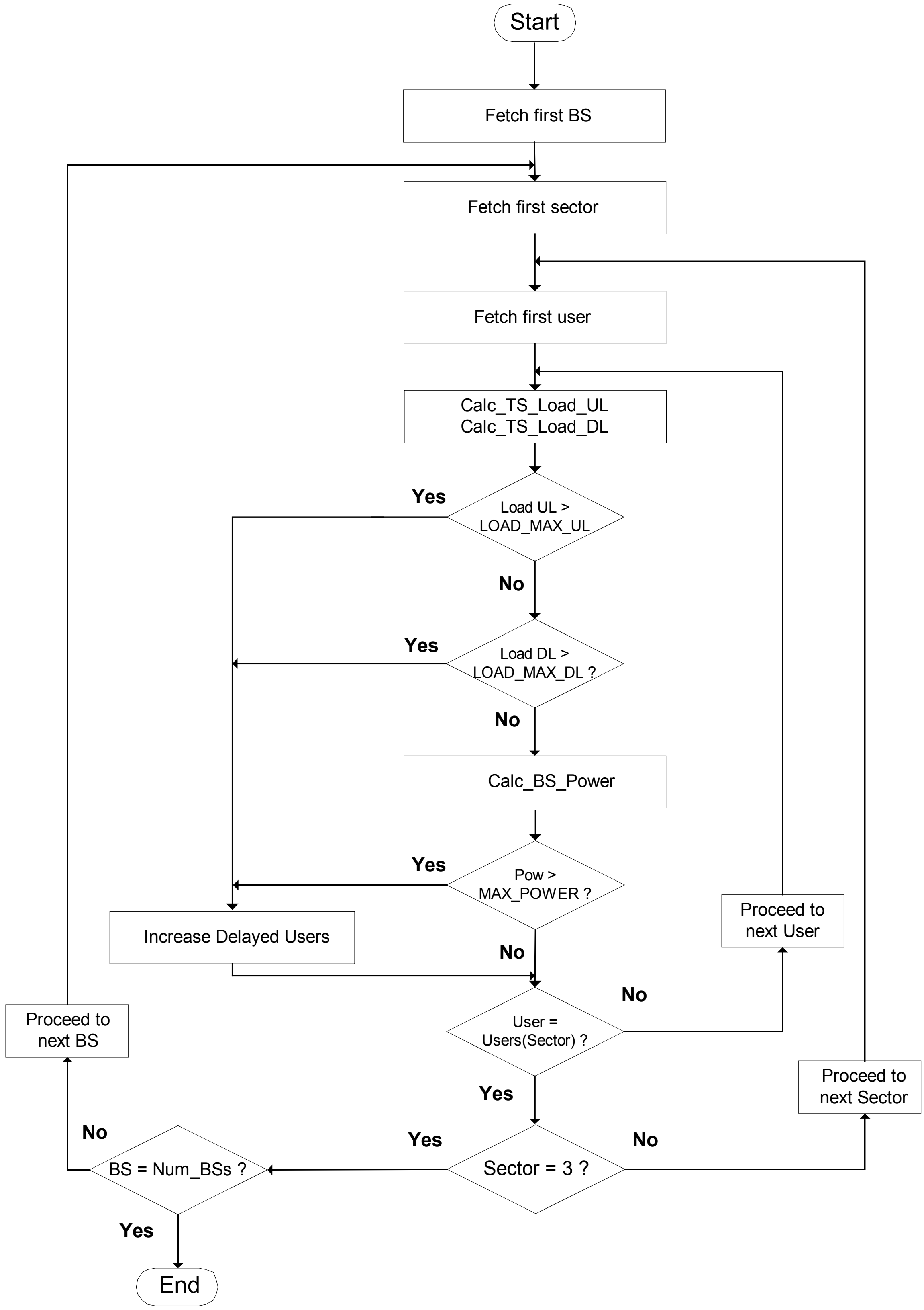


Figure 4.5. Network dimensioning algorithm, for the TDD mode.

4.5 Optimisation Algorithm

The objective of the algorithm described in this section is to provide optimum (near optimum) locations of TDD BSs co-located with a FDD network. This optimisation algorithm is included in the network, Figure 4.6.

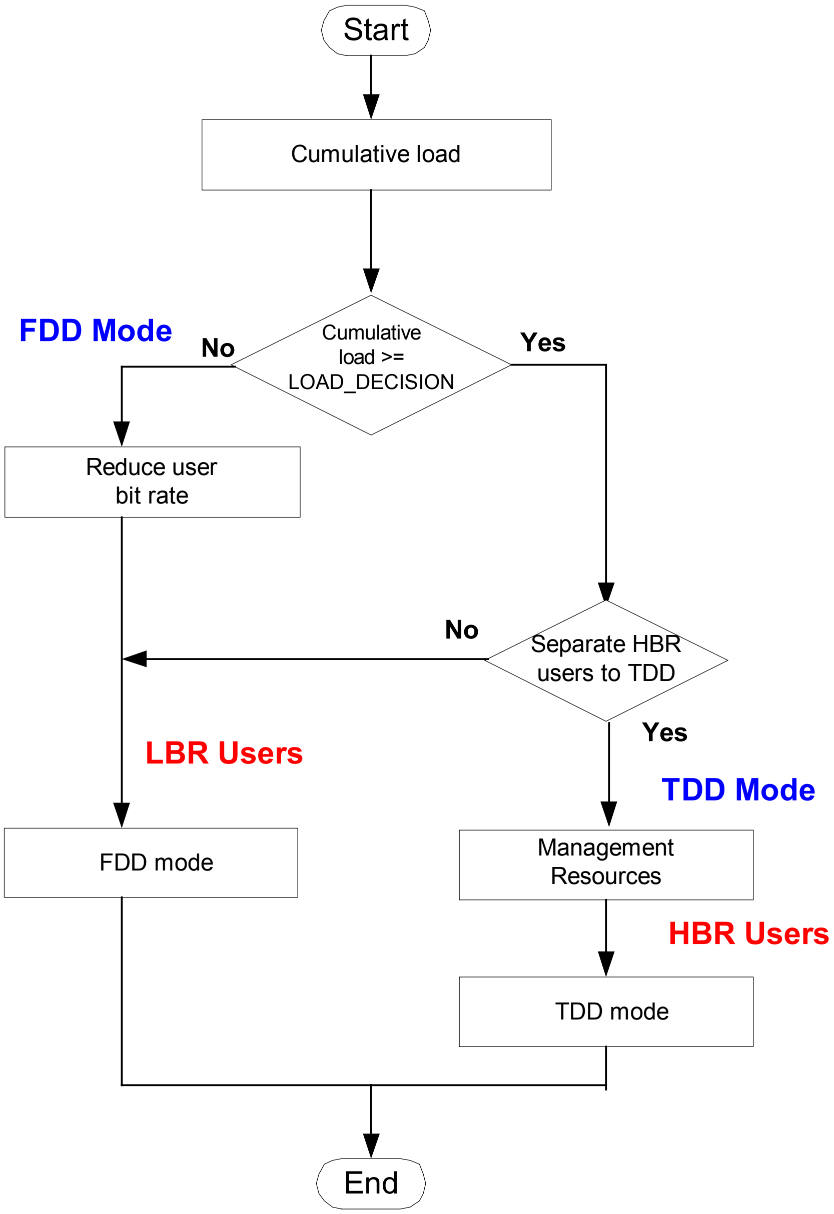


Figure 4.6. Optimisaton algorithm.

This algorithm begins by calculating the cumulative load for all users served in DL in the FDD network, Figure 4.7. Then, the cumulate load is compared to *LOAD_DECISION* (input parameter). When the load is less than *LOAD_DECISION*, the reduction bit rate algorithm is executed, Figure 4.8, to reduce FDD users bit rate to a bit rate greater or equal than *RB_DECISION* (input parameter); after this procedure, these users stay in the FDD mode, and the FDD network is optimised (user bit rate is reduced). When the load is greater or equal to *LOAD_DECISION*, two procedures start, first to separate users, Figure 4.9, according to bit rate less than *RB_DECISION,* users stays in the FDD mode, while others go to the TDD one, and second to manage resources, Figure 4.4, only for users in the TDD mode. *LOAD_DECISION* and *RB_DECISION* have values by default: 30% and 128 kbps, respectively.

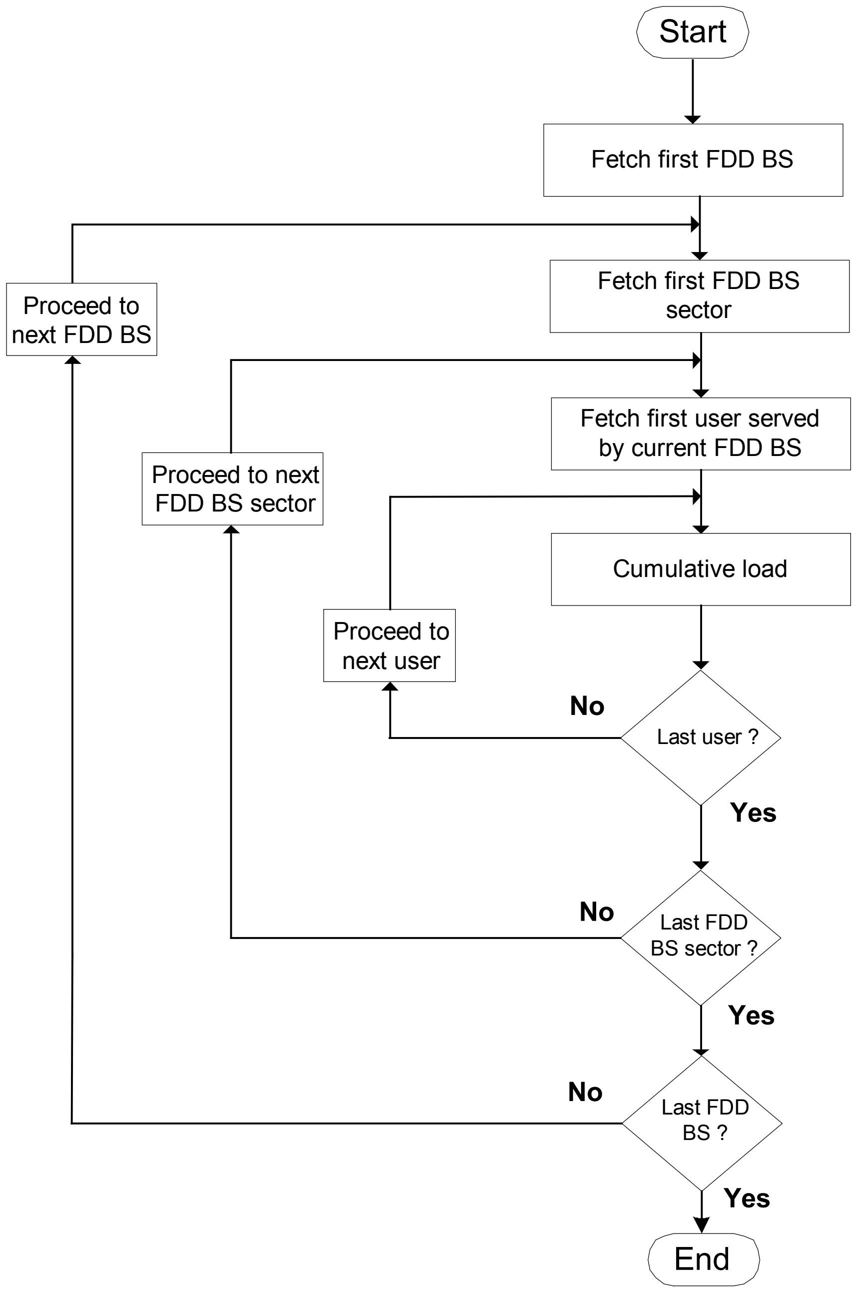


Figure 4.7. Cumulative load algorithm.

The specific input parameters for the optimisation algorithm are:

- bit rate decision (default: 128 kbps);

- high bit rate users, not supported in the FDD network;
- locations of FDD overloaded BS;
- number of FDD overloaded BS;
- load decision (default: 30%).

The cumulative load algorithm, presented in Figure 4.7, is applied only in the FDD mode: the engine goes through all users served by all sectors of all BSs in the network, and cumulates DL load generated by each user. If there are no more BSs in the network, the algorithm finishes.

The reduction bit rate algorithm, presented in Figure 4.8, is applied only in the FDD mode, and the decision to reduce or not the user bit rate depends on the service (user bit rate) and on *RB_DECISION*.

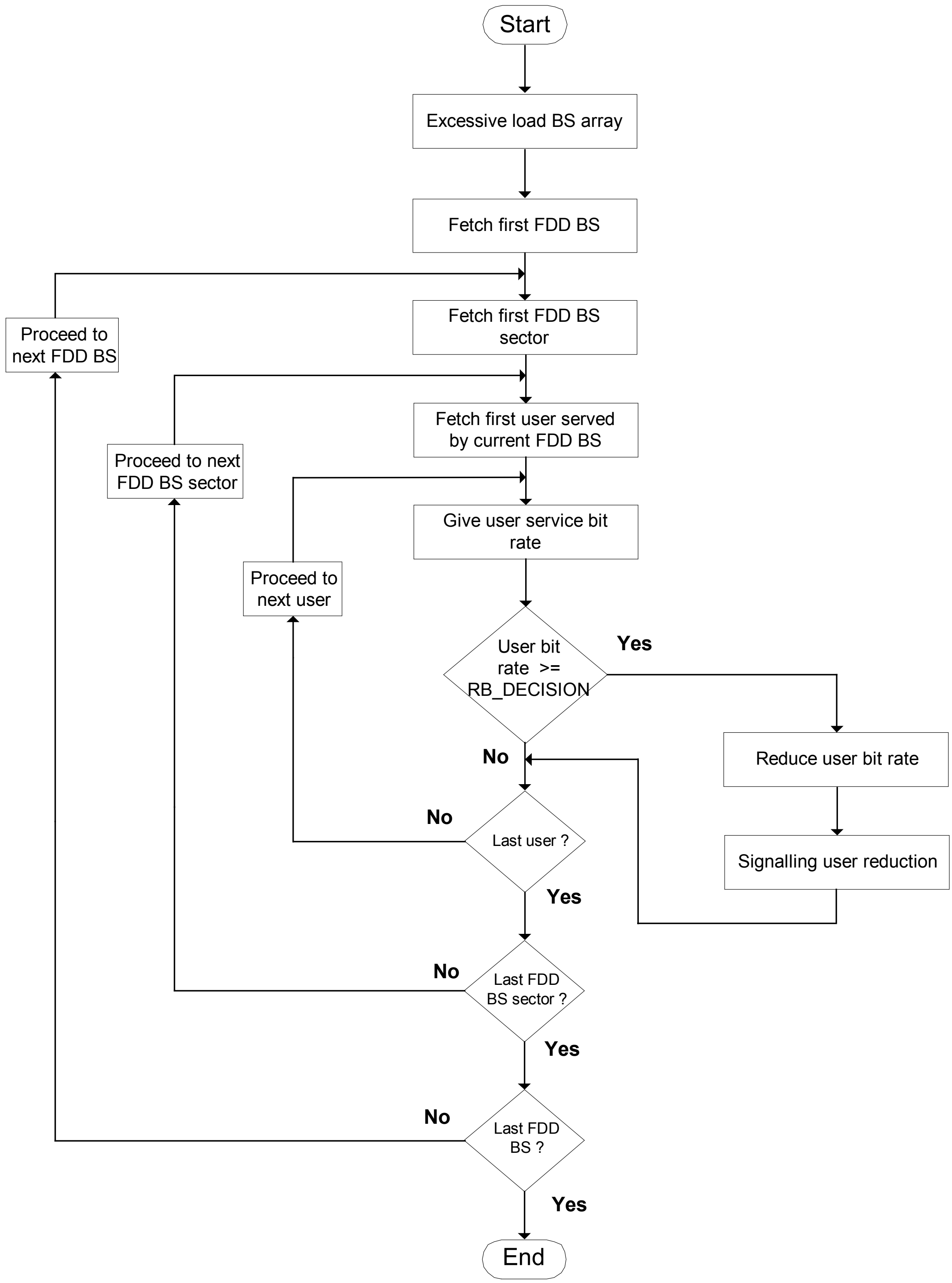


Figure 4.8. Reduction bit rate algorithm.

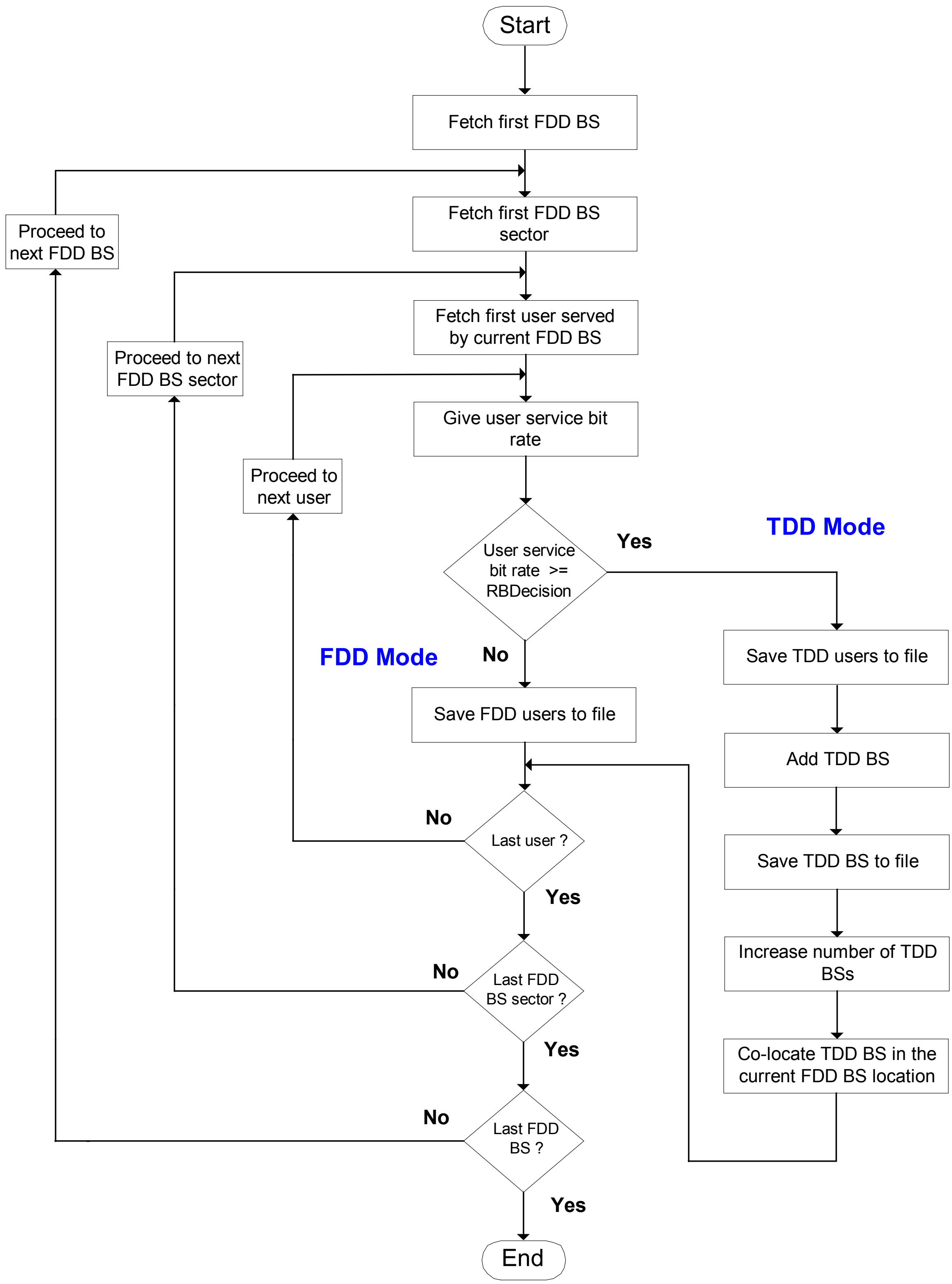


Figure 4.9. Separation HBR users algorithm.

The separation HBR users algorithm, presented in Figure 4.9, is applied only in the TDD mode. The objective is to separate HBR users, the test condition being defined by *RB_DECISION*. HBR users are stored in a file: *data_TDD.txt* (these are TDD users) and LBR users are stored in a file: *data_FDD.txt* (these are FDD users). When detecting HBR users, it is necessary to store them in the respectively FDD BS (in a file: *add_TDD_BS.dat*) co-located with a new TDD BS. The simulations process is repeated, controlled by the tool user.

4.6 Input and Output Parameters

FDD and TDD modes (simulator platform) require some data input parameters:

- Demographic data about city in question (files: *Dados.dat* and *Zonas.dat*);
- Scenarios: vehicular, pedestrian and indoor (file: *Users.txt*);
- BS location data (file: *Network.dat*);
- BS antenna gain (file: *R_pattern.dat*);
- Users spatial traffic distribution, from the *SIM* application (file: *Users.txt*);
- Service configuration (controlled by tool user);
- E_b/N_0 for each service and scenario (file: *Eb_No.dat*);
- Propagation model parameters (controlled by tool user);
- Link budget parameters (controlled by tool user);
- MT and BS configuration (controlled by tool user);
- Slot symmetry (UL/DL), configured by tool user (default: 9/3);
- Number of control slots in a TDD frame, configured by tool user (default: 3);
- TDD frequency, configured by tool user (default: 1900 MHz);
- Operation mode (FDD or TDD), configured by tool user (default: TDD);
- BS maximum throughput, configured by tool user (default: 1920 kbps).

The outputs of the simulator are the following:

- Number of covered users, N_{cov};
- Number of users (UL, N_{Users_UL}; DL, N_{Users_DL}; and total, N_{user});
- Uncovered users, N_{ncov};
- Number of served users (UL, N_{serv_UL}; DL, N_{serv_DL}; and total, N_{serv});
- Number of delayed users, N_d;
- Number of free (C_{free}) and used (C_{used}) codes;
- Load factors (UL – see (3.2) and DL– see (3.4)), bit rate in UL (R_{b_UL}) and in DL(R_{b_DL}), and DL power – see (3.5), all these parameters per timeslot and per BS;
- Sector radius, R;

- Delay probability, P_d (3.17);
- Uncovered probability, P_{ncov} (3.18).

The specific input parameters for the optimisation algorithm are:

- TDD users – *data_TDD.txt*;
- FDD users – *data_FDD.txt*;
- Bit rate decision (default: 128 kbps);
- High bit rate users, not supported in FDD network;
- Locations of FDD BS overloaded (file: *add_TDD_BS.dat*);
- Number of FDD BS overloaded;
- Load decision (default: 30%).

The specific output parameters of the optimisation algorithm are:

- Number of users that suffering the reduction of the bit rate, $N_{USERS\_1920-384}$, $N_{USERS\_384-128}$ and N_{USERS_128-64};
- Number of TDD BS co-located in the FDD network, N_{TDD_BS};
- Number of FDD users whose bit rate was reduced by the network in one unity, RER_{1920}, RER_{384} and RER_{128};
- Average value about FDD users whose bit rate was reduced, $DRER_{1920}$, $DRER_{384}$ and $DRER_{128}$;
- Cell capacity in TDD mode [GB/h], C_{Cap};
- Number of TDD BS with reduction of bit rate, N_{red_BS};
- Bit rate reduced per TDD BS, R_{TDD_BS};
- Number of users reduced per TDD BS, $N_{U\_TDD\_BS}$;
- Bit rate reduced per user (service), $R_{U\_service}$.

4.7 Assessment

The objective of this section is to address the validation of the simulator platform: TDD mode, optimisation algorithm, and sensitivity of the simulator.

FDD simulator has been validated, based on a comparison with the theoretical aspects of the FDD mode, [SeCa04].

Several tests were performed, on the TDD mode. As the service bit rate increases, the maximum number of users that can be allocated in a single timeslot drops, as expected. In the limiting case, services with a bit rate equal to 384 or 1920 kbps do not have enough codes to allow, at least, one user in a timeslot. Another important result, the services quality decrease becomes higher as the frame becomes more symmetric. This is a very important aspect that needed to be proven and validated in the simulator, because one of the greatest sources of interference in the TDD mode is the different asymmetries of the TDD frames between BSs, as seen in the previous chapter.

Finally, it can be seen that the maximum load that a single user can create on a single timeslot is 30.6%. This means that a single user of 1920 kbps sets the maximum load that the system has on any timeslot, and that load is far from the maximum of 70% in DL. It may be expected that when the timeslot has a mixture of several users the load increases. The maximum load that a single user can create on a timeslot is 19.3%, far from the maximum of 50% in UL.

The TDD simulator has been validated, based on a comparison with the theoretical aspects of the TDD mode, Annex E.

The first step, before the validation of the optimisation algorithm, is defining a test scenario, which includes all the default values of the simulator. In this test scenario one has 4 BSs, a total of 1000 users with a WWW, 804 users in the system, and a service throughput of 20% of users with 64 kbps, 40% of users with 128 kbps, and 40% of users with 384 kbps. Another test scenario was defined with the same conditions, except for the number of BSs, which was set to 10. The location of the FDD BSs is in the downtown of Lisbon, which is the area with higher traffic per km. The validation is presented in Annex E.

The sensitivity of the simulator to the number of simulations is very important. Performance parameters blocking, P_b, and delay probabilities, P_d, were taken for evaluation.

Figure 4.10 presents the blocking probability (average and standard deviation) as a function of the number of simulations, while simulations Figure 4.11 presents the delay probability.

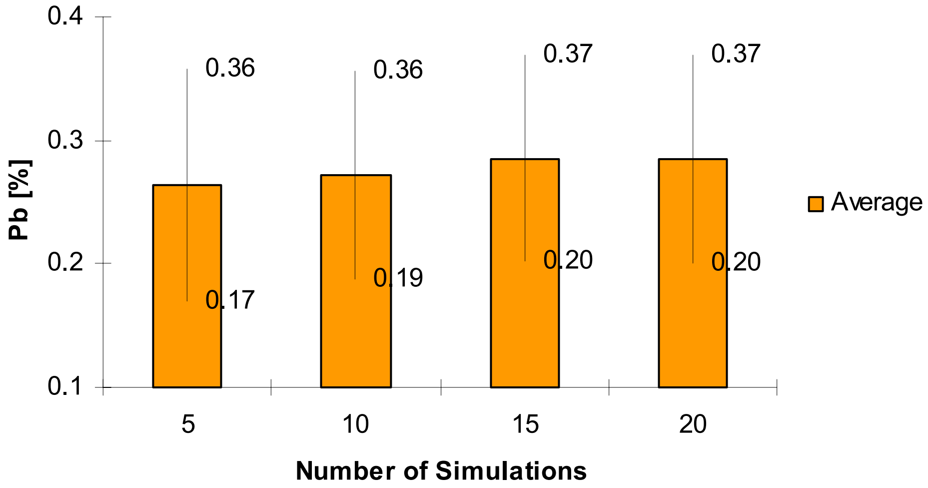


Figure 4.10. Blocking probability as a function of the number of simulations.

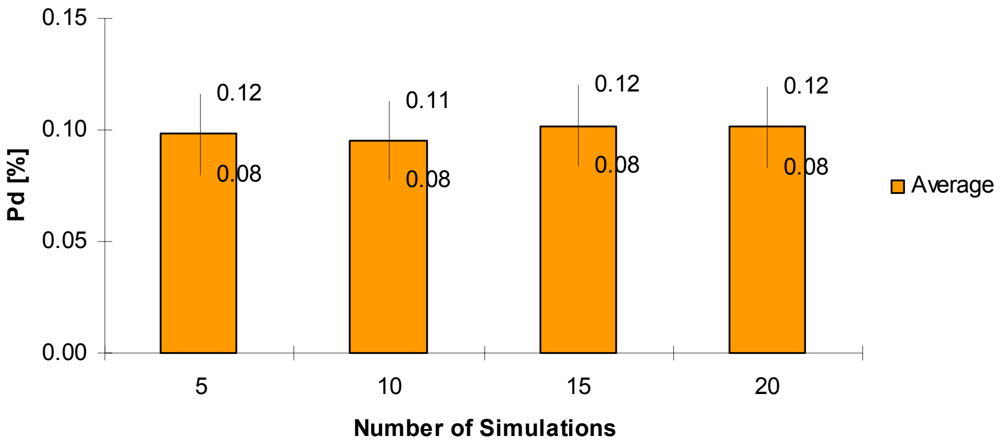


Figure 4.11. Delay probability as a function of the number of simulations.

By analysing the results, it can be concluded that the simulator stays stable after 10 simulations, hence, for performance analyses, this number of simulations was taken.

Chapter 5

Analysis of Results

The present chapter provides the analysis of results. After an introduction to the scenarios (demographics, geography and users profile), details about services considerations (bit rate and service penetration) follow. The reasons for the choice of the reference scenario are included as well. Finally, simulations results are present.

5.1 Scenario Description

This section focuses on the scenario inherited from the existing simulator, and afterwards on the evolution to the final scenario used in the simulations of this work. Cellular planning is quite scenario dependent, therefore, a scenario that represents an acceptable or typical service area is required, aiming to accomplish good results. In cellular networks, there are three well-known scenarios: rural, suburban and urban. The most important is the urban one, due to traffic load (population density), propagation issues, and scenario network dependency. A non-uniform urban scenario must be analysed in order to include several urban aspects.

The existence of a previous scenario was taken into account, although a scenario fit to the FDD mode may not be aproppriate to the TDD. Thus, there was the need to analyse that scenario prior to any study, in order to find if it fits the objectives of the current work. The existing scenario covers the geographic area of Lisbon, i.e., an urban area with high density zones as well as open green areas, Figure 5.1. For more details on geographic or morphological carachteristics, refer to [SeCa04].

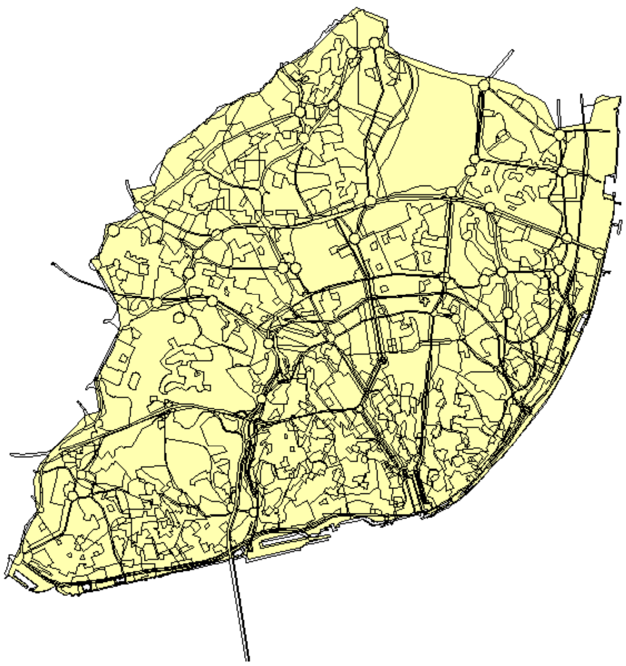
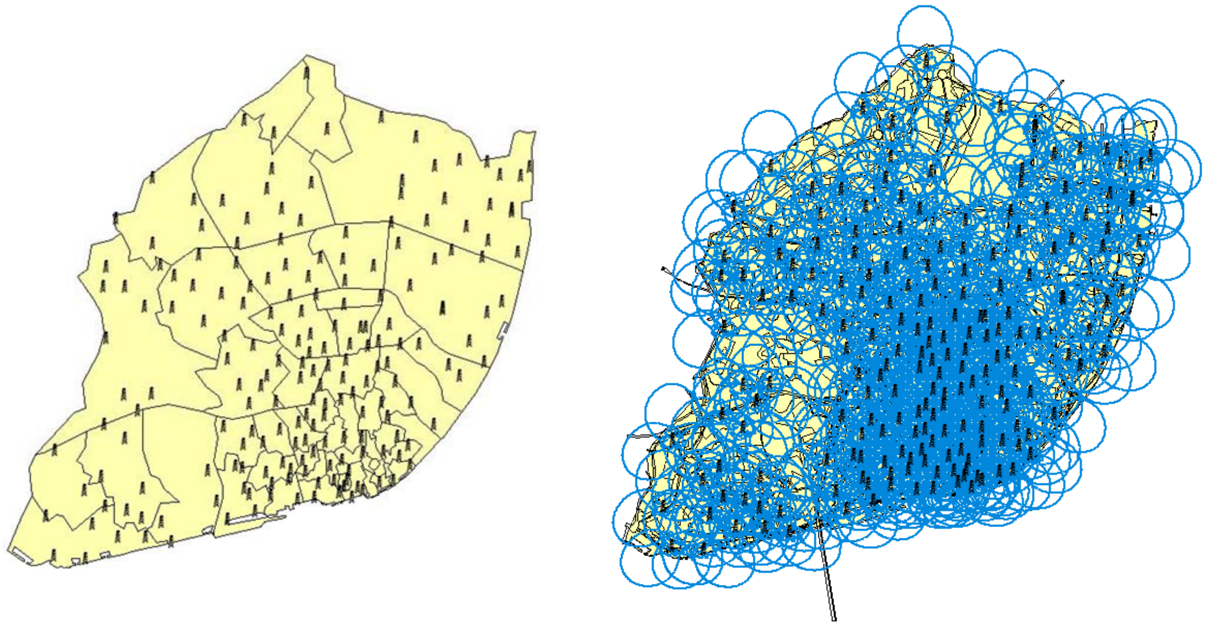


Figure 5.1. Lisbon metropolitan area (extracted from [SeCa04]).

For the existing FDD simulator, the penetration rates of HBR services are not high, voice and circuit based services have larger penetration rates, and the higher existing bit rate is 384kbps. These service characteristics do not fit the TDD mode, as HBR services are needed.

The existing scenario has a cellular network [SeCa04] and [Voda02] associated to it. This cellular network is comprised of 194 BSs, mapped according to terrain/users characteristics and densities. Figure 5.2 shows the cellular deployment and the coverage offered by that deployment in the FDD mode.



(a) BS location. (b) FDD cellular coverage.

Figure 5.2. Cellular deployment.

Having characterised the network and the area of interest from the initial scenario, it is still necessary to analyse how many users were considered in that scenario. The work presented in [SeCa04] concluded that for the whole metropolitan area of Lisbon, the existing cellular network was capable of serving a total of 9000 users. However, there was the need to check if the area used in the FDD mode was suitable for the TDD mode and studies that were to be made. By simply taking the existing cellular deployment as TDD mode, the obtained cellular coverage is sparse, Figure 5.3, due to the fact that the radius of a TDD BS is smaller than the one of an FDD BS.

Also, the kind of operation to be analysed in the TDD mode must be taken into account the need to model HBR services.

Figure 5.4 shows the population density per km^2. It can be seen that the downtown of Lisbon has a mean value of 25 000 to 50 000 habitants per km^2, whether the suburbs show a mean of 5 000 to 10 000.

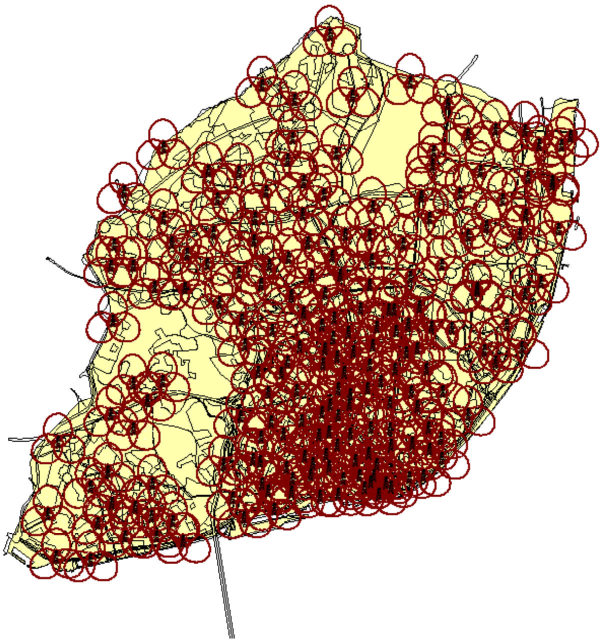


Figure 5.3. Cellular coverage for the TDD mode in the whole metropolitan area of Lisbon.

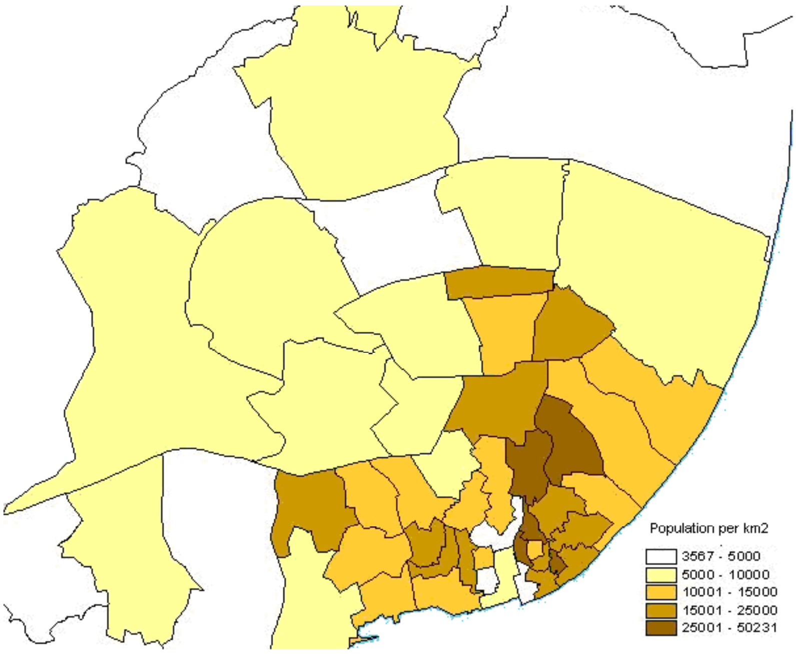


Figure 5.4. Population density on interest area (adapted from [CMLi06]).

Therefore, in order to obtain HBR users and high values of network load in the TDD mode, the area of interest was reduced to the areas where user densities are higher. Figure 5.5, shows the new service area, i.e., only the downtown.

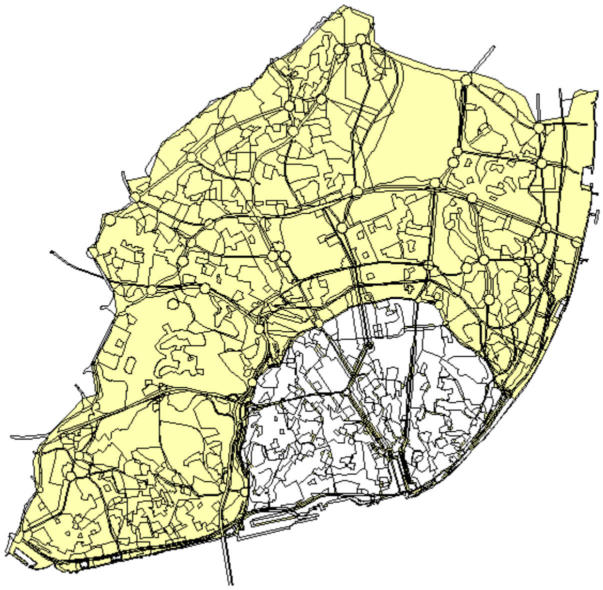
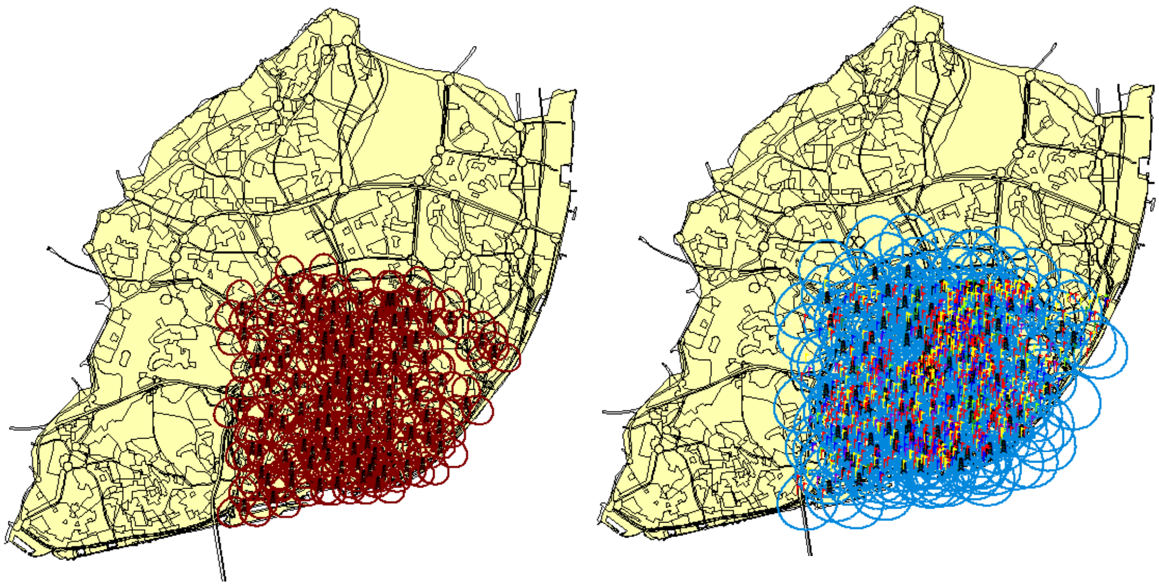


Figure 5.5. New area of interest for the TDD mode (in white).

The scenario is comprised of 29 districts, including four of the most populated districts of the whole metropolitan area. Figure 5.6 shows the coverage of the 94 BSs in the area of interest for both modes. It can be seen that, in the FDD mode the area is almost completely covered, while in the TDD one there are still some coverage holes. Coverage considerations are made later in this document.



(a) TDD mode.

(b) FDD mode.

Figure 5.6. Downtown of Lisbon – area of interest.

Before starting simulations, it was necessary to create some different scenarios, from voice centric (more then 50% of LBR users) to data centric (more then 50% of HBR users), and evaluate network performance in both modes. Table 5.1 shows the characteristics of the six different test scenarios that were assumed in order to find the one that would fit the TDD requirements. The characteristics of the services presents in all scenarios are according to Section 2.4.

Table 5.1. Different test scenarios and corresponding services penetration rates.

Service	**Bit rate [kbps]**	**CS / PS**	**Service Penetration [%]**					
			1	**2**	**3**	**4**	**5**	**6**
Speech telephony	12.2	CS	70	50	30	30	30	30
VoIP	16	PS						
Video telephony	64	CS	4	5	7	5	4	2
Location based	64	PS	3	5	6	5	3	1
MMS	64	PS	3	5	7	5	3	2
Email	128	PS	10	15	20	15	10	5
Video streaming	384	PS	2	5	7	10	12	15
File download	384	PS	3	5	8	10	13	15
Web browsing	1920	PS	5	10	15	20	25	30

Figures 5.7 and 5.8 present the service and radio bearer distributions, respectively, for the six scenarios. The first two scenarios are clearly CS centred, while the last two are clearly PS centred with HBR services.

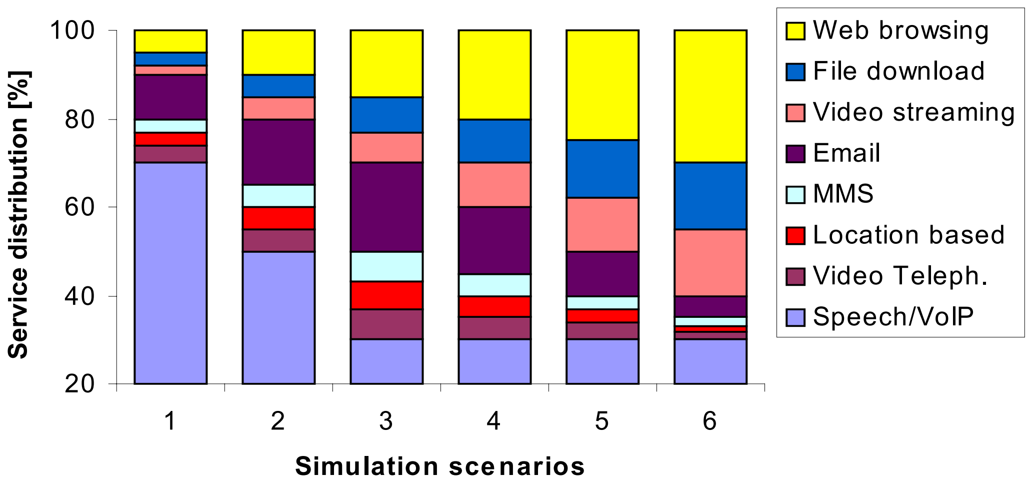


Figure 5.7. Service distribution for the six scenarios under study.

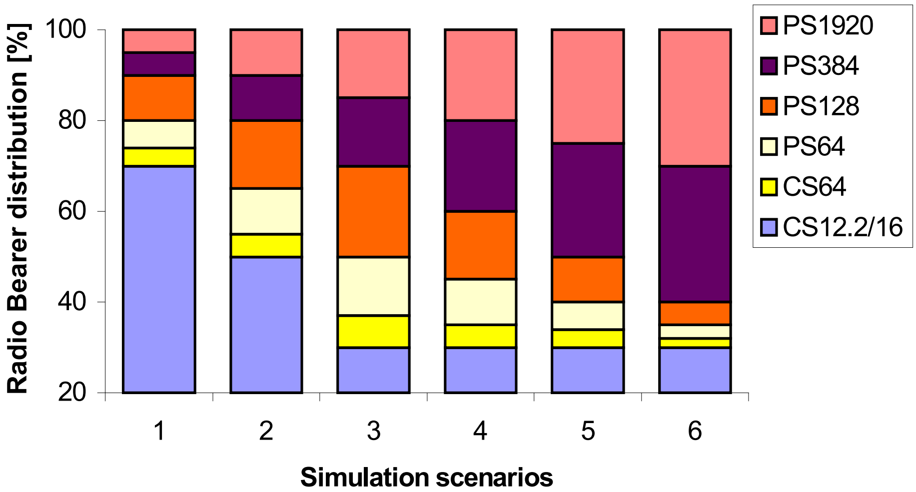


Figure 5.8. Radio bearer distribution for the six scenarios under study.

The simulator platform requires some input parameters, which have default values, present in Table 5.2 to Table 5.4 global parameters about all BSs, Table 5.2, propagation model, Table 5.3, and configurations associated to UL, Table 5.4.

Table 5.2. Simulation settings – default parameters.

Input parameters	Values
Maximum DL load factor [%]	70
Maximum UL load factor [%]	50
BS Maximum power [dBm]	38 for FDD and 21 for TDD
Active set for FDD	3
Scenario	Pedestrian
Frequencies	4 to FDD and 1 to TDD

Table 5.3. Propagation model – default parameters.

Input parameter	Values
Building height [m]	24
BS height [m]	Building height + 1
Street width [m]	24
Width between buildings centers [m]	48
Departing angle from the closest building [º]	90
MT height [m]	1.8

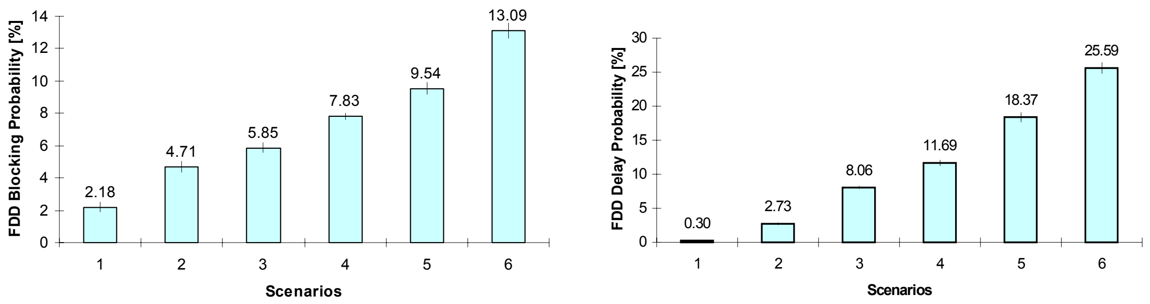
Table 5.4. UL service – default parameters.

Input parameters	Values
Speech telephony [kbps]	12.2 or 16 (VoIP)
Video telephony [kbps]	64
Location based, MMS [kbps]	
Email [kbps]	
Video streaming [kbps]	
File download [kbps]	
Web browsing [kbps]	

5.2 Choice of a Reference Configuration

The criteria for the choice of a scenario were taken as blocking and delay probabilities for the FDD mode, expected to be less than 2 %. All performance parameters are presented Annex H. After analysing the simulations for the six scenarios, the number of users for the FDD mode was decreased from 3 500 to 2 941.

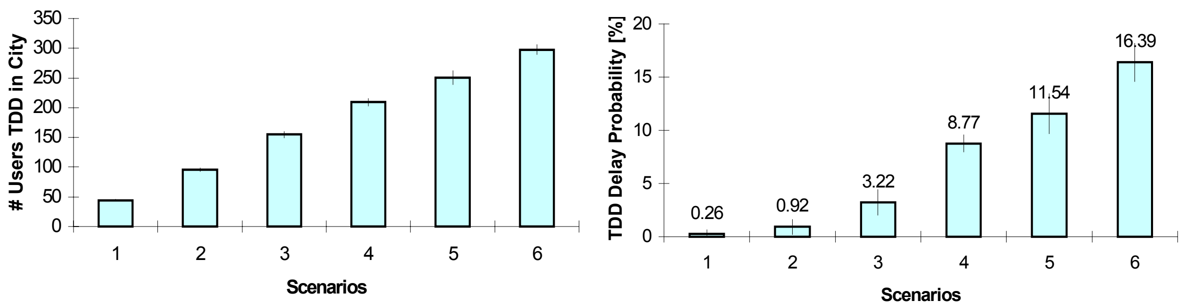
Figure 5.9 presents blocking and delay probabilities. Taking the desired users' profile into consideration, scenario 3 seems a good trade-off, hence, further reduction on the number of users had to be performed. All these performance parameters can be seen in Annex G.



(a) Blocking. (b) Delay.

Figure 5.9. FDD blocking and delay probabilities for the six scenarios.

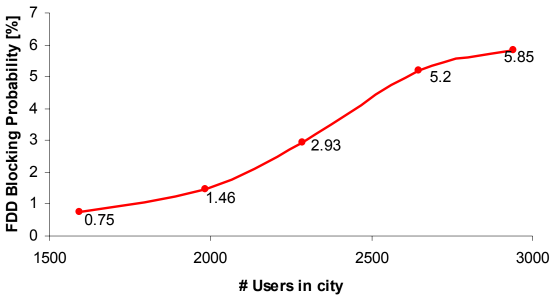
Figure 5.10 presents the number of TDD users and the delay probability. The number of users increases when the scenario tends to HBR traffic, as expected, corresponding to an increase of delay probabilities.



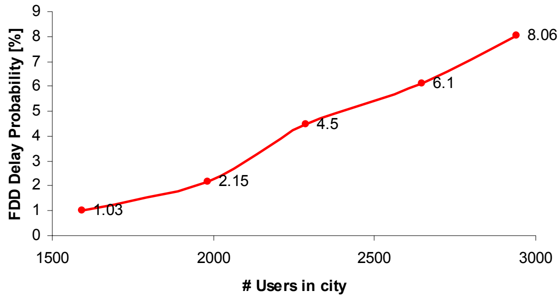
(a) Users. (b) Delay.

Figure 5.10. Number of TDD users in city and delay probability for the six scenarios.

Figure 5.11 presents results for a further reduction on the number of users.



(a) Blocking.



(b) Delay.

Figure 5.11. FDD blocking and delay probabilities for the six scenarios after reduction of users.

By analysing these results, a good solution is 1 983 users, because blocking probability is less then 2% and delay probability is nearly 2%.

Figure 5.12 presents the users profile for the chosen scenario, Scenario 3, with 1 983 users.

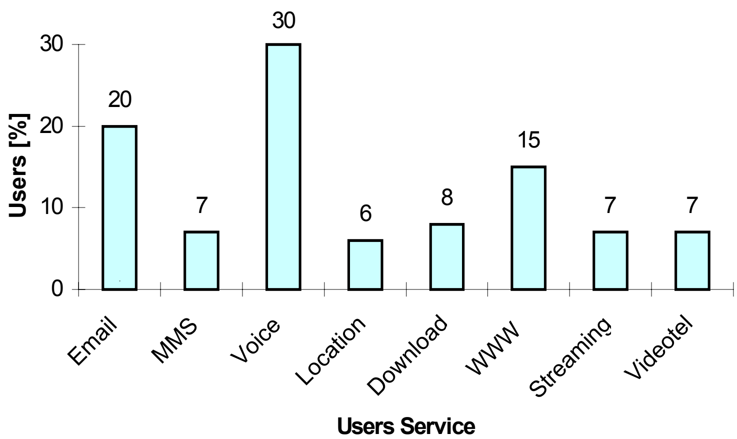


Figure 5.12. Users profile for the FDD mode.

Table 5.5 shows results from 10 simulations performed with the reference scenario, for the FDD mode.

Table 5.5. Performance parameters for Scenario 3 with 1 983 users for the FDD mode.

3rd Scenario	FDD mode				
	Maximum	Average	Std. Dev.	Minimum	Obs.
Load UL [%]	53.15	28.11	13.42	0.85	BS Sector
Load DL [%]	60.25	24.24	11.46	0.71	BS Sector
Uncovered probability [%]	9.83	8.97	0.63	7.92	System
Blocking probability [%]	1.68	1.46	0.22	0.93	System
Delay probability [%]	2.63	2.15	0.31	1.53	System
# TDD BS	58	56.10	2.00	53	System

Table 5.6 shows results for the TDD mode.

Table 5.6. Performance parameters for Scenario 3 with 1983 users for the TDD mode.

Bit rate decision = 128kbps; Load decision = 30%; TS Asymmetry: 9:3	TDD mode				
	Maximum	Average	Std. Dev.	Minimum	Obs.
# Users in the City	112	95.40	8.98	83	System
Uncovered users proba.[%]	25.89	18.91	4.16	11.49	System
Delay probability [%]	3.70	1.64	1.43	0.00	System
BS Capacity [GB/h]	25.40	14.50	9.64	1.79	per BS
Used Codes BS DL [%]	95.87	95.20	0.35	94.64	per BS
Free Codes BS DL [%]	5.36	4.80	0.35	4.13	per BS
Used Codes BS UL [%]	84.55	82.47	1.45	80.61	per BS
Free Codes BS UL [%]	19.39	17.53	1.45	15.45	per BS
TS Used BS DL [%]	65.79	61.02	4.71	51.28	per BS
TS Free BS DL [%]	48.72	38.98	4.71	34.21	per BS
TS Used BS UL [%]	40.35	37.62	1.77	35.19	per BS
TS Free BS UL [%]	64.81	62.38	1.77	59.65	per BS
Bit rate reduction BS [Mbps]	2.90	2.21	0.39	1.84	per BS
BS with reduction RB [%]	48.72	34.29	7.98	23.08	System

For all scenarios, 10 simulations were performed, leading to a simulation period of around 120h (roughly 5 days), and generating approximately 2 GB of data.

5.3 Bit Rate Decision Analysis

The modification of the bit rate decision threshold (between FDD and TDD) has a strong impact on the number of users put in TDD, this being an important parameter to be analysed. The following values were considered: 64, 128 and 384 kbps.

After analysing the data one can see that the load in FDD does not show a strong impact on the network. On the opposite, the load in the TDD mode (including codes and TSs) has an essential importance. The load per BS in DL changes from nearly 40% (with a bit rate decision of 64 kbps) up to 70% (with a bit rate decision of 384 kbps), which is caused by the required number of TDD BSs coming from the optimisation algorithm. Figure 5.13 presents the most important parameter – number of TDD BSs needed – in the performance of the optimisation algorithm, and naturally in the TDD mode. In this figure, one can see that a more restrict bit rate decision threshold causes a reduction on the amount of TDD BSs. Less TDD

BSs implies less TDD users (HBR ones), which means that less resources are needed per BS (see Figure 5.17).

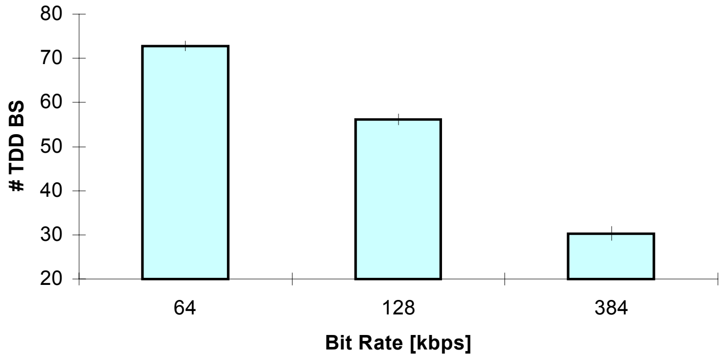
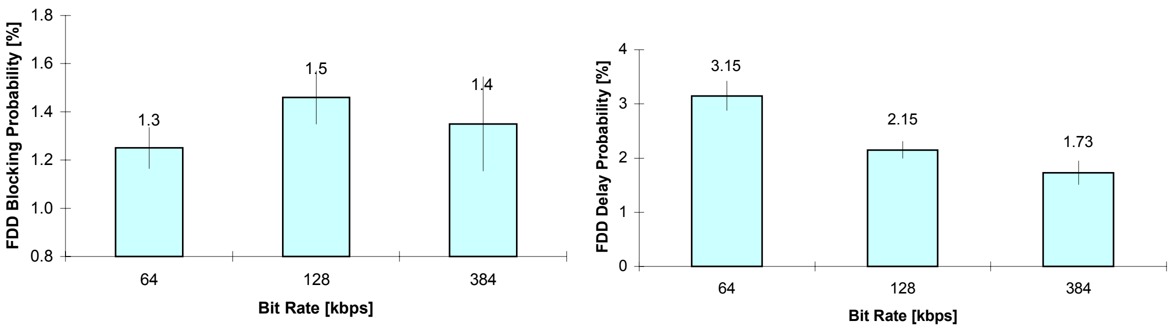


Figure 5.13. Number of TDD BSs needed as a function of the bit rate decision threshold.

Figures 5.14 and 5.15 present the impact of this decision threshold blocking and delay probabilities. Blocking (only in FDD) does not have a considerable change (around 1.3 to 1.5 %). On the other hand, delay presents a substantial variation in both modes, decreasing when the bit rate decision threshold increases. Focussing on Figure 5.15, there are two causes for the major change: the first one (at 64 kbps) is due to the biggest increase of users in the TDD mode, Figure H.10; the second one (for 384 kbps) is that traffic is mainly from HBR users, and when the TDD mode does not support more users two decisions are taken, reduction of user bit rate in 3 steps and user delay.

As mentioned for other probabilities, uncovered users probability (Figure H.4 and H.11, FDD and TDD, respectively) has a similar behaviour: in FDD, it has a tendency to stabilise (in an interval from 6 to 8%); in TDD it follows the behaviour of the delay probability, caused by the increase of TDD users (see Figure H.10).



(a) Blocking. (b) Delay.

Figure 5.14. Probabilities in the FDD mode as a function of the bit rate decision threshold.

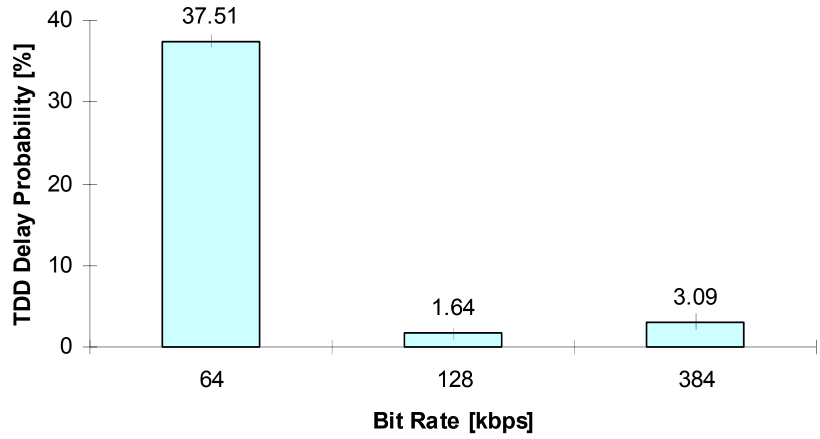


Figure 5.15. Delay probability in the TDD mode as a function of the bit rate decision threshold.

As previously mentioned, in the TDD mode, the load includes used codes and TSs. Figure 5.16 shows the used codes per BS in DL and UL. In DL they change in the interval of 95% to 96%, i.e., the change is not significant even with a different number of TDD BSs, which is a consequence of the good optimisation of the management resources algorithm (see Figure 4.5). In UL, the difference is large, due to the number of users (see Figure H.10). It is important to mention that less codes are needed in UL – only 5 codes per user (see Table 3.1) maximum (included HBR users); Figure H.10 presents the free codes in both links, and the behaviour is complementary.

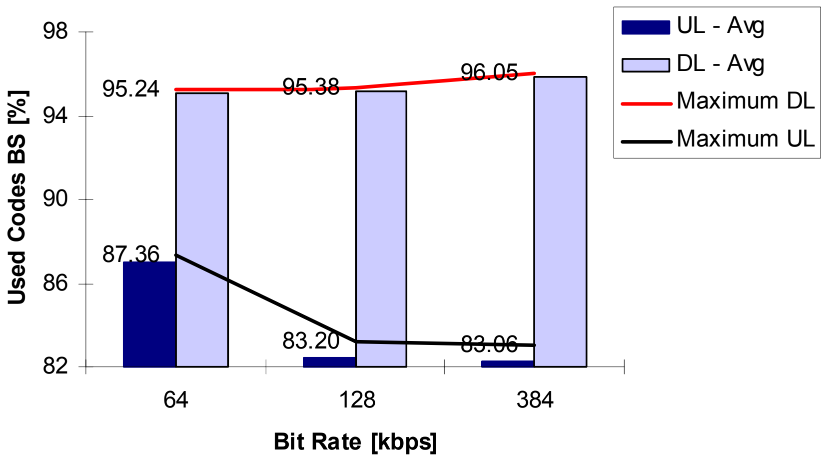


Figure 5.16. Used codes per BS in DL and UL as a function of the bit rate decision threshold.

Figure 5.17 shows the variation of used TSs in DL. As expected, when the threshold is 64kbps there are less TSs needed. UL variation confirms that the network in UL supports lees users, but that users are delay limited by TSs in DL, caused by the management resources algorithm.

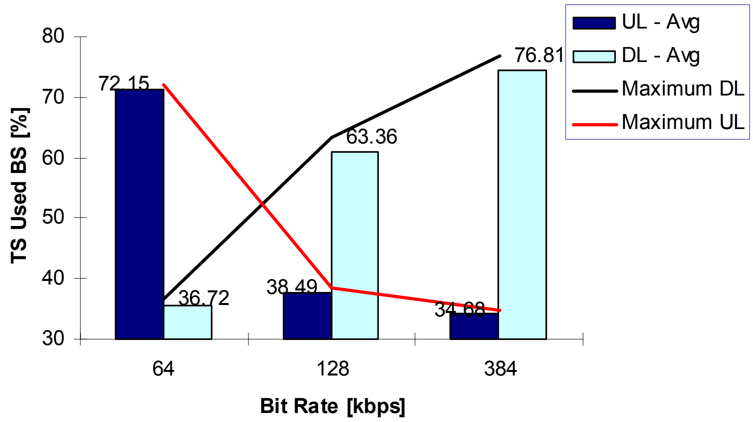


Figure 5.17. TSs used per BS for DL and UL as a function of the bit rate decision threshold.

Other performance parameters suffer the impact of changing the bit rate decision threshold. For example, DRER (percentage of users that have a reduction of bit rate from 1920 to 384kbps, and 128 to 64kbps), presented in Figure H.5, suffers a small decrease for HBR users, and the same is verified in Figure H.6.

The developed optimisation algorithm allows that some HBR users stay in FDD, but with a reduction of the service bit rate. As well as DRER, but for TDD, there are two output parameters that are associated to the cumulative bit rate reduced per BS, Figure H.12, and it can be said that with a bit rate decision of 384kbps more users suffer a reduction, near to 3Mbps on average per BS. Figure H.13 presents the percentage of TDD BSs that provide a reduction of bit rate service. Finally, another performance parameter of TDD mode is BS capacity, in GB/h, presented in Figure H.9. This output parameter confirms that the increase of HBR users generates a high load in DL, a high number of codes in DL per user, and a consequent increase of TS, leading to an increase of capacity.

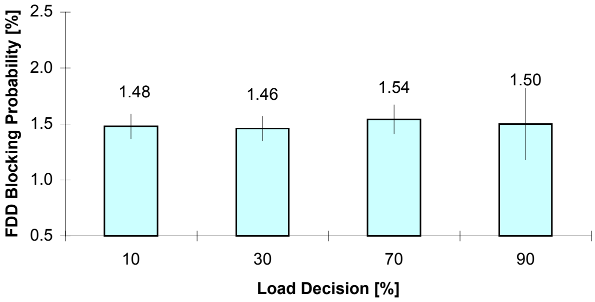
For all data presented in this section and in Annex H, the simulation period was around 60h (roughly 3 days), generating approximately 1 GB of data.

5.4 Load Decision Analysis

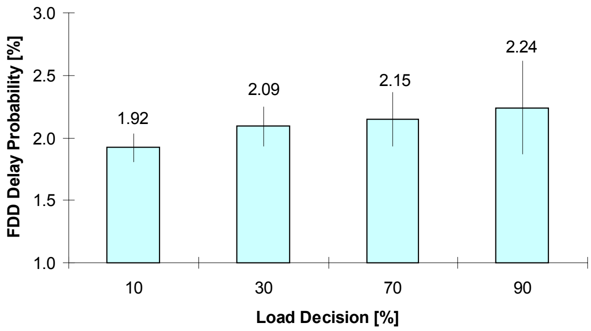
The load decision threshold parameter is the percentage of load in the FDD mode moved to the TDD one, i.e., a 90% of load decision threshold means that almost all the load in FDD was transferred to TDD, and only 10% stays in FDD.

As it can be noted in Figures I.1, I.2, I.3 and I.4, the modification of the load decision threshold has a strong impact on the number of HBR users in TDD, and almost all users that have a user bit rate above 128 kbps go to TDD mode.

Figure 5.18 presents blocking and delay probabilities. Load decision threshold does not affect too much the blocking probability, and the delay probability changes slowly, i.e., they are almost insensitive to the variation of the load decision threshold.



(a) Blocking.



(b) Delay.

Figure 5.18. Blocking and delay probabilities in the FDD mode as a function of the load decision threshold.

Figure 5.19 presents the number of TDD BSs, which increases with the load decision threshold, because more load goes to TDD, hence, the network needs more TDD BS.

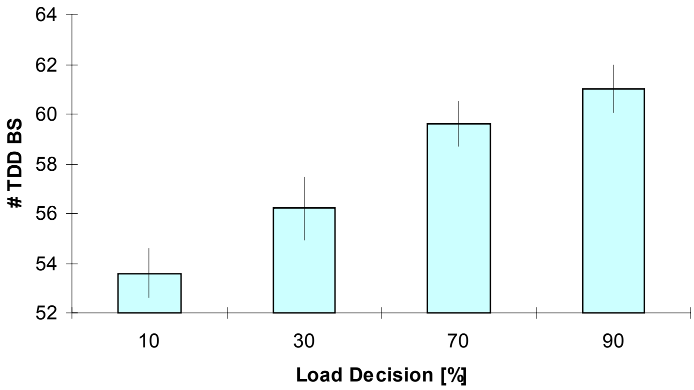


Figure 5.19. Number of TDD BSs needed as a function of the load decision threshold.

In TDD, the load in both links (UL and DL) influences network performance in terms of reduction of service bit rate (see Figure I.13), because one HBR user uses 2/3 TS (maximum) and the load in DL for one TS represents near to 30% of the total load, meaning that 3 TSs correspond near to 90 % of the load. In UL, the load is low for all values of the load decision threshold, near to 15%.

In Figure 5.20, the delay probability for the TDD mode can be observed. The variation of this performance parameter is not large.

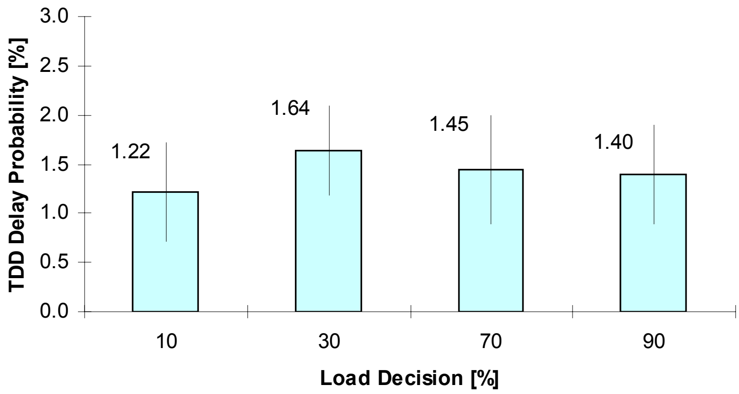


Figure 5.20. Delay probability in the TDD mode as a function of the load decision threshold.

Figure I.13, presents the evolution of bit rate reduction per BS, which is related to the increase of number of TDD BSs and of HBR users; for 10 or 30%, reductions are 2 Mbps, and 70% or 90%, reductions are above 2.5 Mbps. Capacity increases also when the load decision increases, reaching maximum value (for 90% of the load) of 19 GB/h on average (see Figure I.10).

Figure 5.21 shows used codes per BS in DL and UL. Used codes in DL are stable around 95% until 70% of load decision threshold, and decrease for 90% of load decision threshold, which is the increase of BSs that provide reductions of service bit rate (Figure I.14), hence, an increase of free codes. In UL there is stability close to 83%.

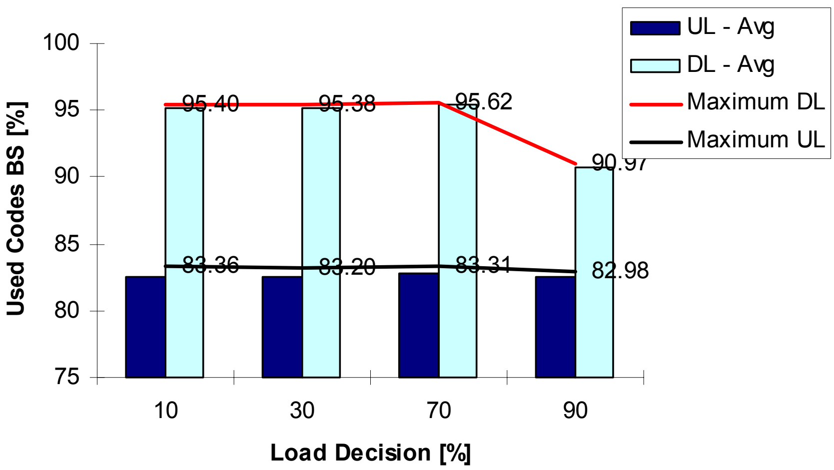


Figure 5.21. Used codes per BS in DL and UL as a function of the load decision threshold.

Figure 5.22 shows used TSs per BS in DL and UL. As expected, when the load decision threshold is lower, there are fewer users, thus, less TSs are needed. When the load decision threshold is higher, more HBR users exist and consequently more TSs are needed, which is valid for both links.

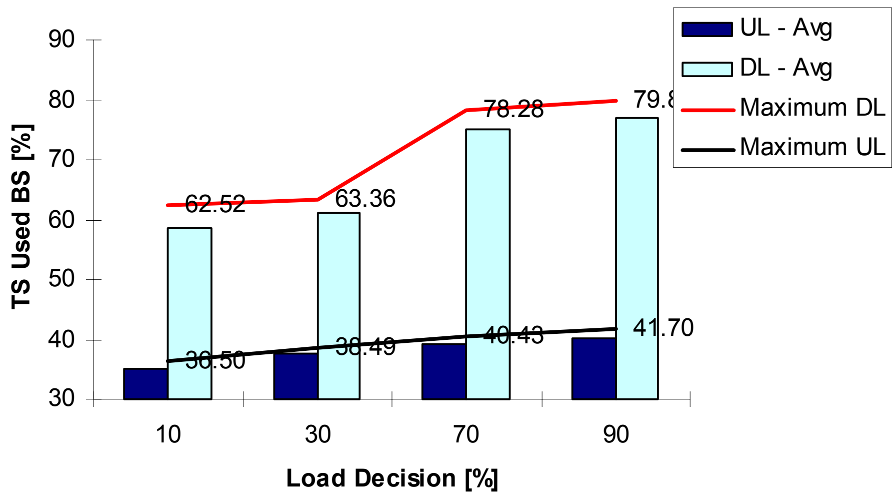


Figure 5.22. TSs used per BS for DL and UL as a function of the load decision threshold.

For all data presented in this section and in Annex I, a simulation period of around 72h (roughly 3 days) was used, generating approximately 1.5 GB of data.

5.5 TS Asymmetry Analysis

This section addresses the impact caused by the variation of TS asymmetry.

Figure 5.23 presents TS asymmetry impact on delay probability. Only two asymmetries have average values lower than 5%, because HBR users need resources, i.e., TSs. For example, users with a 1920kbps need 9 TSs for DL, but with the reduction of bit rate, they are reduced to 512kbps, and requiring 3 TSs. The delay probability increases when DL TSs are less than 8. When asymmetry is 11:1, delay is caused by TSs needed for UL (all TDD users have 64 kbps in UL).

By analysing the uncovered users probability, Figure J.2, one can see that for almost all asymmetries it is near to 20%, except in the extremes (11:1 and 1:11), due to the management resources algorithm.

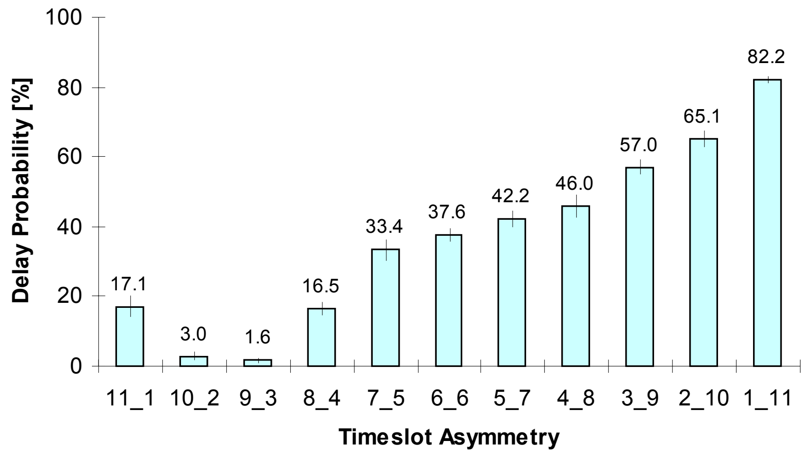


Figure 5.23. Delay probability in the TDD mode as a function of the TS asymmetry.

Figure 5.24 presents TS asymmetry impact on used codes. BSs are near maximum capacity in DL, used codes decreasing in DL when there are more TSs in UL, caused by few TSs in DL. In UL, used codes increase as a consequence at the asymmetry change.

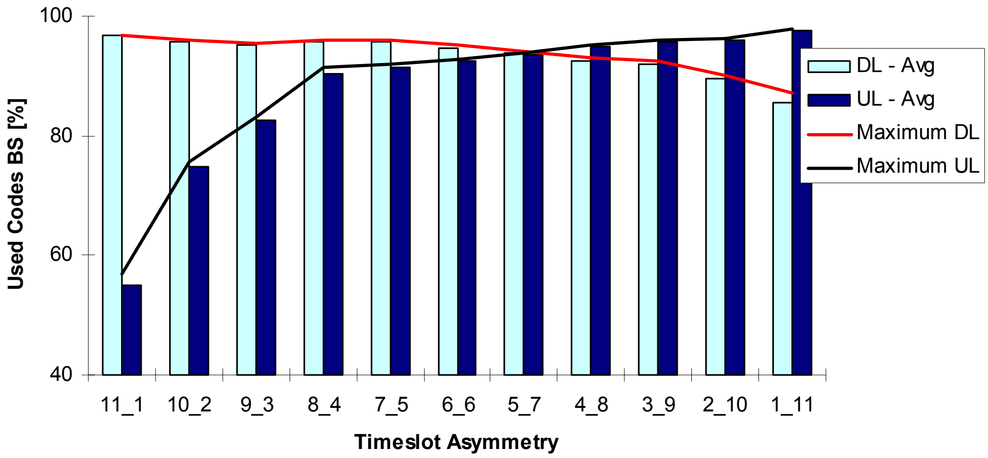


Figure 5.24. Used codes per BS in DL and UL as a function of the TS asymmetry.

Figure 5.25 presents TS asymmetry impact on TSs per BS. Allocated TSs are proportional to the needed bit rate. In DL, maximums values are verified when asymmetry is 10:2 or 9:3 which agree with Figure 5.23.

The evolution of BS capacity when TS asymmetry change is presented in Figure J.3. This evolution has two maximum, 15 GB/h and 14.5 GB/h, for 10:2 and 9:3 asymmetries, respectively. It is important to mention that with a decrease of DL TSs leads to a decrease in BS capacity, as shown in Figure J.3.

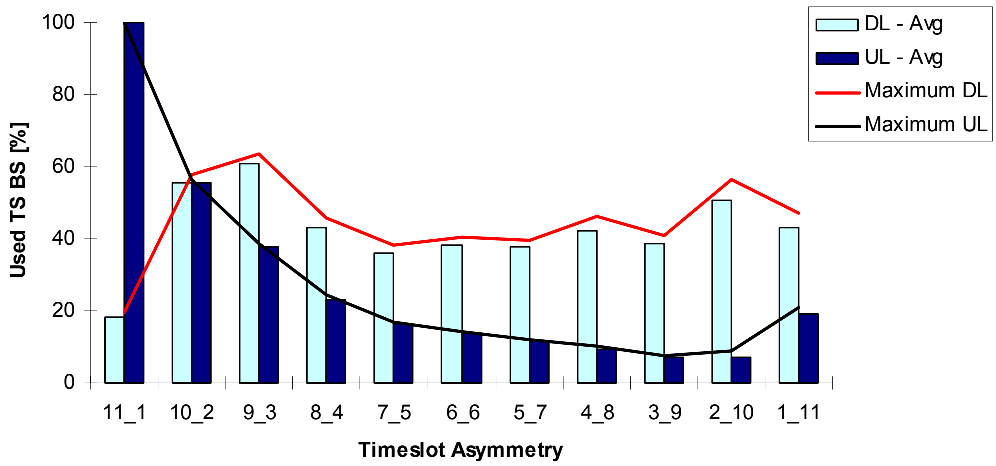


Figure 5.25. TSs used per BS for DL and UL as a function of the TS asymmetry.

For all data presented in this section and in Annex J, a simulation period of around 120h (roughly 5 days) was performed, generating approximately 4 GB of data.

Chapter 6

Conclusions

This chapter presents conclusions and points out aspects to be developed in future work.

The main objective of this thesis was to develop an algorithm to optimise UMTS networks for non-uniform traffic distributions, using TDD BSs co-located with FDD ones.

The analysis was performed with the aid of a newly developed simulation platform, considering several scenarios. The objective of the optimisation algorithm is to help FDD coverage in hot spot areas, providing an optimal (near optimal) location and optimisation of TDD BSs. This is not a problem of dimensioning and optimising a new network, but rather a problem of adapting to an existing one, coping with a constant increase of traffic/users in hot spot areas, i.e., HDR areas with asymmetric traffic.

This work begins in Chapter 2 by an overview of UMTS, and its FDD and TDD modes. A description of system architecture is provided with all network elements of UTRAN and the main functions of each elements. Radio interface aspects are also provided including: spectrum WCDMA parameters, channels overview, a simple description of power control methods, and TDD frame structure with symmetry/asymmetry DL/UL allocation of TS. The chapter ends with a description of services and applications supported by 3G networks, including service classes and characteristics of services.

Chapter 3 addresses radio network planning and optimisation aspects including capacity, coverage, interference, and link budget for the two modes of operation (FDD and TDD). Several optimisation algorithms from literature are presented. All papers present strategies to implement and optimise new networks, and not to adapt to existing ones.

Chapter 4 provides a functional description of the simulator platform developed in this thesis. The algorithm explained here is responsible by managing codes and TSs in TDD, making that 1920kbps users have a reduction to 512kbps, or even 384kbps if no resources are available. The objective of the algorithm is to balance resources in a fair way; it tries to support all users with the best quality possible. At the end of the chapter, input and output parameters are presented, and the assessment of the optimisation algorithm based on a comparison with theoretical aspects is shown. Finally, an analysis on the number of simulation is given for a given scenario, for two performance parameters, blocking and delay probabilities; 10 simulations are chosen.

Chapter 5 provides the analysis of results for all tested scenarios. After introducing the scenarios characterisation (demographics, geography and users profile), details about services considerations (bit rate and service penetration) follow and then the reasons for the choice of reference scenario and configurations are given. The scenario represents TDD traffic in the downtown of Lisbon.

Simulations use three main parameters as test; bit rate decision, load decision and TS asymmetry. The parameter to which the TDD mode is more sensitive is TS asymmetry, because HBR services require data transmission growingly asymmetric frames, with benefits DL compared to UL. Non-real-time services need a frame structure significantly asymmetric, like 10:2, 9:3 or 8:4. From simulations, one can conclude that the best asymmetry is 9:3 with a lower delay probability (1.6%), the best lower value for reduction of bit rate, and the best usage of BS capacity.

The second most important parameter in the optimisation algorithm is bit rate decision threshold. This parameter decides which are the users that go to the TDD mode and which stay in FDD. There are two realistic values to be applied in network planning, 128 and 384kbps, because the main objective is to route HBR users to TDD. The most adequate value is 128kbps, because more users are routed to TDD, having the disadvantage of the increase of the reduction bit rate for 1920kbps users. For a threshold (bit rate) of 384 kbps, there are less users in TDD.

For the load decision threshold parameter, four possibilities were taken: 10%, 30%, 70% or 90%. It gives the percentage of load to be transferred in DL for TDD. One can group load decisions thresholds of 10 and 30%, and 70 and 90%. Naturally, when the load in TDD increases, so does the number of TDD BSs. The load decision threshold does not have a strong impact on the performance of the network, as the two others parameters do, because this allows for a global load control. The best value for load decision threshold is 30%, since the reference scenario is not totally with data services (nearly 60% for PS and 40% for CS).

As a main conclusion, one can say that for the reference scenario, the best optimisation is with an asymmetry of 9:3, a bit rate decision threshold of 128 kbps, and a load decision threshold of 30%.

The optimisation algorithm developed in this thesis is the novelty of it. It outputs a fundamental performance parameter, number of TDD BSs to co-locate with FDD ones.

This is not at all a finalised work, mainly due to the complexity of the subject, and also to the variety of possible studies that can be continued. A wide range of issues can be improved, leading to an evaluation of more realistic networks in multi-service non-uniform scenarios. Several improvements are proposed as suggestions for future investigation:

- Development of a better solution for the management resource algorithm, because the current algorithm penalises HBR users.
- Inclusion of HSDPA (High Speed Downlink Packet Access) and HSUPA (High Speed Uplink Packet Access) to increase DL bit rate to 14.4Mbps.
- Analysis of a pure TDD network.
- Inclusion of priority queues depending on the QoS type in the algorithm, and priority of packets.
- Inclusion the inter-to-intra cell interferences and evaluating its impact [Gonc07].
- Performance of an in-depth analysis of other scenarios, namely with different traffic profiles, and of their impact in overall network performance.
- Extension to other systems with dual mode functioning, e.g., WiMax.

Annex A

COST-231 Walfish-Ikegami Model

This annex provides a presentation of the COST-231 Walfish-Ikegami propagation model adequate to analyse scenarios with urban characteristics.

The COST-231 Walfish-Ikegami propagation model [DaCo99] is adequate to analyse scenarios with urban characteristics, as it considers data that may model this type of environments: building heights and separation, road widths and orientation with respect to the direct radio path. It makes the distinction between direct paths with line-of-sight or with non-line-of-sight.

The COST-231 Walfish-Ikegami model was based on measurements performed in Stockholm, combined with some results of the Ikegami and the Walfish-Bertoni models [Corr99]. It is a mixture of an empirical model with a deterministic one, and typical values that characterise the environment are inserted, based on topographical building database.

Figure A.1, specifies the parameters used in the COST-231 Walfish-Ikegami model.

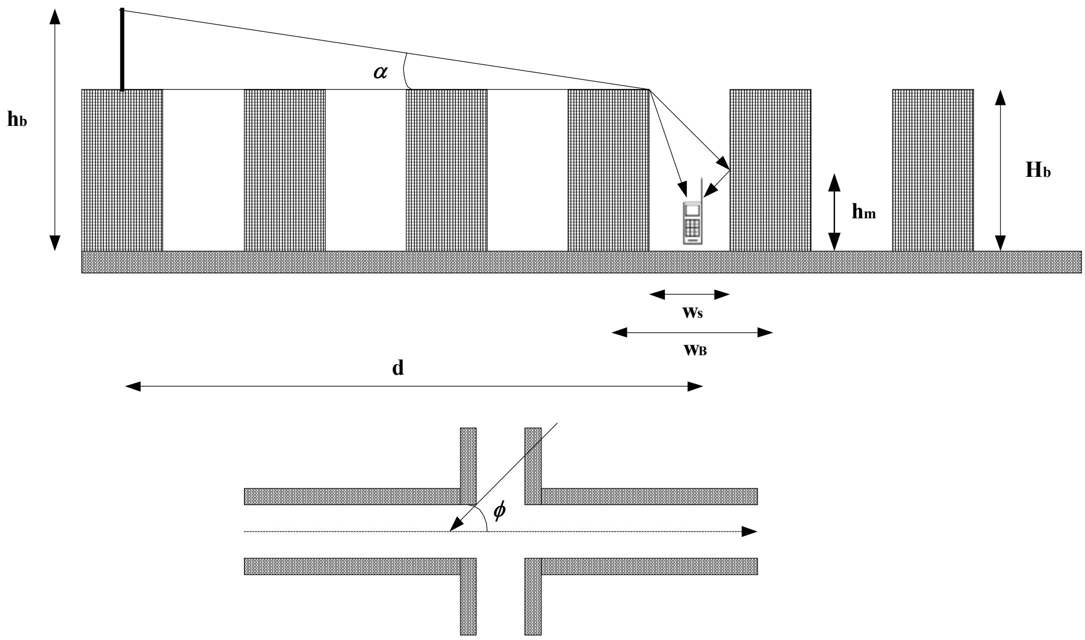


Figure A.1. Parameters used in the COST-231 Walfish-Ikegami model (based on [Corr99]).

If there is line-of-sight between MT and BS, the propagation losses are obtained through:

$$L_{p[\text{dB}]} = 42.6 + 26 \cdot \log\left(d_{[\text{km}]}\right) + 20 \cdot \log\left(f_{[\text{MHz}]}\right), \qquad \text{for } d \geq 0.02 \text{ km.} \tag{A.1}$$

If the line-of-sight is obstructed, the path loss estimation is given by the following equation:

$$L_{p[\mathrm{dB}]} = \begin{cases} L_{o[\mathrm{dB}]} + L_{rts[\mathrm{dB}]} + L_{msd[\mathrm{dB}]} \\ L_{o[\mathrm{dB}]} \end{cases}, \qquad \text{for } L_{rts} + L_{msd} \leq 0, \tag{A.2}$$

where each of these components reflect:

- L_o, free space loss;
- L_{rts}, roof-top-to-street diffraction and scatter loss;
- L_{msd}, multi-screen loss.

The free space loss is given by:

$$L_{o[\mathrm{dB}]} = 32.4 + 20 \cdot \log\left(d_{[\mathrm{km}]}\right) + 20 \cdot \log\left(f_{[\mathrm{MHz}]}\right). \tag{A.3}$$

The roof-top-to-street diffraction and scatter loss is obtained through:

$$L_{rts[\mathrm{dB}]} = -16.9 - 10 \cdot \log\left(w_{s[\mathrm{m}]}\right) + 10 \cdot \log\left(f_{[\mathrm{MHz}]}\right) + 20 \cdot \log\left(H_{B[\mathrm{m}]} - h_{m[\mathrm{m}]}\right) + L_{ori[\mathrm{dB}]},$$

(A.4)

where:

$$L_{rts[\mathrm{dB}]} = \begin{cases} -10 + 0.354 \cdot \phi\left[^{\mathrm{o}}\right] \text{ for } 0^{\mathrm{o}} \leq \phi \leq 35^{\mathrm{o}} \\ 2.5 + 0.075 \cdot \left(\phi\left[^{\mathrm{o}}\right] - 35\right) \text{ for } 35^{\mathrm{o}} \leq \phi \leq 55^{\mathrm{o}} \\ 4.0 + 0.114 \cdot \left(\phi\left[^{\mathrm{o}}\right] - 55\right) \text{ for } 55^{\mathrm{o}} \leq \phi \leq 90^{\mathrm{o}} \end{cases}. \tag{A.5}$$

The multi-screen loss may be calculated via:

$$L_{msd[\mathrm{dB}]} = L_{bsh[\mathrm{dB}]} + k_a + k_d \cdot \log\left(d_{[\mathrm{km}]}\right) + k_f \cdot \log\left(f_{[\mathrm{MHz}]}\right) - 9 \cdot \log\left(w_{B[\mathrm{m}]}\right), \tag{A.6}$$

where:

$$L_{bsh[\mathrm{dB}]} = \begin{cases} -18 \cdot \log\left(1 + h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]}\right) & h_b > H_B \\ 0 & h_b \leq H_B \end{cases}, \tag{A.7}$$

$$k_a = \begin{cases} 54 & h_b \le H_B \\ 54 - 0.8 \cdot \left(h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]} \right) & d \ge 0.5 \text{ km and } h_b \le H_B \\ 54 - 1.6 \cdot \left(h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]} \right) \cdot d_{[\mathrm{km}]} & d < 0.5 \text{ km and } h_b \le H_B \end{cases}, \tag{A.8}$$

$$k_d = \begin{cases} 18 & h_b \le H_B \\ 18 - 15 \cdot \dfrac{h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]}}{H_{B[\mathrm{m}]}} & h_b \le H_B \end{cases}, \tag{A.9}$$

$$k_f = \begin{cases} -4 + 0.7 \cdot \left(\dfrac{f_{[\mathrm{MHz}]}}{925} - 1 \right), & \text{for meduim sized cities and suburban centres} \\ 5 \cdot \left(\dfrac{f_{[\mathrm{MHz}]}}{925} - 1 \right), & \text{for metropolitan centres} \end{cases} \tag{A.10}$$

In case the data on the structure of the buildings and roads is unknown, it is recommended to use the following values:

- Building separation (w_B) ϵ [20, 50] [m];
- Widths of roads (w_s), $w_s = 0.5 \times w_B$;
- Heights of buildings (H_B), $H_B = 3 \times \{\text{number of floors}\} + H_{roof}$;
- Roof height (H_{roof}), H_{roof}
- Road orientation with respect to the direct radio path (ϕ),$\phi = 90º$.

The validity ranges of the COST-231 Walfish-Ikegami model correspond to:

- Frequency (f) ϵ [800, 2000] [MHz];
- BS height (h_b) ϵ [4, 50] [m];
- MT height (h_m) ϵ [1, 3] [m];
- Distance (d) ϵ [0.02, 5] [km].

Annex B

Link Budget

In order to perform radio network planning, among other things, it is essential to estimate the propagation loss as a function of a given propagation environment (indoor, outdoor, urban, rural, etc). This key parameter makes the estimation of several other main network planning parameters possible, like average mobile received power, cell coverage, interference and load factor. This annex presents the link budget used in the simulator and, at the end, different radius corresponding to the several service bit rates.

In order to perform radio network planning, one needs to establish the link budget for coverage, capacity and optimisation reasons. Reference [HoTo00] presents the link budget algorithm, which enables the estimation of the allowed maximum propagation loss L_{Pmax}. A common parameter between propagation models and link budget algorithms is the path loss, L_{Pmax},

$$L_{Pmax[\mathrm{dB}]} = P_{t[\mathrm{dBm}]} + G_{t[\mathrm{dBi}]} + G_{r[\mathrm{dBi}]} + G_{SH[\mathrm{dB}]} - P_{Smin[\mathrm{dBm}]} - \sum L_{x[\mathrm{dB}]} - \sum F_{M[\mathrm{dB}]}, \quad \text{(B.1)}$$

where:

- L_{Pmax} is the maximum propagation loss allowed for a given service;
- P_t is the transmitted power (delivered to the antenna);
- G_t is the maximum transmitter antenna gain;
- G_r is the maximum receiver antenna gain;
- G_{SH} is the soft handover gain, only FDD mode;
- P_{Smin} is the receiver sensitivity for a given service bearer;
- L_x represents additional attenuations in a link, which may be user body loss L_{UB}, cable loss L_C, and others (car loss) L_{Other};
- F_M represents fading margins, i.e., fast fading F_{FM}, and slow fading margin F_{SM}.

The Equivalent Isotropic Radiated Power (EIRP), depends on P_t and G_t as follows:

$$EIRP_{[\mathrm{dBm}]} = P_{t[\mathrm{dBm}]} + G_{t[\mathrm{dBi}]}, \quad \text{(B.2)}$$

where P_t is defined by:

$$P_{t[\mathrm{dBm}]} = P_{Tx[\mathrm{dBm}]} - L_{C[\mathrm{dB}]}, \quad \text{(B.3)}$$

and P_{Rx}, is defined as follows:

$$P_{Rx[\mathrm{dBm}]} = P_{r[\mathrm{dBm}]} - L_{C[\mathrm{dB}]}, \quad \text{(B.4)}$$

where:

- P_{Tx} is the transmitter output power;

- P_r is the antenna received power;
- P_{Rx} is the receiver input power.

A major parameter in radio network planning is P_{Smin}, because it depends on the service type (energy of bit over noise and bit rate), therefore, different L_{Pmax} and cell radius are expected for each service. P_{Smin}, is defined as follows:

$$P_{Smin[\mathrm{dBm}]} = \frac{E_b}{N_0}_{[\mathrm{dB}]} - G_{P[\mathrm{dB}]} + N_{[\mathrm{dBm}]}, \tag{B.5}$$

where:

- E_b/N_0 is a relation between energy of bit and noise density, which depends of the service, mobile speed, receiver algorithms, and BS antenna structure;
- G_P is the processing gain, which depends on the relation between chip rate and bit rate (3.7), for the FDD mode and (3.9) for the TDD mode;
- N is the total effective noise plus interference power.

N can be written as:

$$N_{[\mathrm{dBm}]} = 10\log(10^{P_{N[\mathrm{dBm}]}/10} + 10^{P_{I[\mathrm{dBm}]}/10}), \tag{B.6}$$

where the receiver interference power P_I , is given by:

$$P_{I[\mathrm{dBm}]} = 10\log(10^{\left(P_{N[\mathrm{dBm}]}+M_{Im[\mathrm{dB}]}\right)/10} - 10^{P_{N[\mathrm{dBm}]}/10}), \tag{B.7}$$

and the receiver noise power P_N , is given by:

$$P_{N[\mathrm{dBm}]} = P_{\mathrm{N0}[\mathrm{dBm/Hz}]} + 10\log\left[3.840_{[\mathrm{Mcps}]}\right], \tag{B.8}$$

where:

- M_{Im} is the interference margin;
- P_{N0} is the receiver noise density.

The receiver noise density, P_{N0} depends on the thermal noise density N_0 and on the noise factor, F_N.

$$P_{\mathrm{N0}[\mathrm{dBm/Hz}]} = N_{0[\mathrm{dBm/Hz}]} + F_{N[\mathrm{dB}]}. \tag{B.9}$$

Using propagation models and link budgets algorithms, it is possible to estimate the interference load in a given area, therefore in a given cell (BS). To estimate the amount of supported traffic (capacity) per BS, it is very important to calculate the interference, because cellular systems that use a frequency reuse factor of 1 are typically strongly interference-limited by the air interface. Therefore, the amount of interference and cell capacity must be estimated.

All equations presented, since the beginning of this annex, are adapted for FDD mode, therefore, there are some differences in the link budget comparing to TDD mode, present in Section 3.3.

UMTS network the maximum cell radius depends directly on the service bit rate of each service. Theoretically LBR services will imply higher radius and conversely, HBR services will imply lower radius. Table B.1, presents BS radius results for the different services bit rates chosen and 1983 users in the city. As expected maximum radius for 16 kbps services is three times bigger than 1920 kbps services. In average, 1920 kbps has a mean cell radius of 60 m while 16 kbps have 180 m.

Table B.1. BS radius for different services bit rates.

Bit rate service [kbps]	BS radius [km]			
	Maximum	Average	Minimum	Std. Dev.
16	0.31	0.18	0.10	0.07
64	0.26	0.17	0.10	0.05
128	0.21	0.12	0.04	0.05
384	0.16	0.08	0.04	0.03
1920	0.11	0.06	0.03	0.03

Annex C

Flowcharts for FDD

This annex presents the flowcharts of the most important parts of the simulator, focusing on FDD. This mode was based on an existing FDD simulator.

In [SeCa04], an algorithm for users generation, *SIM* was developed. The first step of the algorithm present in Figure C.1 is to compute the number of users with a defined service.

SIM creates a list of users the algorithm for adding users, being presented in Figure C.2.

In Figure C.3, the network dimensioning algorithm for FDD is presented, based on the algorithm develop in [SeCa04] for the FDD simulator.

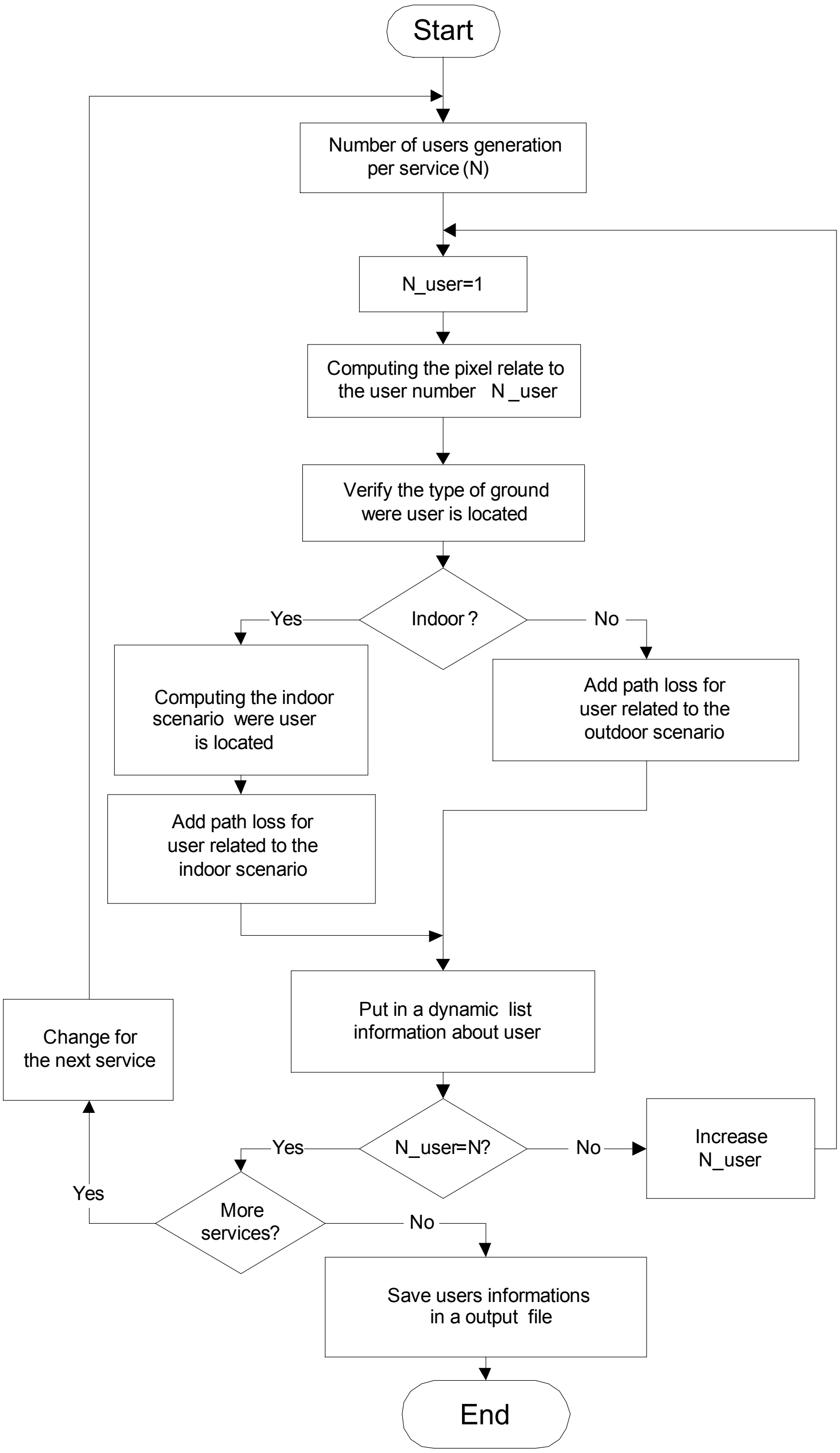


Figure C.1. Users generation algorithm (adapted from [SeCa04]).

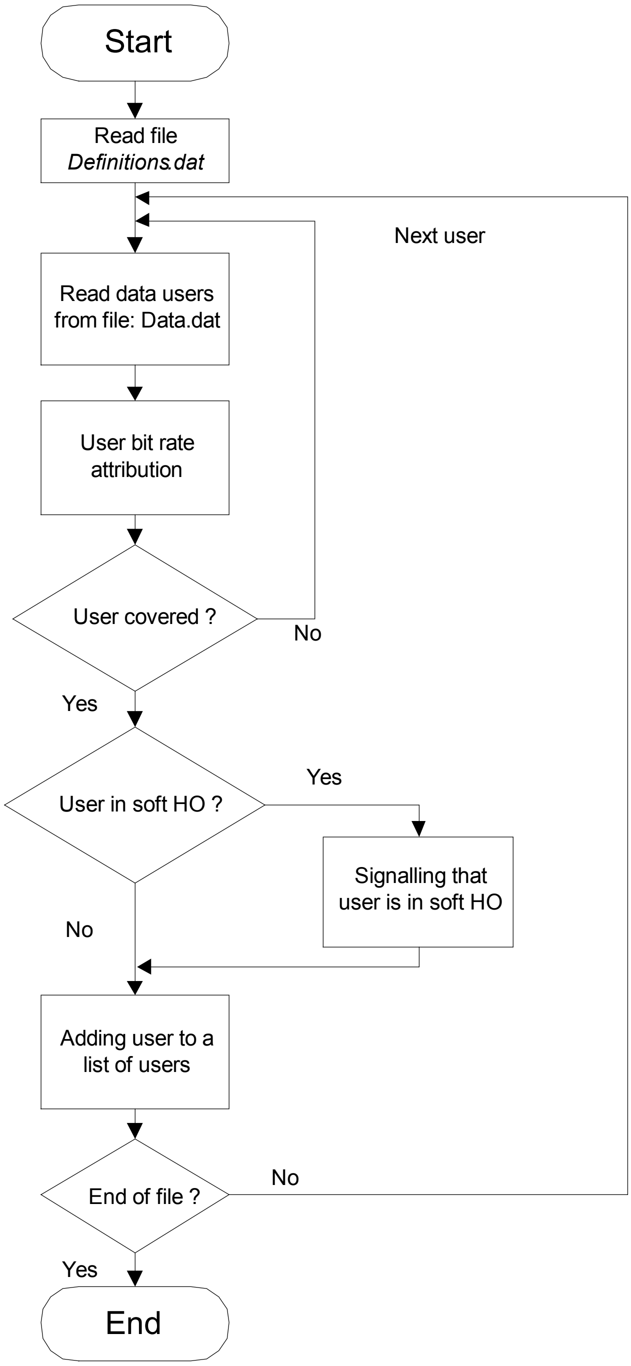


Figure C.2. Algorithm for adding users in a list of users (adapted from [SeCa04]).

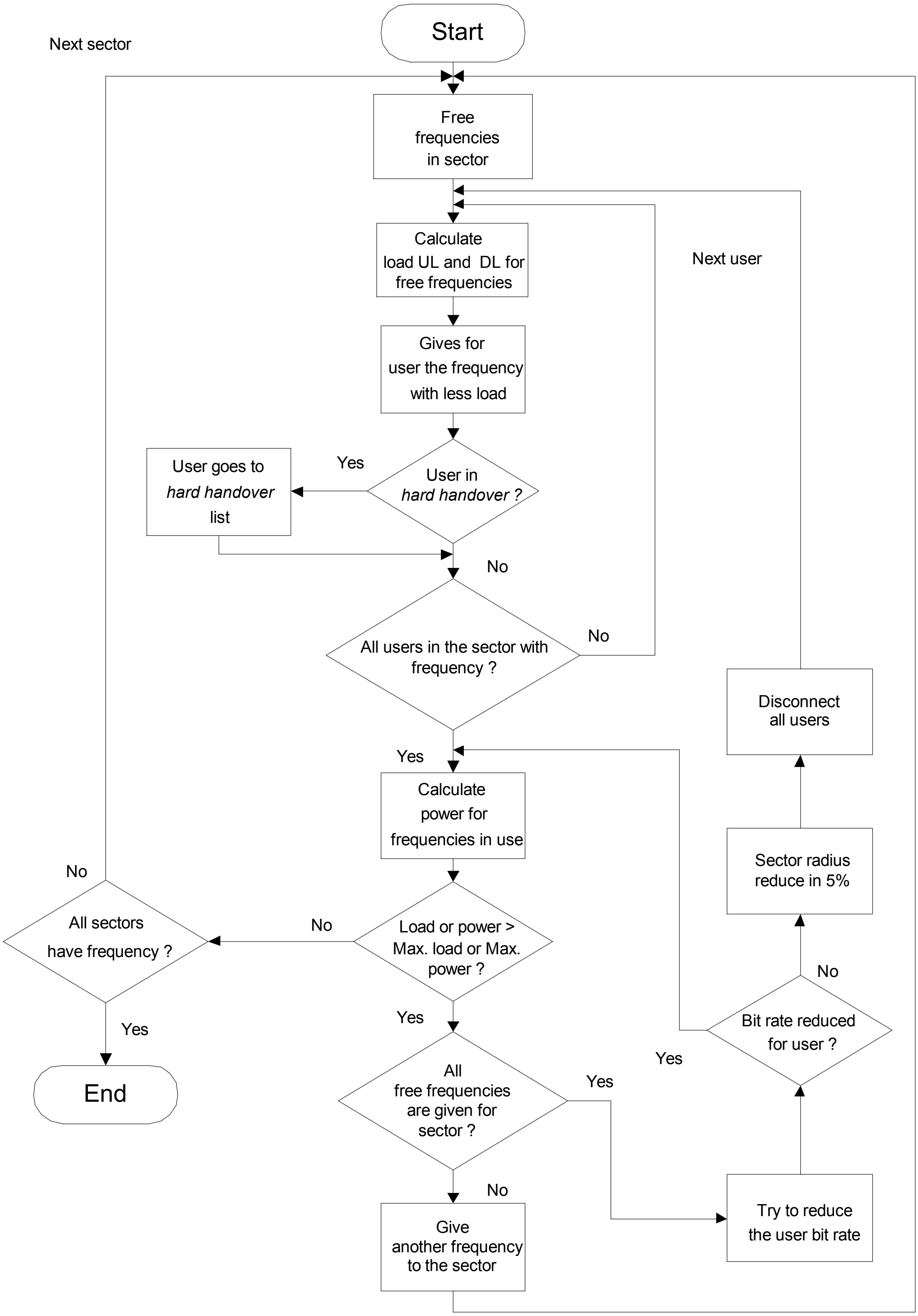


Figure C.3. Network dimensioning algorithm, for FDD mode (adapted from [SeCa04]).

Annex D

Flowcharts for TDD

This annex presents the flowcharts of the most important parts of the simulator. It presents the new developed algorithms for TDD and all the modified flowcharts to adapt both modes.

In order to correctly understand the flowcharts presented in this annex, and also to clarify all the processes of the simulator, it is necessary to summarise the variables used in the flowcharts. Table D.1 shows the several variables and constants that are used.

Table D.1. Description of the several flowcharts variables and constants.

Flowchart Variable/Constant	Description
LOAD_MAX_UL, LOAD_MAX_UL	Maximum Allowed Load in UL and DL.
Load DL, Load UL	Cumulative Load in UL and DL.
MAX_POWER	Maximum Allowed BS TX Power.
Users (Sector), Users (TSlot)	Number of users per Sector and per TS.
Num_BSs	Number of BSs in the system.
Load (TSlot), Bit rate (TSlot)	Cumulative values of Load per TSlot and Bit rate per TSlot.
Load (UL), Load (DL)	Instantaneous Load in UL and DL.
UL_TSLOTS, DL_TSLOTS, MAX_SLOTS, CONTROL_TSLOTS	Number of UL TSs, DL TSs, Maximum Available TSs and Control and Signalling TSs.
Bit rate (UL), Bit rate (DL)	Instantaneous Bit rate in UL and DL.
RB_MAX	Maximum Allowed Bit rate per BS (Throughput).
Pow (TSlot), Pow (User)	Cumulative BS TX Power per TS and BS TX Power for User.
LOAD_DECISION	DL load decision, resulting from cumulative DL load for each user.
RB_DECISION	DL user bit rate decision, for separate HBR users to TDD network.

Figures D.1 and D.2 present the load per TS in UL and DL algorithms. For both algorithms, first it is necessary to calculate the codes needed for a given service and determine codes allocation per TS in UL and DL, see Figures D.3 and D.4.

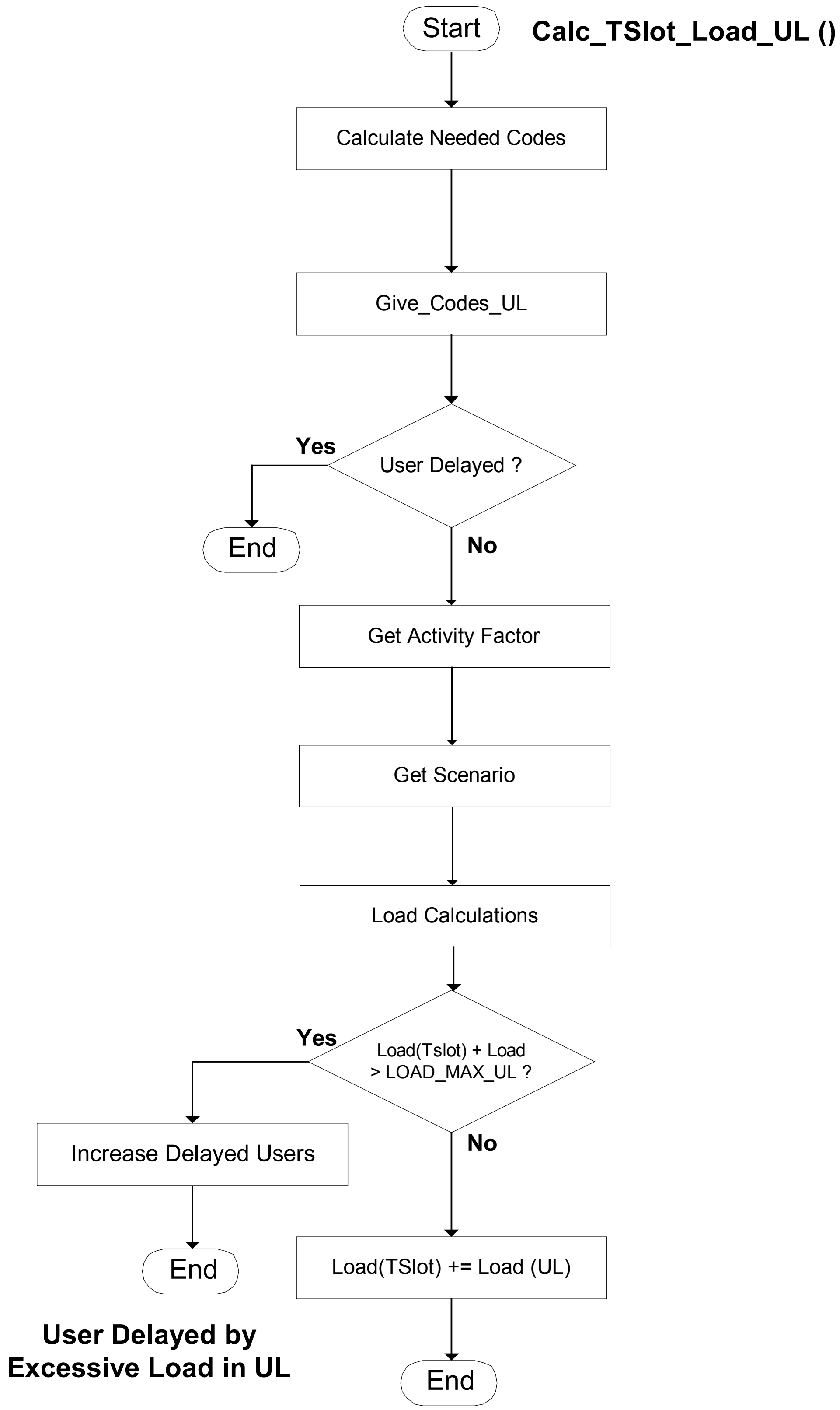


Figure D.1. Load per TS in UL algorithm.

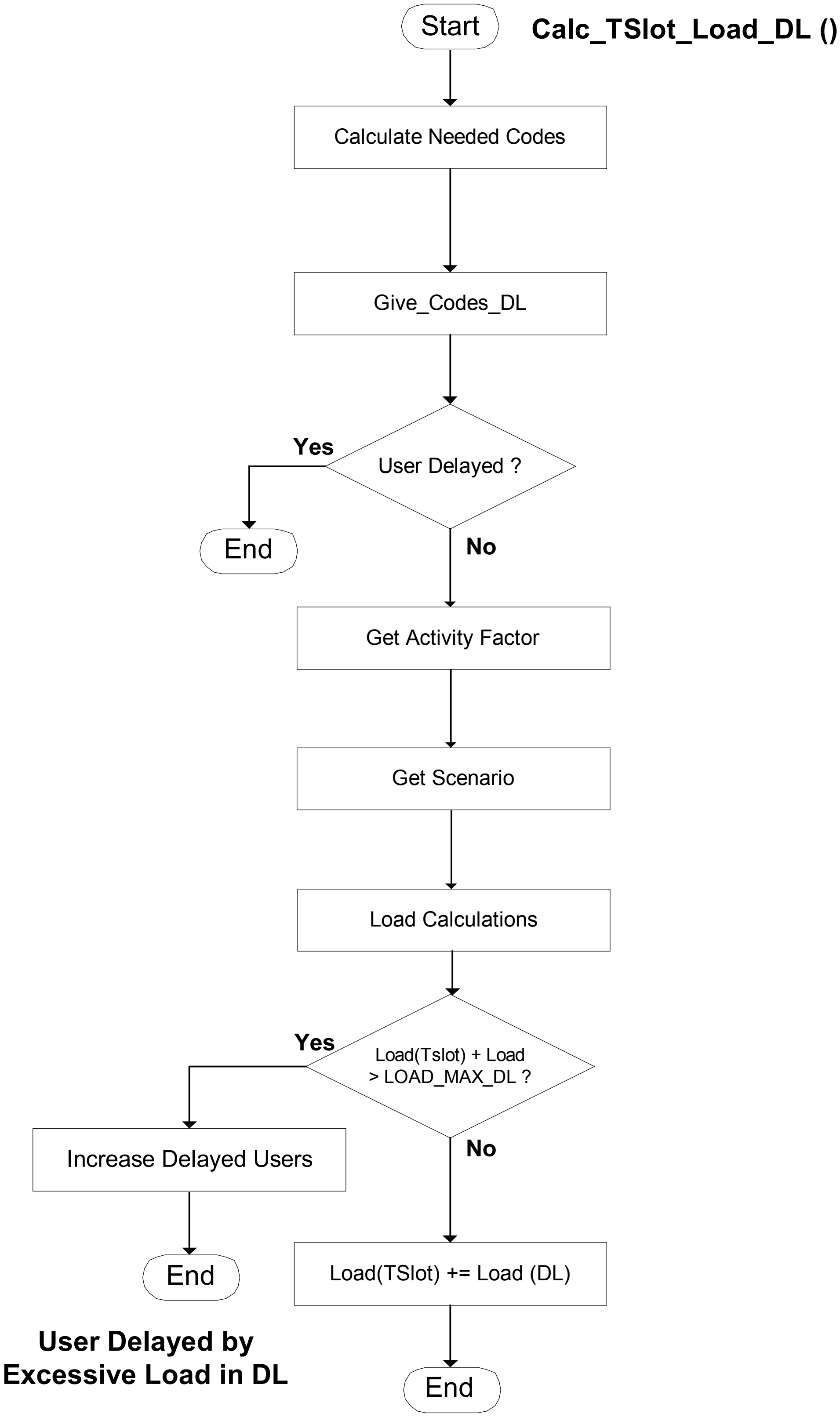


Figure D.2. Load per TS in DL algorithm.

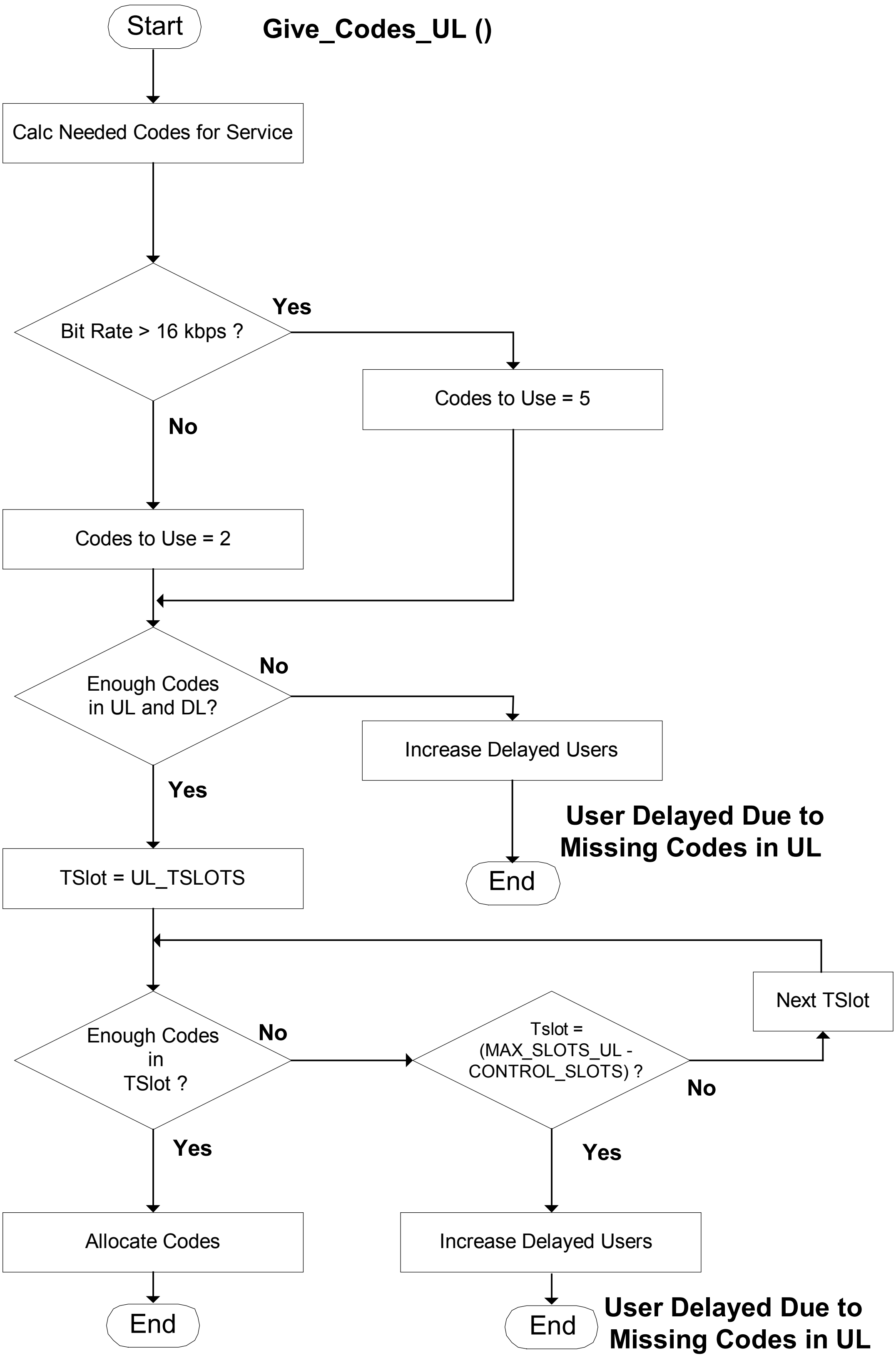


Figure D.3. Codes allocation per TS in UL algorithm.

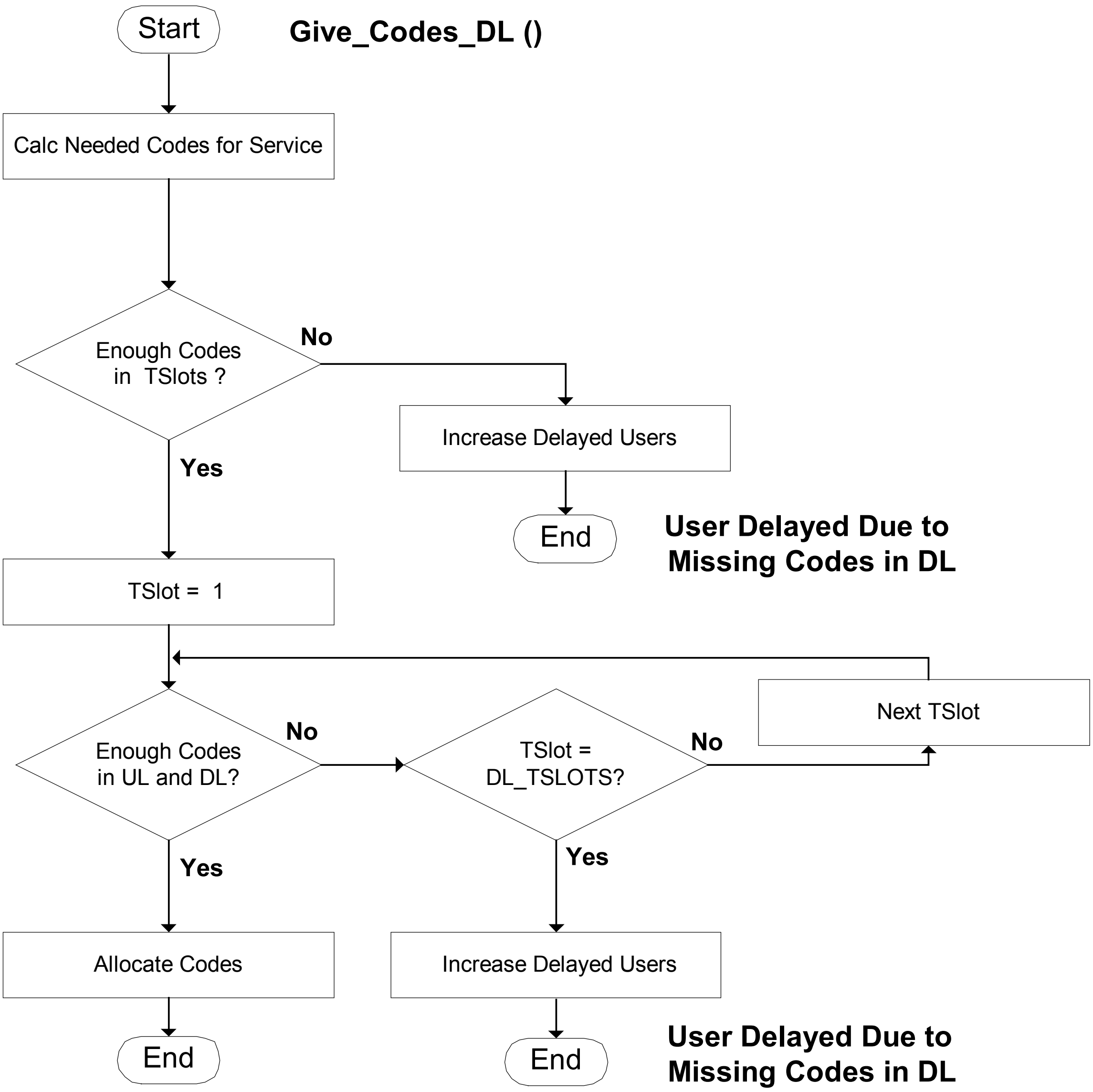


Figure D.4. Codes allocation per TS in DL algorithm.

Figure D.5 presents the algorithm for calculating power per BS in DL, for which it is needed to calculate BS power per TS, Figure D.6.

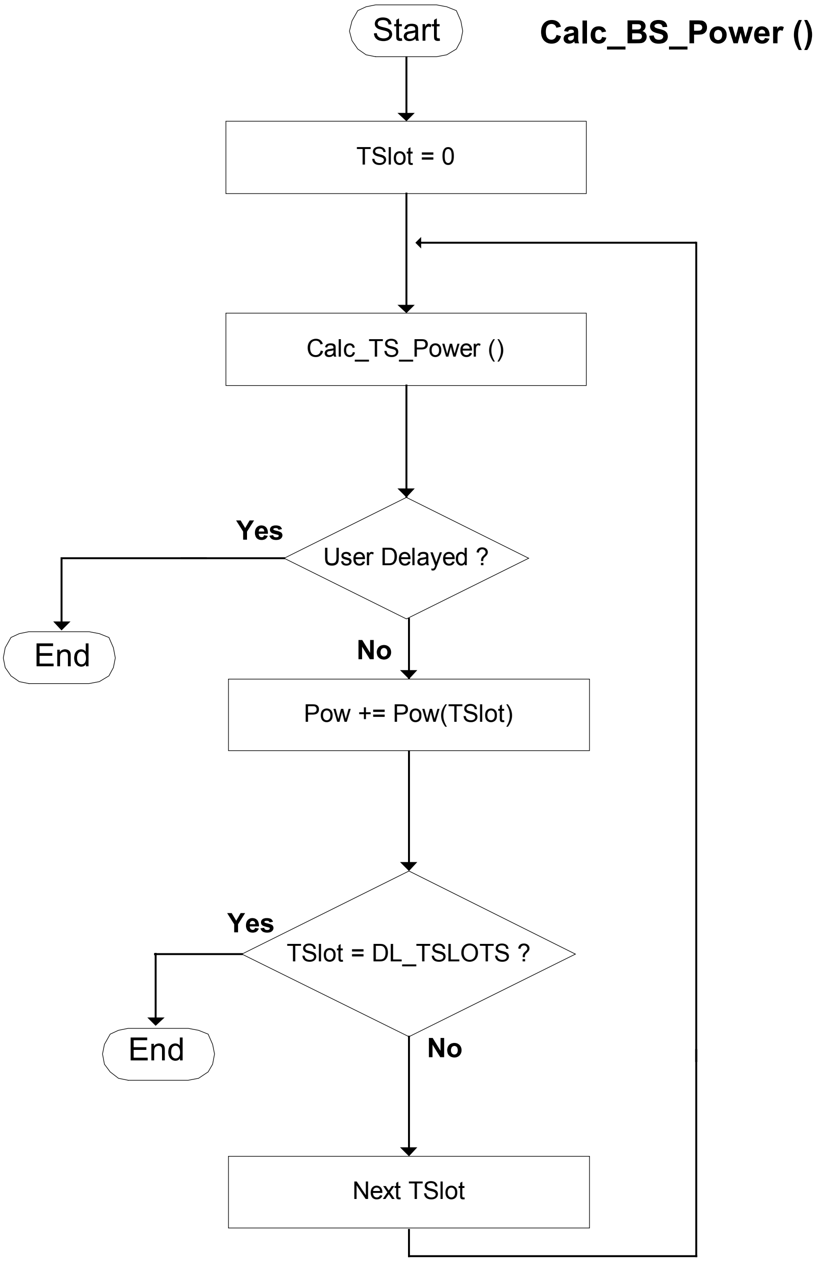


Figure D.5. BS transmit power algorithm.

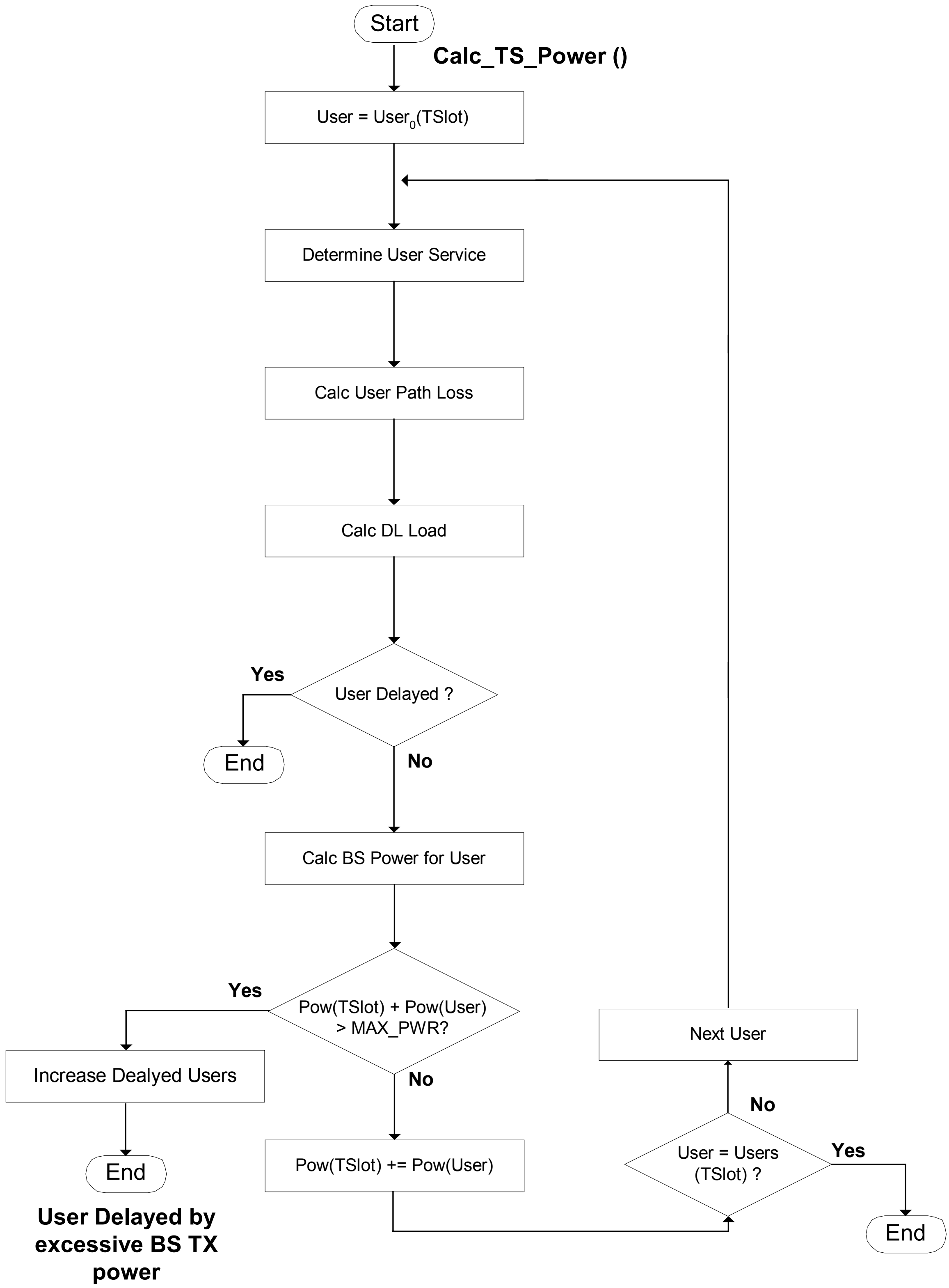


Figure D.6. BS power per TS algorithm.

Figures D.7 and D.8 present algorithms for the allocation of users in TS for both links.

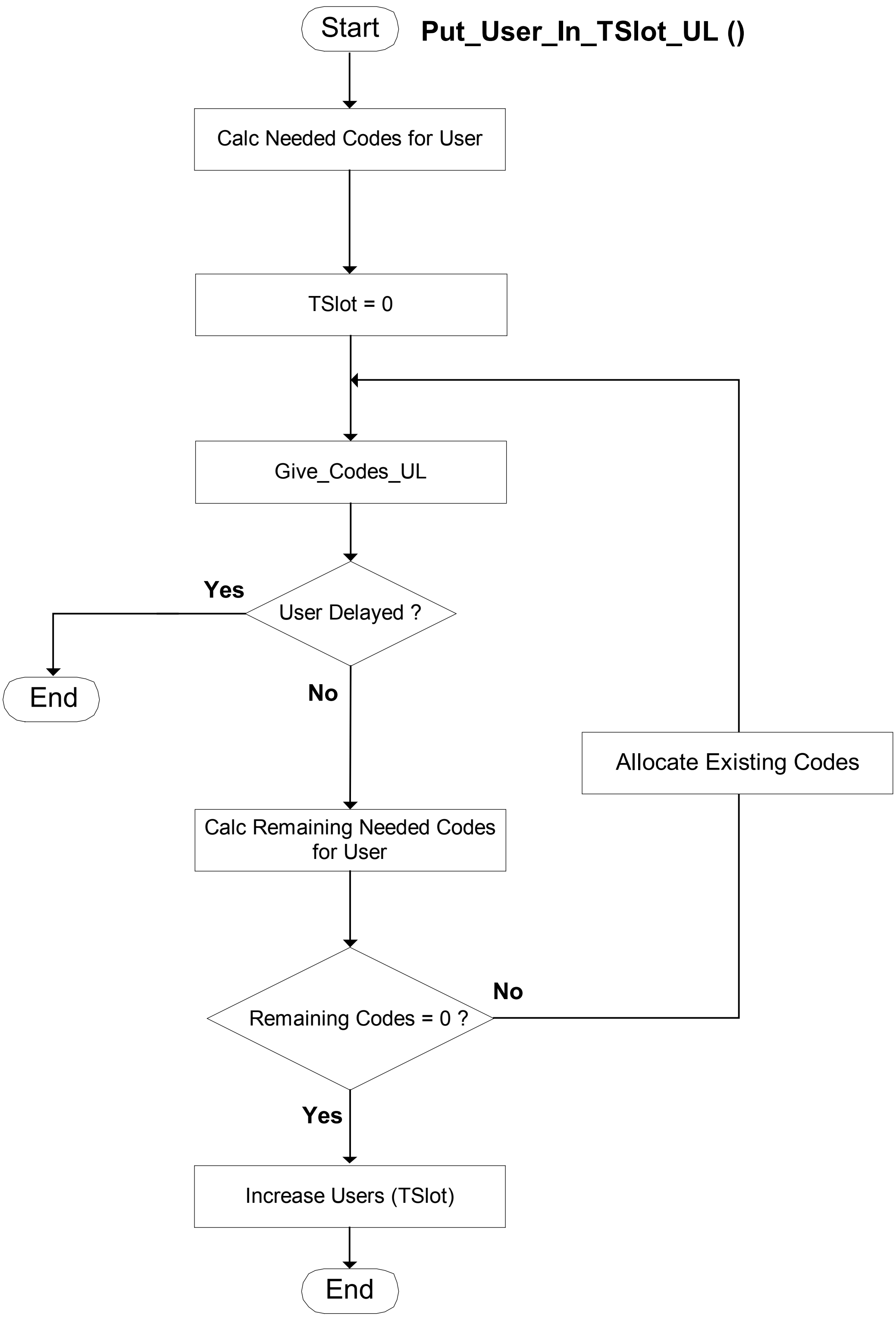


Figure D.7. Users allocation TS in UL algorithm.

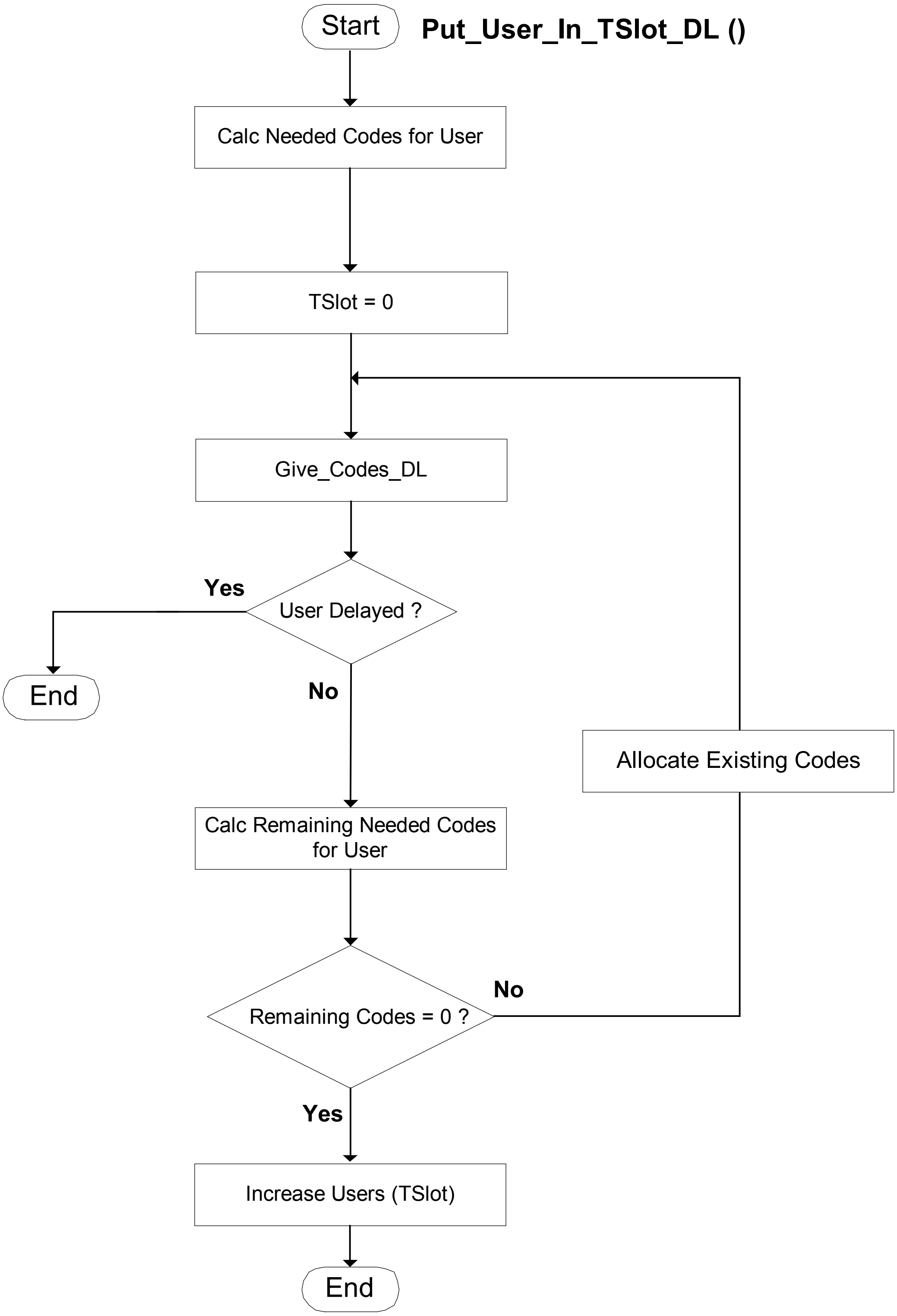


Figure D.8. Users allocation TS in DL algorithm.

The last two algorithms, presented in Figures D.9 and D.10, are necessary to calculate bit rate in each TS for UL and DL.

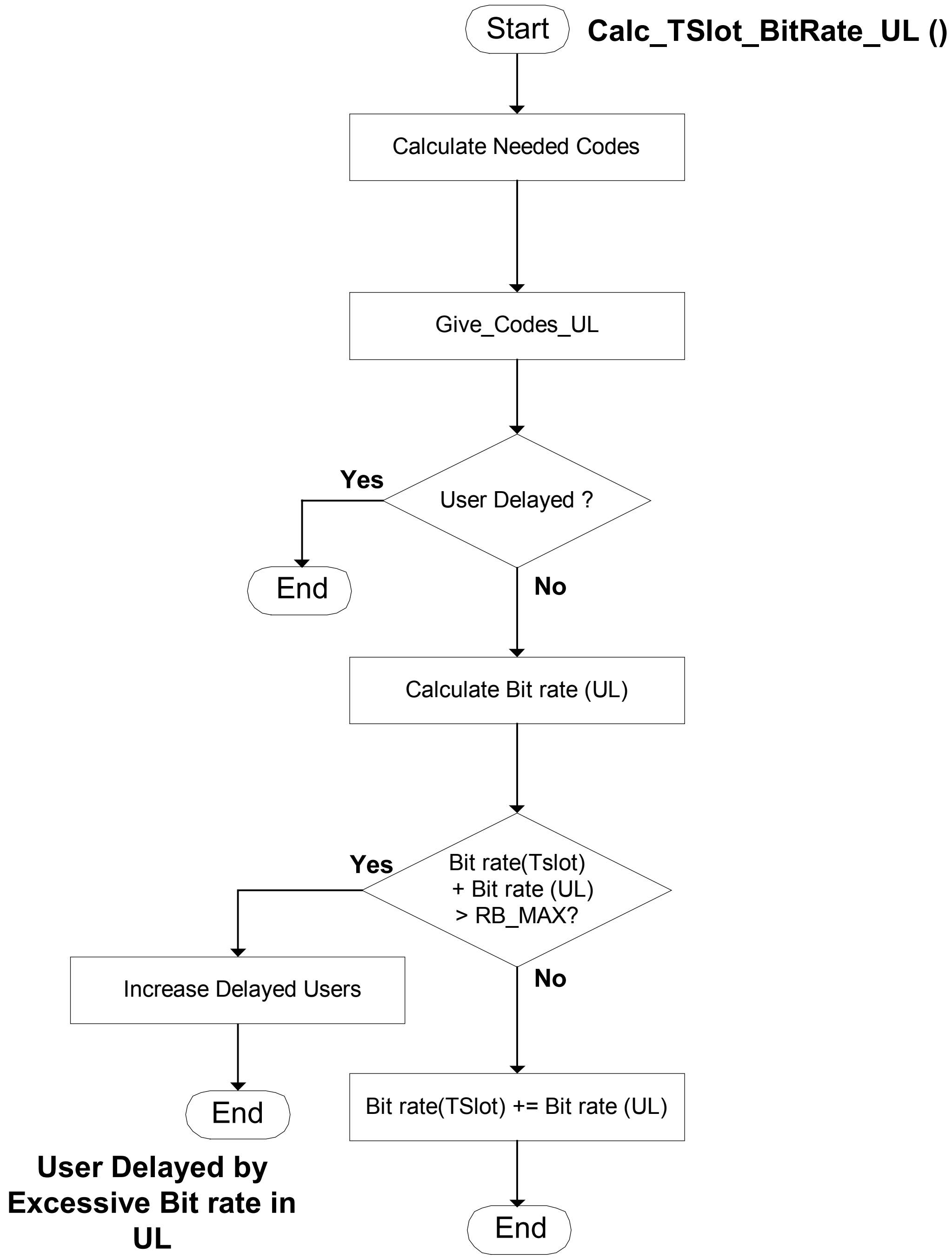


Figure D.9. Bit rate allocation TS in UL algorithm.

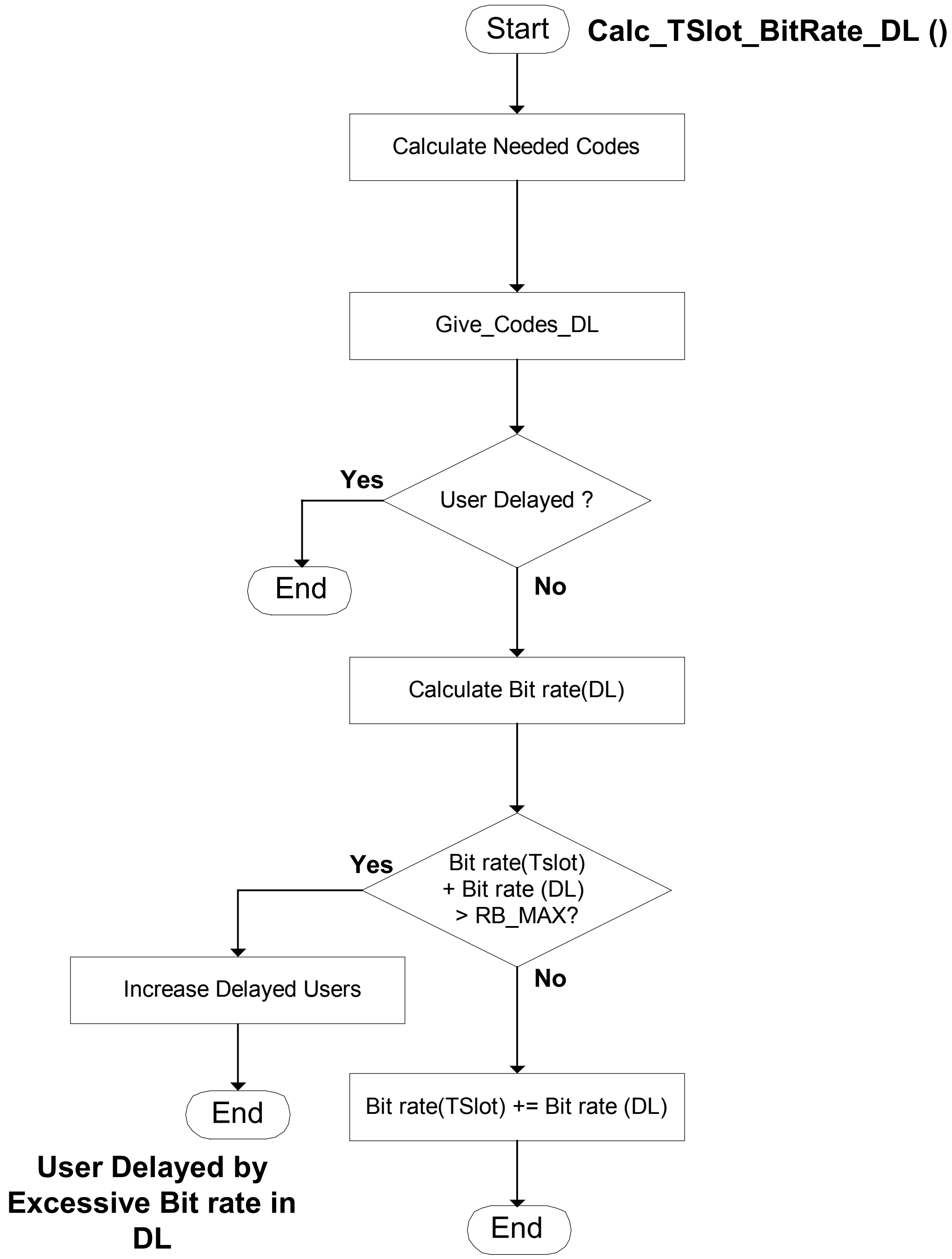


Figure D.10. Bit rate allocation TS in DL algorithm.

Annex E

Validation of the TDD Simulator

In this annex, the validation of the TDD simulator is presented, based on a comparison with theoretical aspects.

The assessment covers only the TDD simulator, as the FDD one was already made in [SeCa04]. The calculation of the number of codes needed for each service is based on the assumption that a single code supports a bit rate of 13.8 kbps, Table E.1.

Table E.1. Number of codes per service.

Service bit rate [kbps]	Needed codes
16	2
64	5
128	10
384	28
1920	140

The first step of the validation is to make sure that the simulator calculates the correct number of needed codes per each service. The practical values refer from now on to the values obtained in the simulator. Theoretical values, whenever applied, refer to values obtained through calculations. The test scenario for the subsequent simulations is a network composed of a single BS, a total of 3 000 users in the system with varying services according to the simulation results needed. The BS location was carefully chosen so that, at least, 1 000 users would be covered. In the current scenario, from the total 3000 users, the BS covers 1 200.

The first results from the simulator had to be the ones related with the number of codes that it allocates to each service, Figure E.1. The simulator correctly allocates the needed codes per service.

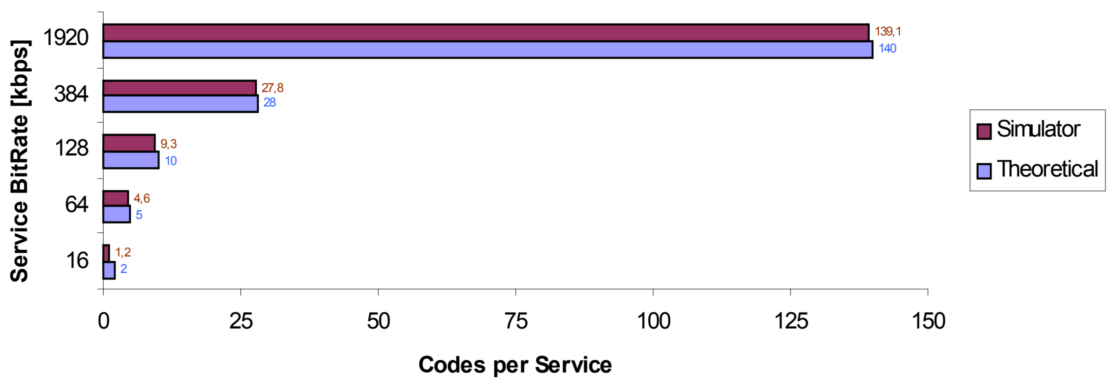


Figure E.1. Number of needed codes per service.

Knowing that each TS (first validation) has a total of sixteen codes to allocate, one can find the number of users that can be servicing at the same time in one TS. The number of users is calculated knowing how many codes are necessary for each service. As so, the second validation to be made was to make sure that the TDD simulator correctly allocates the codes of one TS for the several services, resulting in the maximum number of users of each service that a single TS can sustain, Figure E.2.

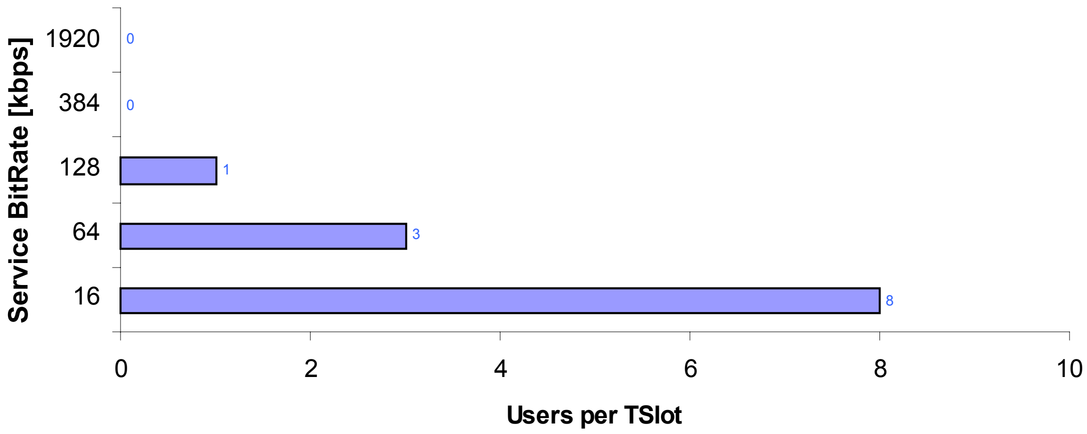


Figure E.2. Maximum number of users that a TS can sustain.

As seen, the maximum number that the simulator allocates in single TS follows the theoretical calculations. For a service of 16 kbps, which consumes two codes, there can only be a maximum of eight users in one TS, because eight users using two codes each will sum up to the maximum available sixteen codes per TS. As the service bit rate increases, the maximum number of users that can be allocated in a single TS drops, as expected. In the limit case, the services with a bit rate equal to 384 or 1920 kbps will not have enough codes to allocate, at least, one user in a TS.

The theory states that to find the number of TS needed for each service, the relation between the codes needed for each service and the maximum codes per TS should be determined. As the service bit rate increases, the number of codes also does and the number of TS needed for one user of each service also increase. For services with bit rates lower then 128 kbps, one TS is enough to make sure that one user is servicing. For the service of 384 kbps, due to the fact that the number of needed codes is superior to sixteen, it is necessary to use more than one TS to allocate one user of this kind of service, namely three TSs. For the service with the highest bit rate, 1920 kbps, nine TSs is necessary. This is why the recommended frame asymmetry has, at least, nine TS in DL. If less then nine TS are reserved for the DL, it is impossible to have 1920 kbps users servicing. This theory is confirmed by the simulator results, as seen in Figure E.3, and validates the simulator in this aspect.

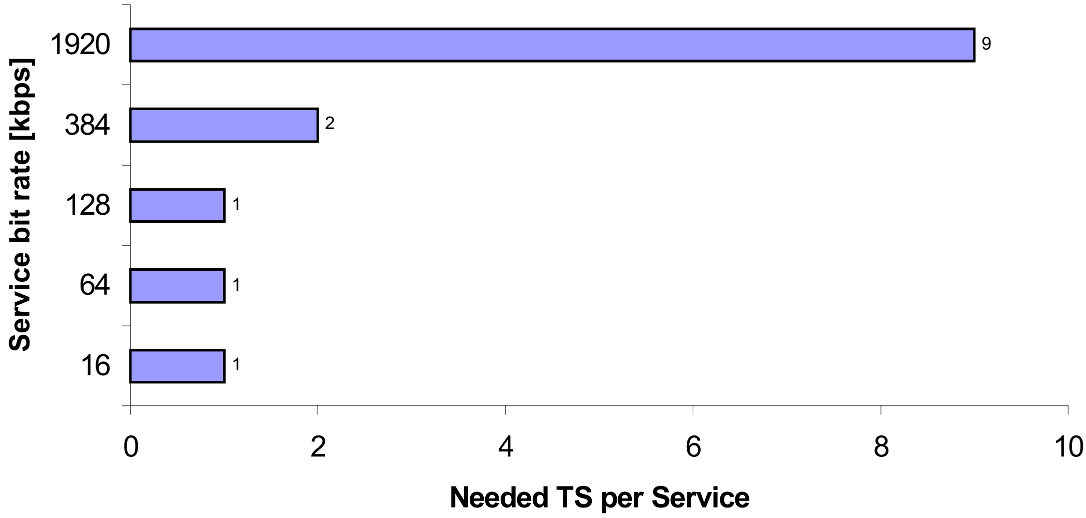


Figure E.3. Number of TSs needed for one user of each service.

The asymmetry of the TDD frame is very important in what regards system capacity. The TDD mode is suitable for highly asymmetrical services, which means that considerable differences must exist in UL and DL. As so, it is expected that, as the frame tend to be symmetrical, the services present some kind of degradation. This is a theoretical aspect that would be very important to confirm with some simulator results.

Theory states that as the TDD frame becomes symmetrical, the number of DL users and services become progressively less, while in the UL the opposite happens, Figure E.4

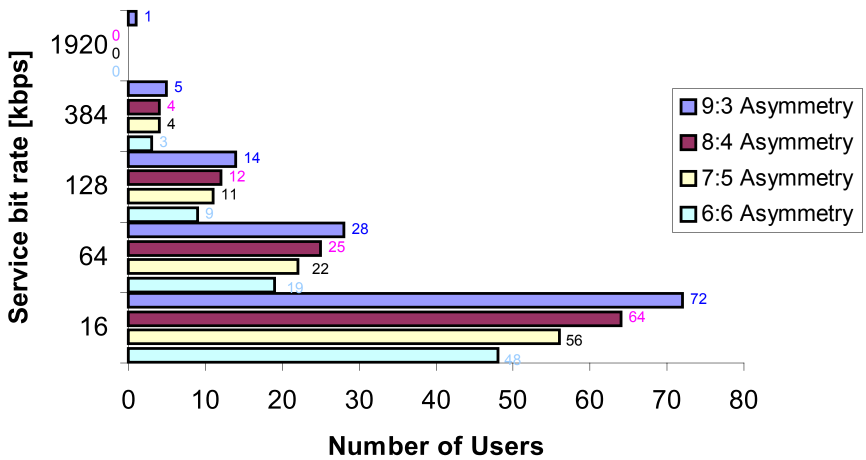


Figure E.4. Maximum number of users in DL per bit rate for different TDD frame asymmetries.

As seen in Figure E.4 as the frame becomes more symmetric, the number users drop rapidly as well as the services performance, i.e., a limit situation occur when the frame is completely symmetric, six TSs UL and six TSs DL, leading to a mean reduction of the number of users of 34%. The results of the simulator confirm the theory, and the services degradation becomes greater as the frame becomes more symmetric.

As referred before, UL suffers an increase of load as the frame becomes symmetric. As more TSs are allocated in UL, there are more users servicing in that links, and the system load increase rapidly in a direction where it should happen the opposite. As expected and shown in Figure E.5, the number of users in UL becomes more as more TSs are allocated in that link. This leads to an excessive load in UL and the overall system performance drop. The results from the simulator can be seen in Figure E.5 and follow the theory.

This validation is very important because in order to correctly evaluate the effects of the frame symmetry in the interference, it is necessary to be sure that the simulator works correctly with different frame symmetries. This validation was successful and allows future simulations without having doubts if the frame symmetry is working correctly.

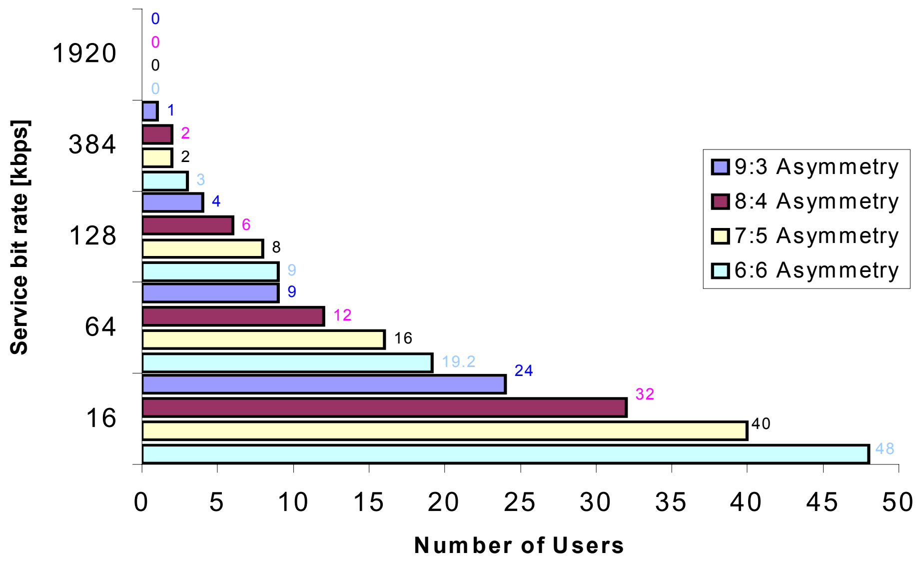


Figure E.5.Maximum number of users in UL per bit rate for different TDD frame asymmetries.

A closer look to the codes allocation scheme shows that the number of codes given to each service may, potentially, lead to what was defined as bit rate leakage, i.e., the difference between the necessary bit rates for each service, defined as target bit rate, and the bit rate available from the codes allocated, defined as system bit rate. For example, the 16 kbps service needs two codes to work. Two codes mean that two times 13.8 kbps is allocated, i.e., 27.6 kbps, for a service that only needs 16 kbps. The bit rate leakage is 11.6 kbps.

The comparison between the theoretical values (system bit rate) and the simulator results are show in Figure E.6. As expected, the values are not completely equal because the simulator makes the calculations based on the number of codes allocated for each service bit rate. Yet, this inequality allows the appearance of the bit rate leakage, which is an interesting parameter to consider. The bit rate leakage is lower as the bit rate of the service becomes closer to an integer multiple of the base bit rate of 13.8 kbps.

Figure E.7 shows the simulator results for the values of bit rate leakage per service. These two figures allow the validation of the simulator in what concerns the bit rate per service calculations.

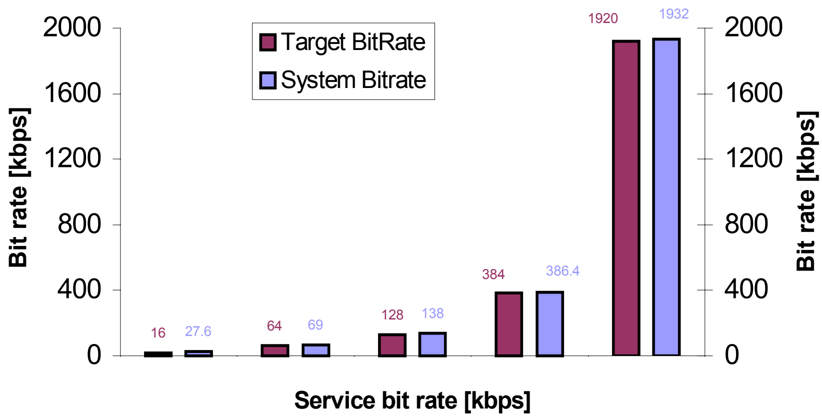


Figure E.6. Comparison between system and target bit rate.

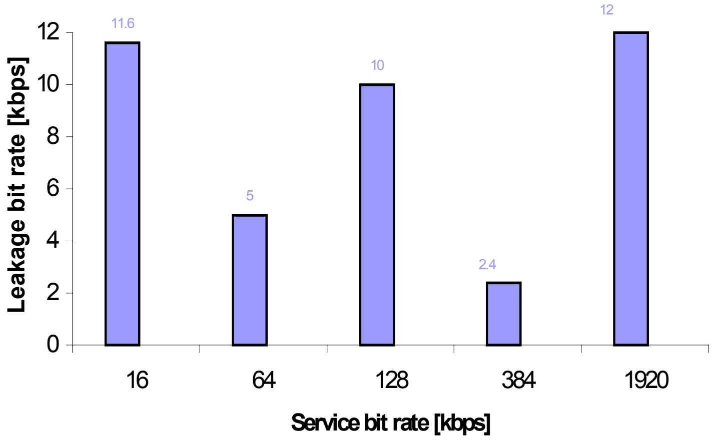


Figure E.7. Bit rate leakage per service bit rate.

One of the most important parameters that must be analysed in the network is the load. In the TDD mode the load concept is analysed on a per TS basis. Thus, any TDD simulator must be able to correctly calculate the load per TS as a function of the different existing services. In that way, it is important to validate the simulator results in what concerns the maximum load that TSs can impose onto the system and the number of users that generate that load. It is important to analyse the maximum load that a single user of each service imposes on one TS. As so, theoretical values of the load that one user creates over one TS were calculated and crosschecked with the ones created by the simulator. This comparison is very important because it validates the simulator in what concerns load calculations per TS. The results are shown in Figure E.8. In order to find the maximum values, the simulations and calculations were made considering the scenario as vehicular.

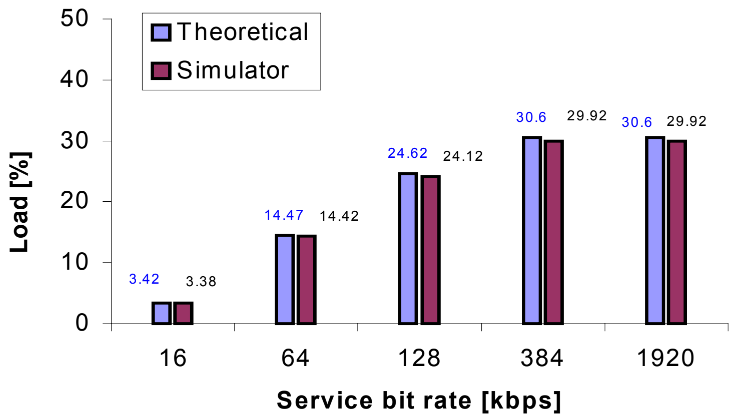


Figure E.8. Maximum load that a user can generate on one TS in DL

It can be seen that the maximum load that a single user can create on a single TS is 30.6%. This means that a single user of 1920 kbps sets the maximum load that the system will have on any TS, and that that load is far from the maximum of 70% in the DL direction. It may be expected that when the TS has a mixture of several users the load increase.

In UL, the comparison between the results of the simulator and the theoretical values can be seen in Figure E.9. Again, the maximum load that a single user can create on one TS is 19.3%, far from the maximum of 50% in UL.

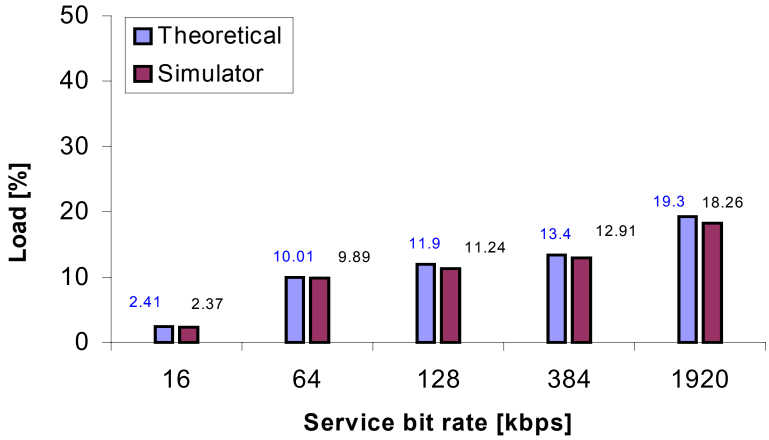


Figure E.9. Maximum load that a user can generate on one TS in UL.

After having the results of the load of one user, the next analysis was to find the maximum load that a certain service would create on a single TS and the number of users that would cause that value. The results shown in Figure E.10 refer to the maximum DL load that the several services cause on a single TS and also the number of users needed to cause that load, i.e., eight users of a 16 kbps service cause a maximum load of 27.84% on one TS. Four users of 64 kbps cause a maximum load of 46.32% for one TS. Note that the fact that four 64 kbps users being allocated in one TS is not strange, when the maximum supported users is three. This happens because with three users in TS, there is still 1 code remaining. As another user entering in the system, it sees one of its five codes allocated in the TS and the other four in the following TS. This other code has its contribution to the total load in the TS, thus, the maximum load can be determined.

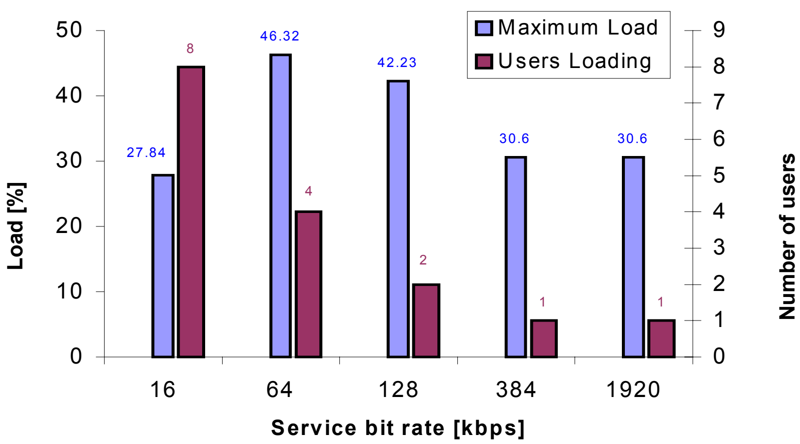


Figure E.10. Maximum DL Load in one TS.

Per TS, the maximum load that is observed is 46.32%, far from the maximum of 70%. Note that a single user of 1920 kbps causes a load of 30.6% in one TS. In UL, the load is expected to be smaller than in DL. The maximum UL load per TS is shown in Figure E.11 and confirms the expected behavior of the simulator.

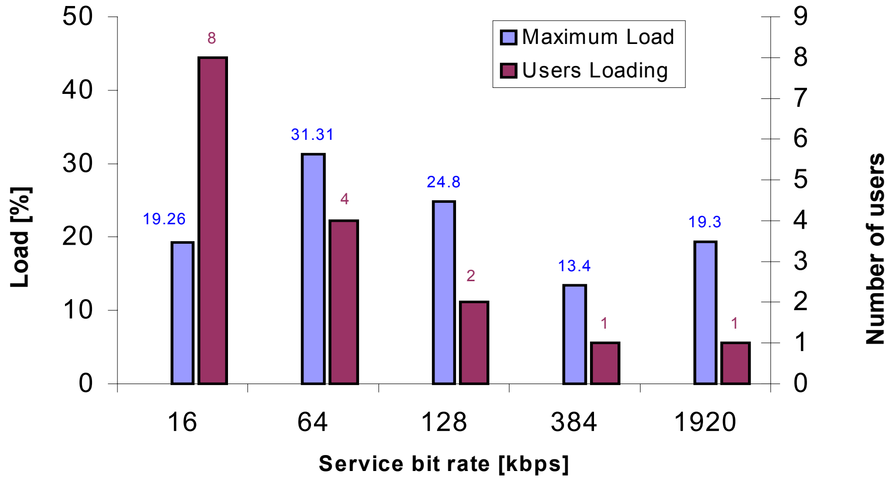


Figure E.11. Maximum UL Load in one TS.

The users definitions determine that there are three different scenarios available: pedestrian, indoor and vehicular. Each one has its own distinct characteristics and a comparison was made among them to analyse the expected differences.

Figure E.12 shows the simulation results for the load calculations of one user considering the three different scenarios can be in. It can be seen that the indoor and pedestrian scenarios have almost no differences due to very similar characteristics between them. The vehicular service presents higher loading as a result of higher values of E_b/N_0. As expected, in the same conditions and scenarios, the UL load is smaller than the one in DL. This theoretical aspect is completely confirmed by the simulation results.

After having the presented values of the several simulations, additional network simulations were made in order to discover if the simulator was working as supposed. The objective was to see the performance of the simulator and obtain some of the most important network indicators as served and uncovered users and uncoverage and delayed probabilities. The simulation conditions include a total of 1 000 VoIP users (16 kbps), within a pedestrian scenario and the network varies from one to a total of thirty BSs.

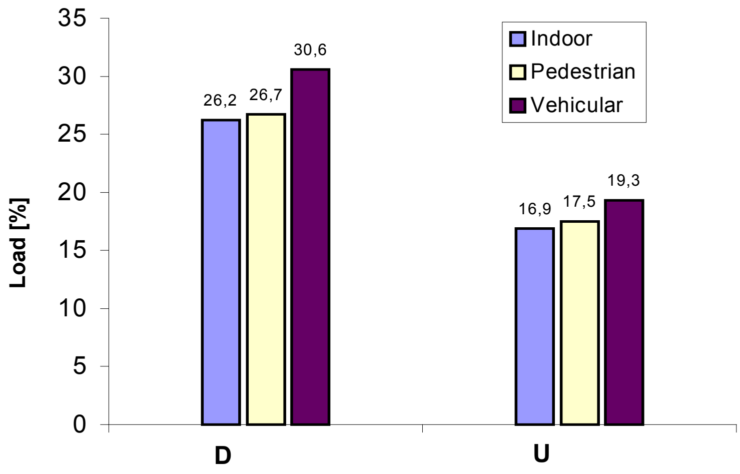


Figure E.12. Load in DL and UL for one user and several scenarios.

The first result is shown in Figure E.13 and refers to the number of served users. As expected, as the number of BSs is increased, the number of served users also increases. In what concerns the uncovered users, as the number of BSs increases, the number of users without coverage decreases, as expected. Note that with only one BS the number of uncovered users is approximately 800, which is explained by the fact that a TDD cell has a smaller radius compared to an FDD one.

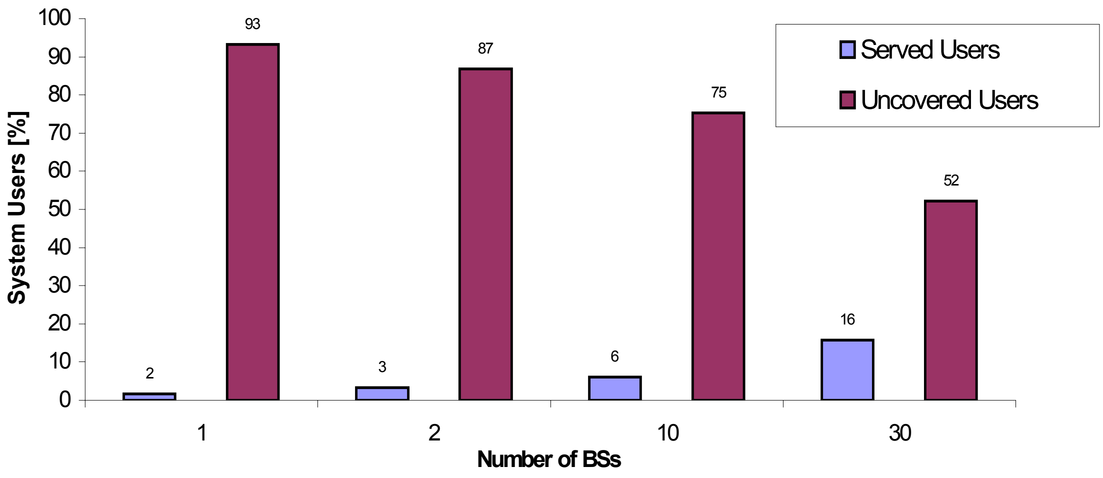


Figure E.13. Served and uncovered users as a function of the number of BSs.

Uncoverage and delay probabilities, shown in Figure E.14, are expected that, as the network BSs increase and the number of uncovered users decrease. The scenario was chosen as pedestrian so that the results could, at this point, be the most realistic possible, when several scenarios are not considered. As the major part of the users is servicing under a pedestrian scenario, it was assumed that this was a good tested.

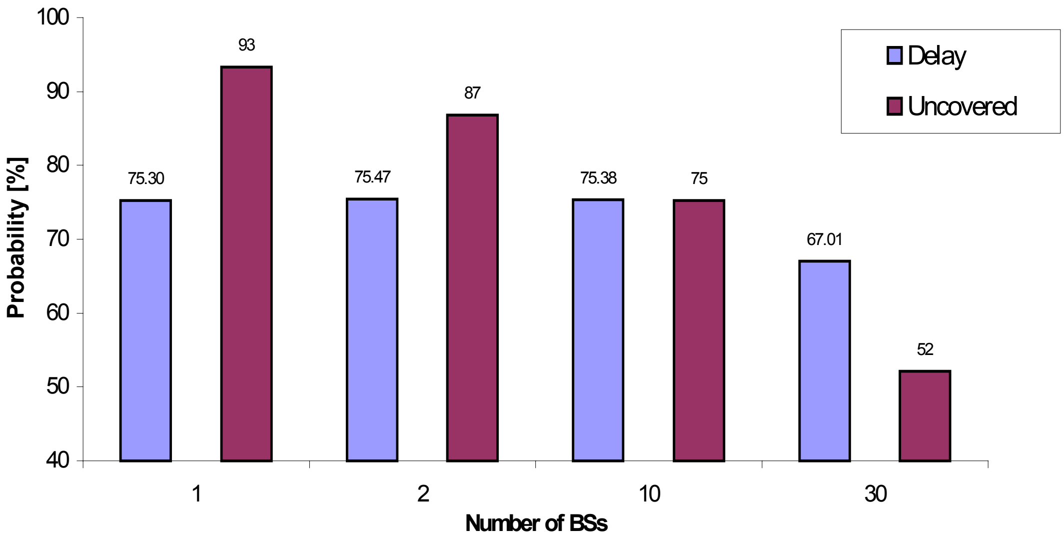


Figure E.14. Delay and uncoverage probability as a function of the number of BSs.

This annex presented the several validations made to the TDD simulator. Several theoretical calculations were made so that the simulator results could be crosschecked with them. The TDD simulator shows a good performance and the TS allocation engine is working correctly, which allow one step further into the modeling of the optimisation simulations and calculations. Next paragraphs are dedicated to present a validation of the optimisation algorithm.

Table E.2, presents the results of optimisation algorithm based on initial conditions described earlier. In this table, it can be seen (for 804 WWW users – average value) that the number of users served increases while the number of FDD BSs increase, the same being verified for TDD BSs co-located, however this increase is according to the need to serve more HBR users.

Table E.2. Results for test scenario.

	# FDD BS	# TDD BS	# FDD Users	# TDD Users	Users in the system	Served users	Uncov. users	P_d [%]
4 BS	4	2	26	4	804	30	774	13.3
10 BS	10	7	94	32	804	126	678	25.4

Table E.3, presents the state of the network before reduces user bit rate algorithm starts (algorithm provided by FDD simulator). In this table, it can be see that not all 384 kbps and 128 kbps users go to the TDD network, because the DL load factor did not reach load decision threshold; this fact proves the validation of the implemented algorithm, based on the theoretical developed algorithm.

Table E.3. Number of users before bit rate reduction for test scenario.

# FDD BS	FDD			TDD	
	Users 64 kbps	Users 128 kbps	Users 384 kbps	Users 128 kbps	Users 384 kbps
4	13	9	4	3	1
10	36	38	20	24	8

Table E.4 presents the state of the FDD network after reducing user bit rate algorithm starts. In this case, all the HBR users (384 kbps and 128 kbps) present in the FDD network have a reduction of bit rate, users with a bit rate of 384 kbps are reduced to 128 kbps and the same for 128 kbps, but for 64 kbps.

Table E.4. Number of users after bit rate reduction for test scenario.

# FDD BS	FDD		
	Users 64 kbps	Users 128 kbps	Users 384 kbps
4	22	4	0
10	74	20	0

In Table E.5, four performance parameters are present: $RER_{384\text{-}128}$, $DRER_{384\text{-}128}$, $RER_{128\text{-}64}$ and $DRER_{128\text{-}64}$. This output parameters gives a notion of how many users (in a total of users served by the FDD network) have a reduction of bit rate – average value, *DRER* – and quantity of users that have a reduction of bit rate. Analysing the table, all 384 kbps users are reduced to 128 kbps and all 128 kbps users are reduced to 64 kbps – *RER*. The averages of users reduced are: 13.3 % (4 FDD BSs) and 15.8 % (ten FDD BSs) for 384 kbps users; 30 % (four FDD BSs) and 30.2 % (10 FDD BSs).

Table E.5. RER and DRER for test scenario.

# FDD BS	FDD			
	$RER_{384\text{-}128}$ [%]	$DRER_{384\text{-}128}$ [%]	$RER_{128\text{-}64}$ [%]	$DRER_{128\text{-}64}$ [%]
4	100	13.3	100	30.0
10	100	15.8	100	30.2

For the next step in the validation process, another simulation is provided, called first simulation. This consists of changing load decision threshold, the results being presented in Table E.6.

Table E.6. Results for first simulation.

Load decision threshold [%]	# FDD BS	# TDD BS	# FDD users	# TDD users	Users in the system	Served users	Uncov. users	P_d [%]
90	4	4	11	14	804	25	779	56.0
	10	10	64	47	804	111	693	42.3
70	4	3	17	12	804	29	775	41.4
	10	6	88	37	804	125	679	29.6
10	4	2	28	8	804	36	768	22.2
	10	4	109	19	804	128	676	14.8

Analysing Table E.6, the increase of P_d can be verified with the increase of load decision threshold, because the condition of load is: $1-LOAD\_DECISION$, so there is more sensitivity to the increase of the DL load factor. On the other hand, this implies more TDD BSs needed to cover more HBR users, i.e., with a load decision threshold of 90 %, it is necessary the same number of FDD and TDD BSs.

Table E.7 presents the state of the network before reducing user bit rate algorithm starts; it can seen that there are more users in the TDD network with a load decision threshold high.

Table E.7. Number of users before bit rate reduction for first simulation.

Load decision threshold [%]	# FDD BS	FDD			TDD	
		Users 64 kbps	Users 128 kbps	Users 384 kbps	Users 128 kbps	Users 384 kbps
90	4	4	3	4	12	2
	10	15	32	17	29	18
70	4	4	11	2	6	6
	10	31	43	14	22	15
10	4	9	12	7	6	2
	10	36	49	24	12	7

Table E.8 presents the state of the FDD network after reducing user bit rate algorithm starts; such as test scenario, after reduction there are not 384 kbps users and 128 kbps users are all the users which have a bit rate of 384 kbps before the reduction algorithm starts.

Table E.8. Number of users after bit rate reduction for first simulation.

Load decision threshold [%]	# FDD BS	FDD		
		Users 64 kbps	Users 128 kbps	Users 384 kbps
90	4	7	4	0
	10	47	17	0
70	4	15	2	0
	10	74	14	0
10	4	21	7	0
	10	85	24	0

In Table E.9, four performance parameters are present: $RER_{384\text{-}128}$, $DRER_{384\text{-}128}$, $RER_{128\text{-}64}$ and $DRER_{128\text{-}64}$.

Table E.9. RER and DRER for first simulation.

Load decision threshold [%]	# FDD BS	FDD			
		$RER_{384\text{-}128}$ [%]	$DRER_{384\text{-}128}$ [%]	$RER_{128\text{-}64}$ [%]	$DRER_{128\text{-}64}$ [%]
90	4	100	16.0	100	12.0
	10	100	15.3	100	28.8
70	4	100	6.89	100	37.9
	10	100	11.2	100	34.4
10	4	100	19.4	100	33.3
	10	100	18.8	100	38.3

In the end of this first simulation, it can be concluded that load decision threshold has a strong and high impact on the decision of transferring users (HBR users) to the TDD network, as theoretically expected. The higher the decision load more users (number of users duplicate comparing with test scenario simulation) go to the TDD network, and naturally more TDD BSs are needed.

The next step in the validation process is the second simulation. This consists of changing bit rate decision threshold, the results being presented in Table E.10.

Analysing Table E.10, it can be verified that the decrease of bit rate decision threshold implies more users being transferred to the TDD network, and naturally more TDD BSs co-located. This can be confirmed by analysing the P_d parameter.

Table E.10. Results for second simulation.

Bit rate decision threshold [kbps]	# FDD BS	# TDD BS	# FDD users	# TDD users	Users in the system	Served users	Uncov. users	P_d [%]
384	4	2	21	4	804	25	779	16.0
	10	4	96	11	804	107	697	10.3
64	4	2	26	7	804	33	771	21.2
	10	7	79	25	804	104	700	24.0

Table E.11 presents the state of the network before reducing user bit rate algorithm starts; it can be seen, in first line, that there are no 128 kbps users in the TDD network, because bit rate decision threshold is 384 kbps, which confirms the theoretical optimisation algorithm.

Table E.11. Number of users before bit rate reduction for second simulation.

Bit rate decision threshold [kbps]	# FDD BS	FDD			TDD	
		Users 64 kbps	Users 128 kbps	Users 384 kbps	Users 128 kbps	Users 384 kbps
384	4	8	10	3	0	4
	10	35	51	11	0	10
64	4	8	7	11	2	5
	10	21	39	19	19	6

Table E.12 presents the state of the FDD network after reducing user bit rate algorithm starts naturally, in the first line, only the 384 kbps have a reduction of the bit rate, and it can be seen in Table E.13, by analysing $RER_{128\text{-}64}$ and $DRER_{128\text{-}64}$ output parameters that the value, 0 %. This means that 128 kbps users do not have a reduction of bit rate, confirming once more theoretical optimisation algorithm.

Table E.12. Number of users after bit rate reduction for second simulation.

Bit rate decision threshold [kbps]	# FDD BS	FDD		
		Users 64 kbps	Users 128 kbps	Users 384 kbps
384	4	8	13	0
	10	35	62	0
64	4	15	11	0
	10	60	19	0

In Table E.13, four performance parameters are presented: $RER_{384\text{-}128}$, $DRER_{384\text{-}128}$, $RER_{128\text{-}64}$ and $DRER_{128\text{-}64}$.

Table E.13. RER and DRER for second simulation.

Bit rate decision threshold [kbps]	# FDD BS	FDD			
		$RER_{384\text{-}128}$ [%]	$DRER_{384\text{-}128}$ [%]	$RER_{128\text{-}64}$ [%]	$DRER_{128\text{-}64}$ [%]
384	4	100	12.0	0.0	0.0
	10	100	10.3	0.0	0.0
64	4	100	33.0	100	21.2
	10	100	18.3	100	37.5

It can be concluded that bit rate decision threshold has a medium impact on the decision of transfer users (HBR users) to the TDD network, as expect.

The last step in the validation process consists of the third simulation. This is characterised by changing users in the city, to increase the traffic in the system, the results being presented in Table E.14. The variation consists of a strong increase of users (4000 WWW users) and a decrease to 100 WWW users; as it can be seen, this variation has a strong impact in P_d and in the needed TDD BSs, as expected. The specific input parameters of the optimisation algorithm are: bit rate decision threshold: 128 kbps and load decision threshold: 30%.

Table E.14. Results for third simulation.

# Users	# FDD BS	# TDD BS	# FDD users	# TDD users	Users in the system	Served users	Uncov. users	P_d [%]
4000	4	4	112	51	3190	163	3027	35.3
	10	10	321	140	3190	461	2729	31.8
500	4	1	16	5	406	21	385	23.8
	10	6	52	20	406	72	334	27.7
100	4	0	3	0	77	3	74	0.0
	10	0	12	0	77	12	65	0.0

Table E.15 presents the state of the network before reducing user bit rate algorithm starts, all the considerations being maintained.

Table E.15. Number of users before bit rate reduction for third simulation.

# Users	# FDD BS	FDD			TDD	
		Users 64 kbps	Users 128 kbps	Users 384 kbps	Users 128 kbps	Users 384 kbps
4000	4	33	56	23	39	12
	10	92	152	77	103	37
500	4	12	4	0	5	0
	10	21	15	16	10	10
100	4	2	1	0	0	0
	10	5	2	5	0	0

Table E.16 presents the state of the FDD network after reducing user bit rate algorithm starts; once more all 384 kbps and 128 kbps users have a reduction of bit rate, Table E.17.

Table E.16. Number of users after bit rate reduction for third simulation.

# Users	# FDD BS	FDD		
		Users 64 kbps	Users 128 kbps	Users 384 kbps
4000	4	89	23	0
	10	244	77	0
500	4	16	0	0
	10	36	16	0
100	4	3	0	0
	10	7	5	0

In Table E.17, four performance parameters are presented: $RER_{384\text{-}128}$, $DRER_{384\text{-}128}$, $RER_{128\text{-}64}$ and $DRER_{128\text{-}64}$.

Table E.17. RER and DRER for third simulation.

# Users	# FDD BS	FDD			
		$RER_{384\text{-}128}$ [%]	$DRER_{384\text{-}128}$ [%]	$RER_{128\text{-}64}$ [%]	$DRER_{128\text{-}64}$ [%]
4000	4	100	14.1	100	34.4
	10	100	16.7	100	32.9
500	4	100	0.0	100	19.0
	10	100	22.2	100	20.8
100	4	0.0	0.0	100	33.3
	10	100	41.6	100	16.6

It can be concluded that the increase of users implies the increase of TDD BSs, as expected.

Annex F

Simulator User's Manual

This annex presents the user's manual for the developed simulator taking into account that the TDD mode of operation was created and added to the existing simulator.

This user's guide focuses only on the windows to configure the simulator for operation on TDD mode and also to configure the optimisation algorithm parameters. For the correct configuration of the FDD mode refer to [SeCa04].

The first step consists of importing demographical data. These data are comprised of three files, two of them related to the characteristics of the terrain and districts, and the last one related to non-uniform users distribution over the terrain. Figure F.1 shows the window that allows importing these files.

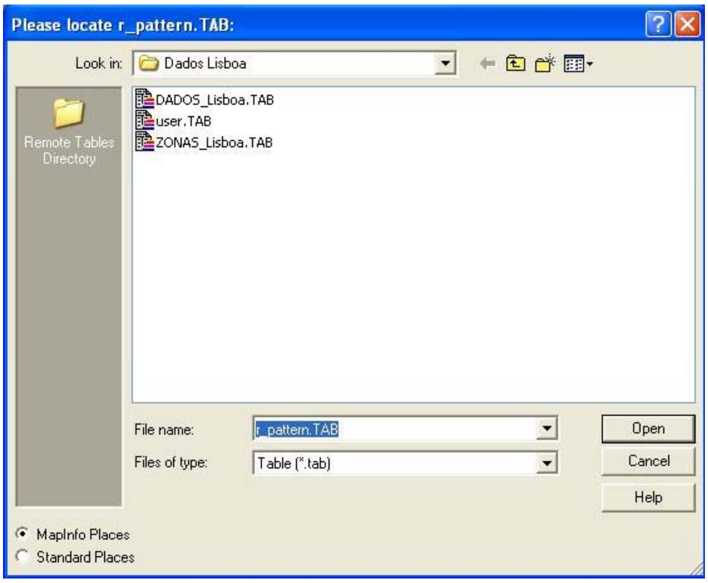


Figure F.1. Window for importing of demographic data.

Figure F.2 shows the simulator main window.

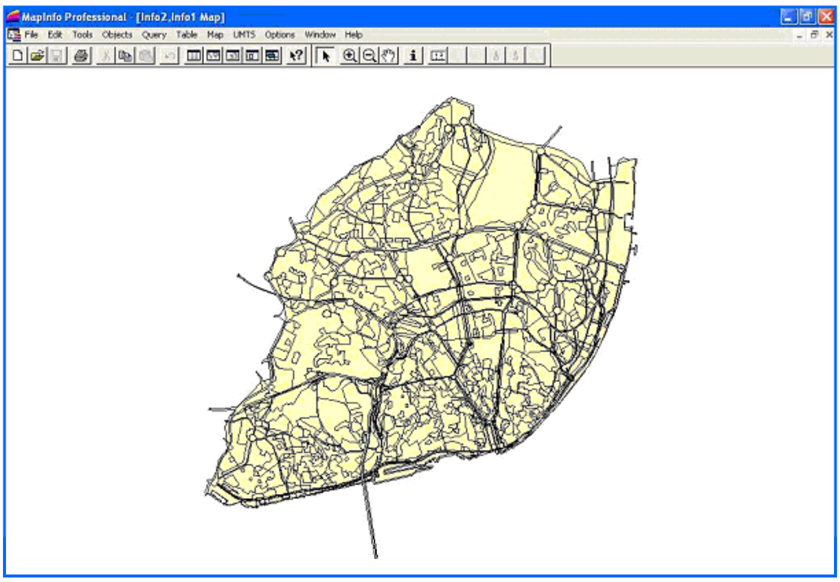


Figure F.2. Simulator aspect with map of Lisbon.

Figure F.3 presents a configuration window of the services penetration rates.

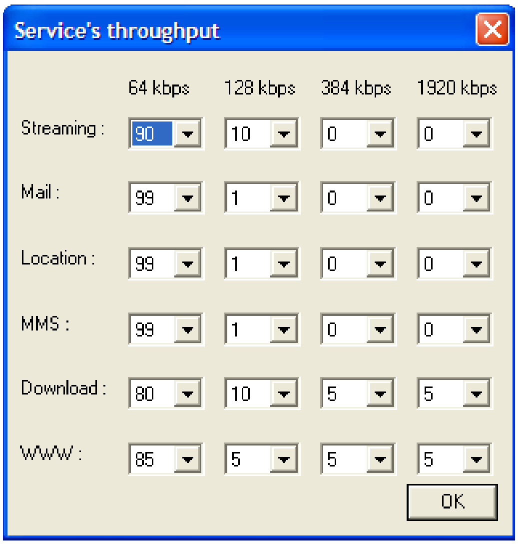


Figure F.3. Service´s throughput window.

In order to visually represent the users in the map and easily relate them to the service, the window shown in Figure F.4 allows assigning a colour to each existing services. Note that the presented values are merely indicative.

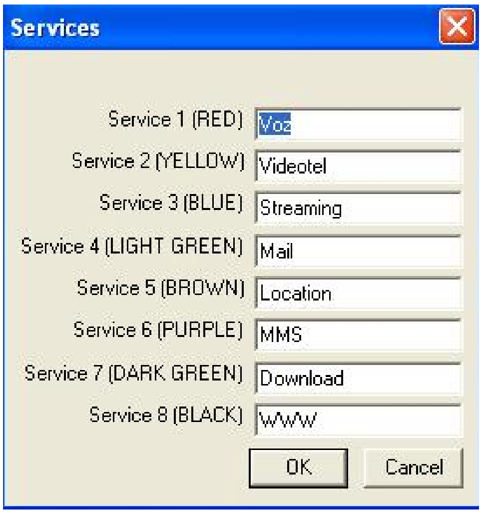


Figure F.4. Existing services in simulator.

Figure F.5 shows the result of importing the terrain and users data, and also the outcome of the relationship between the colours and services as defined in the window of Figure F.4. Also, Figure F.5 presents the result of the configurations made on the penetration rates as shown in Figure F.3.

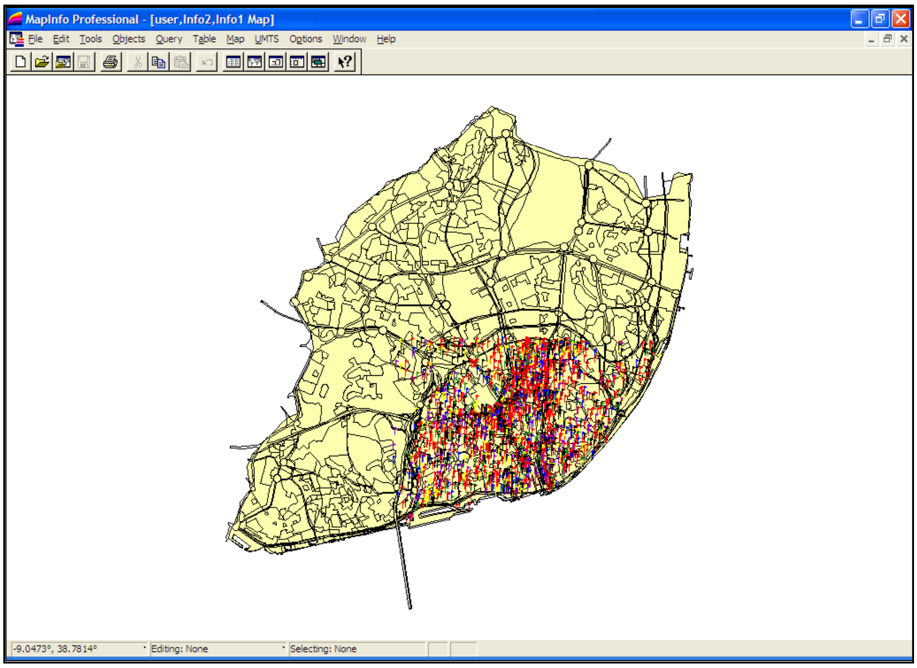


Figure F.5. Reference scenario (Lisbon map) with TDD users inserted.

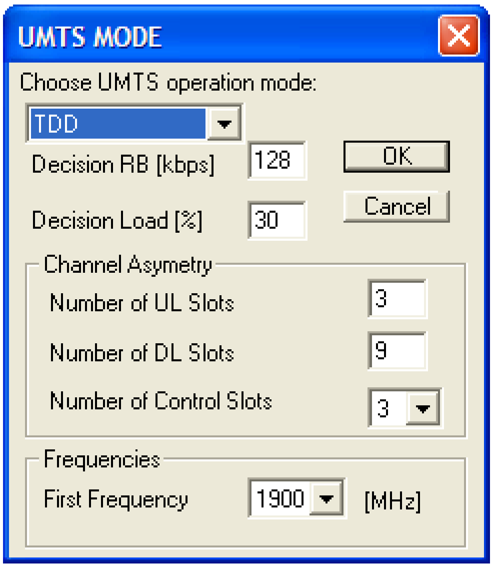


Figure F.6. Configuration window for the UMTS mode and optimisation algorithm.

Figure F.7 shows the propagation model configuration window and its default parameters.

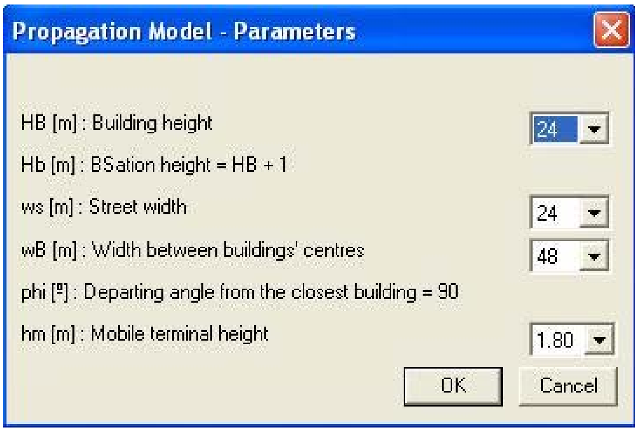


Figure F.7. Configuration window for propagation model.

Figure F.8 shows the network coverage for the TDD mode after inserting the 185 BSs.

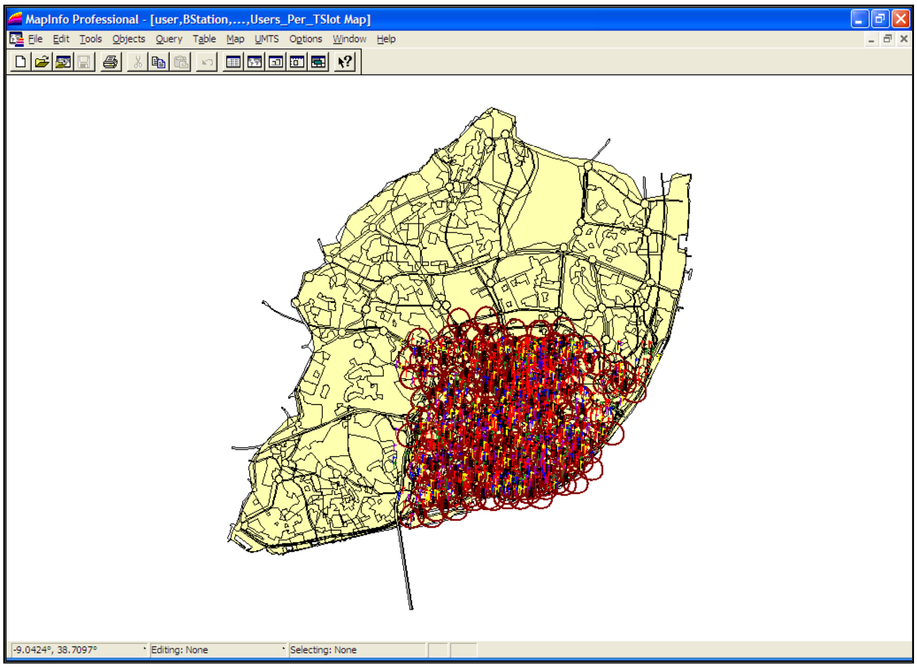


Figure F.8. Coverage map of downtown of Lisbon for the TDD.

Figure F.9 presents an output window with several result and statistics of TDD parameters for all BSs. It is possible to have five different parameters in each of the fifteen TSs of the selected BS. These parameters can be found in greater detail in section 4.6 in Chapter 4.

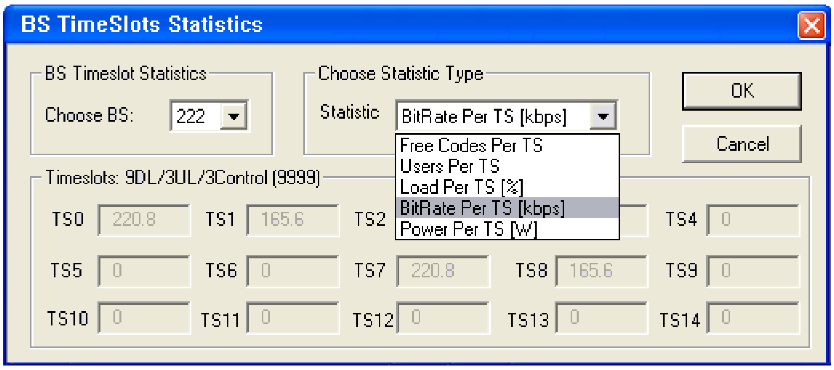


Figure F.9. BS TS statistics in the end of simulation.

The developed simulator generates the following output files:

- *GerirRecursos.data*: statistics of management resources algorithm;
- *Capacity_TDD.out*: statistics of optimisation algorithm;
- *Codes_TS_TDD.out*: statistics of users codes by BS;
- *Data_TDD_Users.out*: statistics of optimisation algorithm;
- *Load_TS_TDD.out*: statistics of users load by BS;
- *Output_TDD.out*: statistics of optimisation algorithm;
- *POWER_TS_TDD.out*: statistics of users power in DL direction by BS;
- *Rb_TS_TDD.out*: statistics of users bit rate by BS;
- *USERS_REDUCED_TDD.out*: statistics of optimisation algorithm;
- *Data_FDD_Users.out*: statistics of optimisation algorithm;
- *Users_TS_TDD.out*: statistics of number of users by TS.

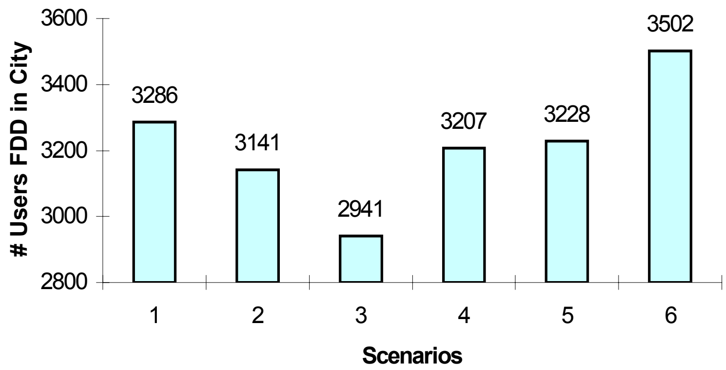
Annex G

Choice of a Reference Scenario

In the current annex, all performance parameters (FDD and TDD mode) resulted from simulations to chose a reference scenario are presented.

The objective of this annex is to present the results obtained before choosing a reference scenario. As referred in Chapter 5, there are ten simulations for each scenario. In the beginning the number of FDD users in the city, Figure G.1, is presented. According to the results the FDD load in DL and UL is near to 30 %, which means that the network is far from imposing restriction (load DL, 70% and load UL, 50%).

Figure G.1. Number of FDD users in city for the six scenarios.



Figures G.2 and G.3 present, for the FDD mode, uncovered probability and the number of TDD BSs needed to support HBR users, respectively.

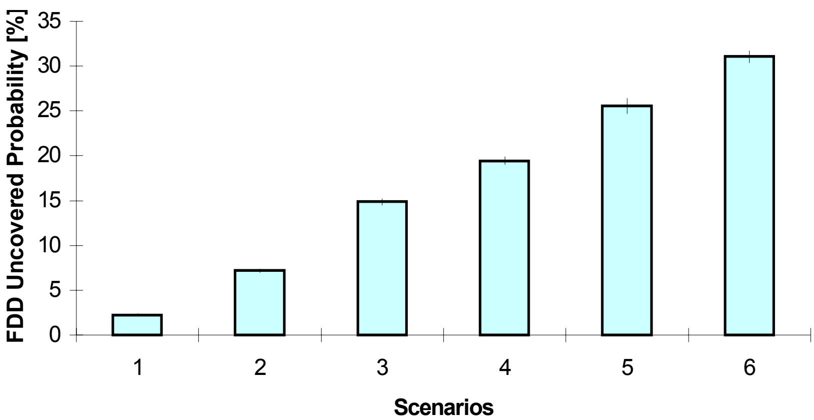


Figure G.2. Uncovered probability in the FDD for six scenarios.

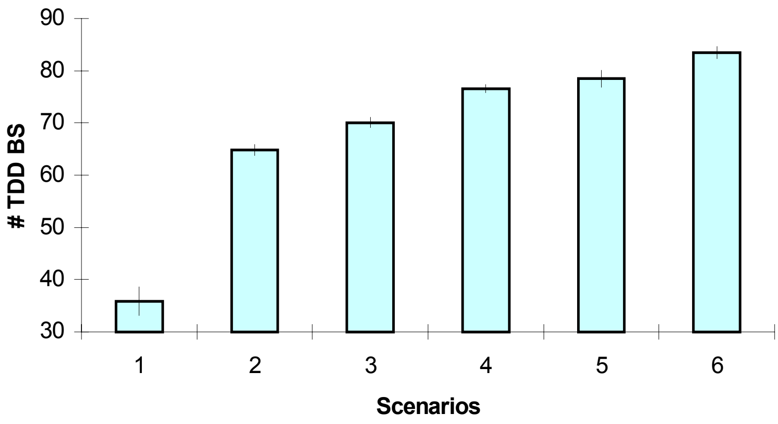


Figure G.3. Number of TDD BS needed in the TDD for six scenarios.

Figures G.4 and G.5 present uncovered probability and BS capacity.

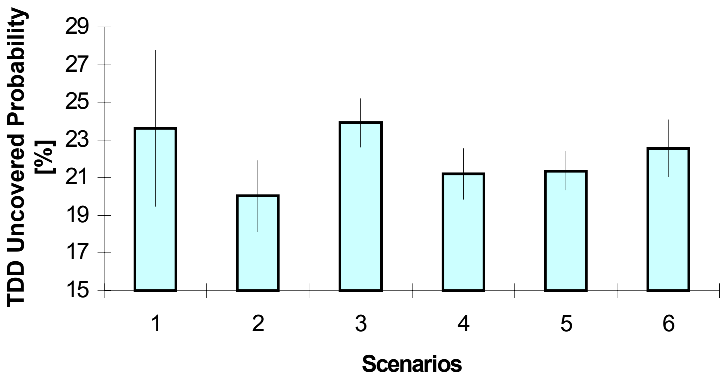


Figure G.4. Uncovered probability in the TDD for six scenarios.

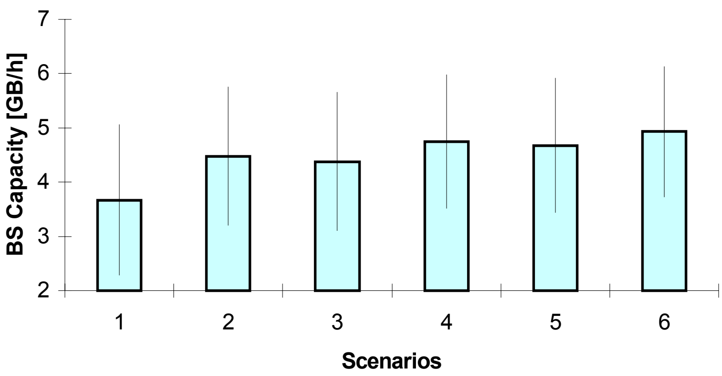


Figure G.5. BS capacity in the TDD for six scenarios.

Figures G.6 and G.7 present used and free codes per BS in DL and UL.

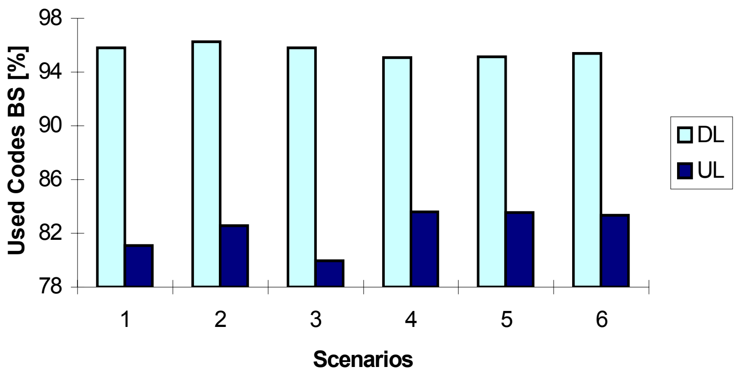


Figure G.6. BS used codes in DL and UL links in the TDD for six scenarios.

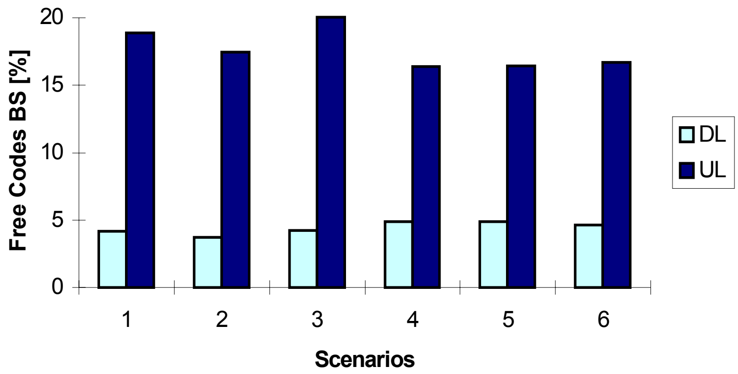


Figure G.7. BS free codes in DL and UL links in the TDD for six scenarios.

Figures G.8 and G.9 present used and free TS per BS in DL and UL.

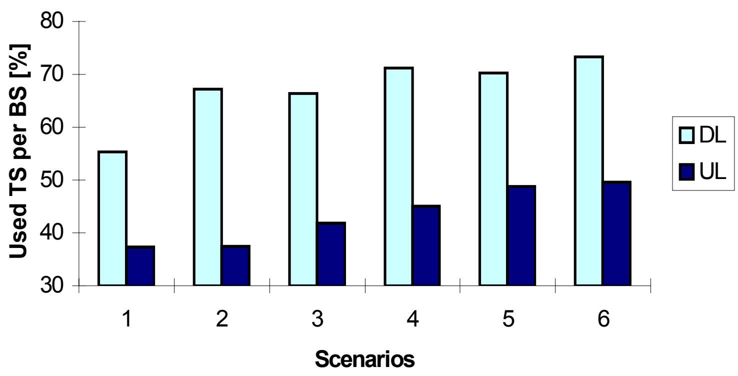


Figure G.8. Used TS per BS in DL and UL links in the TDD for six scenarios.

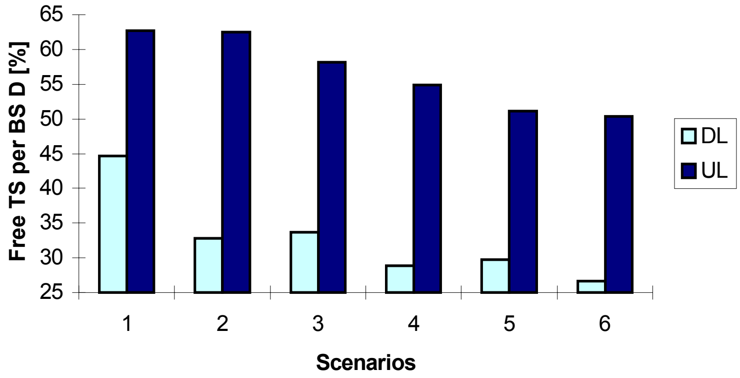


Figure G.9. Free TS per BS in DL and UL links in the TDD for six scenarios.

Figures G.10 and G.11 present bit rate reduction in BS and BSs with a reduction of bit rate.

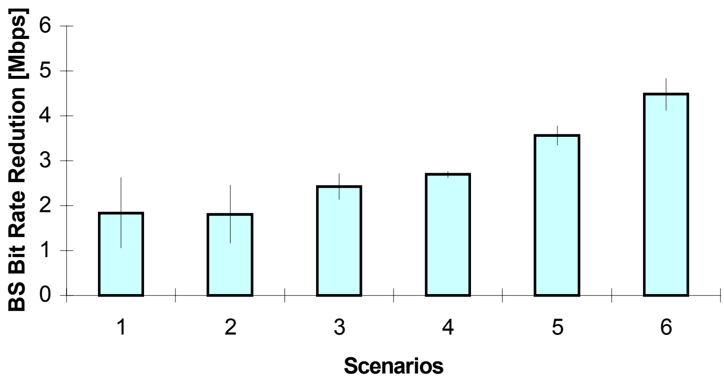


Figure G.10. BS bit rate reduction in the TDD for six scenarios.

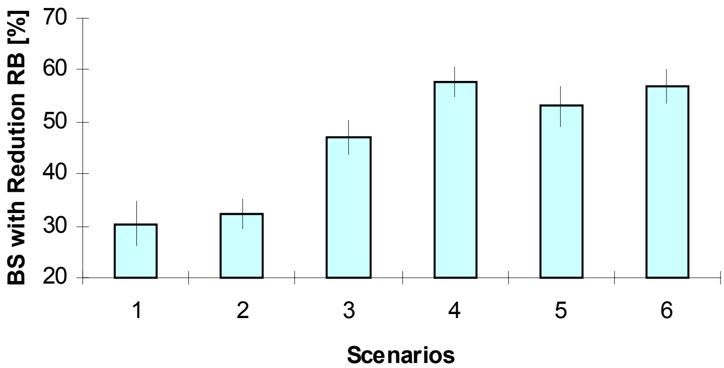


Figure G.11. BS with reduction of bit rate in the TDD for six scenarios.

Annex H

Change off Bit Rate Decision Threshold

In the current annex, all performance parameters (FDD and TDD mode) resulting from simulations to test the change of bit rate decision threshold are presented.

The objective of this annex is to present the results obtained for ten simulations of each scenario. Bit rate decision threshold (optimisation algorithm input – simulator platform input) changes in each of the ten simulations, from 64 kbps, 128 kbps (default value) and 384 kbps. Other optimisation algorithm inputs, like, load decision threshold and asymmetry have default values, 30% and 9:3, respectively.

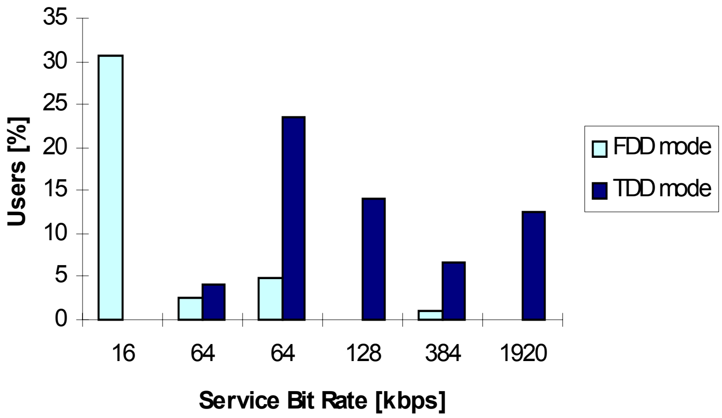


Figure H.1. Intermediate profile for bit rate decision threshold of 64 kbps.

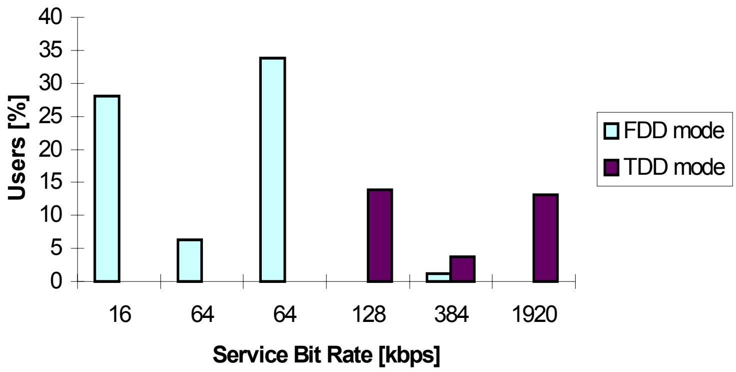


Figure H.2. Intermediate profile for bit rate decision threshold of 128 kbps.

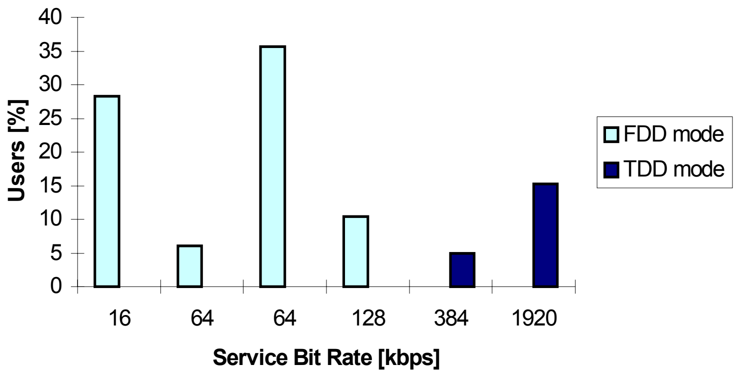


Figure H.3. Intermediate profile for bit rate decision threshold of 384 kbps.

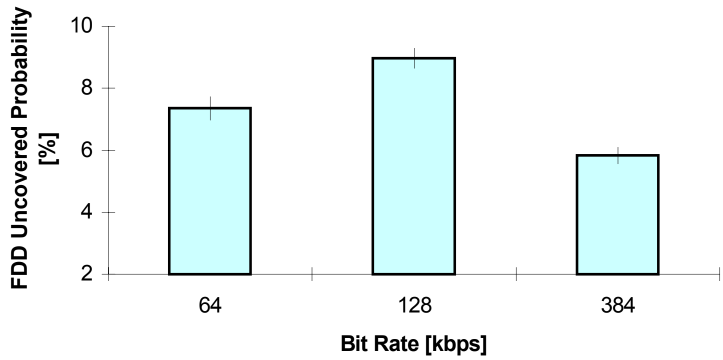


Figure H.4. Uncovered probability in the FDD as function of the bit rate decision threshold.

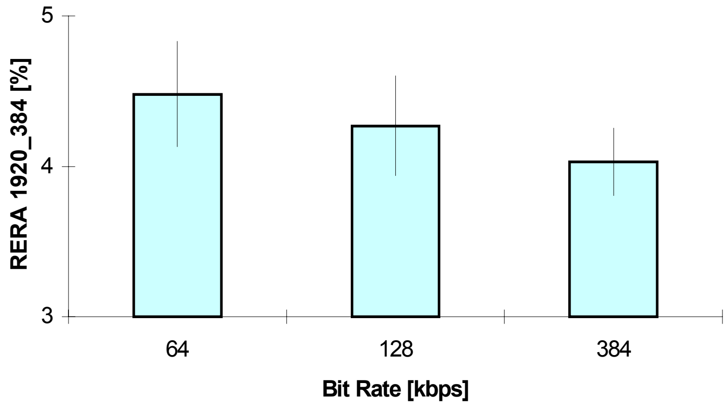


Figure H.5. RERA of users reduced from 1920 to 384 kbps as function of the bit rate decision threshold.

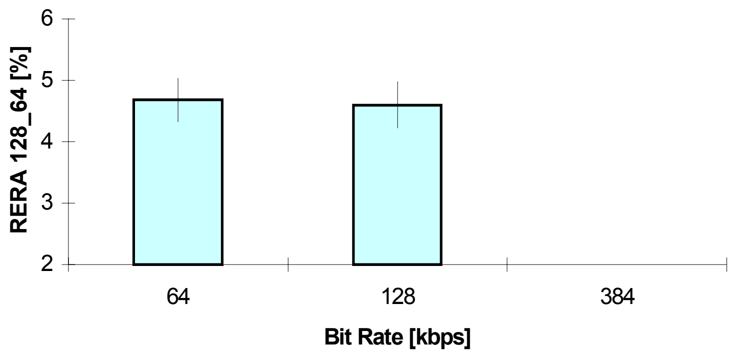


Figure H.6. RERA of users reduced from128 to 64 kbps as function of the bit rate decision threshold.

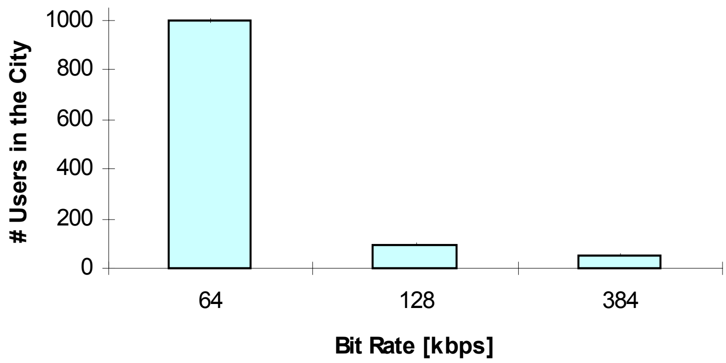


Figure H.7. Number of TDD users in city as function of the bit rate decision threshold.

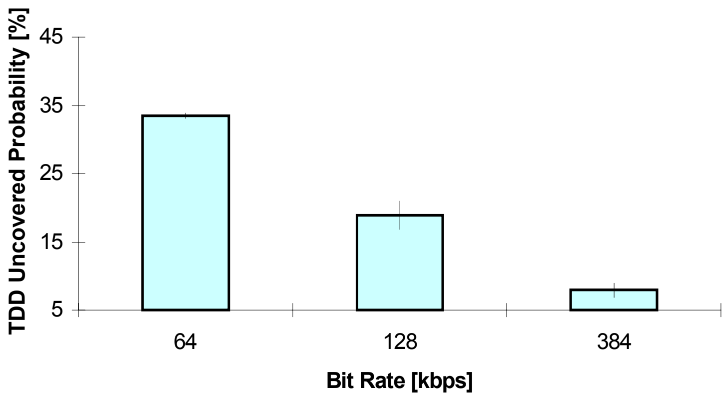


Figure H.8. Uncovered probability in the TDD as function of the bit rate decision threshold.

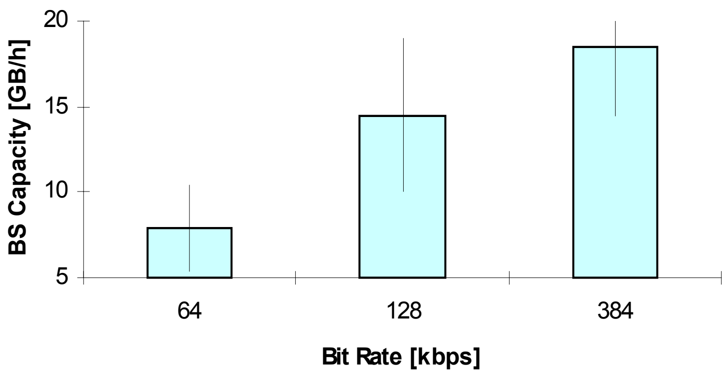


Figure H.9. BS capacity in the TDD as function of the bit rate decision threshold.

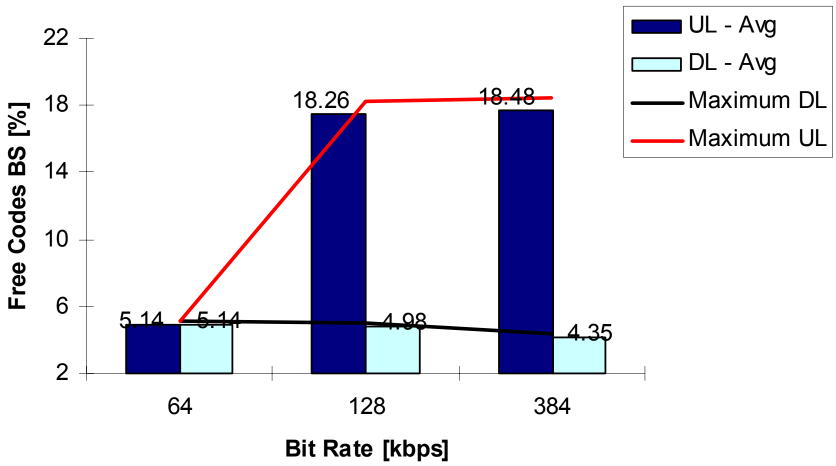


Figure H.10. Free codes BS in DL and UL links as function of the bit rate decision threshold.

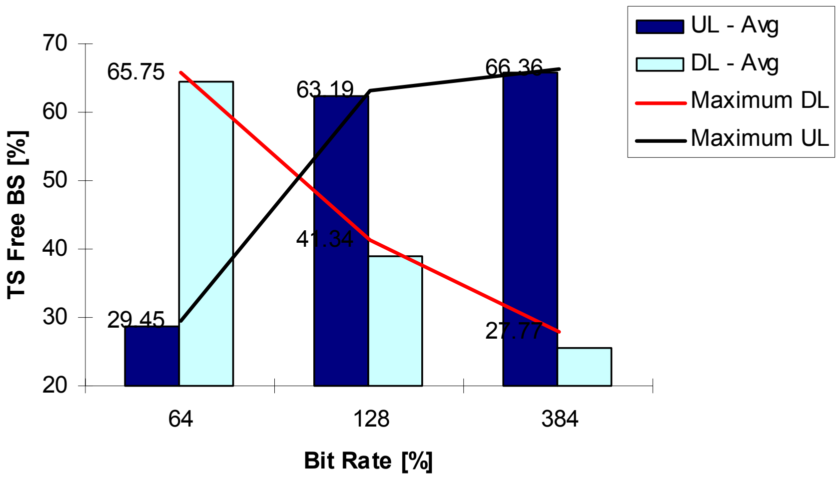


Figure H.11. TS free in BS for DL and UL links as function of the bit rate decision threshold.

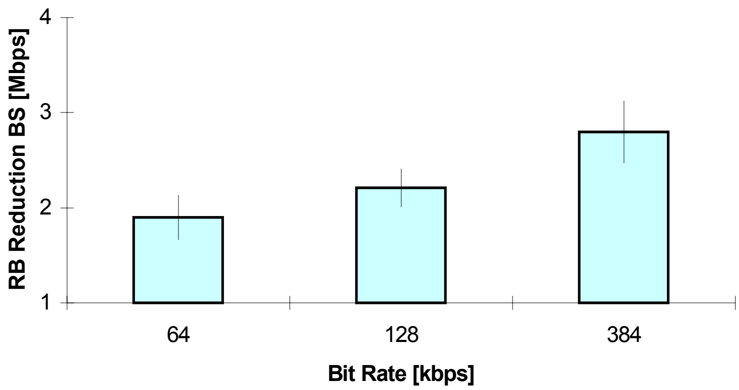


Figure H.12. Bit rate reduced in BS for DL as function of the bit rate decision threshold..

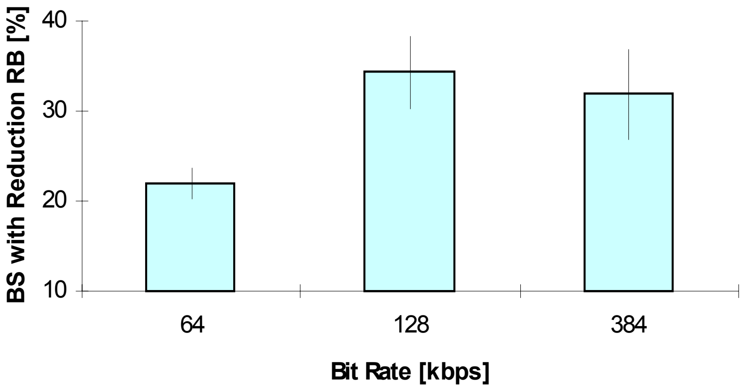


Figure H.13. BS with reduction of bit rate as function of the bit rate decision threshold.

Annex I

Change off Load Decision Threshold

In the current annex, all performance parameters (FDD and TDD mode) resulting from simulations to test the change of load decision threshold are presented.

The objective of this annex is to present the results obtained for ten simulations of each scenario. Load decision threshold (optimisation algorithm input – simulator platform input) changes in each of the ten simulations, from 10%, 30% (default value), 70% and 90%. Other optimisation algorithm inputs, like, bit rate decision and asymmetry have default values, 128 kbps and 9:3, respectively.

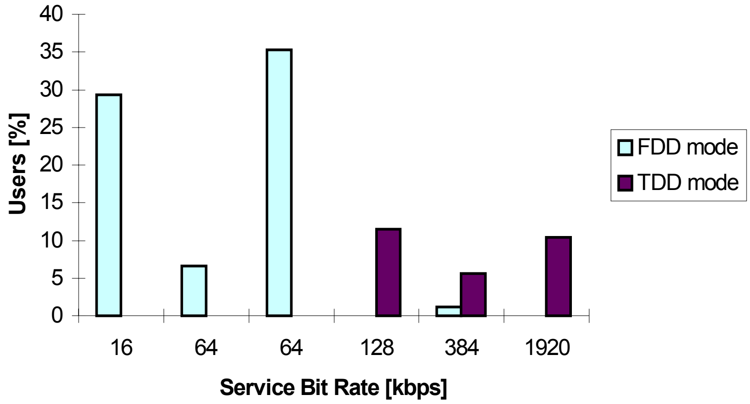


Figure I.1. Intermediate profile for load decision threshold of 10%.

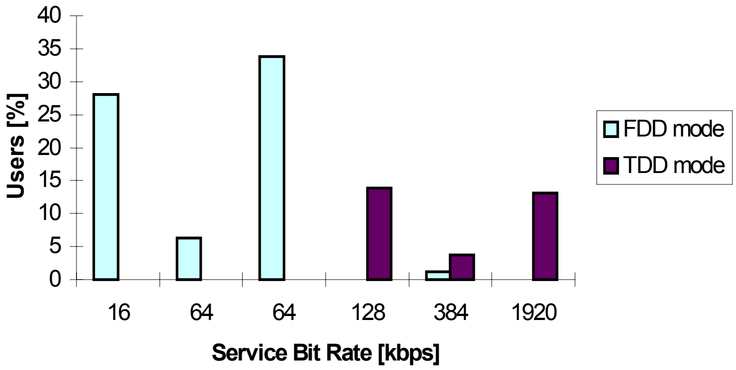


Figure I.2. Intermediate profile for load decision threshold of 30%.

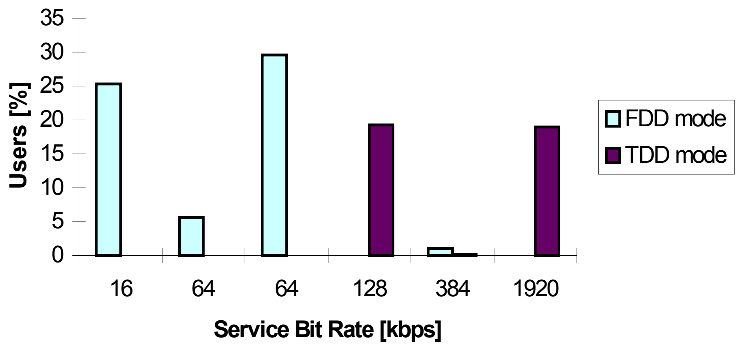


Figure I.3. Intermediate profile for load decision threshold of 70%.

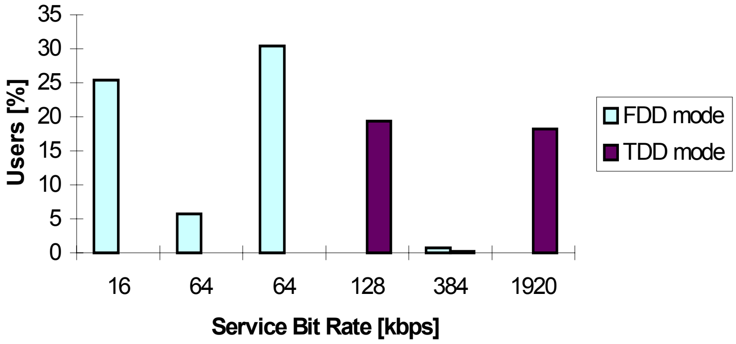


Figure I.4. Intermediate profile for load decision threshold of 90%.

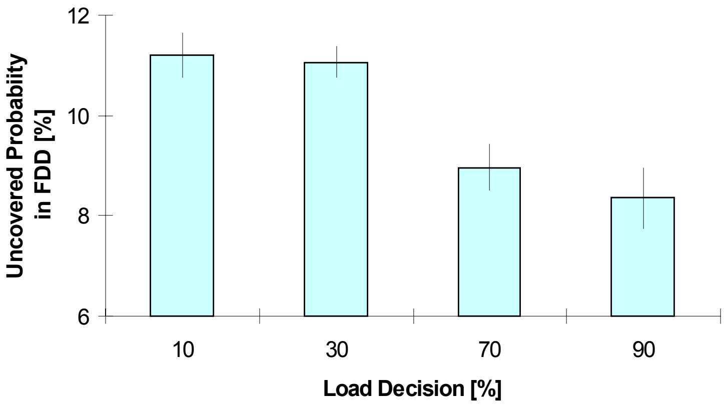


Figure I.5. Uncovered probability in the FDD as function of the load decision threshold.

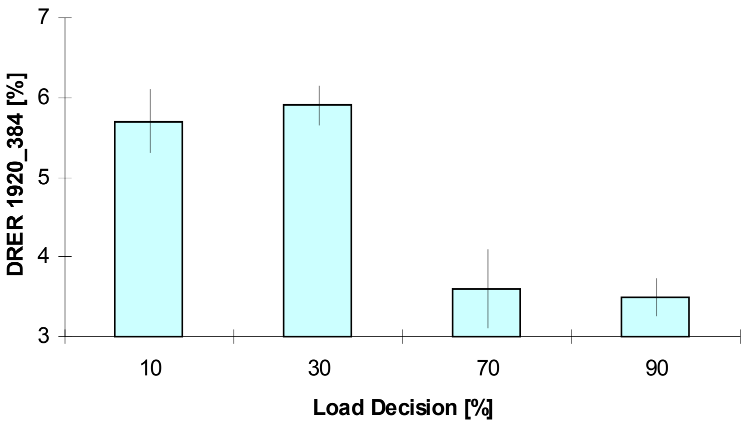


Figure I.6. DRER of users reduced from 1920 to 384 kbps as function of the load decision threshold.

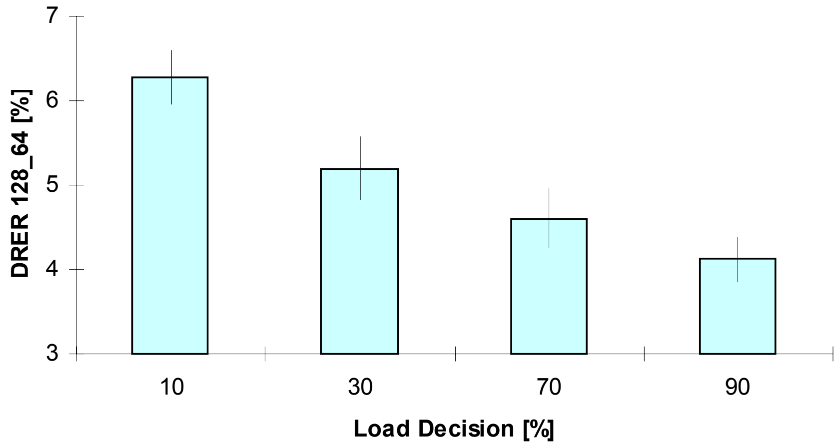


Figure I.7. DRER of users reduced from 128 to 64 kbps as function of the load decision threshold.

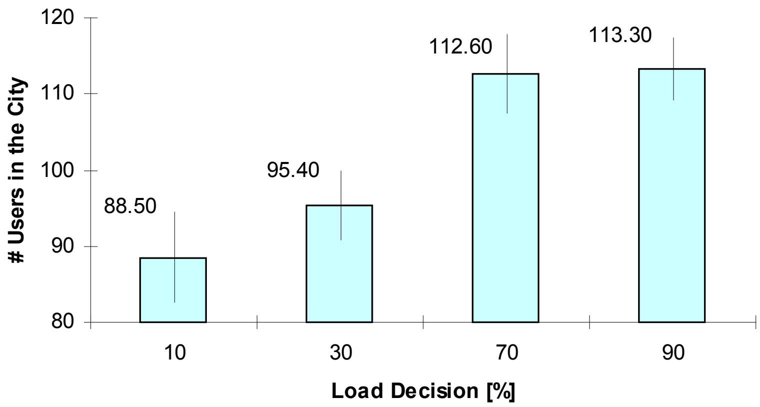


Figure I.8. Number of TDD users in city as function of the load decision threshold.

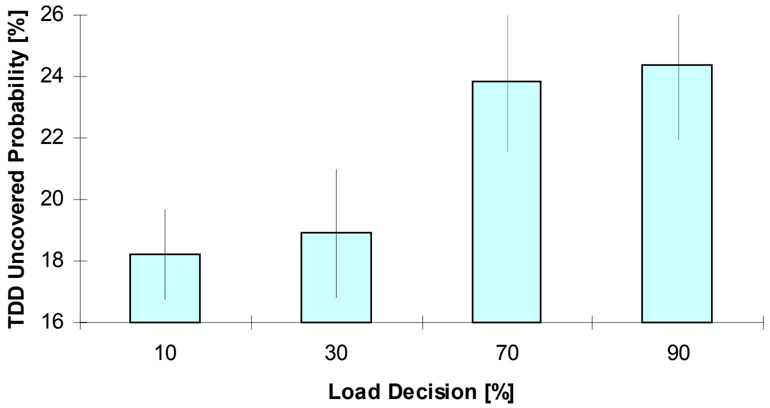


Figure I.9. Uncovered probability in the TDD as function of the load decision threshold.

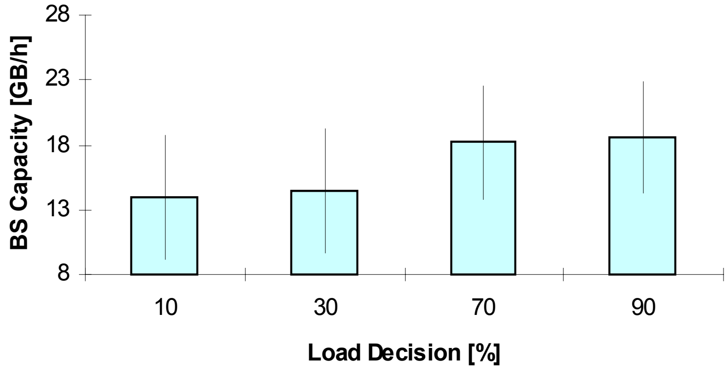


Figure I.10. BS capacity in the TDD as function of the load decision threshold.

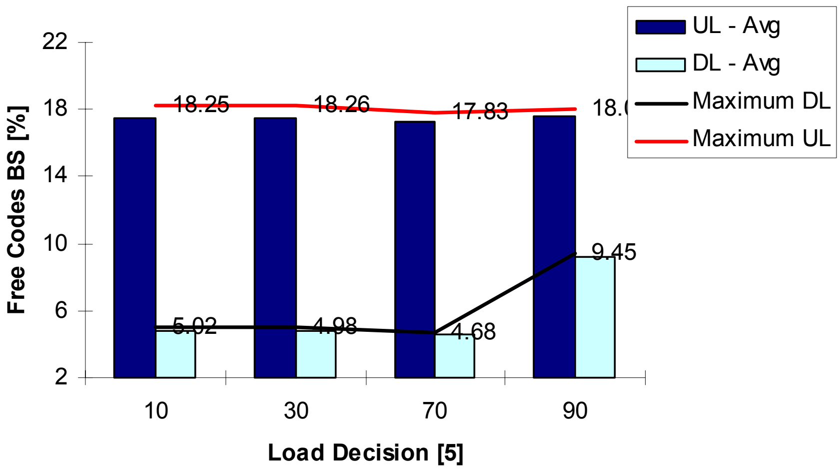


Figure I.11. Free codes BS in DL and UL links as function of the load decision threshold.

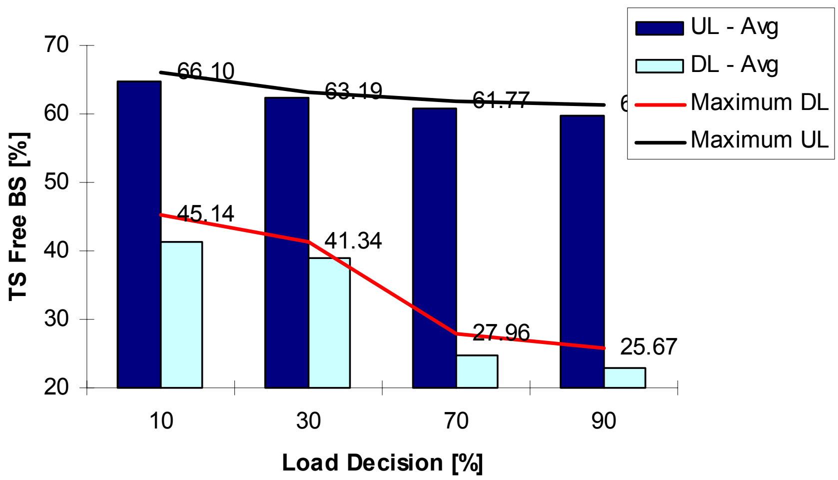


Figure I.12. TS free in BS for DL and UL links as function of the load decision threshold.

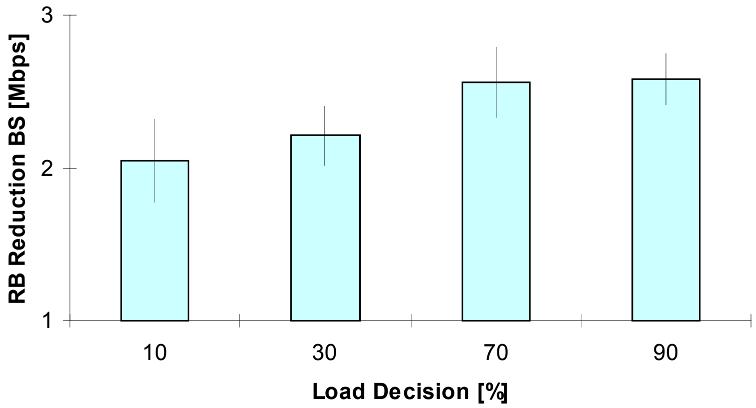


Figure I.13. Bit rate reduced in BS for DL as function of the load decision threshold.

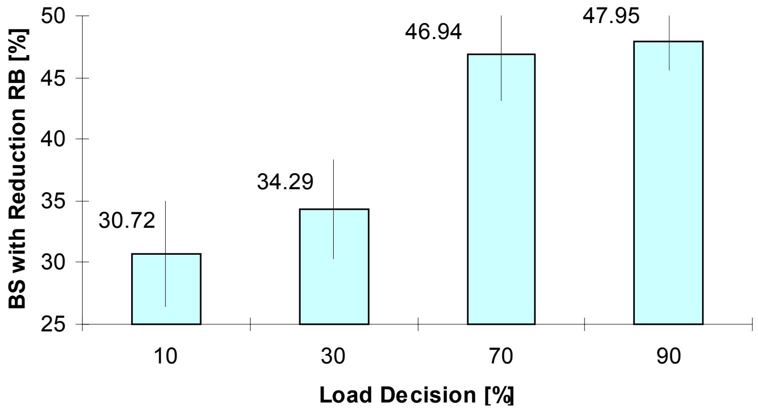


Figure I.14. BS with reduction of bit rate as function of the load decision threshold.

Annex J

Change off
Timeslot Asymmetry

In the current annex, all performance parameters (FDD and TDD mode) resulting from simulations to test the change of TS asymmetry are presented.

The objective of this annex is to present the results obtained for ten simulations of each scenario. TS asymmetry (optimisation algorithm input – simulator platform input) changes in each of ten simulations, from 11:1, 10:2, 9:3 (default value), 8:4, 7:5, 6:6, 5:7, 4:8, 3:9, 2:10 and 1:11. Other optimisation algorithm inputs, like, bit rate and load decision threshold have default values, 128 kbps and 30%, respectively.

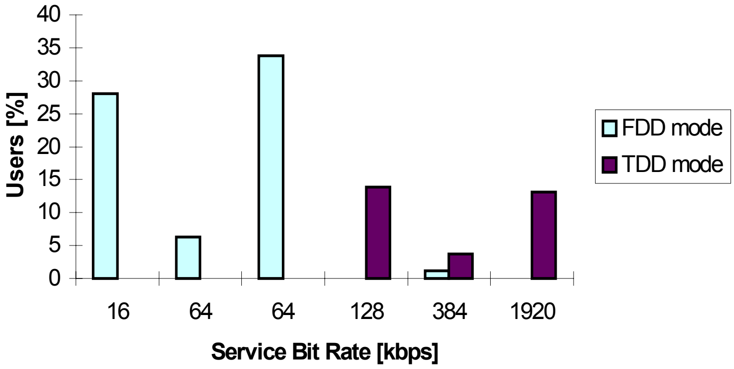


Figure J.1. Intermediate profile for all asymmetries.

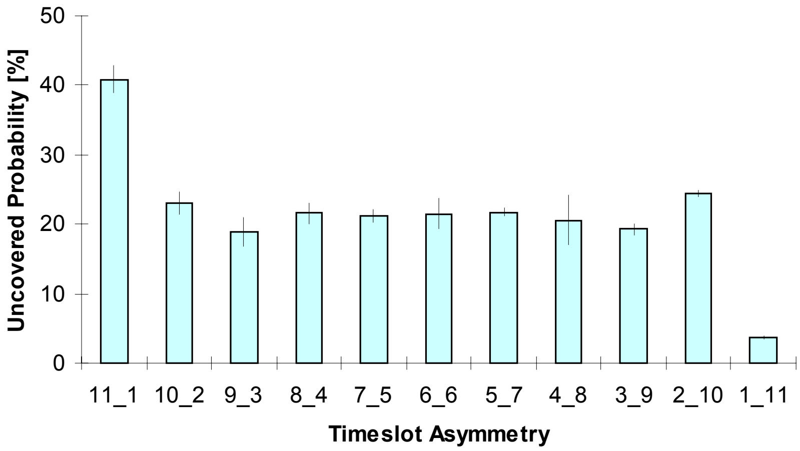


Figure J.2. Uncovered probability in the TDD as a function of TS asymmetry.

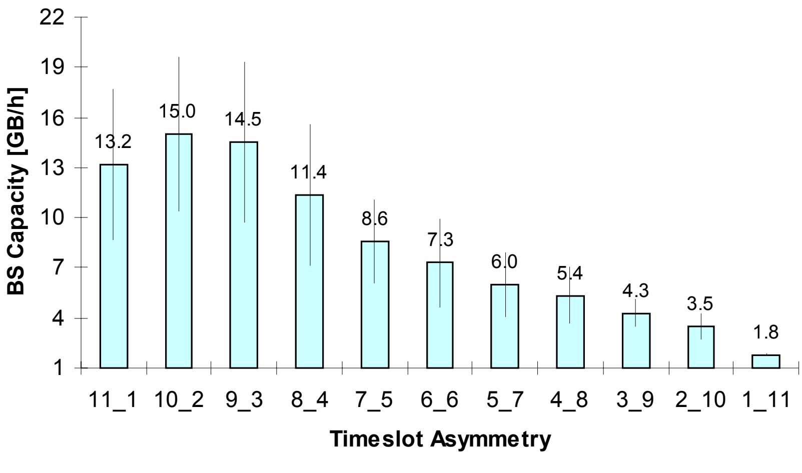


Figure J.3. BS capacity in the TDD as a function of TS asymmetry.

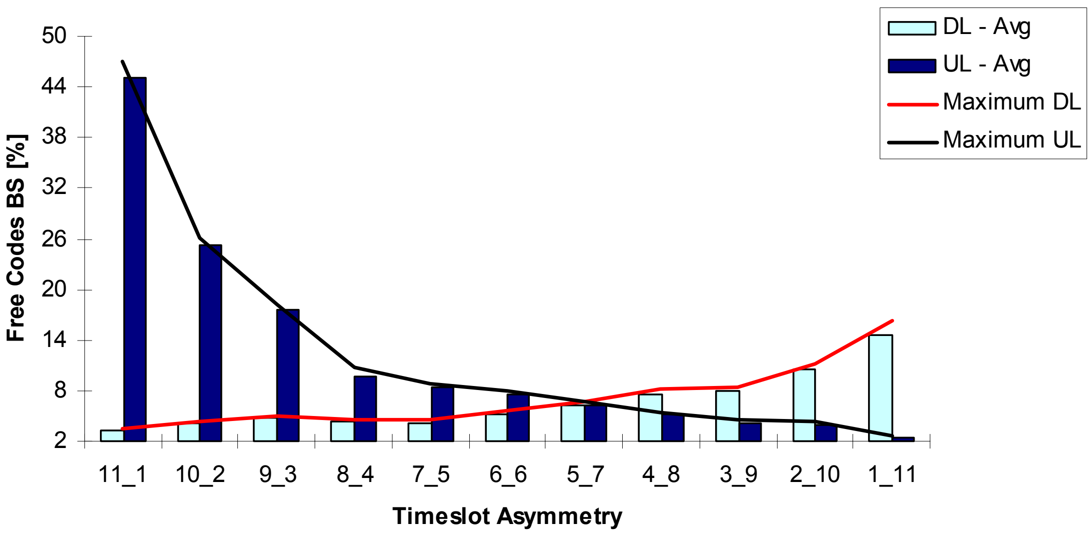


Figure J.4. Free codes BS in DL and UL links as a function of TS asymmetry.

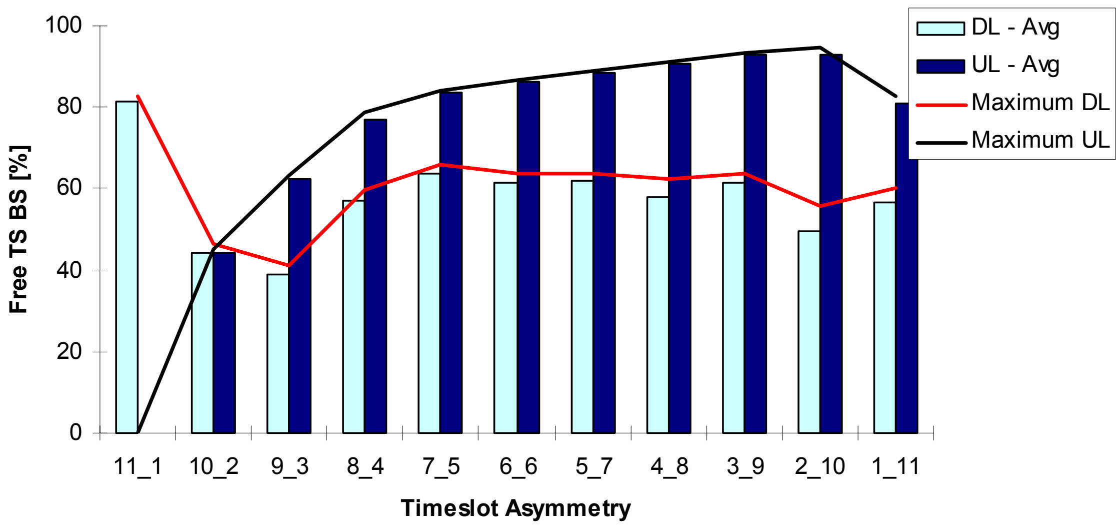


Figure J.5. TS free in BS for DL and UL as a function of TS asymmetry.

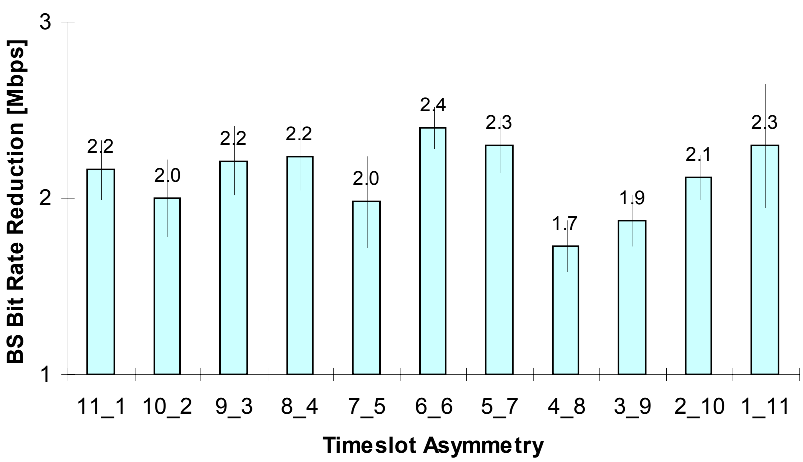


Figure J.6. Bit rate reduced in BS for DL as a function of TS asymmetry.

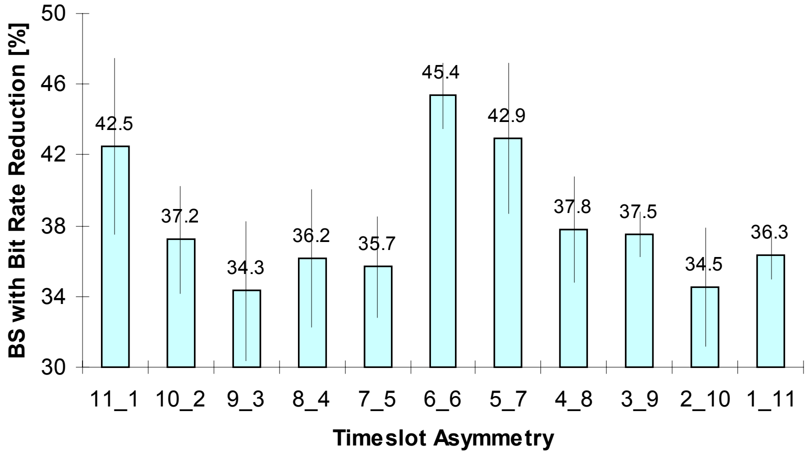


Figure J.7. BS with reduction of bit rate as a function of TS asymmetry.

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