Managing Capacity for a Real Multi-Service UMTS/HSPA Radio Access Network

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To my parents and sister
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Resumo

Atualmente existe uma elevada utilização das redes móveis, pelo que terá de existir gestão eficiente dos recursos da rede. Esta tese de mestrado surge com o objectivo de estudar e desenvolver uma plataforma de simulação multi-serviço baseada em curvas de admissão para redes de 3ª Geração (3G). Estas curvas definem o limite máximo de utilização dos recursos, para uma determinada Qualidade de Serviço (QoS) definida.

Para realizar este objectivo, foi estudado e implementado o modelo de Erlang-B Multidimensional. Os seus parâmetros de entrada são considerados, tendo em conta estatísticas reais. Depois, as curvas de admissão são apresentadas e validadas. As estatísticas usadas são de uma operador móvel real, o que implica estudar indicadores de desempenho (conhecidos por Key Performance Indicators (KPIs)) provenientes do fornecedor de equipamento específico da operadora.

São estudadas curvas de admissão para 4 células diferentes, e apresentam-se resultados diferentes no caso de estatísticas com ou sem fins de semana. No primeiro caso, os erro entre a posição das estatísticas e a curva de admissão rondam os 5,4% enquanto, no segundo caso, os erros diminuem para 2,5%. Outra análise realizada é relativa à potência de transmissão das Estação Base (EB). Existem células com 30% de potência a mais do que a necessária enquanto outras células têm uma escassez de 40% de potência. Contudo, o ritmo de transmissão de dados associada a cada utilizador é mais baixa do que a prometida pela operadora. No final, é feita uma análise da parametrização de potência na EB, sendo apresentado o seu valor otimizado, de acordo com o intervalo entre a curva de admissão e as estatísticas.

Palavras-chave: Redes Móveis, High Speed Packet Access, Capacidade, Modelo de Erlang-B Multidimensional
Abstract

Nowadays, the mobile networks utilization is high, which implies that an efficient resource network management must exist. This project has the goal to study and develop a simulation multi-service platform based on admission curves for Third Generation (3G) networks. These curves define the maximum limit of resource utilization for a certain defined Grade of Service (GoS).

To achieve this goal, the Multidimensional Erlang-B method is studied and implemented. Its input parameters are considered, taking into account real statistics. After, the admission curves are presented and validated. The used statistics are from a real mobile operator, which implies to study the Key Performance Indicators (KPIs) for the operator’s specific vendor.

4 different cells are studied and they show different results, depending on the input statistics. If they include weekend days, the error between the statistics position and the admission curve is around 5.4% while if they do not include weekend days, the error decreases to 2.5%. Another analysis is related with the Base Station (BS) transmit power. There are cells with 30% more power than necessary and other cells with 40% lack of power. However, the data rate assigned to each user is lower than the promised by the operator. In the end, an analysis of the BS parameterized power is performed, with the optimized value as output, according with the interval between the admission curve and the statistics.

Keywords: Mobile Networks, High Speed Packet Access, Capacity, Multidimensional Erlang-B Model
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List of Symbols

\( \alpha \)  Orthogonality factor

\( \beta \)  Soft Handover Overhead

\( \Delta I \)  Estimated increase of interference

\( \Delta n \)  Load factor of the new User Equipment (UE)

\( \Delta P_{\text{total}} \)  Load increase in the downlink

\( \delta \)  Blocking probability limit

\( \eta \)  Activity Factor

\( \lambda \)  Arrival rate

\( \mu \)  Service rate

\( \rho \)  Offered traffic for Erlang-B

\( AR \)  Admission Region

\( C \)  Number of circuits for Erlang-B

\( C_{\text{ch, SF, k}} \)  Channelization code

\( d \)  Duty Cycle

\( E_b/N_0 \)  Energy per bit to noise power spectral density ratio

\( E_c/I_0 \)  Energy per chip to interference level ratio

\( E_s/N_0 \)  Energy per symbol to noise power spectral density ratio

\( i \)  Interference from other cells to interference from own cell ratio

\( I_{\text{threshold}} \)  Interference threshold set by the radio network planning

\( I_{\text{total current}} \)  Interference estimation caused by the new UE

\( I_{\text{total}} \)  Received wideband interference power

\( I_{TTI} \)  Inter TTI interval
\( J \) \: Number of carriers

\( K \) \: Carrier capacity

\( L \) \: Auxiliary Blocking Probability

\( M \) \: Mapping Matrix

\( n \) \: Load Factor

\( n_{\text{DL,threshold}} \) \: Maximum downlink load factor increment

\( n_{\text{DL}} \) \: Load factor in downlink

\( n_{\text{UL,threshold}} \) \: Maximum uplink load factor increment

\( n_{\text{UL}} \) \: Load factor in uplink

\( \Delta n \) \: Load factor of the new UE

\( p_B \) \: Blocking probability from Erlang-B

\( P_{\text{CCH}} \) \: Power for CCH channels

\( P_{\text{DCH}} \) \: Power for DCH channels

\( P_{\text{DSCH-TX}} \) \: Power required for one user in HSDPA

\( P_{\text{DSCH-TX}} \) \: Used power for the HSDPA service

\( P_{\text{HSDPA}} \) \: Power allocated for HSDPA

\( P_{\text{max NodeB}} \) \: Maximum Node B transmission power

\( P_N \) \: Noise power

\( p_n \) \: Average probability of a UE being in a \( n \)-way soft handover

\( P_{\text{threshold}} \) \: Power threshold set by the radio network planning

\( P_{\text{total}} \) \: Power for all services of 3G

\( P_{\text{TOT Non HS}} \) \: Power for non HSDPA services

\( R \) \: Data rate

\( R_{\text{achievable (MAC-hs)}} \) \: Date rate achievable according with the CQI

\( R_{\text{MAC-d}} \) \: Bit rate on MAC layer

\( R_{\text{target}} \) \: Target data rate

\( S \) \: Number of services

\( V_{\text{TBS}} \) \: Transport Block Size (TBS)
W Chip Rate
Y Normalization constant in Multidimensional Erlang-B Method
Acronyms

2G Second Generation
3G Third Generation
3GPP 3rd Generation Partnership Project
4G Fourth Generation
ACI Adjacent Channel Interference
ACK Acknowledgement
AICH Acquisition Indication Channel
AMR Adaptive Multirate
ARQ Automatic Repeat Request
ATM Asynchronous Transfer Mode
BCCH Broadcast Control Channel
BCH Broadcast Channel
BLER Block Error Rate
BPSK Binary Phase-Shift Keying
BS Base Station
BSIC Base Station Identity Code
BTS Base Transceiver Station
CCCH Common Control Channel
CCH Control Channel
CCI Co-Channel Interference
CDF Cumulative Distribution Function
CDMA  Code Division Multiple Access
CN   Core Network
CPCH  Common Packet Channel
CPICH Common Pilot Channel
CQI   Channel Quality Indicator
CS   Circuit Switch
CTCH  Common Traffic Channel
DCCH  Dedicated Control Channel
DCH  Dedicated Transport Channel
DPCCH Dedicated Physical Control Channel
DPCH Dedicated Physical Channel
DPDCH Dedicated Physical Data Channel
DSCH Downlink Shared Channel
DTCH Dedicated Traffic Channel
E-AGCH E-DCH Absolute Grant Channel
E-DCH Enhanced DCH
E-DPCCH Enhanced DPCCH
E-DPDCH Enhanced DPDCH
E-HICH E-DCH Hybrid ARQ Indicator Channel
E-RGCH E-DCH Relative Grant Channel
EFP Erlang Fixed Point
FACH Forward Access Channel
FEC Forward Error Correction
GBR Guaranteed Bit Rate
GGSN Gateway General Packet Radio Service (GPRS) Support Node
GMSC Gateway MSC
GoS Grade of Service
GPRS  General Packet Radio Service
GSM  Global System for Mobile Communications
HARQ  Hybrid ARQ
HLR  Home Location Register
HS-DPCCH  High-Speed Dedicated Physical Control Channel
HS-DSCH  High Speed Downlink Shared Channel
HS-PDSCH  High-Speed Physical Downlink Shared Channel
HS-SCCH  High Speed Shared Control Channel
HSDPA  High-Speed Downlink Packet Access
HSPA+  Evolved High Speed Packet Access
HSUPA  High-Speed Uplink Packet Access
ITU  International Telecommunication Union
KPI  Key Performance Indicator
LTE  Long Term Evolution
MAC  Medium Access Control
MCCH  MBMS point-to-multipoint Control Channel
ME  Mobile Equipment
MSC  Mobile Switching Center
MSCH  MBMS point-to-multipoint Scheduling Channel
MTCH  MBMS point-to-multipoint Traffic Channel
NACK  Negative Acknowledgement
OVSF  Orthogonal Variable Spreading Factor
PCCH  Paging Control Channel
PCCPCH  Primary Common Control Physical Channel
PCH  Paging Channel
PICH  Paging Indicator Channel
PS Packet Switch

QCI QoS Class Identifier

QoS Quality of Service

QPSK Quadrature Phase Shift Keying

RAB Radio Access Bearer

RACH Random Access Channel

RAN Radio Access Network

RLC Radio Link Control

RNC Radio Network Controller

RNS Radio Network Sub-System

RRM Radio Resource Management

SCCPCH Secondary Common Control Physical Channel

SCH Synchronisation Channel

SF Spreading Factor

SGSN Serving General Packet Radio Service (GPRS) Support Node

SHCCH Shared Channel Control Channel

SHO Soft Handover Overhead

SIR Signal-to-Interference Ratio

TBS Transport Block Size

TFCI Transport Format Combination Indicator

TFI Transport Format Indicator

TTI Transmission Time Interval

UE User Equipment

UMTS Universal Mobile Telecommunications System

USCH Uplink Shared Channel

USIM UMTS Subscriber Identity Module
**UTRAN**  UMTS Terrestrial Radio Access Network

**VLR**  Visitor Location Register

**WCDMA**  Wideband Code Division Multiple Access
Chapter 1

Introduction

This chapter describes the motivation of this project and respective goal. The structure is also described here.

1.1 Motivation

Currently, Third Generation (3G) has a penetration around 80% worldwide, and 85% penetration is expected in 2020 [1], see Figure 1.1. The 3G coverage also depends on the radio environment: in urban areas, the coverage was around 89% in 2015 while, in rural areas, was just around 29% [2]. In fact, the used traffic from the network is increasing, and the operators will have to manage the increasing capacity.

Moreover, the data rates claimed by the subscribers are also higher, asking for a greater effort from the operators to answer all these needs.

Another claim is related with the admission control and quality, since users are required to have low call dropping and call blocking ratios.

Hence, the operator has to improve the management of the network resources. An used technique is the admission control, approached in this thesis. The admission control will define a curve, which is
resource limited. This curve will depend on the required Quality of Service (QoS) and on the desired blocking probability.

The admission region will also control usage between services, since, in 3G, there are services like voice, streaming or HSDPA, therefore a real multi-service working platform.

### 1.2 Objectives

This thesis addresses the need to manage the BS capacity, helping with congestion control and QoS provisioning [3].

The result will be an admission control curve, depending on some cell characteristics, which will be defined throughout the thesis. The curve will balance traffic between two services.

To the admission curve representation, real network performance statistics from the respective BS will be added, in order to compare the theoretical capacity curve with the real BS behaviour. This will help to understand if the BS has more or less radiating power than it should, or if the target data rate is too ambitious.

To perform the simulations, the software Matlab 2015a © and the Visual Studio © were used.

### 1.3 Thesis Outline

This document is organized as follows: the chapter 2 overviews Wideband Code Division Multiple Access (WCDMA), the system architecture and also the HSDPA and High-Speed Uplink Packet Access (HSUPA) technologies; the chapter 3 describes the radio network planning and radio network management; the chapter 4 will present and discuss four admission control methods; in chapter 5, the implementation of the algorithm with cell characteristics is shown as well as the traffic determination from the real statistics; the chapter 6 presents the results of different scenarios and BSs and, in chapter 7, conclusions will be drawn.

### 1.4 Publications

One paper was written under this thesis work, which was submitted to the 10th congress of the Portuguese Committee of Union Radio-Scientific Internationale (URSI), in Lisbon, Portugal, on 18th of November of 2016:

Chapter 2

WCDMA System Architecture

In this chapter, the WCDMA will be introduced and some aspects of Universal Mobile Telecommunications System (UMTS) network and architecture will be addressed. Another aspects that will be described are the network layers, such as the physical and data link layers, and the respective channels, the Radio Resource Management methods and the coverage and capacity performance. Finally, HSDPA and HSUPA will also be addressed.

Most of the information is based on [4].

2.1 Introduction to WCDMA

WCDMA is the adopted air interface in 3G, in particular in UMTS, aiming to improve communication quality, high quality image and video transfer and to achieve higher data rates. Some requirements are, for example, transmission rates up to 2 Mbit/s and the coexistence with the Second Generation (2G) systems (Release 99).

UMTS started to use the following spectrum: from 1920 MHz to 1980 MHz, for uplink, and from 2110 MHz to 2170 MHz, in the downlink. However, new bands were added by International Telecommunication Union (ITU), such as 806 MHz to 960 MHz, 1710 MHz to 1885 MHz and 2500 MHz to 2690 MHz [5]. Also, UMTS can be deployed in the frequency bands of the 2G.

Through the years, some releases were developed, starting with Release 99, followed by Releases 5 up to 8, see Figure 2.1.

![Figure 2.1: Standardization and commercial operation schedule for WCDMA and its evolution (based on [4]).](image-url)
The Release 99 was responsible for the first UMTS deployment, using Code Division Multiple Access (CDMA). The Release 5 integrated the HSDPA technology and the Release 6 upgraded the system with the HSUPA technology. The last two releases, 7 and 8, introduced the Evolved High Speed Packet Access (HSPA+) and Long Term Evolution (LTE), respectively. The achieved bit rates for each release are shown in the Table 2.1.

### Table 2.1: Bit rates for each release (source: [4]).

<table>
<thead>
<tr>
<th>Release</th>
<th>Bit Rate Uplink [Mbit/s]</th>
<th>Bit Rate Downlink [Mbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>0.384</td>
<td>0.384</td>
</tr>
<tr>
<td>5</td>
<td>0.384</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>5.7</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>28</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>160</td>
</tr>
</tbody>
</table>

Release 99 has some services such as person-to-person services and content-to-person services. The person-to-person services can be Circuit Switch (CS), where the Adaptive Multi-rate (AMR) voice is included, with bit rates from 4.75 kbit/s to 12.2 kbit/s, and Packet Switch (PS), where it is included the conversational, streaming, interactive and background classes, with bit rates of 8, 16, 32, 64, 128, 144, 256 and 384 kbit/s. The content-to-person services are all PS and includes functions such as web browsing, audio and video streaming. It exists service prioritization, where the voice is normally the highest priority service, followed by person-to-person PS services and finally, content-to-person services.

### 2.2 System Architecture

The logical network elements are organized by similar functionality. The network elements are grouped in the following way:

- **User Equipment (UE);**
- **Radio Access Network (RAN);**
- **Core Network (CN).**

The **UE** is the device available at the end-user. It has two parts: the Mobile Equipment (ME) and the UMTS Subscriber Identity Module (USIM). The ME is the device itself and the USIM is the SIM card.

The **RAN**, in UMTS, is called UMTS Terrestrial Radio Access Network (UTRAN). The main goals and characteristic are the radio functionalities, like Soft Handover and Radio Resource Management (RRM) algorithms, but also:

- To combine the CS and PS services, using the air interface protocol and the connection from UTRAN to the CN;
• To ensure Global System for Mobile Communications (GSM) compatibility, in order to avoid the acquisition of more equipment;

• To use Asynchronous Transfer Mode (ATM) transmission as the main mechanism in UTRAN transport;

• The utilization of IP-based transport as an alternative transport mechanism from the Release 5 of UMTS.

UTRAN is composed of one or more Radio Network Sub-System (RNS). A RNS has one Radio Network Controller (RNC) and one or more NodeBs. The NodeB manages the data flow between the interface Iub and Uu. The RNC is responsible to control the NodeBs which are connected to it.

The **CN** responsibility is to switch and route the calls and also to act as the connection to external networks. The main elements are:

• Home Location Register (HLR);

• Mobile Switching Center (MSC) / Visitor Location Register (VLR);

• Gateway MSC (GMSC);

• Serving General Packet Radio Service (GPRS) Support Node (SGSN), where GPRS General Packet Radio Service;

• Gateway General Packet Radio Service (GPRS) Support Node (GGSN).

In the logical network of UMTS, the interfaces are defined as following:

• Cu interface - between the ME and the USIM;

• Uu interface - responsible to connect the mobile part to the fixed part of the network. It connects the UE with the RAN;

• Iu interface - associates the RAN to the CN;

• Iur interface - responsible to assure the soft handover between RNCs;

• Iub interface - links the NodeB with the RNC.

In Figure 2.2, it is noticeable the location of the network elements and the interfaces that connect them.
2.3 Radio Interface Architecture

The radio interface is divided into three layers [6]:

- Layer 1 - Physical Layer;
- Layer 2 - Data Link Layer (where it is included the Medium Access Control (MAC) and the Radio Link Control (RLC));
- Layer 3 - Network Layer.

Figure 2.3 presents the layers and their interactions for UMTS.

Between the Physical Layer and the Data Link Layer, the transfer is done on the transport channels, and they are characterized by how and with what kind of characteristics data is transferred. Additionally,
in the Data Link Layer, it contains logical channels, which are characterized by what type of data is transmitted.

### 2.3.1 Physical Layer

The main responsibility of the physical layer is to transport data services to the MAC and higher layers. Other functions are [7]:

- Soft handover;
- Error detection;
- Forward Error Correction (FEC) encoding / decoding of transport channels;
- Frequency and time synchronization.

The physical layer has transport channels, which are mapped in the physical channels, as illustrated in Figure 2.4.

#### Transport Channels

The created data in higher levels is carried by the transport channels. Each transport channel is accompanied by Transport Format Indicator (TFI), with the information of the arriving time of a specific transport channel, from the higher levels. In the physical layer, all the information from TFI is combined into the Transport Format Combination Indicator (TFCI). The TFCI is sent in the physical control channel, in order to inform the receiver which transport channels are available.

There are two types of transport channels: dedicated channels and common channels. The first ones are identified by one code, one frequency and each one is only used by one user. The common channels are shared with all the users in one cell. They are listed in the following page [8].
• Dedicated Channels
  – Dedicated Transport Channel (DCH) is used to carry user or control information between the UTRAN and the UE.

• Common Channels
  – Broadcast Channel (BCH) works in downlink in order to transport information from the UTRAN, such as random access codes and access slots in the cell, to all the terminals in the cell. The BCH is transmitted with a low fixed bit rate;
  – Forward Access Channel (FACH) works also in downlink and it is responsible to carrier control information to the terminals in a given cell. The FACH uses slow power control;
  – Paging Channel (PCH) is used in downlink and it is useful to carry information related with the paging procedure;
  – Random Access Channel (RACH) is a shared channel used to send control information from the terminal to the network;
  – Uplink Shared Channel (USCH) carries dedicated control or traffic data;
  – Downlink Shared Channel (DSCH) was only used in Release 99 and 4, always associated with a DCH, was shared with all the users and it transported dedicated user data or control information.

Physical Channels

There are several physical channels, as shown in Figure 2.4. They are listed below [9]:

• Primary Common Control Physical Channel (PCCPCH), which is always broadcasting the system identification and the access control information;

• Secondary Common Control Physical Channel (SCCPCH), carrying control information and messages for UEs registered in the network;

• Dedicated Physical Data Channel (DPDCH), used to transmit user data;

• Dedicated Physical Control Channel (DPCCH), used to transfer control information;

• Synchronisation Channel (SCH), necessary to the UEs to be able to synchronize with the network;

• Common Pilot Channel (CPICH), transmitted by the NodeB to all the UEs to determine the time that the signal demodulation will take.

Some of these physical channels are only for control and signalling information, such as the CPICH, SCH, PCCPCH, SCCPCH, RACH, Acquisition Indication Channel (AICH) and Paging Indicator Channel (PICH). These control channels require specific power and specific channelization codes.
2.3.2 Data Link Layer

Medium Access Control (MAC)

The MAC layer is included in the Data Link Layer and some functions are [10]:

- Mapping between logical and transport channels;
- Selection of appropriate Transport Format for each Transport Channel depending on instantaneous source rate;
- Priority handling between data flows of one UE;
- Priority handling between UEs by means of dynamic scheduling.

As in Figure 2.3, the MAC layer transports the data on logical channels, which can be control channels or traffic channels. The control channels are:

- Broadcast Control Channel (BCCH), responsible for broadcasting the system control information;
- Paging Control Channel (PCCH), used to transfer paging information;
- Common Control Channel (CCCH), used to transmit control information between the network and the UE;
- Dedicated Control Channel (DCCH), necessary for transmitting dedicated control information between the network and the UE;
- Shared Channel Control Channel (SHCCH);
- MBMS point-to-multipoint Control Channel (MCCH);
- MBMS point-to-multipoint Scheduling Channel (MSCH).

The transport channels are:

- Dedicated Traffic Channel (DTCH);
- Common Traffic Channel (CTCH);
- MBMS point-to-multipoint Traffic Channel (MTCH).

Similarly to layer 1, where the transport channels are mapped on the physical channels, in the MAC layer, the logical channels are mapped on the transport channels, as seen in Figure 2.5.
Radio Link Control (RLC)

The RLC is also included in the Layer 2 and the main functions are [11]:

- Segmentation and reassembly;
- Concatenation;
- Padding;
- Transfer of user data;
- Duplicate detection;
- Flow control.

2.4 Channelization Codes

When a transmission from a single source occurs, channelization codes are introduced, in order to distinguish the users. The codes are based on Orthogonal Variable Spreading Factor (OVSF), allowing the Spreading Factor (SF) to be changed without modifying the orthogonality between codes. For that, it is possible to make a channelization code tree, where each level has a different SF, as shown in Figure 2.6.

The SF is the ratio between the chip rate and the information rate. In UMTS, the chip rate is equal to 3.84 Mchip/s [13]. As in Figure 2.6, the available number of codes depends on the SF, which means that if it uses a SF of 4, only 4 codes are available, but if the SF is 128, the available number of codes is 128. So, the maximum number of codes is a limitation for the maximum number of users served at the same time. Moreover, a single user can use one or more codes [14].

Each channelization code is defined by $C_{ch, SF, k}$, where SF is the Spreading Factor of the code and $k$ is the code number, between 0 and SF-1.

The control channels also use codes, and some of them are allocated in a specific channelization code, which also depends if it is used in uplink or in downlink. For example, in uplink, the DPCCH always
Code allocation deals with the problem of how different codes are allocated to different connections. The channelization codes used for spreading are Orthogonal Variable Spreading Factor (OVSF) codes that preserve the orthogonality between a user's physical channel [1].

The OVSF code is shown in Fig. 1. Each level in the code tree is described as $C_{SF, code}$, where the spreading factor (SF) is ranging from 4 to 512 for the chip rate of 4.096 Mcps. A code can be assigned to a UE if and only if no other code on the path from the specific code to the root of the tree or in the sub-tree below the specific code is assigned.

![Figure 1: Code-tree for generation of Orthogonal Variable Spreading Factor (OVSF) codes](source: [12]).

For example, a random assignment of large-SF codes to low data rate channels may preclude a large number of small-SF codes. It inefficiently limits the number of remaining codes that could be used by other users. On the contrary, it will be advantageous to assign:

- $C_{4,1} = (1,1,1,1)$
- $C_{4,2} = (1,1,-1,-1)$
- $C_{4,3} = (1,-1,1,-1)$
- $C_{4,4} = (1,-1,-1,1)$
- $C_{8,1}$
- $C_{8,2}$
- $C_{8,3}$
- $C_{8,4}$

Figure 2.6: Channelization Code Tree (source: [12]).

The modulation and the coding rate causes differences in the data rate. The higher the modulation and the coding rate are, the higher the data rate [15]. That depends on the bits that each symbol carries, for example, the Binary Phase-Shift Keying (BPSK) carries one bit per symbol and the Quadrature Phase Shift Keying (QPSK) carries two bits per symbol, which means that, with QPSK, it is possible to double the BPSK bit rate.

The uplink direction has an I/Q code multiplexing, since it uses the DPDCH and DPCCH [16]. The DPCCH has a fixed SF of 256 but the DPDCH has a variable SF from 4 to 256 and respective data rate is informed by the DPCCH. The modulation used in uplink is the BPSK [17].

The data rate depends on the number of codes that are used. If it is used a single code, the maximum user data rate is 960 kbit/s, with a SF of 4, which corresponds to a user throughput of around 450 kbit/s. To increase the data rate, it is necessary to use parallel code channels, with a maximum of 6. This will increase the data rate until 2 Mbit/s, with coding rate of 1/2.

In the downlink direction, the information is transmitted in the downlink DCH, mapped in the Dedicated Physical Channel (DPCH) (control or data). The downlink DPCH can use closed-loop or open-loop transmit diversity. The closed-loop transmit diversity uses the feedback information from the UE to adapt the weights of the BS in order to maximize the received power in the UE and to reduce the interference. In the open-loop transmit diversity, the information is coded and sent from multiple antennas, avoiding the signalling overhead, sent from the UEs [18].

The modulation, in this case, is the QPSK [17]. The data rate depends also on the SF, which can be from 4 until 512, and the variation of the data rate is between 936 kbit/s, with 1/2 rate coding with
spreading code 4, (which can be higher with 4 parallel codes, up to 2.8 Mbit/s) until 1 to 3 kbit/s, with spreading 512.

2.6 High-Speed Downlink Packet Access

HSDPA was included in Release 5 of UMTS and it aims to increase the packet data throughput, reduce delay and achieve high peak rate, with adaptive modulation and hybrid Automatic Repeat Request (ARQ) [19]. The modulation in HSDPA starts with QPSK but it is introduced 16-QAM modulation [20]. HSDPA also uses link adaptation, i.e., it adjusts the modulation and the coding parameters in every Transmission Time Interval (TTI), which is 2 ms long.

In HSDPA, the downlink scheduling was moved from the RNC to the NodeB. With this change, the scheduling decisions are made with minimum latency, closer to the radio interface.

Aside the channels from Release 99 that are also used in Release 5, such as DCH, DSCH and FACH, new transport and physical channels appeared with Release 5. The transport channel that carries the data is called High Speed Downlink Shared Channel (HS-DSCH). The new downlink physical channels are High Speed Shared Control Channel (HS-SCCH) and High-Speed Physical Downlink Shared Channel (HS-PDSCH) and the new uplink physical channel is High-Speed Dedicated Physical Control Channel (HS-DPCCH) [8, 16]. The HS-SCCH is the channel that carries the physical layer information necessary to decode the data from High Speed Downlink Shared Channel (HS-DSCH), the HS-PDSCH is used to carry the HS-DSCH and the HS-DPCCH has the information related to the Automatic Repeat Request (ARQ) acknowledgements (Acknowledgement (ACK) and Negative Acknowledgement (NACK)) and downlink Channel Quality Indicator (CQI).

The HS-SCCH has a SF equal to 128 and the SF of the data channel HS-DSCH is always equal to 16. Each channelization code corresponds to one HS-PDSCH code, with a maximum of 15, since the last code is used for signaling. One user can use 1 code up to 15 codes, at the same TTI, however it is usual to spend 5, 10 or 15 codes. This means that, in the minimum, there is only one HSDPA user, when the user needs 15 HS-PDSCH codes and, in the maximum, 3 HSDPA users, when each user utilizes 5 HS-PDSCH codes [21].

As mentioned, in the downlink direction is carried the data and, in the uplink, is carried control information. This control information consists in CQI, which has a HS-DSCH sub-frame with the Transport Block Size (TBS), the number of HS-PDSCH codes and the modulation. The Transport Block Size (TBS) and the maximum number of HS-PDSCH codes depends also on the mobile category, which will introduce the minimum inter-TTI interval as well. This interval is the time that is necessary for the ME to decode, between the beginning of the TTI and the beginning of the following TTI. The CQI depends on the propagation conditions and on the distance from the ME to the BS [22].

With the information from the CQI, it is possible to calculate the achievable maximum data rate \( R_{\text{achievable\ max}} \), given by:

\[
R_{\text{achievable\ max}} = \frac{V_{\text{TBS}}}{0.002 \times I_{\text{TTI\ min}}} \tag{2.1}
\]
where $I_{TTI\min}$ is the minimum inter-TTI interval and $V_{TBS}$ is the transport block size.

In Table 2.2, there are examples of different mobile categories and respective maximum number of HS-PDSCH codes, minimum inter-TTI interval and $V_{TBS}$. This represents how the data rate on the HS-DSCH can change every TTI, with the reported CQI.

<table>
<thead>
<tr>
<th>Category</th>
<th>Max HS-PDSCH codes</th>
<th>Min inter-TTI interval</th>
<th>$V_{TBS}$ [bits]</th>
<th>$R_{achievable\ max}$ [Mbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>3</td>
<td>7 298</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>2</td>
<td>7 298</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1</td>
<td>7 298</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>1</td>
<td>14 411</td>
<td>7.2</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>1</td>
<td>27 952</td>
<td>14.4</td>
</tr>
</tbody>
</table>

In HSDPA, the data transmission does not occupy the channel all the connection time, but only a data burst. This means that the data is transmitted during a couple of milliseconds and then the user leaves the channel [23]. In real life, this can be exemplified as the opening of a web page. When it is clicked to open, all the data is downloaded to the browser and, in the following seconds or minutes, the user is seeing the content, without downloading more data. This concept does not exist in voice, as seen.

Since the data burst exists, it can happen that the channel is completely free for some time, if no user allocated to that BS is downloading data. On the other side, since each user only consumes a couple of TTIs, it is possible to allocate a lot of users, because the HS-PDSCH codes are only allocated to the UE when the user is downloading data. Otherwise, the UE is allocated to a downlink code from the control channels.

Since the UTRAN has to take in consideration the UE capabilities, some parameters of terminal radio access capabilities are defined by 3rd Generation Partnership Project (3GPP). Some of this parameters are related with the Physical Layer, such as [24]:

- The maximum sum of bits of all transport blocks being received at a time instant (from the DCH, FACH, PCH and DSCH transport channels);
- The maximum number of simultaneous transport channels, since the UE has process limitation;
- The maximum number of transport blocks received within TTIs that end within the same 10 ms interval;
- The maximum number of bits of a HS-DSCH transport block received within a HS-DSCH TTI;
- The maximum number of DPCH codes to be simultaneously received;
- The minimum inter-TTI interval in HS-DSCH, which is the distance between the beginning of a TTI and the beginning of the following one;
- Support of 2 ms TTI for E-DCH;
Some of the capabilities depend on the UE category, such as the minimum inter-TTI interval, which are available in the tables from the technical specification [25]. Depending on the UE category, it is possible to say what modulation can be used, and also the number of HS-DSCH codes.

2.7 High-Speed Uplink Packet Access

HSUPA was designed to have identical functions in the uplink as the HSDPA introduced in the downlink. However, it does not have adaptive modulation because it does not support high order modulation schemes.

The channels DCH, Common Packet Channel (CPCH) and RACH, from Release 99, are also used in Release 6, but it is also introduced the transport channel Enhanced DCH (E-DCH), the uplink physical channels Enhanced DPDCH (E-DPDCH) and E-DPCCH and the downlink physical channels E-DCH Absolute Grant Channel (E-AGCH), E-DCH Relative Grant Channel (E-RGCH), E-DCH Hybrid ARQ Indicator Channel (E-HICH).

The E-DCH is the uplink transport channel that carries the user data and it is allocated to each user, totally independent from the others UEs. It is mapped to the uplink physical channels mentioned before. The E-DPDCH just carries the user data while the E-DPCCH carries the control information related with E-DPDCH, retransmission information and information related with the data rate.

In the downlink direction, the channels help with the introduction of Hybrid ARQ (HARQ) feedback and to facilitate uplink scheduling. The E-AGCH is a shared channel that provides more available data rate to the UE, in case that data rate has to be increased for a certain amount of time. The E-RGCH and E-HICH are dedicated channels and the responsibilities are increasing or decreasing the uplink transmission rate and informing the UE about the reception of a packet in the Base Transceiver Station (BTS), respectively [26].

The HSUPA NodeB scheduler has some operations such as:

- It measures the noise level in the BS in order to decide if it is necessary to allocate more traffic or to readjust the data rates of the users;

- It checks the uplink feedback to see if any user can transmit in higher bit rates, depending on the buffer status or the transmit power available;

- The scheduler can also choose which users need a readjust of the data rate, depending on the priorities from the RNC.

The RNC, in HSUPA, must inform the BS about the maximum data rate that each user has subscribed and it also can set different priorities, depending on the used service.
Chapter 3

Radio Network Planning and Management

3.1 Radio Network Planning

3.1.1 Power Allocation

The BS is parameterized with a maximum transmit power, $P_{\text{Total}}$, which has to be divided by all the transport channels. Without HSDPA, this division is between the dedicated channels, $P_{\text{DCH}}$ and the control channels, $P_{\text{CCH}}$, so:

$$P_{\text{total}} = P_{\text{DCH}} + P_{\text{CCH}}$$

(3.1)

The $P_{\text{CCH}}$ is calculated as the sum of the parameterized values of each downlink control channel. In [4] there are some typical values for the power of the downlink control channels, and they are enumerated in the Table 3.1.

<table>
<thead>
<tr>
<th>Downlink Common Channel</th>
<th>Power Relative to CPICH [dB]</th>
<th>Activity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPICH</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Primary SCH</td>
<td>-3</td>
<td>10</td>
</tr>
<tr>
<td>Secondary SCH</td>
<td>-3</td>
<td>10</td>
</tr>
<tr>
<td>PCCPCH</td>
<td>-5</td>
<td>90</td>
</tr>
<tr>
<td>PICH</td>
<td>-8</td>
<td>100</td>
</tr>
<tr>
<td>AICH</td>
<td>-8</td>
<td>100</td>
</tr>
<tr>
<td>SCCPCH</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

With HSDPA, there will be another parameter related with the power available for that service, $P_{\text{HSDPA}}$, so the total power, $P_{\text{Total}}$, is defined as equation (3.2) [27].
\[ P_{total} = P_{HSDPA} + P_{DCH} + P_{CCH} \] (3.2)

However, the voice is normally a priority service, when related with PS and HSDPA services [28]. This implies that there is only enough power available for HSDPA after the voice users being served. Additionally, the power for each service floats along time, as shown in Figure 3.1.

![Figure 3.1: Power allocation for CCH, DCH and HSDPA (based on [29]).](image)

The control channels always have priority, using always the same power.

### 3.1.2 Capacity Upgrade Paths

The downlink capacity of a BS has to be verified and optimized regularly, and, in extreme cases, when the traffic increases, it must be upgraded in different ways:

- Increasing the BS maximum transmission power [30], without raising the control channels power. As in Figure 3.2, the traffic increases with the increase of the maximum downlink transmit power;

![Figure 3.2: Antenna diversity gain with branch reception for the case of constant maximum transmit power of the mobile (based on [31]).](image)

- More power amplifiers if the power amplifier is split between sectors;
• Two or more carriers if the operator’s frequency allocation allows. In Figure 3.3 is possible to analyse the capacity progression with the number of carriers and with the number of power amplifiers;

![Figure 3.3: Capacity upgrade path for 3-sector macro site (based on [4]).](image)

• Transmit diversity with a second power amplifier per sector. It is possible to see in Figure 3.4 the relation between the gain in dB with the diversity of antennas.

![Figure 3.4: Antenna diversity gain with branch reception for the case of constant maximum transmit power of the mobile (based on: [4]).](image)
3.1.3 Erlang Traffic Model

The voice traffic is measured in Erlangs, which is the basic unit in telecommunications. As in [32], an Erlang "represents the amount of traffic intensity carried by a channel that is completely occupied (i.e. 1 call-hour per hour or 1 call-minute per minute). For example, a radio channel that is occupied for thirty minutes during an hour carries 0.5 Erlangs of traffic".

Usually, the traffic is measured in the busy hour, which is the hour of the day, in the busiest time of the year, when the network is highly loaded. This helps in the network planning, to make sure that there is enough capacity to serve almost all the users in that busy hour.

To calculate the traffic of a channel, there are other two concepts, which are GoS and circuits. The GoS, or blocking probability, is the probability that all channels will be busy when a phone call is made.

With the traffic and the number of circuits, it is possible to calculate the blocking probability. For that, the formula of Erlang-B was defined as:

\[
p_B = \frac{\rho^C}{\sum_{x=0}^{C} \frac{\rho^x}{x!}}
\] (3.3)

where \(p_B\) is the blocking probability, \(\rho\) is the offered traffic and \(C\) is the number of circuits [33].

There are two other ways to define the traffic, in Erlangs, which are related with the occupation of the circuits. The first one is defined as the ratio between the arriving call rate and the completed calls rates:

\[
\rho [\text{Erlang}] = \frac{\text{Call arrive rate [calls/s]}}{\text{Call departure rate [calls/s]}}
\] (3.4)

The other one is simply the number of user calls multiplied by the average time that each user occupies the circuit (holding time):

\[
\rho [\text{Erlang}] = \text{Users} \times \text{Circuits Utilization Time}
\] (3.5)

where \(\text{Users}\) is the finite number of users and \(\text{Circuits Utilized Time}\) is the fraction of utilized time of the circuit [34].

The Erlang-B model can only be used if the capacity is hard blocked, i.e., the system capacity is limited by the amount of hardware. If the system is soft capacity limited, which means that it is limited by the interference, the Erlang-B model will give pessimistic results.

The Erlang-B model can be called as the follow:

\[
\rho(C, \delta)
\] (3.6)

where \(\delta\) is the blocking probability limit, or by:

\[
p_B(C, \rho).
\] (3.7)
3.2 Radio Resource Management

The RRM algorithms are necessary for an efficiency utilization of the air interface resources. Some algorithms will be discussed here, such as Power Control, Handover, Measurement of Air Interface Load, Admission Control and Load Control. In Figure 3.5, it is identified the location of the considered algorithms.

![Diagram showing typical locations of RRM algorithms in a WCDMA network](https://www.olloclip.com/https://github.com/Templarian/WindowsIcons/issues/135
User Equipment
- Power Control
- Fast Power Control
- Fast Load Control
Base Station
- Outer loop power control
- Handover control
- Packet scheduling
- Admission control
- Load Control
Radio Network Controller

**Figure 3.5:** Typical locations of RRM algorithms in a WCDMA network (based on [4]).

3.2.1 Power Control

Power Control is the balance between good quality of service, which asks for more power and low levels of interference, which can be achieved with less power. The mostly used example is between two UEs, when one UE is closer to the BS than the other. In the downlink, the transmit power to the further UE should be higher than the closer one, because the Path Loss is proportional to the distance. With this strategy, the received power in the UEs would be the same.

The **open loop power control** is used in the initial power setting [35], when it starts a communication between the BS and the UE. It consists on estimating the path loss and, after that, to define the transmit power for that value. It is the most inefficient and inaccurate algorithm of power control because it only compensates for path loss and slow fading, disregarding the medium and fast fading [36].

The **fast power control** is the proper solution for power control and it is often used in the uplink direction. It consists in the measurement of the Signal-to-Interference Ratio (SIR) and its comparison with the target SIR. If the measured SIR is higher than the target SIR, the BS will advise the UE to decrease the transmit power, but if the measured SIR is lower than the target one, the transmit power from the UE will increase. In the downlink direction, the technique is the same. However, if the UE is the cell edge, it will suffer other cell interference, which implies that UE received power increases.
The **outer loop power control** is important to maintain the quality of service, but with the lower power possible. It works in the uplink and downlink, because both have fast power control. In the uplink, it runs in the RNC and is responsible for setting the target SIR. In the downlink, it is located in the UE and its function is to intersect the BLER.

### 3.2.2 Handover

The handovers can be defined as intra-frequency, inter-system (between UMTS and GSM) or inter-frequency, in the same technology.

The **intra-frequency handover** is called soft-handover algorithm and is defined in [37] as "soft handover in which the mobile station adds and removes radio links in such a manner that the UE always keeps at least one radio link to UTRAN".

The algorithm uses the CPICH $E_{c}/I_{0}$ as the handover measurement quantity and it comes from the measured cells in the active set and neighbour set. The active set is composed of the cells that form a soft handover connection to the UE and the neighbour set is the list of cells that the UE measures, but where the $E_{c}/I_{0}$ is not strong enough to add in the active set.

The soft handover algorithm has, in general, the following steps:

- If the measured $E_{c}/I_{0}$ is higher than the best measured $E_{c}/I_{0}$ in the active set (less an interval), the cell is added to the active set;
- If the measured $E_{c}/I_{0}$, which is in the active set, is lower than the $E_{c}/I_{0}$ of the best cell in the active set (less an interval), the cell is removed from the active set;
- If the active set is full and the best candidate cell has a $E_{c}/I_{0}$ higher than the $E_{c}/I_{0}$ of the worst cell in the active set, the worst cell is removed and the best candidate is added.

The soft handover can add three different types of gain in the system, increasing the coverage and capacity of the network. The first is the macro diversity gain, which is related to slow fading. The micro diversity gain is related to the fast fading. And, the last, the downlink load sharing, related with the received power from multiple Node Bs.

The Soft Handover Overhead (SHO), represented by $\beta$ is a metric that indicates the handover activity in the network, which is reported by the BS. It is define as:

$$\beta = \sum_{n=1}^{N} n \cdot P_n - 1$$  \hspace{1cm} (3.8)

where $N$ is the active set size and $P_n$ is average probability of a UE being in n-way soft handover.

The **inter-system handover** occurs between UMTS and GSM and it can happen due to coverage or load balancing reasons. The measurement quantity is defined by the vendor but it could be the BLER or the required transmission power. When the UE reaches the target quantity, it measures the signal power of the GSM frequencies and, if it finds a measurement that is higher than the target, the UE decodes the Base Station Identity Code (BSIC) of the best GSM candidate and informs the BS.

The **inter-frequency handover** often happens because the operators have two of three frequencies
available. The procedure is the same as in intra-frequency handover, depending on the metric $E_b/N_0$.

### 3.2.3 Measurement of Air Interface Load

This algorithm is needed in systems where the interference levels have importance in terms of RRM. It measures the air interface load.

The uplink load factor can be estimated based on the wideband received power or on the throughput. The load factor, $n_{UL}$, based on wideband received power, is:

$$n_{UL} = 1 - \frac{P_N}{I_{total}}$$

where $P_N$ is the noise power and $I_{total}$ is the received wideband interference power. The load estimation based on the throughput is given by:

$$n_{UL} = (1 + i) \cdot \sum_{j=1}^{N} \frac{1}{1 + \left(\frac{E_b}{N_0}\right)_j \cdot R_j \cdot \eta_j}$$

where $i$ is the ratio between the interference from other cells and the interference from the own cell, $N$ is the number of users, $W$ is chip rate, $R_j$ is the bit rate of user $j$, and $\eta_j$ is the activity factor of user $j$.

The downlink load factor, $n_{DL}$, is estimated based also on the power or on the throughput. The power-based load factor is given by:

$$n_{DL} = \frac{P_{Total}}{P_{max\,Node\,B}}$$

where $P_{total}$ is the downlink transmission power and the $P_{max\,Node\,B}$ is the maximum Node B transmission power.

The throughput-based load factor is equal to:

$$n_{DL} = \sum_{j=1}^{N} v_j \cdot \left(\frac{E_b}{N_0}\right)_j \cdot \left[\left(1 - \alpha_j\right) + i_j\right]$$

where $\alpha_j$ is the orthogonality factor and $i_j$ is the ratio of other cell to own cell BS power, received by user $j$.

For more information, about interference and load factors calculation, consult Appendix A.

### 3.2.4 Admission Control

The admission control algorithm operates in the RNC and has to decide if it accepts or rejects a new session request. If it overlaps with handover control, it can also decide if an existing session drops or not. This decisions are based on the growth of the network load and also the QoS, with the goal to maximize the number of sessions in the cell and minimize the number of blocked and dropped sessions [38]. This algorithm runs in the uplink and downlink and, if only the bearer is admitted in both directions, the UE is added to the network.
There are different admission control algorithms, with different criteria, like the total received power in the NodeB, relative to the noise level, and also the downlink transmit power.

The wideband power-based admission control strategy is based on the interference estimation caused by the new UE, $I_{\text{total current}}$, and the basic test is:

$$I_{\text{total current}} + \Delta I = I_{\text{threshold}}$$  

(3.13)

where $I_{\text{threshold}}$ is interference threshold set by the radio network planning and $\Delta I$ is the estimated increase of interference, calculated by two different methods.

In the downlink, it depends on the downlink transmit power, $P_{\text{total}}$:

$$P_{\text{total}} + \Delta P_{\text{total}} = P_{\text{threshold}}$$  

(3.14)

where $P_{\text{threshold}}$ is the power threshold, also set by the radio network planning and $\Delta P_{\text{total}}$ is the load increase in the downlink.

Another method is based on the throughput, and, in the uplink direction, the UE is only accepted if:

$$n_{UL} + \Delta n < n_{UL\text{threshold}}$$  

(3.15)

where the $n_{UL}$ is the load factor before the acceptance of the new UE, $\Delta n$ is the load factor of the new UE and $n_{UL\text{threshold}}$ is the maximum uplink load factor increment.

In the downlink, the UE is accepted if:

$$n_{DL} + \Delta n < n_{DL\text{threshold}}$$  

(3.16)

where $n_{DL}$ is also the downlink load factor before the UE be accepted, $\Delta n$ is the same as in the previous equation and $n_{DL\text{threshold}}$ is maximum downlink load factor increment. The uplink and downlink load factors are calculated as in 3.2.3.

### 3.3 Capacity and Coverage

Both coverage and capacity are important issues in order to analyse the performance of the network. Normally, coverage is more critical in the uplink and capacity is more crucial in the downlink.

**Coverage** indicates the cell range and it is, among others, limited by the transmit power of the UEs, which is around 21dBm (125mW), against the transmit power from the BS, which is around 40dBm - 46dBm (10W - 40W). Factors like the BS receiver sensitivity and processing gain also affects the uplink coverage. The processing gain is the ratio between the spread bandwidth with the unspread bandwidth and it depends on the chip rate and on the data rate:

$$\text{Processing gain} = 10 \times \log_{10} \left( \frac{\text{Chip rate}}{\text{Data Rate}} \right)$$  

(3.17)
This means that with the data rate increase, the processing gain gets lower, and the coverage will decrease, since higher the processing gain, lower the receiver sensitivity will be.

However, if the service is non guaranteed bit rate, the cell range does not need to decrease, but it is only possible to give lower bit rate for a while. In Figure 3.6 the relation between the uplink bit rate in guaranteed bit rate service and the range of the cell is presented.

![Figure 3.6: Uplink range of real time guaranteed bit rates in suburban area (based on: [4]).](image)

There are several techniques to increase the coverage of the cell, such as Adaptive Multirate Speech Codec, Multipath Diversity and Soft Handover.

Since the UE has worse receiver techniques than the BS, the capacity of a BS is more limited in downlink direction to assure that all UEs receive the data, especially caused by the the orthogonal codes or by performance gain of downlink transmit diversity.

The orthogonal codes are used to separate users in a cell, but in a multipath channel, some orthogonality is lost and the UEs can interfere with each other. The interference impact is presented in Figure 3.7, where the number of connections in a multicell is much lower than in a single cell, with good orthogonality. Even so, in this last case, the capacity is limited by the number of codes, which depends on the SF, as explained in the section 2.4.

However, if there is not enough orthogonal codes, it is possible to add a new scrambling code, which will give a new set of orthogonal codes, but the sets are not orthogonal between each other.

The capacity will define the available throughput and it depends on the number of users. In Figure 3.8, it is possible to notice that cell throughput increases with the number of users in the cell, but after a certain number, it saturates and even decreases. This is caused by the increasing of signalling channels and respective overheads, which will use BS dedicated data resources.

The capacity can also be displayed in a scale based on the maximum number of users, for each service. In [4] an estimation is performed, and shown in Figure 3.9. The limitation in the case of AMR 12.2 kbit/s voice service is the uplink noise rise. The 64 kbit/s PS video service sets the maximum downlink power of the cell, and also the uplink noise rise when there are good radio conditions. In the 384 kbit/s PS data service, the limitation is always the maximum downlink power of the cell.
Figure 3.7: 384 kbit/s data capacity in multicell and single cell cases (based on [4]).

Figure 3.8: Cell throughput depending on the number of users (based on [4]).

Figure 3.9: Estimated cell capacities based on single cell measurements (based on [4]).
In HSDPA, the capacity has to be shared between both releases and the coverage depends on the throughput that it is assigned to the users. The throughput to each user depends on the number of users allocated to the cell.

The downlink data rate depends on the reported CQI. The users further away from the BS will report a worst CQI than the users closer to the BS. So, if the users are near the border of the cell, the data rate will be lower. Of course, this depends on the size of the cell. If it is a macrocell, on a rural area for example, the throughput will be lower than in a microcell, in an urban scenario.

However, even if the cell is planned to cover a certain area, it is possible to just serve the users closer to the cell, with higher data rate, having only a percentage of the total area of the cell coverage, as in Figure 3.10.

![Figure 3.10: Minimum average user throughput depending on the percentage of coverage cell (source: [4]).](image)

The capacity depends on the number of users that are allocated to that BS but also on the number of users using the dedicated services, such as voice, because it is a priority service. As more power is allocated to the DCH, less power is available for HSDPA service. In Figure 3.11 is visible the variation of HSDPA and DCH throughput with the allocated HSDPA power.

The last aspect is the average throughput to each HSDPA user, which depends on the simultaneous users sharing the HS-DSCH, but also on the $E_s/N_0$, known as energy per symbol to noise power spectral density ratio, i.e., $E_s/N_0$ is the signal quality experienced. The variation of the average throughput is not directly proportional to the number of HSDPA users. For example, with 1 HSDPA user is possible to register 800 kbit/s of throughput, with 4 users the throughput is equal to 400 kbit/s and with 8 users a throughput of 220 kbit/s will be achieved. The throughput decreases by a factor of two when the number of users decreases by a factor of four. The reason is the multi-user diversity gain. If a BS has $M$ antennas and $K$ allocated users for HSDPA, the BS chooses the $M$ best users from the $K$ available,
cell throughput is slightly lower in the case of code-multiplexing. This is caused by the higher overhead from having two HS-SCCHs per cell as well as the additional scheduling constraints from having to schedule two users per TTI. The cell capacity with all 15 codes is approximately 2.0 Mbps when code-multiplexing is used.

7.3.4 HSDPA capacity with Release 99

We consider the case where five HS-PDSCH codes and one HS-SCCH code are allocated for HSDPA transmission per cell. This can be considered a typical initial roll-out scenario for HSDPA. The remaining channelization codes are used for the transmission of Release 99 channels. Figure 7.15 shows the average cell throughput on HSDPA and the DCH vs the allocated HSDPA power, as well as the total cell throughput that is the sum of the throughput on HSDPA and the DCH. As expected, HSDPA cell throughput increases the more HSDPA power that is being allocated, while DCH throughput simultaneously decreases. The maximum cell throughput is observed to equal 1.3 Mbps for 7-W HSDPA power allocation. Hence, the introduction of HSDPA with five HS-PDSCH codes brings a capacity gain of 70% over Release 99, which typically offers a capacity of 780 kbps. The capacity gain comes from fast link adaptation and HARQ, and multiuser diversity comes from using proportional fair scheduling. Hence, it is evident that the performance of HSDPA vs DCH depends on how the common transmission resources are shared between these two channel types. However, total cell throughput does not vary significantly with HSDPA transmit power allocated.

![Figure 7.15: Average cell throughput as a function of allocated HSDPA power per cell.](image)

Figure 3.11: Cell throughput depending on the HSDPA power (source: [21]).

and the obtained gain factor is equal to $M \times \log(\log(K))$ [39].

It is also possible to give all the power to a single user (and the other users would have zero power), in order to the first user achieve high peak data rate for a time interval [21].
Chapter 4

Traffic Management Methods

This chapter describes the development of the method that will define the admission curve, for two services. Four methods were tested, along with results and comments.

4.1 Introduction

The admission curve is set in a Cartesian X-Y graph and it has, in the axes, the traffic for each service, in Erlang. All the methods have five input parameters:

- Number of carriers, represented by $J$;
- Carrier capacity, represented by $K$;
- Number of services, represented by $S$;
- Mapping matrix, represented by $M$;
- Blocking probability limit, represented by $\delta$.

The mapping matrix is a representation of the carrier capacity utilization, by service, where the lines symbolize the carrier and the columns symbolize the service. This means that, the line 1 and column 1 indicates how many capacity units will be used to allocate one user to the carrier and service 1. The units of capacity can be, for example, bandwidth.

To uniformize all examples from different methods, the following numerical input parameters will be used:

- $J = 2$;
- $K = [30 \ 30]$, which means that both carriers have the same capacity;
- $S = 2$;
- $M = \begin{bmatrix} 1 & 4 \\ 4 & 1 \end{bmatrix}$. 
• \( \delta = [2, 2]\% \), indicating that both services have the same blocking probability.

With this numerical inputs, it is possible to take that, in carrier 1, the service 1 will need 1 unit of bandwidth while the service 2 will need 4 units. So, it is possible to allocate 30 users to the service 1 (if the service 2 is not in use) but only 7 users maximum in service 2, since the total carrier capacity divided by the 4 units of bandwidth per user is \( 30/4 = 7.5 \), which has to be rounded down. Since one user occupies one circuit, a new matrix appears, \( C \), with \( J \) lines and \( S \) columns, which indicates the maximum number of circuits available for each carrier, to each service. The numerical values are

\[
C = \begin{bmatrix}
30 & 7 \\
7 & 30 \\
\end{bmatrix}.
\]

Applying the Erlang-B model, discussed in section 3.1.3, and using the maximum number of circuits, the maximum traffic in carrier 1, for service 1, is \( \rho_{(30 \text{ circuits}, \ 2\%)} = 21.93 \text{ Erl} \) and, for service 2, is \( \rho_{(7 \text{ circuits}, \ 2\%)} = 2.94 \text{ Erl} \).

To arrive in an admission curve, all the methods are simulated several times, one time for each pair of offered traffic \( \rho = (\rho_1, \rho_2) \), starting with \( \rho_1 = 0 \) and \( \rho_2 = 0 \) and ending when the admission curve crosses the x axis.

The following sections present several admission control methods. The methods from sections 4.2 and 4.3 are based in [40], the method from section 4.4 is based in [41] and [42] and the method presented in section 4.5 is based in [43].

### 4.2 Reduced Load Approximation

This method assumes that the blocking events for the different resources are independent. The goal is to calculate the blocking probability, \( p_B \), and compare it with the blocking probability limit represented by \( \delta \), in order to establish the border line.

The Reduced Load Approximation is an iterative method, which starts to define a matrix of auxiliary blocking probabilities, denominated by \( L \), with \( J \) lines and \( S \) columns. The first values are defined randomly, with a value between 0 and 1. After, the method starts with equation (4.1) and goes to equation (4.2).

\[
\tilde{\rho}_{js} = \rho_s \prod_{k \neq j} (1 - L_{ks}) \tag{4.1}
\]

where \( \rho_s \) is the offered traffic for service \( s \), belonging to the vector of offered traffic \( \rho = [\rho_1, \rho_2] \), and \( \tilde{\rho}_{js} \) belongs to a matrix of auxiliary traffics defined by \( \tilde{\rho}_j = (\tilde{\rho}_{j1}, \ldots, \tilde{\rho}_{jS}) \). \( \tilde{\rho}_j \) is then applied in:

\[
L_{js} = p_B (C_{js}, \tilde{\rho}_{jS}) \tag{4.2}
\]

where \( p_B \) is blocking probability calculated by the Erlang-B formula as in section 3.1.3 and \( C_{js} \) is the maximum number of circuits for carrier \( j \) and service \( s \).

After this two equations stabilize, it is calculated the blocking probability for each service, \( p_{B, s} \), with equation (4.3).
The admission region is given by:

\[ AR(\delta) = \{ \rho : p_{B,s}(\rho) \leq \delta, 1 \leq s \leq S \} \]  

Figure 4.1 shows the admission curve as a function of the offered traffic for service 1 and 2, with the Reduced Load Approximation method.

The problem about this method is that it considers the blocking probability of a resource and a service in isolation, i.e., the service 1 can use all the capacity from the carrier 1 that service 2 would still have capacity to operate, so it does not take into account the dependencies between services. When \( \rho_1 \) increases, there is less available bandwidth for service 2, so the traffic for service 2 should decrease with the increment of traffic for service 1. In Figure 4.1 this does not happen, since when \( \rho_1 = 1 \) Erl, \( \rho_2 \) is equal to 2.94 Erlangs as when \( \rho_1 = 0 \) Erl.

In order to solve the missing dependency, the following simulation has a different way to calculate \( p_{B,s} \):

\[ p_{B,s} = \sum_{a=1}^{j} \sum_{b=1}^{s} L(a, b) \]  

Figure 4.2 shows the admission curve with the new improvement.

However, in Figure 4.2 is not perceptible if the result is correct or not, so a new test will be made, for the case of \( M = \begin{bmatrix} 1 & 2 \\ 1 & 2 \end{bmatrix} \) and \( K = [20 \ 20] \). The admission curve is in Figure 4.3, with these new input
In Figure 4.3, the offered traffic for service 2 (y-axis) keeps equal to 5.1 Erl until service 1 (x-axis) matches 8 Erl. This discredits the Reduced Load Approximation Method since the traffic for service 2 should decrease when the traffic for service 1 increases.
4.3 Single Resource Intersection

This method consists in the calculation of two isolated regions, for each carrier, and the union of both will be the admission region for both carriers. Each region is up limited by a line, represented by $SIR^j$.

To design the curve, the maximum traffic for each service is calculated, when the other one is not in use. So, in carrier 1, if service 1 is being used and service 2 is not, the $\rho_1$ is equal to 21.93 Erl and, on the other hand, if only service 2 is being used, $\rho_2 = 2.94$ Erl. The same happens in carrier 2.

In Figure 4.4 displays the limiting lines with the Single Resource Intersection method, for both carriers.

![Figure 4.4: Single Resource Intersection method.](image)

The simulation shows the decreasing of the offered traffic for service 2 when the service 1 starts to be used. However, the admission curve is too optimistic, since the curves are linear and it would not work when the matrix $M$ indicates that the required bandwidth for the first carrier is different for the second carrier, for example, when the matrix $M$ is equal to $\begin{bmatrix} 10 & 5 \\ 5 & 1 \end{bmatrix}$. For this matrix, the admission region is in Figure 4.5, with the Single Resource Intersection method.

4.4 Reduced Load Approximation with Erlang Fixed Point (EFP)

This method is also iterative between three equations. It starts to define blocking probabilities auxiliary, randomly, denominated by $L_j$, one for each carrier, with a value between 0 to 1. After, a blocking probability for each service, $p_{B,s}$, is calculated by equation (4.6).
$p_{B,s} = 1 - \prod_{i=1}^{J} (1 - L_i)^{M_{js}}$ \hfill (4.6)

where $M_{js}$ is the line $j$ and column $s$ of the mapping matrix $M$. With $L_s$, an auxiliary traffic for each carrier, $\rho_{aux,j}$, is computed by:

$$\rho_{aux,j} = (1 - L_j)^{-1} \sum_{i=1}^{S} M_{ji} \cdot \rho_i \cdot (1 - p_{B,i})$$ \hfill (4.7)

where $\rho_s$ is the offered traffic for service $s$, given by the vector $\rho = (\rho_1, \rho_2)$. Now, a new blocking probability auxiliary, $L_j$ is given by the Erlang-B formula:

$$L_j = p_B(K_j, \rho_j)$$ \hfill (4.8)

where $K_j$ is the carrier $j$ capacity, announced in the vector $K$ and $p_B$ is the Erlang-B formula, as in section 3.1.3. The $L_j$ is substituted again in equation (4.6), repeating all the process until it converges to a stable result of $p_{B,s}$.

$p_{B,s}$ is compared with $\delta_s$, which is the blocking probability limit from vector $\delta$ and it is possible to determine the admission line. The obtained admission region with this method is represented in Figure 4.6.

The admission curve is not correct, since the offered traffic for service 2, when $\rho_1 = 0$, is higher than the 2.94 Erl, value calculated in section 4.1, but it has dependency between services.
4.5 Multidimensional Erlang-B model

The Multidimensional Erlang-B model appeared with the necessity to calculate the blocking probability of a group of independent streams, with arrival rate of $\lambda_i$ and service rate of $\mu_i$.

In this method, it is calculated the probabilities of being in the different states and, after, it is calculated the blocking probability. The probability of being in one state depends on the used bandwidth from each service. The mapping matrix is very important in this case, in order to understand how much bandwidth is necessary to serve one user.

A state is defined as $(i,j)$, and a increment of 1 indicates that one more user is served. This means that, with the numerical values announced in section 4.1, the state $(1,1)$ is the case of one user using service 1 and one user using service 2 and, consequently, 5 units of bandwidth are spent, because the service 2 needs 4 units of bandwidth. Generalizing, having the matrix $M$ equal to $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ and the state represented by $(i,j)$, the state probability is the probability to be using $i*a$ capacity for service 1 and $j*b$ capacity for service 2.

With this state definition, it is possible to design a diagram that shows the dependencies between the states and the resources limits, see Figure 4.7.

The state transition diagram (Figure 4.7) assumes that the horizontal direction represents the service 1 and the vertical direction represents the service 2. If it moves from the state $(0,0)$ to state $(1,0)$, means that it is using $1*a$ circuit for service 1 and $0*b$ circuits for service 2. But if it goes into the top direction,
to the state (0,1), it means that it is using 0*a circuits for service 1 and 1*b for service 2.

To calculate the state probability, the formula is given by:

\[ p(i, j) = Y \cdot \frac{\rho_1^i}{i!} \cdot \frac{\rho_2^j}{j!} \]  \hspace{1cm} (4.9)

where \( \rho_1 \) and \( \rho_2 \) is the pair of offered traffic, from vector \( \rho \) and \( Y \) is a normalization constant calculated by:

\[ Y = \frac{1}{\sum_{\nu=0}^{K} \frac{(\rho_1 + \rho_2)\nu}{\nu!}} \]  \hspace{1cm} (4.10)

where \( K \) is the capacity, as in Section 4.1.

The blocking probability depends on the available bandwidth. Taking the numerical values as example, in resource 1, service 1 is blocked when it does not have any free bandwidth. However, service 2 is blocked when it does not have any unit of bandwidth, but also when it only has one unit of bandwidth, two or three. If it has four units of bandwidth, it is already possible to add one more connection of service 2. So, with an offered traffic \( \rho_1 \) and \( \rho_2 \), the blocking probability, represented by \( p_b \), for service 1 is:

\[ p_b(1) = p(i + j = 30) = p(30, 0) + p(26, 1) + p(22, 2) + \ldots + p(2, 7) \]  \hspace{1cm} (4.11)

and for service 2 is in equation (4.12).
\[ p_{b}(2) = p(i + j = 30) + p(i + j = 29) + p(i + j = 28) + p(i + j = 26). \] (4.12)

Since it has two carriers, the blocking probability has to be calculated for both of them, and after that, the maximum blocking probability between the two carriers is compared with the blocking probability limit.

Applying the previous method in Matlab, Figure 4.8 was obtained, with input parameters equal to the explicit in Section 4.1.

![Multidimensional Erlang-B](image)

**Figure 4.8:** Multidimensional Erlang-B.

This last simulation is in accordance with the expected values. When \( \rho_{1} \) is equal to 0, *i.e.*, no user is using the service 1, \( \rho_{2} \) is equal to 2.94 Erl and the same when \( \rho_{2} \) is equal to zero.

### 4.6 Assumption of different values

In this section, admission curves will be presented from different tests in order to corroborate the method.

In the first simulations, it is just changed the blocking probability limit. Figure 4.9 has the two admission curves, for \( \delta = [2 \ 2] \% \) and \( \delta = [5 \ 5] \% \), both applied with the Multidimensional Erlang-B model.

The curve ascends with the increasing of the blocking probability. With higher blocking probability, more users can be added to the network, because less GoS is required and more calls are lost.

The next change is on matrix \( K \), and the following simulation has two cases for matrix \( K \), one with
Figure 4.9: Multidimensional Erlang-B with different blocking probabilities limit.

more capacity for each resource, $K = [40\ 40]$ and another with $K = [20\ 10]$. The matrix $M$ stays the same and the blocking probability limit is 2% for each resource. The admission curve for the three cases, $K = [30\ 30]$, $K = [40\ 40]$ and $K = [20\ 10]$ is shown in Figure 4.10.

Figure 4.10: Multidimensional Erlang-B with different matrix $K$.

Analysing the results, it is possible to see that with higher $K$, the offered traffic is also higher, since
the increasing of capacity means that more users can be allocated to the BS. Also, when both entrances of \( K \) are equal, the curves are symmetric in the sense that when \( \rho_2 = 0 \), \( \rho_1 \) is equal to the same value as \( \rho_2 \) when \( \rho_1 = 0 \). In the other hand, when the entrances of \( K \) are not the same, the curve is not symmetric, i.e., in the example of \( K = [20 \ 10] \), when \( \rho_2 = 0 \), \( \rho_1 \approx 0.25 \) and when \( \rho_1 = 0 \), \( \rho_2 \approx 1.7 \).

The last simulation is with a different matrix \( M \), equal to \( \begin{bmatrix} 5 & 2 \\ 2 & 1 \end{bmatrix} \). Figure 4.11 presents the two cases with the Multidimensional Erlang-B method.

![Figure 4.11: Multidimensional Erlang-B with different matrix \( M \).](image)

When matrix \( M \) is symmetric, the curve is also symmetric, as explained before, when \( \rho_2 = 0 \), \( \rho_1 \) is equal to the \( \rho_2 \) when \( \rho_1 = 0 \). When \( M \) is not symmetric, the curve assumes different values in the axes intersection. Another thing to notice is that the slope decreases faster when \( M = \begin{bmatrix} 5 & 3 \\ 3 & 1 \end{bmatrix} \) because the service 1 uses more resource units than the service 2.

After the implementation of the four methods, the chosen method is the last one, the Multidimensional Erlang-B model. The admission curves shown in Figures 4.9, 4.10 and 4.11 demonstrate that the variation occurs as expected, specially when compared with the previous models, explained in Sections 4.2, 4.3 and 4.4. Also, in [40], some admission curves are presented, with the respective input parameters. So, the final simulations were made with the Multidimensional Erlang-B method and the results matched.
Chapter 5

UMTS/HSPA Traffic Algorithm Implementation

This chapter will present the calculations of input parameters for the Multidimensional Erlang-B Model, defined in the section 4.5. The model has, as input, the mapping matrix $M$ and the carrier capacity $K$, however, in a real environment, parameters are not established in that format.

Since it was provided real statistics from an operator, they had to be studied in order to find the necessary values to calculate the necessary specification to implement the chosen model in chapter 4.

5.1 Introduction

The goal in this step is to find the maximum number of possible users to allocate in a given cell, for each service. In the case of voice, the bit rate is fixed - 12.2 kpbs - but, in HSDPA, the number of users depend on the operator’s target data rate. This is done with the calculation of power slots for each service. This power slots are the necessary power to serve a user, and, when summed, they have to be equal to the total power of the BS.

In Figure 5.1, the power is divided by both services. To calculate the power slots, it is assumed that $P_{total, BS}$ is allocated only for the DCH channels or for HSDPA service, without forgetting to take the power allocated for control channels ($P_{CCH}$), as defined in section 3.1.1.

Another important aspect is the time when it is wanted to calculate the admission curve. The mostly used is the busy hour, where almost all the BS transmit power is used. This is specially important for HSDPA service, as will be seen in section 5.4.

To calculate the maximum number of power slots for each service, cell characteristics will be calculated, namely Energy Per Bit for voice and $P_{DSCH-TX}$ for HSDPA. The formulas for this characteristics were based in [44], however improvements were made since the characteristics were not fully representative of the cell behaviour, specially in the TTI utilization and data rate ratios. The power slots and cell characteristic notation is not presented in [44], which means that a deep analysis had to be done.
5.2 Key Performance Indicators

Key Performance Indicator (KPI) is a metric that indicates the performance of a mobile network. In UMTS, the mandatory ones are defined by the 3GPP in [45]. Each KPI indicates a specific measure, such as, the average number of CS users, the mean transmit power, the throughput, among others. The KPIs are reported by the BS and they can be measured every half an hour, every hour or other relevant interval.

Some KPIs are vendor specific, which means that they must be studied taking that fact into consideration. In this master thesis, the KPIs are from Huawei and the number of studied KPIs was 360, in intervals of half an hour. This statistics are taken from a particular software, provided by Celfinet.

Here is introduced a description of the most used KPIs [46]:

- **VS.RB.AMR.DL.12.2**
  
  It indicates the average number of Adaptive Multirate users with a bit rate of 12.2 kbit/s. In other words, it is the average number of voice users in the BS at the same time, during that specific half an hour.

- **VS.HSDPA.UE.Mean.Cell**
  
  It indicates the average number of HSDPA users, with no specific data rate. In this case, the average is made by 5 seconds samples, so it counts the number of served users in each 5 seconds interval and then it makes the average of all the 5 seconds samples of the half an hour.
• **VS.MeanTCP**
  This KPI indicates the mean used downlink transmit power for all the services, such as control channels, voice and HSDPA.

• **VS.MeanTCP.NonHS**
  It shows the mean used downlink transmit power for the dedicated and control channels, so it does not include the used power for HSDPA.

• **VS.HSDPA.MeanChThroughput**
  It indicates the mean throughput of the HSDPA service, given to each user.

• **MAXTXPOWER**
  It indicates the maximum power that a BS can transmit.

Additional KPIs can be consulted in appendix B.

### 5.3 Determination of the number of voice users

The voice users are allocated on the dedicated channels, represented by $P_{DCH}$ in Figure 5.1. However, the DCH has more allocated services, which are AMR in different bit rates and PS in Release 99, which includes the conversational, streaming, interactive and background classes. In order to understand the utilization of this services, the available statistics were analysed and the conclusion is that, in downlink, only the interactive service, at 8 kbit/s and 64 kbit/s had some users, particularly in two days (from the 38 available). For this reason, the $P_{DCH}$ can be assumed to be equal to the power required to serve voice users.

When the network is only allocated to the voice service, the power is divided by the DCH channels and the CCH channels. The sum of both powers can be called $P_{TOT\ Non\ HS}$.

The $P_{CCH}$ is explained in section 3.1.1 and it is measured in W. This power is taken from the statistics and it is assumed that the BS is always transmitting power for the control channels, even when there is no traffic. Since it exists statistics from the 24 hours of the day, it is possible to find a half an hour without traffic, so the $P_{CCH}$ is equal to the minimum power registered in the BS.

The first thing to do in order to find the maximum number of users allowed in a BS is to calculate the cell characteristic. In voice, the cell characteristic is named of *Energy Per Bit* and it is given by:

$$ energyPerBit \ (mJ/kb) = \frac{\sum_{samples} (P_{DCH} \times R_{MAC-d}^2)}{\sum_{samples} (R_{MAC-d}^2 \times R_{MAC-d}^2)} $$  \hfill (5.1)

The *samples* are all the statistics that were collected from the BS, from all the days, in periods of half an hour.

The $P_{DCH}$ is represented in W and is the power taken from the statistics, registered by the KPI VS.MeanTCP.NonHS, less the $P_{CCH}$. 

The $R_{MAC-d}$ is the observed bit rate for the downlink connection of DCH, which corresponds only for the voice service, since the other services are not considered, and it is the average number of voice users multiplied by the bit rate for voice, which is 12.2 kbit/s.

After the calculation of the Energy Per Bit, the number of users can be determined. This number will become in the bit rate given by $R_{MAC-d(j)}$, which is the effective bit rate per bearer. However, there is only one bearer, for voice, so the equation (3.1) is applied and it obtains the following form:

$$P_{TOT Non HS} = P_{CCH} + \text{energyPerBit} \times R_{MAC-d(\text{voice})}$$

(5.2)

where $P_{TOT Non HS}$ comes in W and $R_{MAC-d(\text{voice})}$ in kbit/s.

Afterwards, to take the maximum number of voice users, it is necessary to calculate the division between $R_{MAC-d(\text{voice})}$ and 12.2 kbit/s, since each user has that specific bit rate.

The Energy Per Bit was tested, with an estimated curve and a regression curve. The estimated curve is calculated with the equation (5.2), with input the observed $R_{MAC-d}$ and output the power for DCH plus CCH channels (identified by MeanTCP:NonHS (estimated)). The regression curve will be drawn with the statistics, where the x axis is the observed $R_{MAC-d}$ as well and the y axis is the MeanTCP:NonHS (regression), taken from the KPIs. The regression curve will have as many points as the number of available statistics.

If the correlation between the MeanTCP:NonHS (estimated) and MeanTCP:NonHS (regression) is close to 1, the Energy Per Bit can really describe the cell.

This test is made in a cell that belongs to an urban scenario, and the obtained statistics include 26 days. The calculated Energy Per Bit was 0.045 mJ/kb.

The estimated curve, shown in Figure 5.2, is linear ($y = ax + b$), where $y$ is the MeanTCP:NonHS (estimated), $a$ is the Energy Per Bit, $x$ is the $R_{MAC-d}$ and $b$ is the $P_{CCH}$, as in:

$$\text{MeanTCP:NonHS (estimated)} = \text{energyPerBit} \times R_{MAC-d} + P_{CCH}$$

(5.3)

![Figure 5.2: Estimated curve, with curve equation (5.3).](image)

The regression curve 5.3 is based only in the statistics.
MeanTCP.NonHs = 0.0428*RMAC-d + 5.3996

Figure 5.3: Regression curve for the experimental data.

The resulted correlation, in this cell, is 0.79, which is enough to show that the approximation with Energy Per Bit is a good characteristic of the cell. In appendix C results are shown for other cases.

Since it is possible to know, from the statistics, the maximum power in a BS, the goal is to calculate the $R_{MAC-d(j)}$ and divide it by 12.2 kpbs:

Table 5.1: Number of voice users.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{TOT Non, HS}$[dBm]</td>
<td>46</td>
</tr>
<tr>
<td>$P_{CCH}$[dBm]</td>
<td>36.04</td>
</tr>
<tr>
<td>Energy Per Bit [mJ/kb]</td>
<td>0.0212</td>
</tr>
<tr>
<td>$R_{MAC-d(j)}$[kbit/s]</td>
<td>1685.63</td>
</tr>
<tr>
<td>Nr. users</td>
<td>138</td>
</tr>
</tbody>
</table>

In this cell, the maximum number of users is equal to 138.

5.4 Number of HSDPA users determination

In HSDPA, the cell characteristic is the $\bar{P}_{DSCH-TX}$, which is also the required power to serve one user, with a certain $R_{target}$. To make the analogy with Figure 5.1, the $\bar{P}_{DSCH-TX}$ is the power for a slot $P_{HSDPA}$.

However, the $\bar{P}_{DSCH-TX}$ depends on parameters, from the statistics, that changes every half an hour. This means that it will be computed a new characteristic each half an hour, or, as explained in section 5.1, for the busy hour of each day.

The $\bar{P}_{DSCH-TX}$ is calculated based on the used power for HSDPA service, multiplied by a ratio that indicates the utilization of the TTIs and also by a ratio that indicates the data rate attributed to the users. The reason of this multiplication is caused by the burst of data, as explained in section 2.6.
The equation of $P_{DSCH-TX}$ can be expressed as:

$$P_{DSCH-TX} = \frac{P_{DSCH-TX} \times d \times \eta}{I_{TTI}} \quad (5.4)$$

where $P_{DSCH-TX}$ is the used power for HSDPA, $d$ is the duty cycle, $\eta$ is the activity factor and $I_{TTI}$ is the inter TTI interval.

The power indicated by $P_{DSCH-TX}$ is equal to the used power for HSDPA in that half an hour. In the language of KPIs, it is equal to the difference between $VS.MeanTCP$ and $VS.MeanTCP.NonHS$.

The $d$ stands for duty cycle and it is a ratio of data rates, between the data rate target and the achievable data rate. It is given by:

$$d = \frac{R_{target} (MAC-hs)}{R_{achievable} (MAC-hs)} \quad (5.5)$$

This duty cycle will make a balance of the power according with the data rate that the BS should achieve and the data rate that the BS can give to a user, according to the used CQI from the UEs. It will help to adapt the power to the need of the users, without wasting power.

The $R_{target}$ is defined by the operator, and it should be a measure of QoS by itself. The $R_{achievable}$ is explained in section 2.6, but here it is introduced the BLER, since it is available in the statistics [47]. The $R_{achievable}$ is calculated as:

$$R_{achievable} (MAC-hs) = \frac{V_{TBS} \times (1 - BLER)}{0.002 \times I_{TTI}} \quad (5.6)$$

As explained in section 2.6, the achievable data rate depends on the CQI, because the $V_{TBS}$ indicates the TBS, taken from the CQI tables. In the statistics, there are KPIs that return the used CQI, as announced in appendix B, called $VS.UsedCQI$, from 0 to 30. However, the sum of the used CQIs is different of the average number of HSDPA users, reported in the KPI $VS.HSDPA.UE.Mean.Cell$, since one user can send more than one CQI.

To solve this situation, it is necessary to compute the Cumulative Distribution Function (CDF) of the used CQIs and calculate the median, every day, at its busy hour. After that, the median is compared with the mean value to understand if the number of used CQIs higher than the mean value is excessively different of the number of used CQIs lower than the mean value. Moreover, a test will be made to the statistics in order to understand if they have a normal distribution, with a given significance level.

Two different days and different cells are shown in Figure 5.4 and 5.5, but both from an urban scenario.

To demonstrate that the statistics are normally distributed, the Lilliefors test is used. The null hypothesis for this test is that the error is normally distributed [48].

Both CDFs, when verified by the Lilliefors test, gave true to the rejection of the null hypothesis at the 2% significance level. This means that the statistics have a normal distribution with 98% certainty [49]. It can be assumed that the average number of users are representative of the possible positions in the cell and there are users near the BS but also in the border of the cell, hence, the mean of them conducts
After finding the median CQI every day, it is calculated the mean value of all days and that is the input, which is introduced in the CQIs tables. But it is also needed the mobile category as input to find the TBS.

The mobile category comes in the KPI `VS.HSDPA.UE.Mean.CAT`, from 1 to 32, and it is an average value. This means that the sum of all KPIs is equal to the average value of HSDPA users, indexed to the KPI `VS.HSDPA.UE.Mean.Cell`.

Now, it is only necessary to consult the CQIs tables. There is a table for each UE category. Table 5.2 corresponds to the UE category 14, which coincides with the most declared one in the analyzed statistics.

Returning to equation (5.6), the $V_{TBS}$ is already identified, but it is still missed the BLER and the $I_{TTI}$.

The BLER is taken from the statistics, which has a formula that relates a couple of KPIs, as in
Table 5.2: CQI mapping for category 14 (based on [25]).

<table>
<thead>
<tr>
<th>CQI value</th>
<th>$V_{TBS}$ [bit]</th>
<th>CQI value</th>
<th>$V_{TBS}$ [bit]</th>
<th>CQI value</th>
<th>$V_{TBS}$ [bit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>137</td>
<td>11</td>
<td>1483</td>
<td>21</td>
<td>6554</td>
</tr>
<tr>
<td>2</td>
<td>173</td>
<td>12</td>
<td>1742</td>
<td>22</td>
<td>7168</td>
</tr>
<tr>
<td>3</td>
<td>233</td>
<td>13</td>
<td>2279</td>
<td>23</td>
<td>9719</td>
</tr>
<tr>
<td>4</td>
<td>317</td>
<td>14</td>
<td>2583</td>
<td>24</td>
<td>11418</td>
</tr>
<tr>
<td>5</td>
<td>377</td>
<td>15</td>
<td>3319</td>
<td>25</td>
<td>14411</td>
</tr>
<tr>
<td>6</td>
<td>461</td>
<td>16</td>
<td>3565</td>
<td>26</td>
<td>17237</td>
</tr>
<tr>
<td>7</td>
<td>650</td>
<td>17</td>
<td>4189</td>
<td>27</td>
<td>21754</td>
</tr>
<tr>
<td>8</td>
<td>792</td>
<td>18</td>
<td>4664</td>
<td>28</td>
<td>23370</td>
</tr>
<tr>
<td>9</td>
<td>931</td>
<td>19</td>
<td>5287</td>
<td>29</td>
<td>24222</td>
</tr>
<tr>
<td>10</td>
<td>1262</td>
<td>20</td>
<td>5887</td>
<td>30</td>
<td>25558</td>
</tr>
</tbody>
</table>

The $I_{TTI}$ is the Inter Transmission Time Interval interval, as explained in section 2.6, but it is canceled in the equation (5.4), so it does not have to be in the statistics.

With these variables, it can be calculated the $R_{achievable}$, in the simulation. All values are taken from the statistics. Some examples are presented in Table 5.3, for different cells and different hours.

Table 5.3: Values for $R_{achievable}$ with different CQIs and BLERs.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Hour</th>
<th>CQI</th>
<th>$V_{TBS}$ [bit]</th>
<th>BLER [%]</th>
<th>$R_{achievable}$ [Mbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17:00</td>
<td>17</td>
<td>4189</td>
<td>27.61</td>
<td>1.52</td>
</tr>
<tr>
<td>2</td>
<td>15:00</td>
<td>18</td>
<td>4664</td>
<td>21.87</td>
<td>1.82</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>20</td>
<td>5887</td>
<td>33.35</td>
<td>1.96</td>
</tr>
</tbody>
</table>

The last variable from the equation (5.4) is $\eta$, which stands for Activity Factor. This activity factor will give an utilization ratio of the TTIs. In the numerator, it will be the number of used TTIs, which means, the number of time slots of 2 ms in that half an hour that were used to transmit data. In the denominator, it will be the total number of TTIs scheduled with data to transmit. In each 2 ms time slot, it is possible to have more than one scheduled TTI.

The activity factor will be different each half an hour and it is a percentage, between 0 to 100%. The numerator is given by the KPI $VS.HSDPA.All.ScheduledNum$ and the denominator is given by the KPI $VS.HSDPA.DataTtiNum.User$. The $VS.HSDPA.All.ScheduledNum$ has values between 0 to 900 000, since, in the maximum, it is only possible to have 900 000 TTIs in one half an hour. On the other hand, the $VS.HSDPA.DataTtiNum.User$ has no maximum number.

An example of activity factor calculation is shown in Table 5.4.

In this moment, all the values, necessary to calculate the $\bar{P}_{DSCH-TX}$, by equation (5.4), are determined. It will be calculated for the busy hour of each day, and after it will be made an average value of all days. The mean $\bar{P}_{DSCH-TX}$ will be the cell characteristic.
Table 5.4: Different values for Activity Factor.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Hour</th>
<th>VS.HSDPA.All.ScheduledNum</th>
<th>VS.HSDPA.DataTtiNum.User</th>
<th>Activity Factor [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15:00</td>
<td>850500</td>
<td>7003574</td>
<td>12.14</td>
</tr>
<tr>
<td>2</td>
<td>17:00</td>
<td>629550</td>
<td>1245324</td>
<td>50.55</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>342900</td>
<td>542791</td>
<td>63.17</td>
</tr>
</tbody>
</table>

In Table 5.5 is possible to see the variation of the $P_{DSCH-TX}$ with the CQI and the $R_{target}$. The tests are made in one single cell, at the same hour (cell 1, at 17:00).

Table 5.5: Variance of $P_{DSCH-TX}$ with CQI and $R_{target}$.

<table>
<thead>
<tr>
<th>CQI</th>
<th>$R_{target}$ [kbit/s]</th>
<th>$P_{DSCH-TX}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>800</td>
<td>1.76</td>
</tr>
<tr>
<td>17</td>
<td>1200</td>
<td>2.64</td>
</tr>
<tr>
<td>17</td>
<td>500</td>
<td>1.10</td>
</tr>
<tr>
<td>15</td>
<td>800</td>
<td>2.22</td>
</tr>
<tr>
<td>23</td>
<td>800</td>
<td>0.76</td>
</tr>
</tbody>
</table>

The values are related with the $R_{target}$ and the CQI, as expected. If the $R_{target}$ increases, the required power for user must be higher as well, since the increasing of data rate implies more effort from the BS, i.e., more power. Moreover, if the CQI increases, the required power for user can be lower since higher CQI means that the UE is closer to the BS.

With the $P_{DSCH-TX}$ calculated, it is possible to compute the maximum number of users (or number of power slots, as an analogy to Figure 5.1) that it is possible to fit with the available power for HSDPA ($P_{HSDPA}$). This means that the maximum number of HSDPA users is calculated by:

$$Nr. \text{ power slots}_{HSDPA} = \frac{P_{HSDPA}}{P_{DSCH-TX}}$$

(5.7)

Of course, the number of power slots must be an integer, so the fraction is rounded down. Some values are shown in Table 5.6, for different cells.

Table 5.6: Number of power slots.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Hour</th>
<th>$P_{HSDPA}$ [W]</th>
<th>$P_{DSCH-TX}$ [W]</th>
<th>Nr. power slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17:00</td>
<td>35.75</td>
<td>1.63</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>19:00</td>
<td>14.26</td>
<td>0.37</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>15.95</td>
<td>0.49</td>
<td>32</td>
</tr>
</tbody>
</table>

When compared with the voice users, shown in Table 5.1, it is admissible to have more voice users than HSDPA users, with the same allocated power. Since the bit rate for voice is lower than the data rate for HSDPA, this results make sense.
5.5 Code Utilization

Another restriction in communications can be the number of available codes, as discussed in section 2.4. It is possible to make an analysis in the available statistics, in order to perceive if the number of codes is really a limitation.

In Release 99, it is possible to apply the formula (B.2), and the result is an average value of the code utilization in that half an hour. In the statistics used in this project, the maximum value is 45.18% of the 256 codes available for Release 99, although the average value is around 9%. This emphasizes that in Release 99, the codes are not a limitation in this project.

In HSDPA, the code utilization is given directly by a KPI, named VS.PdschCodeUsed.Mean. The maximum number of used codes in all the statistics is 10.45, where the maximum can be 15, since the SF of HSDPA is 16, but one code is used for signalling. The average value is around 2 codes in 16.

Moreover, there is also a KPI which indicates the average number of codes not used in that half an hour. This KPI takes in consideration the codes that are spent in Release 99, which means that the presented KPI indicates the available codes for any service.

A couple of examples are shown in Table 5.7, in order to understand the KPIs. The examples are taken from the busiest half an hour of each available cell. Also, it is important to remember that for voice, the SF is 256 and for HSDPA is 16.

Table 5.7: Used and available codes from statistics.

<table>
<thead>
<tr>
<th>Cell</th>
<th>R99 Code Utilization [%]</th>
<th>Number of free codes for HSDPA</th>
<th>Number of codes used for HSDPA</th>
<th>Number of available codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.82%</td>
<td>7</td>
<td>2.92</td>
<td>5.19</td>
</tr>
<tr>
<td>2</td>
<td>36.98%</td>
<td>9</td>
<td>3</td>
<td>5.89</td>
</tr>
<tr>
<td>3</td>
<td>35.04%</td>
<td>9</td>
<td>4.11</td>
<td>4.71</td>
</tr>
<tr>
<td>4</td>
<td>16.14%</td>
<td>12</td>
<td>2.67</td>
<td>9.65</td>
</tr>
</tbody>
</table>

In column Number of available codes, from Table 5.7, it is perceptible that the available number of codes is high, around 40% of the total 16 codes, from the SF tree, as indicated in Figure 2.6. This means that it is not necessary to take the code limitation in to account, in this project.

In the following section the admission curve is reached, where the inputs are the number of power slots for each service.

5.6 Admission Curve Set Up

To design the admission curve, it is used the Multidimensional Erlang-B Model, presented in section 4.5. In this case the number of carriers is equal to one, so the matrix $M$ is just a vector and the vector $K$ is just a number.

The vector $M$ and the capacity $K$ are constructed taking in to account the maximum number of power slots for each service. If, for example, service 1 has higher number of power slots, the algorithm starts
with matching the capacity $K$ to the maximum number of power slots allowed for service 1 and the first position of vector $M$ to 1. The second position of vector 2 is equal to the number of power slots of service 1 divided by the number of power slots of service 2.

However, the second position of the vector $M$ can be a decimal value and, for the Multidimensional Erlang-B Model, it must be an integer. This means that the algorithm has to be continued and the method multiplies both of the vector positions until both are integers. When the $M$ is a integer vector, after $x$ multiplications, the capacity $K$ is then multiply by the factor $x$.

In Table 5.8, a numerical example is identified, when the maximum number of users for voice is 4 and for HSDPA is 3.

**Table 5.8: Steps to find the matrix $M$.**

<table>
<thead>
<tr>
<th>Step</th>
<th>$K$</th>
<th>$M_1$</th>
<th>$M_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>4</td>
<td>1</td>
<td>4/3</td>
</tr>
<tr>
<td>2nd</td>
<td>8</td>
<td>2</td>
<td>8/3</td>
</tr>
<tr>
<td>3rd</td>
<td>12</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

In the third step, the vector $M = [3 \ 4]$ is already an integer one, so is the final one. Since it was necessary three steps, $K$ is equal to $4 \times 3$.

Another input is the blocking probability. In voice, the input blocking probability is around 1-2%, since it is the average value of Release 99 in CS [50] and also the usual values used by the operators. On the other hand, for HSDPA there is no definition of blocking probability as in voice. So, for this project, the blocking probability in HSDPA is the probability of having a user with lower data rate than the $R_{\text{target}}$.

Since the number of HSDPA users in the statistics is an average value, and since the distribution of the reported CQIs follows a log-normal one, as noticed in Figure 5.4 and 5.5 and announced in [21] in “A log-normally distributed CQI measurement error at the UE with a standard deviation of 1 dB”, it is possible to assume that the number of HSDPA users that have a data rate lower than the average throughput is equal to the number of HSDPA users which data rate is higher than the average throughput.

This means that the average throughput is similar to the median throughput, so the blocking probability for HSDPA can be equal to 50%.

At this moment, all the inputs to design the admission curve are calculated: the capacity $K$, the vector $M$ and the blocking probability. Additionally, it is only necessary to add the $R_{\text{target}}$ defined by the operator.

In the next chapter is discussed how to add the statistics in order to validate the algorithm.

### 5.7 Used traffic determination in statistics

The admission curve is represented in axes on which units are Erlangs. This means that the statistics of both services has to be transformed in traffic. In the case of voice, Erlang is already an used measurement, but in the case of HSDPA, some adaptations have to be made.
To calculate Erlangs in the voice service, the average number of AMR users, in 12.2 kpbs, is taken. It is important to notice that it is only related with the busy hour, which is half an hour of a day.

The KPI $\text{VS.RB.AMR.DL.12.2}$ means that, in any instant of time, the number of allocated users to the BS, to the voice service, is equal to the average number of voice users. As in the example of section 3.1.3, if it is registered a $x$ average number of voice users in half an hour, meaning that the channel is carrying $x$ Erlangs in half an hour or $x/2$ Erlang in the whole hour.

In HSDPA, reference [51] presents a good solution to calculate the traffic in Erlangs, as:

$$ A = \frac{\lambda}{\mu} $$

where $\lambda$ is the consumption in bps and $\mu$ is the data channel capacity, also in bps. However, the statistics do not have the channel capacity, so another solution is going to be developed.

The main idea is the same as in voice, but in HSDPA the average throughput is different for each day and different of the $R_{\text{target}}$, on which the curve is designed. This means that it has to be introduced a ratio with these two data rates, in order to scale the statistics in the same order of magnitude as the curve. The ratio is equal to:

$$ \text{ratio} = \frac{\text{Throughput}_{\text{sample}}}{R_{\text{target}}} $$

Furthermore, the HSDPA service does not use all the TTIs, as announced before, with the KPI $\text{VS.HSDPA.All.ScheduledNum}$. So, unlike the voice traffic, where it was just necessary to multiply the average number of users for 30 min, divided by the 60 min, here it is possible to know how much of the half an hour is really used with data transmission.

One TTI has a duration of 2 ms, so the estimation is:

$$ \text{Traffic} = \text{Average HSDPA users} \times \text{ratio} \times \frac{\text{VS.HSDPA.All.ScheduledNum} \times 2 \text{ms}}{3.6 \times 10^6 \text{ms}} $$

Some examples of traffic, according with analysed statistics, are in Table 5.9 and 5.10. In Table 5.10, the values are refered to cell 1, at 17:00, which is the cell’s busy hour.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Day</th>
<th>Hour</th>
<th>Average Number Voice Users</th>
<th>Voice Traffic [Erl]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28/04</td>
<td>17:00</td>
<td>16.60</td>
<td>8.30</td>
</tr>
<tr>
<td>3</td>
<td>19/09</td>
<td>9:30</td>
<td>1.55</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>27/05</td>
<td>12:00</td>
<td>6.42</td>
<td>3.21</td>
</tr>
</tbody>
</table>

In the following chapter, the results will be shown and discussed.
Table 5.10: HSDPA traffic from the statistics.

<table>
<thead>
<tr>
<th>Day</th>
<th>Average Number HSDPA Users</th>
<th>VS.HSDPA.All.ScheduledNum</th>
<th>$R_{target}$ [Mbit/s]</th>
<th>Throughput [Mbit/s]</th>
<th>HSDPA Traffic [Erl]</th>
</tr>
</thead>
<tbody>
<tr>
<td>27/04</td>
<td>9.41</td>
<td>421650</td>
<td>1</td>
<td>0.97</td>
<td>2.15</td>
</tr>
<tr>
<td>30/04</td>
<td>28.74</td>
<td>810000</td>
<td>1.2</td>
<td>0.28</td>
<td>3.05</td>
</tr>
<tr>
<td>31/05</td>
<td>17.86</td>
<td>332550</td>
<td>1.5</td>
<td>0.83</td>
<td>1.82</td>
</tr>
</tbody>
</table>
Chapter 6

Case Study Analysis and Validation

In this chapter, several results are shown and comments are drawn. The input parameters will be changed, like the cell, the $R_{\text{target}}$ and voice blocking probability.

6.1 Introduction

In section 6.2, it will be shown the simulated admission curves, for different cells, with different statistics from 2016 and also with different $R_{\text{targets}}$ and blocking probabilities.

The compared $R_{\text{targets}}$ are mainly the average of all throughputs, the minimum and the maximum. The CQI is not inputted by the user, but taken from the statistics.

In the beginning, all the tests were made in the busy hour, however it will be tested in different hours to validate the algorithm.

6.2 Case Studies

The first result is from cell 3, in an urban scenario, in the busy hour, which is from 17:00 to 17:30. The $R_{\text{target}}$ is equal to the average throughput of all days and the KPI $\text{VS.MeanTCP}$ indicates that almost all power that the BS can handle is in use, which is 46 dBm. This means that, more or less, half of the statistics should be below the admission curve and the other half above the curve.

The blocking probability for voice is equal to 1%, which is an average value, announced in section 5.6 and for HSDPA is 50%. The number of statistics are 38 days and the median CQI is 21, which corresponds to a $V_{TBS}$ of 6554 bits, as in table 5.2. The $R_{\text{target}}$ is 939.67 kbit/s.

The resulted admission curve for cell 3 in its busy hour is in Figure 6.1.

As expected, the statistics are around the admission curve. The values above the curve have lower throughput and some points below the curve are using less power than the maximum BS transmit power. In a real situation, a lot of factors interfere with the results, for example, if it is weekend or week day. Normally, in the weekends, the throughput attributed to each user is higher than in the week days, specially if the BS is located in an business area.
Figure 6.1: Admission curve and statistics for cell 3.

In Figure 6.2 is visible the variation of the throughput per user and the average number of HSDPA users in the cell, along the days.

Figure 6.2: Variation of the average number of HSDPA users and throughput along the days.

Analysing the Figure 6.2, if it is a week day, the number of HSDPA users is higher, and the throughput for each user is lower. Additionally, in the weekend days, the mean power is lower as well, so it will cloud the admission curve in Figure 6.1.

It is interesting to see that on May 30th, which corresponds to a Monday, it has a low number of
HSDPA users. The reason is that May 30th is the Spring Bank Holiday, in United Kingdom [52], where the statistics are from.

The next result is from cell 4, also an urban scenario, at the same half an hour (17:00 to 17:30). Two admission curves are shown side by side, in Figures 6.3 and 6.4, where the difference is in the blocking probability for voice. The $R_{\text{target}}$ is equal to 1.55 Mbit/s, which is the same as the mean value of all throughputs. The median CQI is 18 and the number of statistics is 36.

![Figure 6.3](image1.png) **Figure 6.3**: Admission curve for cell 4 with voice blocking probability equal to 1%.

![Figure 6.4](image2.png) **Figure 6.4**: Admission curve for cell 4 with voice blocking probability equal to 0.1%.

The BS maximum power is 43 dBm (19.95 W), however, at this hour, the average used power is 40.72 dBm (11.79 W), which corresponds to less 8.16 W than the maximum power of the BS. Even the day that uses more power, it is less 4.75 W than the BS maximum power, so the statistics should be above the curve. This means that the admission curve which reflects better the cell behaviour is the one in 6.3, with 1% of voice blocking probability. This admission curve is consistent with Figure 6.1, where the voice blocking probability is also equal to 1%.

The statistics above the line 6.3 corresponds mostly to days where the throughput is higher than the $R_{\text{target}}$.

In cell 1, it is done the same test as in Figures 6.3 and 6.4. However, in this cell, the BS maximum transmit power is equal to 46 dBm (39.81 W) and the mean transmit power is 43.4 dBm (21.8 W). This means that there is a difference of 18.04 W between the power that the BS can transmit and the real transmitted power. Therefore, it should be a bigger difference between the curve and the statistics, when compared with the previously figures.

The admission curves are shown in Figures 6.5 and 6.6, with 39 days of statistics, in the busy hour (from 17:00 to 17:30), with a CQI equal to 17 and a $R_{\text{target}}$ equal to 780 kbit/s.

As expected, the statistics in Figure 6.5 are much below the curve since the difference between the powers are quite high. Moreover, it continues to be consistent that the blocking probability for voice equal to 1% is more adequate than equal to 0.1%.
In cell 2, it is done a test with the $R_{\text{target}}$ equal to the minimum throughput registered in the 38 days of statistics. Moreover, the average transmit power is equal to 39.64 dBm (9.20 W) and the BS maximum transmit power is equal to 42 dBm (15.85 W).

The expected result is that the statistics should be below the admission curve, but, with blocking probability for voice equal to 1% and for HSDPA equal to 50%, the admission curve is given by Figure 6.7.

Figure 6.5: Admission curve for cell 1 with voice blocking probability equal to 1%.

Figure 6.6: Admission curve for cell 1 with voice blocking probability equal to 0.1%.

Figure 6.7: Admission curve for cell 2, with $R_{\text{target}}$ equal to the minimum throughput.

The reason for some statistics being above the admission curve is related with the median used CQI.
With higher CQI and higher TBS, lower will be the $P_{DSCH-TX}$, which means that it will exist more space to allocate users. This conducts to the increment of allowed traffic, which means that the curve would shift up. It is the case of the statistics above the curve, they have higher CQI than the input one.

### 6.3 Validation

This section presents several tests in order to validate the algorithm. Specific days are chosen, from the statistics, denominated by reference values. The admission curve is calculated considering $R_{target}$ and BS transmit power equal to the throughput and to mean used power, respectively, from that chosen reference value.

Since the BS transmit power is changed in the Matlab source code, the reference value should be on the admission curve. Let us define the validation error as the distance between the reference value and the admission curve, since the admission curve is dimensioned for the reference value mean used power.

The admission curves are calculated for two cells and are simulated with input statistics from week days, with or without weekend days.

The first test is done for cell 3 on July 7th 2016, which corresponds to a Thursday, so a week day. The input is the busy hour, from 17:00 to 17:30. The statistics include week and weekend days, with a total number of 38 days. The CQI is equal to 21 and the $R_{target}$ is equal to the throughput registered in that day, which is 534.12 kbit/s. The admission curve has a parameterized transmit power equal to the registered used power in the reference value, which is equal to 45.64 dBm (36.64 W). The admission curve for the cell 3 is in Figure 6.8.

The reference value is above the curve with a validation error of 4.98%. The same test is done for the input statistics from week days only, which corresponds to 29 days. Figure 6.9 presents the admission curve with the same blocking probabilities as in Figure 6.8.

In this measurement, the validation error is equal to 1.02%. For this cell, at the busy hour of July 7th, the admission curve has a better performance when the statistics only have week days than when they have all days (week and weekend days).

The second test is for cell 1, at 13:00 and with a reference value relative to May 27th. The simulations are made for all days of the week and after, only for week days, in order to compare the error between both.

The BS transmit power is manually changed again, matching the used power in the specified half an hour. So, $P_{max_{BS}}$ is equal to 35.56 W and the $R_{target}$ is equal to 521.25 kbit/s.

Figure 6.10 presents the admission curve, obtained with the statistics from all days of the week, which corresponds to 38 days.

The error in Figure 6.10 is equal to 9.43%. Again, the same case is simulated for statistics including week days, in a total of 29 days, and the admission curve is in Figure 6.11.
The error in this case decreases from 9.43% to 7.44%, confirming that the cell characteristics are better defined when the input statistics only include week days.

A last validation of the algorithm is done in cell 3, at 17:00 as well, but with the reference value corresponding to April 27th. The used power in this half an hour is equal to 35.24 W and the throughput...
is 679.78 kbit/s, which will be matched to the $R_{\text{target}}$.

The admission curve for all days is in Figure 6.12, with the same 38 days.

The validation error associated to the admission curve shown in Figure 6.12 is equal to 1.47%. The
Figure 6.12: Admission curve for cell 3 for all days with $P_{\text{max BS}}$ equal to the used power on April 27th.

The error in this last admission curve is equal to 3.41%, which means that there was an increase of the error from week days to working days, opposing the assumption. However, it is still a good validation
of the algorithm since the error keeps small.

This concludes the algorithm validation. In the next section, a new traffic management feature will be introduced, called headroom.

6.4 Headroom

Now, it will be introduced a new feature called headroom. The headroom is a percentage value that indicates if the BS transmits power is in excess or in lack and expresses which transmit power should the BS have allocated.

That headroom is calculated taken in account a reference traffic, which should be a percentile of all the statistics. After the reference traffic calculation, it is computed the difference between the reference traffic and the admission curve.

Since the number of statistics is quite low, the chosen percentile for the reference traffic is 80, so it is compared the difference between the chosen percentile with the admission curve.

The first demonstration is for cell 3, which BS transmit power is 46 dBm (39.81 W). The input $R_{\text{target}}$ is equal to the mean throughput registered in the 38 days of statistics, which is 939.67 kbit/s, and the CQI is equal to 21. Figure 6.14 represents the admission curve with the statistics value and also with the reference traffic, taken from the percentile 80.

![Figure 6.14: Reference traffic for cell 3.](image)

As output, there is a message with the information that the cell has a negative headroom equal to 15.94% and the power should be equal to 45.5 W in order to agglomerate all the users, or, at least, the users that register a traffic lower or equal to the reference one. The change is made manually and
The results are shown in Figure 6.15.

![Admission curve with the BS maximum power changed for cell 3.](image)

**Figure 6.15:** Admission curve with the BS maximum power changed for cell 3.

The curve suffered a shift in the up direction and now it includes the reference traffic and 80% of the statistics.

The second headroom example is for cell 4, at 10:00, which BS transmit power is 43 dBm (19.95 W). The $R_{\text{target}}$ is also equal to the average throughput in the 37 input statistics, which is 1582.84 kbit/s and the CQI is equal to 22. The admission curve and the respective traffic is in Figure 6.16.

The output message carries the information that the headroom is positive, with a percentage of 55.97% and the suggested transmit power is equal to 13.57 W. The change is made and the resulted admission curve is presented in Figure 6.17.

The curve down shifted since the headroom was positive. With this transformation, there is no waste of power in the BS.

This analysis can be really useful to find the proper BS transmit power, according with the past traffic.

After the tool development, it is possible to make a study related with the allocated transmit power, with the statistics of the available BSs. This means that for each cell, at its busy hour, it can be calculated the percentage of power that is in excess or not, when the $R_{\text{target}}$ is equal to the mean throughput of all days in the statistics.

In cell 1, the busy hour is at 13:30, the BS transmit power is equal to 46 dBm (39.81 W) and the $R_{\text{target}}$ is equal to 639.79 kbit/s. The difference between the reference traffic and the admission curve is equal to +30.60%, which means that, at the busy hour, at least, 80% of the statistics are below the curve.

Moreover, the same test can be done to cell 1 but only for week days, the busy hours are the same...
but the $R_{\text{target}}$ turns equal to 630.21 kbit/s, the headroom is equal to $+24.24\%$, which means that the BS has an improvement on the resource allocation. However, the suggestion from the tool is that the BS transmit power should be equal to 31.15 W, which is a difference of 8.66 W, when compared with the parameterized power. Accordingly with this result, it can be concluded that the cell 1 has more
parameterized transmit power than what it should.

In cell 3, the busy hour is from 17:00 to 17:30, and the simulations will be run for week plus weekend days and for week days only. The first result, obtained for all days of the week, with a $R_{target}$ equal to 939.67 kbit/s, gets a headroom equal to -10.68%. On the other hand, for week days only and with a $R_{target}$ equal to 719.14 kbit/s, the resulted headroom is -2.65%. The reason for the negative signal in the headroom is a result of the statistics being above the admission curve, so the BS transmit power should be higher than what really is. The suggested value for the BS transmit power is 40.76 W, which is more 0.95 W than the real value.

This means that, for cell 3, and until the reference traffic, the transmit power is proper for the throughput registered in the statistics.

To finalize, in cell 4, tests were made for the busiest hour and for another hour with a lot of traffic as well. The busy hour is from 13:30 to 14:00 and the second simulated hour is from 17:00 to 17:30.

In the busy hour and for all days of the week, the resulted headroom is -37.60%, while for week days only, the headroom is -39.95%. Since it is a negative value for headroom, the percentile 80 of the statistics is above the curve. At 17:00, the headroom is also negative, with values equal to -4.91% when all days are included in the simulation and equal to -3.47% when the admission curve is only calculated for week days.

The negative values obtained in the four headrooms demonstrate that the BS transmit power is lower than it should, which requires to increase the 43 dBm (19.95 W). Nevertheless, the headroom in the busy hour is lower in the case of when the input statistics have all days instead of the input statistics with only week days, contrary to the usual behaviour noticed in the other cells (and also in cell 4, at 17:00). However, the differences can be justified in part by the lower number of statistics and it should not discredit the conclusion that the admission curves are better characterized in week days only.

In all cells, except in the busy hour of cell 4 (with a small error), there is a significant positive correlation between the headroom and the results obtained in the simulations made for week days only. The BSs are better parameterized for the week days than for weekend days, since the headroom is lower in absolute for the first case (week days).

### 6.5 Introduction of new services

In this chapter, it was always shown admission curves between voice and the HSDPA service. The reason is related with the available statistics, since the 3G users are usually allocated to these two services. However, it was possible to take some days with statistics for PS Release 99.

The PS services are also allocated in to the DCH channels, which means that they also use the Energy Per Bit characteristics, explained in section 5.3. The calculation of the maximum number of users is the same as in voice, but in equation (5.3) the $R_{MAC\text{-dij}}$ will be equal to the bit rate of the PS service multiplied by the average number of users for that service.

Since there are KPIs for each service and each bit rate, for example, $VS.RB.PS.Int.DL.8$, as in appendix B, which indicates the average number of users in a given service and in a given bit rate, it is
possible to calculate the number of users specifically for each case.

In the statistics, the only PS Release 99 service is the interactive service, and with bit rates of 8 and 64 kbit/s. In Figure 6.18 is shown an admission curve for cell 1, in the busiest hour, which relates the voice traffic and the interactive service traffic in 8 kbit/s.

![Admission curve for voice and interactive service, for 8 kbit/s.](image)

**Figure 6.18:** Admission curve for voice and interactive service, for 8 kbit/s.

The maximum BS transmit power, in the simulation from Figure 6.18, was equal to the parameterized one, so a new test can be made, where the goal is to match the BS transmit power to the transmitted power (without HSDPA service) of a reference statistic. The Figure 6.19 shows the new admission curve, with the reference day highlighted.

In fact, the number of statistics are quite low, the obtained admission curve in Figure 6.19 presents an error quite low, which means that the Energy Per Bit is the characteristic for all services allocated in the DCH channels.
Figure 6.19: Admission curve for voice and interactive service, for 8 kbit/s, with maximum BS transmit power equal to the average transmitted power.
Chapter 7

Conclusions

This chapter finalizes this work, and it will summarize conclusions and enumerate aspects to be developed in future work.

7.1 Summary

The goal of this master thesis was to study and develop a simulation multi-service platform based on admission curves for Third Generation (3G) networks. These curves define the maximum limit of resource utilization for a certain defined Grade of Service (GoS).

The admission curve is presented in a x-y graph, where both axes are in Erlangs, representing the traffic. Since the representation is in Erlangs, it is used the Erlang-B Model. Taking in consideration that this project is planned to be a multi-service platform, it was studied and implemented the Multidimensional Erlang-B Model.

To validate the admission curve approach, statistics were added. With them, the used power, the number of users for each service and other important parameters are known.

The thesis used real case studies, applied in the section 6, which enables validation and applicability.

The main results and conclusions are related with the Multidimensional Erlang-B model and the implemented admission curves.

In chapter 4 the proper algorithm was chosen. The Multidimensional Erlang-B Model provided the best results of the four methods, which were studied and implemented. It is the only one that can combine the dependencies between the services and the exact results of the offered traffic for each service. The model was also tested for several examples and it varied according with the expected.

In chapter 5 was presented the cell characteristics for voice and HSDPA services, which described the cell behaviour. Both characteristics depend on real measurements, meaning that they are unique for each cell, specifically, for the cell's busy hour.

For voice, the cell characteristic is the Energy Per Bit. The correlation between the mean used transmit power with the number of voice users was proportional to the number of days in the input statistics, i.e., the correlation gets closer to 1 if the number of statistics increases.
For HSDPA, the cell characteristic is the $P_{DSCH-TX}$, which is the required power to serve one HSDPA user. It was accomplished that the $P_{DSCH-TX}$ is only applicable in the busiest hours, because is closer to zero when the registered traffic is almost null.

Since the number of HSDPA users was given in the network statistics, it can be compared with the computed number of users. That number was given by the division between the used power for HSDPA service by the $P_{DSCH-TX}$. The maximum difference between the registered users in the statistics and the computed number of HSDPA users was, in the maximum, of 10 users. Knowing that a lot of factors can interfere with the $P_{DSCH-TX}$, as the median CQI and the mean used power for HSDPA, it was considered a positive value. Moreover, when the admission curves were computed, the errors were much lower than this.

In chapter 6, two conclusions were drawn: the admission curve is better defined when the input statistics are working days, instead of working days plus weekend days, and it is also better defined when there are more day samples.

In section 6.3, the algorithm validation was done and the maximum validation error was 9.43%, which brings reliability to this research work.

In Figures 6.9 and 6.8, the error decreases from 4.98% to 1.02% with the removal of the weekend days. This proves that the cell characteristics are unique for a cell, since in the weekends the behaviour was different and it changed the admission curves. Figure 6.2 displayed the difference between the number of users and the throughput.

In this project, the maximum days of available statistics was 38, however, if the double or the triple were available, the results would be much better. Table 7.1 overviews the results obtained with different days of statistics.

**Table 7.1:** Error in the admission curves, depending on the number of days and on week days or weekends.

<table>
<thead>
<tr>
<th>Nr. Days</th>
<th>All Days</th>
<th>Week Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>18.59</td>
<td>6.60</td>
</tr>
<tr>
<td>38</td>
<td>7.76</td>
<td>3.56</td>
</tr>
<tr>
<td>11</td>
<td>6.60</td>
<td>3.56</td>
</tr>
<tr>
<td>29</td>
<td>3.56</td>
<td>3.56</td>
</tr>
</tbody>
</table>

In Table 7.1 the error decreases when it is only used week days as the input, in opposition to when all days are used (week and weekend days). Moreover, with the increasing of the number of statistics, the error also decreases, as the case of 11 week days to 29 week days.

A last conclusion goes to the parameterized BS transmit power. From the 4 analysed cells, two of them had more BS transmit power than the necessary, against the other two, which had less transmit power than the required to agglomerate 80% of the statistics. More alarming is the throughput, since the registered throughput in the specifics KPIs are lower than the promised by the operator, which is around 2 Mbit/s. The average throughput in the busy hour is always around 700 kbit/s.

The original Multidimensional Erlang-B method was coded in Matlab ©, leading to high simulation time up to 12 hours. To improve this aspect, the method was rebuilt in C#, which enabled computation time to decrease to 20 seconds.
This project can be useful for monitoring the network performance and also to conclude if the parameterized BS maximum transmit power is higher or lower than the necessary. This will maximize the power efficiency, in order to avoid wasting resources.

### 7.2 Future Work

Further work can be made to evolve this research. Until now, it is concluded for 3G, however it should be done more tests for PS Release 99 services, since there was not enough statistics for that services.

Another tests should be done for rural and suburban scenario, since this was not studied in this master thesis, because there was no statistics for that case. So, no conclusions can be drawn for other scenarios than urban.

Moreover, taking in account that 3G has more than 2 services, it is possible to calculate an admission curve for 3 services. This will be translated in a 3-D graph and the admission curve will be transformed in an admission area, where each axis corresponds to one of the three services.

After the performed validation for 3G, a new goal could be introduced, which is the addition of the LTE technology (4G). LTE was projected to only support PS services, which means that the voice, as in 3G, is not taken in consideration. Therefore, in LTE exists the concept of class as well, known as QoS Class Identifier (QCI). It is standardized, divided in Guaranteed Bit Rate (GBR) and non-GBR, in a total of nine QoS Class Identifiers (QCIs) [53].
Bibliography


[45] 3GPP. Digital cellular telecommunications systems (Phase 2+); Universal Mobile Telecommunications System (UMTS); LTE; Telecommunications management; Key Performance Indicators (KPI) for UMTS and GSM. TS 32.410, 3rd Generation Partnership Project (3GPP), Feb. 2016. Version 13.0.0.


Appendix A

Interference

The interference can be calculated, after obtaining the max path loss. The used formulas in this appendix are based on the reference [4] and [54].

Uplink load is a metric to measure the maximum capacity that a system can support until it does not guarantee the required quality of service. It has been used the uplink load factor, $n_{UL}$, to understand and predict how close is the system to saturate, without do system-level capacity simulations. If $n_{UL}$ is closer to 1, it is closer to reach its maximum capacity.

The system is interference limited, and there are two types of interference: the Adjacent Channel Interference (ACI), which comes from another cells, adjacent to the own cell, and Co-Channel Interference (CCI), which comes from the other cells in the same cluster, and uses the same frequency. The major source of interference is usually the last one.

The first step to calculate the interference is defining the $E_b/N_0$ for user $j$, which is the energy per bit to noise power spectral density ratio:

$$\frac{E_b}{N_0} = \frac{W}{\eta_j \cdot R_j} \cdot \frac{P_j}{I_{TOTAL} - P_j} \quad (A.1)$$

where $W$ is the chip rate, $\eta_j$ is the activity factor for user $j$, $R_j$ is the bit rate for user $j$, $P_j$ is the received signal power from user $j$ and $I_{TOTAL}$ is the total received interference, including the thermal noise. From the expression (A.1) is possible to take $P_j$:

$$P_j = \frac{1}{1 + \frac{W}{(E_b/N_0) \cdot R_j \cdot \eta_j}} \cdot I_{TOTAL} \quad (A.2)$$

The total received interference $I_{TOTAL}$ is the sum of all received power plus the thermal noise:

$$I_{TOTAL} = \sum_{j=1}^{N} P_j + P_N \quad (A.3)$$

where $N$ is the total number of users, $P_N$ is the thermal noise, given by:

$$P_N = 10 \cdot \log \left( k \cdot T \cdot \frac{W}{R_0} \right) + NF \quad (A.4)$$
where $k$ is the Boltzmann constant of $1.381 \times 10^{23}$ J/K, $T$ is temperature in Kelvin, $W$ is the chip rate, $R_b$ is the bearer bit rate and $NF$ is the mobile station receiver noise figure with typical values of 5–9 dB.

The load factor of one user (or one connection), $L_j$, is:

$$L_j = \frac{1}{1 + \frac{W}{(E_b/N_0)_j R_j \eta_j}}$$  \hspace{1cm} (A.5)

With the expression (A.3) and the definition of uplink load factor, $n_{UL}$, as:

$$n_{UL} = \sum_{j=1}^{N} L_j$$  \hspace{1cm} (A.6)

it is possible to conclude that:

$$\frac{I_{TOTAL}}{P_N} = \frac{1}{1 - n_{UL}}$$  \hspace{1cm} (A.7)

This is also called the noise rise, which is defined as the ratio of the total received wideband power to the noise power:

$$\text{noise rise} = \frac{I_{TOTAL}}{P_N}$$  \hspace{1cm} (A.8)

It is still missing the interference from others cells, which is taking in account as the ratio of the interference from others cells ($I_{other}$) and the interference from the own cell ($I_{own}$):

$$i = \frac{I_{other}}{I_{own}}$$  \hspace{1cm} (A.9)

So the uplink load factor, with all the interferences, is defined in the following equation:

$$n_{UL} = (1 + i) \cdot \sum_{j=1}^{N} \frac{1}{1 + \frac{W}{(E_b/N_0)_j R_j \eta_j}}$$  \hspace{1cm} (A.10)

In WCDMA, the users in the same cell use the same frequency, so there will be interference between users.

In the downlink, the load factor, $n_{DL}$, is almost the same, as shown in section 3.2.3 and:

$$n_{DL} = \sum_{j=1}^{N} v_j \cdot \frac{(E_b/N_0)_j}{W/R_j} \cdot [(1 - \alpha_j) + i_j]$$  \hspace{1cm} (A.11)

where $\alpha_j$ is the orthogonality factor in the downlink for user $j$ (when is 1, it is fully orthogonal, when it is 0, there is no orthogonality) and $i_j$ is the ratio of other cell interference to own cell interference, received by user $j$. 

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Appendix B

Key Performance Indicators

In this appendix are shown the used KPIs in this master thesis, from Huawei.

- **VS.HSDPA.UE.Mean.CAT1.6**
  It represents the average number of UEs that are between category 1 to 6. There are KPIs for category 1 until category 32.

- **VS.CQI.0**
  This KPI is the number of CQIs 0 reported by the UEs. This KPI exits for CQIs 0 until 30.

- **VS.UsedCQI0**
  The difference between this KPI and the previous KPI is that this one is the CQI used by the BS, so it has more accuracy to calculate data rates.

- **VS.AckTotal**
  It presents the total number of ACKs in a specific half hour.

- **VS.NackTotal**
  It indicates the total number of Negative Acknowledgements, also in a specific half hour.

- **VS.DtxTotal**
  It counts the number of TTIs of which the NodeB cannot translate the ACK from the UE.

- **VS.DataTtlRatio.Mean**
  It is a ratio of time when there is at least one HSDPA user with data to transmit, in the queue buffer.

- **VS.HSDPA.DataTtlNum.User**
  It is the total number of TTIs in which there is data to transmit in the HSDPA user queue buffer.

- **VS.HSDPA.InactiveDataTtlRatio.Mean**
  It is also a ratio of time of when there is HSDPA users with data to transmit, but none of them is transmitting in the physical layer.
• **VS.HSDPA.All.ScheduledNum**
  
  This KPI indicates the total number of times that all the users are scheduled in a cell.

• **VS.HSDPA.ScheInactiveDataTtiRatio.Mean**
  
  It is a ratio of time of when HSDPA users are queued in the scheduling candidate set but they are not transmitting data.

• **VS.SingleRAB.SF4**
  
  It is the number of single Radio Access Bearer (RAB) that uses Release 99 codes, with a SF of 4. There is also KPIs for SF of 8 until 256.

• **VS.MultRAB.SF4**
  
  It is the same as the previous KPI, but with multi RAB. There is also with SF from 8 until 256.

• **R99 Code Usage**
  
  It indicates the percentage of codes from SF of 256 that are used in the services from Release 99.

• **VS.PdschCodeUsed.Mean**
  
  It provides the mean number of codes used by HS-PDSCHs in a cell, during the half an hour. It exists also the max and the min of this KPI.

• **VS.PdschCodeAvail.Mean**
  
  It specifies the average number of codes that are available in that half an hour for HS-PDSCHs, already without the Release 99 codes utilization.

• **VS.RB.PS.Int.DL.8**
  
  Average number of users for PS Release 99 interactive service with downlink bit rate of 8 kbit/s. There are also KPIs for 16, 32, 64, 128, 144, 256 and 384 kbit/s and for background, conversational and streaming services.

There are two formulas applied in the KPIs that were used: the BLER and the Release 99 Code Utilization.

To calculate the BLER, the formula is given by:

\[
BLER = \frac{V.S.NackTotal + V.S.DtxTotal}{V.S.NackTotal + V.S.AckTotal + V.S.DtxTotal}
\]  

The Release 99 Code Utilization is given by:

\[
CodeUtilization = \sum_{i=4,8,16,32,64,128,256} \frac{V.S.SingleRAB.SF_i + V.S.MultRAB.SF_i}{i} \times 100\%
\]
Appendix C

Tests for Energy Per Bit

In section 5.3 was introduced the cell characteristic for voice, called *Energy Per Bit* and it was performed a test for cell 1. In this appendix, it will be presented more tests, for other three cells, which also belong to an urban scenario. Moreover, it will also be demonstrated if the Energy Per Bit is also valid for cases where the statistics contains less days.

For this second cell, with statistics from 26 days, the calculated Energy Per Bit is equal to 0.014 mJ/kb and the estimated curve is shown in figure C.1:

![Figure C.1: Estimated curve with the equation curve from cell 2.](image)

The regression curve with respective statistics is shown in figure C.2.

The correlation between both results is 0.917.

The Energy Per Bit, in this third cell, with 26 days, is equal to 0.010. The estimated curve is shown in the figure C.3 and the regression curve is in figure C.4

The correlation between the estimated and regression results is 0.930.

In this last cell, the test was made with only 15 days and the obtain results are in figure C.5 and C.6. The obtained correlation was 0.857.

With this correlation results, it is possible to assume that the characteristic Energy Per Bit is a good approximation.
Figure C.2: Regression curve with the equation curve from cell 2.

Figure C.3: Estimated curve with the equation curve from cell 3.

Figure C.4: Regression curve with the equation curve from cell 3.
Figure C.5: Estimated curve with the equation curve from cell 4.

Figure C.6: Regression curve with the equation curve from cell 4.