Study of soft handover in UMTS

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<tr>
<td>3G</td>
<td>Third Generation</td>
</tr>
<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>AAL</td>
<td>ATM Adaptation Layer</td>
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<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
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<td>BCH</td>
<td>Broadcasting Channel</td>
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<tr>
<td>BER</td>
<td>Bit Error Rate</td>
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<tr>
<td>BLER</td>
<td>Block Error Rate</td>
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<tr>
<td>BSC</td>
<td>Base Station Controller</td>
</tr>
<tr>
<td>BTS</td>
<td>Base Transceiver Station</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
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<td>CRNC</td>
<td>Controlling RNC</td>
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<td>DL</td>
<td>Downlink</td>
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<tr>
<td>DPCCH</td>
<td>Dedicated Physical Control Channel</td>
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<tr>
<td>DPDCH</td>
<td>Dedicated Physical Data Channel</td>
</tr>
<tr>
<td>DRNC</td>
<td>Drift RNC</td>
</tr>
<tr>
<td>DRX</td>
<td>Discontinuous Reception</td>
</tr>
<tr>
<td>DS</td>
<td>Direct Sequence</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
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<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FH</td>
<td>Frequency Hopping</td>
</tr>
<tr>
<td>GGSN</td>
<td>Gateway GPRS Support Node</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile telecommunications</td>
</tr>
<tr>
<td>HLR</td>
<td>Home Location Register</td>
</tr>
<tr>
<td>HSS</td>
<td>Home Subscriber Server</td>
</tr>
<tr>
<td>IMS</td>
<td>IP Multimedia System</td>
</tr>
<tr>
<td>IMT-2000</td>
<td>International Mobile Telecommunications 2000</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Packet</td>
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ITU
ME
MGW
MRC
MS
MT
OVSF
PDF
PN
QoS
RNC
RNS
RRC
RSCP
RSSI
SF
SGSN
SIP
SIR
SRNC
SS7
STD
TDMA
TE
TPC
UE
UL
UMTS
URA
USIM
UTRAN
VoIP
W-CDMA

International Telecommunication Union
Mobile Equipment (Domain)
Media Gateway
Maximum Ratio Combining
Mobile Station
Mobile Termination/Terminal
Orthogonal Variable Spreading Factor
Probability Density Function
Pseudo-Noise
Quality of Service
Radio Network Controller
Radio Network Subsystem
Radio Resource Control
Received Signal Code Power
Received Signal Strength Indicator
Spreading Factor
Serving GPRS Support Node
Session Initiation Protocol
Signal to Interference Ratio
Serving RNC
Signalling System no.7
State Transition Diagram
Time Division Multiple Access
Terminal Equipment
Transmission Power Control
User Equipment
Uplink
Universal Mobile Telecommunications System
UTRAN Registration Area
UMTS Subscriber Identity Module
UMTS Terrestrial Radio Access Network
Voice over IP
Wideband - Code Division Multiple Access
Preface

The Internet and second generation wireless telecommunications systems, such as GSM, have enjoyed a simultaneous tremendous growth in penetration in most of the free market countries during the last ten years. Third generation mobile systems are needed to offer high bit rate services as high quality video and images and fast web access. In this research third generation networks are referred to as UMTS (Universal Mobile Telecommunications System). WCDMA (Wideband Code Division Multiple Access) is the main third generation air interface. It operates in the frequency band around 2GHz and will be deployed in Europe. In order to ensure a high quality of service and provide flexibility in the network soft handovers have been implemented in the WCDMA air interface. Soft handover is the situation where a user has two simultaneous connections with the access part of the network. This report gives a detailed description of soft handovers in the UMTS system and analyses the impact of this CDMA-specific handover type on the system performance.

Chapter 1 introduces cellular networks and the handover concept.

Chapter 2 discusses the UMTS system in detail. The WCDMA air interface including spreading, rake receivers and power control are discussed. Also the network architecture with its network elements and the core network are introduced. In the second section of this chapter handovers are introduced. Hard, inter-system and soft & softer handovers are discussed in detail and illustrated with simulation results.

Chapter 3 deals with the modelling of a UMTS network. The OPNET® network modeller with its different layers and editors is presented in a first section. The following part presents the modelling work done. The different models built as also the iterative process of setting goals, building models, simulating them and analysing the results obtained are discussed.
Chapter 4 analyses the probability that the user is in soft handover while simulating simple models. The results obtained are verified by creating analytical models.

Chapter 5 analyses the coverage and the capacity in a general UMTS network and investigates soft handover-related trends and mechanisms affecting these network performance parameters.

Chapter 6 summarises the results of the work done and proposes recommendations for future work.
Acknowledgement

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This research has been completed at Denmark’s Technical University – Center for Communications, Optics and Materials (COM) and submitted as the final year project at the University of Gent Belgium to obtain the degree of “Burgerlijk Electrotechnisch Ingenieur – optie Communicatie”.

Stijn Van Cauwenberge
July 22, 2003 – Lyngby, Denmark
Chapter 1

Introduction

Today mobile wireless communications are commonly seen as one of the most advanced form of human communications ever. The last decade GSM technology has been a leading force in this revolution. Simultaneously with the phenomenal deployment of wireless networks and distribution of user terminals, also the Internet has seen a similar revolutionary growth.

The success of both technologies offers a great opportunity to provide integrated services using a wireless network. In order to support multimedia, web, email and other data services in a broadband wireless network, standards have been proposed by the 3GPP leading to the creation of the Universal Mobile Telecommunications System (UMTS). Besides providing changes in the network infrastructure – the UMTS specifications point out the evolution path from GSM circuit switched networks towards packet switched technologies offering higher transmission rates.

Based on the service requirements the UMTS Terrestrial Radio Access Network (UTRAN) has been designed. A key requirement in the bearer capabilities is the handover. Principally handover is necessary to support mobility of users and to enable the interoperability of different network technologies (e.g. between UMTS and 2nd generation systems as GSM).
The goal of this research is to study some factors that affect the handover process and hence the overall quality of the mobile network. Before going into details of the UMTS handover process, some background information on general concepts in mobile communications will be presented. Also some considerations concerning network modelling and the outline of this project will be discussed in this introductory chapter.

1.1 Cellular networks

The aim of network and service providers to offer a wide variety of – often bandwidth extensive – services to a broad market of users via wireless networks, made the scarcity of the radio frequency spectrum a hot political issue in the telecommunications market. To use the spectrum more efficiently cellular systems were designed. In opposite to “old” communication systems – using one transmitter transmitting at high power levels in a limited channel – a cellular architecture uses many transmitters at low power what makes it able to reuse frequencies. Traditional cellular systems are designed so that adjacent cells use different frequencies. As long as the cells are separated and the signal strength calibrated, there will not be harmful inter-cell interference. The picture on the next page shows the typical layout of a seven-way frequency reuse system often used in GSM networks. Cell 1 makes use of frequency $f_1$, in cell 2 frequency $f_2$ is transmitted… In this example every seventh cell reuses a certain frequency, hence this architecture is said to have a frequency reuse factor of $N = 7$. Sometimes the D/R ratio is used to characterise the frequency reuse. D represents the minimum distance between cells using the same frequencies; R is the radius of the hexagonal cell. For N=7, D/R equals 4.6; following the relation [1]

$$\frac{D}{R} = \sqrt{3N}.$$  \hspace{1cm} (1.1)

In UMTS systems the radio spectrum can be used even more efficient by applying CDMA as multiple access scheme, resulting in a frequency reuse factor of theoretically 1.
During the spectrum assignment process a service provider is usually given a portion of the total spectrum band allocated to one technology. This spectrum band is further divided into smaller slices dedicated to the different base stations in the cells.

On top of this frequency division architecture a suitable multiple access scheme is deployed. In GSM networks Time Division Multiple Access (TDMA) is used to efficiently distribute the bandwidth inside a cell to the users. The UMTS system uses CDMA as multiple access scheme to utilise the bandwidth as efficient as possible. CDMA also enables different data rates for different services in a more flexible way. The next chapter deals with CDMA and the UMTS access part in more detail.

1.2 The handover concept

The freedom to be able to make and receive calls anywhere, at any time, creating a totally new dimension in human communications has frequently been advertised as the main advantage of new wireless systems. Handovers are a key concept in providing this mobility. It makes it possible for a user to travel from one cell to another while having a seamless connection.

Generally a handover is performed when the quality of the link between the base station and the mobile terminal on the move is decreasing. The term “handover” refers to the whole process of tearing down an existing connection and replacing it by a new connection in the cell into which the user is handed over – the so called target cell [2].

Figure 1: seven-way frequency reuse cellular system
From the information about the radio link quality contained in measurement reports, the network controller is able to decide whether a handover to another cell is needed. Knowledge about radio resource allocation in the target cell and the correct release of channels after the handover is completed are vital for a successful handover. The inability to establish a new connection in the target cell is referred to as a “handover failure”. Handover failures occur when no new resources are available in the target cell or when the radio link quality has decreased below acceptable levels before the call could be handed over. The latter scenario being common in GSM networks results into dropped calls.

As the effect of a handover request in the target cell is similar to that of an incoming call, optimization of the resource utilisation is crucial in order to minimize call blocking and call dropping probabilities. But it is commonly accepted that the forced dropping of an existing call is more desirable than the blocking of a new call. Therefore various handover prioritization algorithms have been studied [3]. Some schemes suggest allocating a portion of the total number of channels to handover users. The main disadvantage of this strategy is that fewer channels can be granted to new calls, resulting in rapidly increasing blocking probabilities for new calls.

In order to improve the handover performance (or reduce the high dropped call probabilities in GSM systems) and to accommodate for future capacity increase in 3G systems, advanced handover protocols have been developed. Soft handover enables two simultaneous links between a mobile terminal and two base stations in a different cell. Also the case of a user having two concurrent connections with one base station exists, this is called softer handover. Both operational modes will be discussed in next chapter.

As expanding markets demand increasing capacity there is a trend towards reducing the size of cells in mobile communications systems (besides increasing the used frequency band). This results in more frequent handovers and it is important to remark that this makes a reliable handover mechanism more than ever desirable for efficient operation of any future cellular mobile network.
1.3 Network modelling

In order to carefully plan and dimension future telecommunications networks, modelling is of prime importance. Three modelling methods are commonly used: building analytical models, simulating with network modellers and performing measurements on real systems. Each method has some advantages and drawbacks. Seen the facts that operational UMTS test networks were not available at the time this research was performed\(^1\) and that it is almost impossible to develop a mathematical system model and get some reliable results in a reasonable time, the choice has been made to mainly model and simulate the UMTS network using OPNET® to obtain the results. OPNET® is a modular network management software packet designed for optimizing network performance. It includes a specialized model for UMTS networks, based on the 3GPP specifications.

1.4 Overview

Besides presenting the main findings of this research, the report contains general information about the UMTS system and network modelling.

Chapter 2 introduces the UMTS system. It describes the basics of the network architecture – core and access part and network elements and the handover strategies as specified by the 3GPP. The soft handover concept will be discussed in more detail. Also initial simulation results illustrating the soft handover mechanism and the importance of it on network performance – compared to a system using only hard handover algorithms – are presented.

In the third chapter the attention is drawn to some considerations around network modelling. The functional requirements of the model and the modelling choices made

\(^1\) In Denmark commercial UMTS networks operated by TDC and 3G Hutchinson will be only available until the second half of 2003.
are covered. Also a short walk-through of the possibilities the OPNET® tool offers, is given.

Chapters 4 and 5 present and analyse the results and conclusions of the simulated network models. Chapter 4 focuses on the probability that a user is in soft handover mode. Simulating different simple network models the effect of two parameters on the probability a user is in soft handover is studied: the soft handover threshold and the distance between the mobile user and the base station. The chapter concludes with proposing two analytical models to verify the results obtained.

Chapter 5 discusses issues related to coverage and capacity in a UMTS network. After presenting general considerations about these vital network performance parameters some specific considerations related to soft handover will be presented.

Chapter 6 summarises the results of the work done during the modelling, simulation and analysis of the UMTS network and gives suggestions for future research to be done.
References

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[2] Aruna Uppendra Jayasuriya “Improved Handover Performance Through Mobility Predictions”, University of South Australia, 31 August 2001

   http://keskus.hut.fi/tutkimus/ironet/3g/handover.doc
Chapter 2

Universal Mobile Telecommunication System

In this chapter the concept of third generation mobile communication networks – often referred to as 3G – is introduced. During the whole project the focus is only on UMTS (Universal Mobile Telecommunication System), as this is the main system in the IMT-2000 standardisation framework that will be able to provide true 3G services to a wide range of European users in the foreseeable future. This describing part does not tend to give a complete overview of the technology behind UMTS; the goal being merely to highlight some of the technical requirements necessary to get a good understanding of the handover process and operational aspects of the air interface in general. Especially the correlation between different aspects of this revolutionary technology will be highlighted.

In the first part of this chapter the UMTS network architecture is discussed in more detail. First the terrestrial radio access network part – UTRAN – is analysed. Its main characteristics; the CDMA multiple access scheme (Code Division Multiple Access), different algorithms and system aspects necessary to get a better understanding of the handover concept will pass the revue. In paragraph 2.1.2 the different network elements of the UTRAN layer and the Mobile Equipment with their functionality are discussed. In a next paragraph the focus is switched to the architecture of the core
network part. Although this part of the network is less noticeable for the end user, it has gone through some changes compared to circuit-switched second-generation networks, in order to ensure bandwidth efficiency and enable quality of service.

The other part of this chapter focuses on the handover concept. After a brief discussion of hard and inter-network handovers soft and softer handovers are studied in deep detail. The WCDMA soft handover algorithm is presented and illustrated with simulation results.

2.1 Network architecture

The UMTS network architecture has been specified according to requirements that will offer higher flexibility to users than second-generation networks ever could support. As has been mentioned in the introductory chapter, two requirements are of prime importance.

1. Firstly an efficient resource management scheme is crucial. This contains making an efficient use of the available spectrum bandwidth and using advanced multiple access techniques.

2. The second requirement is the possibility to accommodate for different traffic types.

Networks supporting multimedia services such as voice and video conversations and high speed Internet require different methods to handle applications with diverse characteristics. This includes both the implementation of quality of service (QoS) classes and enabling different data rates.

\footnote{CDMA2000 is the North-American counterpart of the UMTS system in the 3GPP specifications.}
2.1.1 WCDMA Physical Layer

Implementing the above-mentioned requirements in the radio access layer resulted in the choice of Code Division Multiple Access (CDMA) as the multiple access scheme used in third generation networks. CDMA offers a range of desirable features FDMA/TDMA systems did not support. Besides offering a better performance of the radio signal against interference (from other bands and noise) and multi-path fading, CDMA makes it more flexible to serve users with varying data rates and provide them with more privacy. Another important feature is that an additional user – demanding a random amount of bandwidth – can be accommodated without being limited by the number of channels available in the system. The performance degrades gradually as more users cause more interference. As will be explained below, CDMA systems are interference limited.

The IMT-2000 standardisation effort includes different air interface technologies able to offer data rates of 384 kbps and more. Besides real third generation technologies as WCDMA, TD-CDMA, TD-SCDMA and CDMA2000 also the DECT cordless telephone standard and the 2.5G EDGE system are included. The focus is primarily on WCDMA, as it is the most widely adopted third generation air interface. As will be discussed later WCDMA exists in two different duplex modes: FDD and TDD. Although FDD (Frequency Division Duplexing) and TDD (Time Division Duplexing) operation modes have been significantly harmonised, throughout the following chapters only the FDD operation mode of WCDMA is discussed also because the FDD mode is the only mode supporting soft handovers. When describing the WCDMA air interface, implicitly is referred to this so-called UTRA FDD.

In the following pages these important characteristics of the radio layer are explained:

- Spread spectrum systems
- Power control
- Duplex method
- Network capacity
- Multi-path diversity – Rake receiver
• UMTS Channels
• User Equipment Cell states
• Cell Structure

• Spread spectrum systems

CDMA systems are commonly known as spread spectrum systems because to transmit the information, a larger amount of bandwidth than would normally be used, is utilized. This reduces the average power spectral density of the signal and hence reduces generated interference. In contrary to TDMA/FDMA systems, all users are transmitting in the same frequency band, simultaneously. By assigning different spreading codes to all users, distinction can be made between them. As the different codes have a very small – theoretically zero – cross correlation it is possible to de-spread the signal at the receiver and retrieve the desired original data signal for each user even when very low transmitter powers are used. This results in a much more efficient use of the frequency available. The frequency reuse factor, as has been defined in Chapter 1, can theoretically become equal to 1.

The two most common techniques used for spreading a data signal are frequency hopping (FH) and direct-sequence (DS). Although it is really difficult to make a comparison of the overall performance of both methods and different research publications are contradictory whether DS or FH is the best method, it can be said that DS has some clear advantages over FH systems, especially when used for broadband systems at around 2GHz serving many users [1]. A better broadband interference susceptibility performance, higher power efficiency and the possibility to combine multi-path signals are some of the advantages of the DS method\(^3\). Hence this technique was chosen as the CDMA method for the WCDMA air interface in UMTS networks.

In a DS system the data bits are encoded with a pseudo-noise bit sequence (PN). The quasi-random bits the PN sequence consists of are called chips. The key advantage of the DS technique is the built-in redundancy. The fact that every signal contains

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\(^3\) Near-far effects on the other hand form a significant disadvantage for DS systems and require the implementation of elaborate power control algorithms as will be discussed later.
several redundant copies of the original data at the same time results in a ‘processing gain’ achieved during the de-spreading process (see Appendix A).

A fixed chip rate of 3,84 Mcps (Mega chips per second) is used in the UMTS radio network giving a carrier bandwidth of approximately 5MHz, hence the name Wideband CDMA compared to current systems using a smaller bandwidth of about 1MHz. The data that has to be sent over the WCDMA air interface is encoded twice before being modulated and transmitted as can be seen on the picture below.

Figure 2: spreading and scrambling (picture based on [3])

During the first encoding process the data is multiplied with the channelization code. The channelization codes belong to the Orthogonal Variable Spreading Factor (OVSF) code family. The above-described zero cross correlation or orthogonality of these OVSF codes enables to separate different coded channels transmitted over the same air interface. In the uplink direction this code is necessary to separate the physical data (DPDCH) and the control channels (DPCCH) form the same user terminal. In the downlink direction this encoding process ensures the separation of the connections between different users in one cell. OVSF codes also have the great advantage that it is possible to use codes with different spreading factors (different lengths) and still maintain orthogonality, which enables different user data rates. Because a thorough explanation of coding is not relevant here, some details about OVSF codes and the coding process in general are included in Appendix A.

The second encoding step is scrambling. This process rearranges the bit order – following a certain code pattern – and does not increase the bandwidth used. By doing this the different terminals can be distinguished in the uplink direction, in the downlink direction scrambling is necessary to separate the different sectors (cells) of one base station. The scrambling process makes it unnecessary to coordinate the use of codes between different terminals and base stations. The codes used for the
scrambling process belong to the Gold family. Each code has a length of 10ms, resulting in a code length of 38400 chips if a 3,84 Mcps chip rate is used. In some advanced base stations shorter code lengths of 256 chips are used [3].

As mentioned before, one of the disadvantages of Direct Sequence Spread Spectrum (DSSS) systems is that they are very sensitive to the so-called ‘near-far effect’. This means that one overpowered transmitter close to the receiver, could block transmitters having a bigger path loss towards the base station. This disadvantage results in severe power control algorithms to ensure all signals have the same power level at the receiver. Closed-loop and open-loop power control algorithms enabling fast power control are some of the most characteristic features of WCDMA systems. This is discussed in the following section.

- **Power control**

Power control algorithms are vital for operating a WCDMA system. To counter the ‘near-far effect’ it is essential to equalise the received power at the base station for all mobile terminals transmitting in the same frequency band.

Therefore three power control algorithms have been developed for the WCDMA radio link interface: open loop, outer loop and inner (or closed) loop power control.

- **Open loop power control:**

OL power control is the ability of the user equipment (UE) to set its power to a specified value suitable for the receiver. This method is used for setting up initial uplink transmission powers. The desired power level is calculated from measurement information about the pathloss, the target SIR and the interference at the cell’s receiver, broadcasted on the BCH (Broadcasting Channel).

*Figure 3: open loop power control algorithm*

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4 Sometimes less is chosen in order to reduce inter-operator interference.
The tolerance for the open loop power control is set at ±9dB in normal conditions or ±12dB in extreme conditions. The low accuracy of this method is mainly caused by variations of the UE component properties but also temperature differences and the fact that transmission and reception use different frequencies with different link characteristics (see further FDD), cause large deviations [2].

- Closed (inner) loop power control:

CL power control algorithms are the main means to counter the uplink near-far effect. In contrary to GSM systems where only slow power control algorithms are used at a frequency of approximately 2Hz, WCDMA uses fast power control with 1.5 kHz frequency, compensating for slow and fast fading. 1500 Hz is the time slot frequency used in the WCDMA physical layer.\(^5\) This corresponds to one Transmission Power Control (TPC) command per slot. The goal of CL power control is to equalise the received power of all mobile stations at all times. Open loop power control methods, based on characteristics of a downlink pilot channel, are far too inaccurate to accomplish this; mainly because fast fading patterns for UL and DL channels in FDD are practically uncorrelated due to the large frequency separation between those two bands [3]. Hence open loop power control methods are only used in the initial phase of setting up a connection, as explained above.

The fast power control algorithm works as shown on the figure below.

![Closed loop power control algorithm](image)

**Figure 4:** closed loop power control algorithm

Every 667µs (1/1500Hz) the base station compares the estimated SIR of each mobile station’s signal, with a SIR target value. If the measured SIR is higher than the target SIR, the base station will command the MS to power down; in the other case the base

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\(^5\) UMTS uses continuous transmission with frames of 10ms length. Each frame is divided into 15 times slots with a fixed length of 667 µs corresponding to a frequency of 1.5kHz, which is exactly the frequency used for the fast power control algorithm.
station sends a ‘power up’ command. The basic step size to which the user adjusts its transmit power – following received TPC commands – is ±1dB or ±2dB with an accuracy of ±0,5dB. The SIR target value used in the CL power control method is provided by the outer loop power control algorithm, as will be explained below.

- Outer loop power control:
This fairly simple algorithm sets the $E_b/N_0$ target for the fast (closed loop) power control described in the previous section. This method aims at maintaining the quality of communication, while preventing capacity waste and using as low power as possible. With a frequency varying between 10 and 100 Hz, the received and the desired quality of both uplink and downlink SIR are compared$^6$. If the received quality is better than the quality that has to be achieved, the SIR target is decreased, in the other case the SIR target is increased.

![Diagram](image)

**Figure 5:** outer loop power control algorithm

A disadvantage of this method is that it can happen when a mobile has reached its maximum transmission power, the target SIR gets gradually increased as the user’s signal quality is below the desired value and the MS is unable to better the situation because the maximum transmission power is reached. This windup phenomenon can be countered by setting boundaries for the SIR target.

- Handovers
Handovers are an important part of every cellular communication system. In WCDMA two special types of handovers have been introduced; soft and softer handovers, allowing a mobile user to use 2 separate air interface channels when being in the overlapping area of two adjacent sectors. As research of soft and softer

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$^6$ In this case the Block Error Rate (BLER) is a measure for the signal quality, BLER = 0 if CRC is OK (Cyclic Redundancy Check).
handovers is the main topic of this project, the technological details are covered in a separate section: paragraph 2.2.

- Duplex method

Two duplexing methods are used in the WCDMA architecture: Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD). The latter method needs paired frequency bands for DL and UL. The TDD method uses unpaired bands. Normally the spectrum is sold to operators in slices of 2 times 10MHz or 2 times 15MHz per operator. Both duplexing methods have an overall similar performance although some differences exist between them. The TDD mode does not allow large propagation delays between mobile station and base station, as this would cause a collision between transmit- and receive timeslots [4]. This makes TDD systems more suited for environments with low propagation delay; hence TDD operational mode is assigned to pico cells. An advantage of TDD is that a large asymmetry between uplink and downlink data rates is possible, making it well suited for applications with similar characteristics, for example web browsing. With proper network planning the distinctive advantages and disadvantages of both methods can work complementary.

The picture below shows the European UMTS spectrum allocation map.

![European UMTS spectrum allocation](image)

**Figure 6:** European UMTS spectrum allocation (picture taken from [5])

During network planning special care should be taken to avoid interference between FDD and TDD mode, more particularly between the lower TDD band and the FDD uplink bands; around 1920 MHz.
Network capacity
A consequence of using CDMA as multiple access scheme is that capacity of UMTS systems is not hard limited. This means that an additional user entering the system cannot be blocked because of the limited amount of hardware; POTS architectures or GSM systems have a determined amount of links or channels which allows the maximum supportable traffic density to be calculated and planned using statistical models. In a UMTS system every new user will cause an additional amount of interference to the users already present in the system, which will eventually load the system. If a sufficient number of codes is available, the noise rise due to increased load will be the main capacity-limiting mechanism in the network. Cells shrinking because of high load and increasing capacity in cells surrounded by neighbouring cells with low interference are other phenomena showing the interference determined nature of capacity in CDMA networks. The process behind all this is often referred to as ‘soft capacity’. Especially when soft handover is taken into account, these mechanisms can complicate network planning. Chapter 5 studies the relation between the coverage area and the network capacity and illustrates the influence of soft handovers on these two network parameters.

Multi-path diversity – Rake receiver
Multi-path effects normally cause difficulties in wireless transmission systems. One of the advantages of DSSS systems is that signals received via multiple paths with different propagation delays and different signal strengths can even improve the system performance. In order to combine the separate different multi-path components coherently, it is essential to first separate them correctly. In WCDMA systems a Rake receiver is used. A Rake receiver consists of multiple receivers called ‘fingers’. Using phase rotators and equalisers it is possible to split the energy of the different signal components whose phase and amplitude in the constellation diagram has been changed by the channel. After adjusting time delay and signal strength the different components are combined to a signal with higher quality. This process is called Maximum Ratio Combining (MRC). Essential is that only signals with relative delays higher than 1 chip duration can be combined. Using a chip rate of 3,84Mcps this corresponds to 0,26μs or a difference in path length of 78m. This method reduces the effects of fading significantly because when different channels with different characteristics are combined, effects of fast fading are averaged out. The gain
obtained by coherently combining multi-path components is similar to the soft handover gain achieved by combining two or more signals during a soft(er) handover process. This is discussed thoroughly in following sections.

- **Channels**

The UTRA FDD radio interface has logical channels, which are mapped to transport channels\(^7\), which are in turn mapped to physical. The picture below shows the way the different channels are mapped into each other.

![Figure 7: mapping between different channels (picture combined from sources [3] and [6])](image)

Appendix B contains more details about the different UTRA channels. That section discusses the transport channels, as understanding of these channels is essential for performing a good network planning.

- **Cell states**

Seen from the UTRAN point of view a UE can be either in Idle Mode or in Connected Mode. In Idle Mode the terminal is switched on and tuned in to the control channel of a particular cell but the UTRAN part of the network has no information about the UE;

\(^7\) The mapping between the logical channels and the transport channels takes place in the MAC-layer (Medium Access Control).
it can just be addressed by a message (e.g. paging notification) broadcasted to all the
users in one cell. The idle mode state is also called ‘camping on a cell’. The UE can
switch to Connected Mode by requesting to establish a RRC connection. The picture
below, shows the states and transitions for a UE including the GSM/GPRS modes.

Assignment of the different channels to a user and control of the radio resources in
general are performed by the Radio Resource Control protocol (RRC). In UTRA
Connected Mode there are four RRC states the UE can switch between: Cell DCH,
Cell FACH, Cell PCH and URA PCH.

In the Cell DCH state the UE has been allocated a dedicated physical channel in
uplink and downlink.

In the three other states the UE is not allocated a dedicated channel. In the Cell FACH
the UE monitors a RACH channel in the downlink and is allocated a FACH channel
in the uplink direction. Also in this state the UE performs cell reselections; by sending
cell update messages the position of the UE is known on cell level by the RNC.

In both the Cell PCH and the URA PCH state the UE selects a paging channel (PCH),
and uses discontinuous reception (DRX) for monitoring the selected PCH via an
associated PICH [16]. No uplink activity is possible in this state. The only difference
between both states is that in the Cell PCH state the location is known on cell level
according to the last cell update made while in the URA PCH state the location is
known only to UTRAN Registration Area (URA\textsuperscript{8}) level according to the last URA
update made in the Cell FACH state.

\textbf{Figure 8:} UE modes and RRC states (picture based on [15])
Cell structure
During the architecture design of the UMTS system also more attention was drawn to the diversity of the user environment. Indoor, outdoor urban and outdoor rural environments are supported besides different mobility models ranging from stationary users through pedestrian up to very high vehicular speeds. To offer worldwide coverage and enable global roaming a hierarchical layer structure of zones was developed for UMTS. The highest layer consists of satellites covering the whole planet; the lower layers form the terrestrial radio access network – UTRAN. Each layer is built up of cells, the lower the layer, the smaller the geographical area covered by the cell. Therefore small cells have been implemented to support higher user density. Macro-cells offering land wide coverage are combined with micro cells increasing capacity in more densely populated areas and pico-cells installed in so-called hot spots requiring high capacity in a very limited area (airports…). This follows two well-known design principles in deploying cellular networks; smaller cells can be used to increase the available capacity per geographical area, larger cells can extend the coverage area.

As it is obvious the needs and characteristics of an indoor office environment are different to the requirements of a user cruising rural areas at high speed, the UMTS forum has developed six operational environments. For each model the density of potential users per km$^2$ and the foreseen cell types have been identified for low, medium and high mobility scenarios [7].

Figure 9: UMTS mixed cell structure

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8 One URA consists of different cells.
2.1.2 Network elements

In this section the network elements in the UMTS architecture are discussed. The focus is primarily on their functionality related to handovers. The Radio Network Controller (RNC) and the Node B – together forming the Radio Network Subsystem (RNS) – as also the Mobile Station (MS) are introduced. Although the RNC and the Node B belong to the UTRAN part of the network, it was a deliberate choice to deal with the physical layer and the UTRAN architecture in separate paragraphs.

The picture below displays the UMTS network architecture as specified in the 3GPP requirements. Basically the network can be split up into three different parts: the User Equipment domain, the UMTS Terrestrial Radio Access Network (UTRAN) and the Core network part. In paragraphs 2.1.2 and 2.1.3 the different network elements and functional parts are discussed.

![UMTS network architecture](image)

**Figure 10: UMTS network architecture**

- The Mobile Station (MS)

Fancy handheld devices have been one of the main driving factors for the phenomenal success of wireless communications. And it looks very probable that the economical breakthrough of UMTS systems in Europe will also depend a lot on the features and services offered by a new generation of user terminals.
In the available literature the part of the system architecture commonly known as the ‘mobile’, is called the User Equipment Domain (UE). It describes the equipment used by the user to establish a radio connection to the UMTS network and hence access the services offered. The User Equipment can be seen as the counterpart of other network elements as its functionality and procedures implemented are also present in the RNC, Node B and the Core Network.

Principally the UE consists of two functional parts – as can be seen on the picture below: the USIM (UMTS Subscriber Identity Module) domain and the Mobile Equipment (ME) domain.

![Figure 11: User Equipment domain (picture based on [8])](image)

The USIM is commonly known as the SIM card or smart card. This integrated circuit chip contains information related to the user subscription to the operator’s network. The functionality of the UMTS SIM is similar to the GSM SIM card; it provides security functions as secure downloading of applications, user authentication and possible inclusion of payment methods. The USIM can provide some additional functions like the possibility to support more SIM cards or more user profiles on one SIM.

The Mobile Equipment Domain (ME) is often seen as the aggregation of two functional parts – the Terminal Equipment (TE) and the Mobile Termination (MT). The MT is the entity responsible for performing the radio transmission and has a lot of functionality implemented also present in the Node B. Essentially the whole conversion process from data bits to transmittable data is implemented in the TE. This contains functions as Forward Error Correction methods (FEC), power control, radio quality management and spreading/despreading and modulation/demodulation.
The TE contains the end-to-end application, for example the connection between a mobile phone and a portable. The E2E connection is realised using a TE/MT Local Bearer Service, a UMTS bearer service and an external bearer service [9]. Dualities between the UE and other parts of the network are the implementation of Radio Resource Control (RRC), handover and ciphering algorithms similar to RNC functionality. The UE also acts as a counterpart to the core network part with regard to the implementation of Session and Mobility Management and Bearer Negotiation protocols. [10]

- The Node B

The Node B implements the same functionality provided by the Base Transceiver Station (BTS) in GSM networks. Besides performing some basic Radio Resource Management operations, the main function is providing the physical radio link between the UE and the network. Main tasks in terminating the radio interface are channel coding, spreading, modulation and rate adaptation. Also the fast power control algorithm is implemented in the Node B. Most of those methods have been described above.

Concerning handovers, the node B controls softer handover, i.e. the situation where a mobile station is in the overlapping coverage area of two adjacent sectors of the same base station. The Node B is responsible for combining the different uplink signals received from both sectors, sent by one mobile station. The softer handover situation is treated similarly as multi-path signals using maximal ratio combining Rake processing.

The other CDMA specific handover algorithm used in UMTS systems is soft handover. This is the situation where one MS has two or more simultaneous connections to different base stations. In this case the macro diversity combining is done in the Radio Network Controller (RNC). A description of this vital element of the UTRAN is given below. Soft and softer handovers are discussed in detail in section 2.2.3.
The RNC

Again this network element has similar features as its GSM counterpart but besides this logical correspondence it has additional functionality built in. The RNCs are responsible for most of the resource control in the UTRAN access network. The load/overload situation of the network is measured by the RNC and controlled by making different handover decisions. This makes the RNC the key element in the handover processes. More specifically for the soft handover process, the RNC fulfils the important task of combining the multiple data signals received from different mobile stations.

Besides that the RNC also interfaces the Core Network and performs the outer loop power control during setup of a connection. One RNC controls a number of Node B’s, forming the RNS. The RNC controlling one Node B is named the controlling RNC (CRNC). Besides load and congestion control the CRNC also handles admission control and code allocation for the cells served by the controlled Node B’s. The RNC can fulfil two logical roles for one UE UTRAN connection. The RNC that terminates the Iu link to the core network and Radio Resource Control Signalling is called the Serving RNC (SRNC). This RNC is responsible for executing tasks as handover decisions and outer loop power control. For each connection between a UE and UTRAN there is only one SRNC: Every other RNC that controls cells used by the mobile is referred to as Drift RNC (DRNC). A RNC can act as a drift RNC because the mobile user roamed into cells controlled by another RNC while the connection with the core network is still made through the RNC controlling the “old” cells. This scenario is shown on the left side of the picture below. Another situation where two RNC’s are involved is during inter-RNC soft handovers as displayed in the right scenario.

![Figure 12: SRNC and DRNC](image)

9 RRC: Radio Resource Control, a sub-layer of layer 3 (L3) of the UMTS protocol
2.1.3 Core network architecture

As the GSM radio access network is (and will be) still in use during the introductory and initial phase of UMTS operational networks, there is need for one common core network supporting both the GSM and UMTS radio network part. But minimizing the changes needed to the GSM core network was one of the key requirements for the design of the UMTS core network as described in the 3GPP Release 99. Hence the UMTS core network is merely the evolution of the GSM backbone and is not as revolutionary new as the WCDMA radio access network UTRAN. Another need to fulfil by the core network was to provide interoperability with other second and third generation technologies. The ultimate goal being the creation of a core network that can act as a universal core for connecting different radio access and fixed networks as shown in the picture below.

![Figure 13: UMTS core network (picture taken from [11])](image)

- **Release 99**
  The ‘phase 1’ core network – as proposed in the early 3GPP specification releases – consists of a circuit switched and a packet switched part. As a detailed description of the core network is not relevant in the scope of this project, only the Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN) are described. These two network elements form the packet switched part of the UMTS core network and are extensions to the GSM circuit switched part as can also be seen in figure 10 on page 21.
- **Serving GPRS Support Node (SGSN)**

  The Serving GPRS Support Node keeps track of the location of an individual MS (Mobile Station) and performs security functions and access control. The SGSN also exists in GPRS networks, where it connects to the Base Station controller (BSC). In UMTS networks this node is connected to the above-described Radio Network Controller (RNC) over the IuPS interface.

- **Gateway GPRS Support Node (GGSN)**

  The Gateway GPRS Support Node supports the edge routing function of the packet switched GPRS network. To external packet data networks the GGSN performs the task of an IP router. Firewall and filtering functionality, to protect the integrity of the GPRS core network, are also associated with the GGSN along with a billing function.

- **Release 4**

  While release 99 proposed mainly an upgrade of the GSM core network, release 4 of the 3GPP specifications introduced a new more enhanced UMTS core network. The core network was subdivided into the Serving Network Domain, the Home Network Domain and the Transit Network Domain. This makes it possible to separate functions as routing traffic, managing the user’s subscriber information and communication with remote parties respectively.

  ![Figure 14: functional view of the core network](image)

  To manage the different services the IP Multimedia System (IMS) was introduced. This IPv6 based packet switched network enables provision of both real-time and non
real-time traffic services to the user. On protocol level the SS7 signalling protocol has been replaced by an IP based Session Initiation Protocol (SIP).

Different control functions are implemented in the Home Subscriber Server (HSS). This network element has to fulfil the functions previously carried out by the Home Location Register (HLR) such as static user subscription and handling of security information.

The Mobile Switching Center (MSC) implements most of the connection management functionality. Basically it forms the interface between the radio system and fixed network technologies. The MSC server handles the mobility management; including the tasks previously performed by the Visitor Location Register (VLR). One MSC server can control multiple Radio Network Subsystems (RNS). Some connection management subtasks are carried out by the Media Gateway (MGW). Implementing the connection management in a MSC server increases the functionality as adding new servers can increase capacity.

- **Release 5**

Release 5 of the 3GPP standards promotes an IP-only architecture. The Media Gateway becomes redundant, because tasks like media conversion (ex. CS phone call to VoIP) are no longer needed, as all traffic eventually is packet switched.

The Asynchronous Transfer Mode (ATM) has been standardized as the UMTS core transmission medium. Basically ATM Adaptation Layer type 2 (AAL2) handles circuit switched connections; AAL5 is designed to deal with packet switched data traffic.
2.2 Handovers

Handovers are the basic means of providing mobility in cellular architectures. In UMTS systems different handover types have been introduced to cope also with other requirements as load control, coverage provisioning and offering quality of services. In this paragraph the different handover types are presented and a motivation why they have been implemented in the UMTS system architecture is given. This section also tries to give an impression of the impact of handovers on the network performance and highlights some of the possible drawbacks of these methods on network capacity and signalling load.

Handover aims to provide continuity of mobile services to a user travelling over cell boundaries in a cellular infrastructure. For a user having an ongoing communication and crossing the cell edge, it is more favourable to use the radio resources in the new cell – also called the target cell – because the signal strength perceived in the “old” cell worsens as the user penetrates the target cell. The whole process of tearing down the existing connection in the current cell and establishing a new connection in the appropriate cell is called “handover”. The ability of a cellular network to perform efficient handovers is crucial to offer attractive services as real-time applications or streaming media as planned in third generation networks. Especially the number of “handover failures” – the situation in which the handover procedure cannot be completed – has to be further reduced compared to previous generation cellular communication systems as GSM. The cause for a handover failure ranges from signalling failures to the lack of resources in the target cell, making it impossible for a new user to be accommodated. In high performance networks where there is a trend towards the use of smaller cells to increase the capacity, the handover process becomes even more important as more frequent handovers are needed.

An efficient handover algorithm can only be implemented with the help of appropriate resource and user location management. Resource management means that there exists a way to establish, maintain, release and control connections in the radio access layer. In UMTS systems the major part of the control signalling between UE and UTRAN is done by the Radio Resource Control (RRC) protocol [3]. Some of the
functions implemented in the RRC protocol that are important in our discussion around handovers are cell selection, UE measurements, SRNS relocation and control of radio bearers, physical and transport channels. Most of the RRC functionality is implemented in the RNC.

User location management means keeping track of the UE’s location. Some of this information is stored in functional entities in the core network: the Home Subscriber Server (HSS) and the Mobile Switching Center (MSC)\textsuperscript{10}; but mainly the RRC protocol operating between the UE and UTRAN – the RNC – fulfils connection mobility functions related to handovers.

WCDMA handovers can be classified in different ways. Some research works distinguish intra-frequency, inter-frequency and WCDMA to GSM intersystem handovers. In this discussion another classification is used. Hard, inter-system and soft & softer handovers are discussed separately as this reflects more the scope of this research while the first classification is merely focussed on the measurement method used.

As has been mentioned earlier this chapter, only UTRA FDD mode supports soft and softer handovers. Hard and inter-system handovers are supported in both TDD and FDD mode.

2.2.1 Hard handover

Hard handover is the handover type where a connection is broken before a new radio connection is established between the user equipment and the radio access network. This is the handover type used in GSM cellular systems where each cell was assigned a different frequency band. A user entering a new cell resulted in tearing down the existing connection before setting up a new connection at a different frequency in the target cell. The algorithm behind this handover type is fairly simple; the mobile

\textsuperscript{10} As has been mentioned before the HSS and MSC have similar functionality implemented as their GSM logical counterparts: the HLR and VLR.
station performs a handover when the signal strength of a neighbouring cell exceeds the signal strength of the current cell with a given threshold.

In UMTS hard handovers are used to for example change the radio frequency band of the connection between the UE and the UTRAN. During the frequency allocation process for UMTS, it has been planned that each UMTS operator will have the possibility to claim additional spectrum to enhance the capacity when a certain usage level will be reached. In this case several bands of approximately 5MHz will be in use by one operator, resulting in the need for handovers between them.

Hard handovers are also applied to change the cell on the same frequency when no network support of macro diversity exists [3]. Otherwise stated, when a UE with a dedicated channel allocated, roams into a new cell of a UMTS network, hard handover is chosen when soft or softer handover is impossible.

A third case of hard handovers are the so-called inter-mode handovers. This allows for changes between the FDD and the TDD UTRA modes. This handover type is sometimes also classified as inter-system handover as the measuring methods used are very similar to WCDMA-GSM handovers. Although from technical point of view these inter-system handovers can be seen as a type of hard handovers, they are discussed in a separate paragraph.

The main problem surrounding hard handovers in GSM systems are the – sometimes high – blocking probabilities experienced by users entering a new cell. This probability can be reduced by giving priority to handover users over new users, which can be done by for example reserving a certain part of the capacity in each cell for users with ongoing communication. On the other hand this results in a less efficient use of the capacity of the cellular systems or higher blocking probabilities for new users. These considerations and other CDMA-specific arguments have lead to the choice of additional handover types to coexist in the WCDMA access network: soft and softer handover algorithms counter some of the disadvantages of CDMA systems and hence increase overall system performance. Typically hard handovers are only used for coverage and load reasons, while soft and softer handover are the main means of supporting mobility.
2.2.2 Inter-system handover

Inter-system handovers are necessary to support compatibility with other system architectures. Mainly handovers between UTRAN and the GSM radio access network will be vital during the rollout of UMTS networks. In the initial deployment phase of 3G networks it is very likely that rural areas will not yet be covered by the WCDMA network. Thus GSM networks will still be used to provide coverage in those areas. On the other hand it looks probable that the additional capacity provided by WCDMA networks will be used to unload the urban GSM network. In the later releases of the 3GPP specifications handovers to other systems than GSM are included.

The signaling procedure for handing over a UMTS user to the GSM system is shown below. This example is illustrative for the general procedure followed during handovers. This procedure generally consists of carrying out of measurements, reserving resources and the performing the actual handover.

![Figure 15: inter-system handover procedure from UTRAN to GSM (picture based on [3])](image)

When switching the connection to another system architecture there is need for a measurement on the frequency used by the other system. When there is no full dual receiver¹¹ available the transmission and reception are halted for a short time to perform measurements on the other frequencies. This is called the compressed mode.

As can be seen on the picture below the data transmission is compressed in the time

¹¹ A full dual transceiver is able to transmit and receive in two different frequency bands simultaneously.
domain without losing data. By doing this a transmission gap is created during which measurements can be made.

![Figure 16: compressed mode (picture based on [12])](image)

As FDD and TDD mode make use of different frequencies, inter-mode handovers also make use of compressed mode to perform measurements on other frequencies needed during the handover.

### 2.2.3 Soft and softer handover

Soft and softer handover are the CDMA specific handover types implemented in the UMTS system and form one of the most characteristic features of the revolutionary WCDMA access method. In this paragraph the impact of implementing this handover types on the system design is discussed in detail and also the algorithms behind these methods as described in 3GPP specification TR 25.922 are analysed.

![Figure 17: soft vs. softer handover](image)

A soft or softer handover occurs when the mobile station is in the overlapping coverage area of two adjacent cells. The user has two simultaneous connections to the UTRAN part of the network using different air interface channels concurrently. In the case of soft handover the mobile station is in the overlapping cell coverage area of
two sectors belonging to different base stations; softer handover is the situation where one base station receives two user signals from two adjacent sectors it serves. Although there is a high degree of similarity between the two handover types there are some significant differences.\(^\text{12}\)

In the case of softer handover the base station receives 2 separated signals through multi-path propagation. Due to reflections on buildings or natural barriers the signal sent from the mobile stations reaches the base station from two different sectors. The signals received during softer handover are treated similarly as multi-path signals. In the uplink direction the signals received at the base station are routed to the same rake receiver and then combined following the maximum ratio combining technique. In the downlink direction the situation is slightly different as the base station uses different scrambling codes to separate the different sectors it serves. So it is necessary for the different fingers of the rake receiver in the mobile terminal to apply the appropriate de-spreading code on the signals received from the different sectors before combining them together. According to [3] soft handover occurs in 5-10% of the connections. Due to the nature of the softer handover there is only one power control loop active.

For soft handover the situation is very similar in the downlink direction. In the mobile station the signals received from the two different base stations are combined using MRC Rake processing. In the uplink direction on the other hand there are significant differences. The received signals can no longer be combined in the base station but are routed to the RNC. The combining follows a different principle; in the RNC the two signals are compared on a frame-by-frame basis and the best candidate is selected after each interleaving period; i.e. every 10, 20, 40 or 80ms. As the outer loop power control algorithm measures the SNR of received uplink signals at a rate between 10 and 100Hz, this information is used to select the frame with the best quality during the soft handover.

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\(^{12}\) Note that although the situation is described for two overlapping cells higher values are possible. As will be discussed later, the number of cells the mobile station can have simultaneous connections with is called the active set size.
2.2.3.1 3G TR 25.922

This paragraph discusses the handover process as described in TR 25.922 of the 3GPP specifications [13]. Basically the soft handover is composed of two main functions:

- Acquiring and processing measurements
- Executing the handover algorithm

Before starting the in-depth analysis of these functions some terms used for describing the handover process have to be defined:

- Set: list of cells or Node B’s
- Active set: list of cells having a connection with the mobile station
- Monitored set: list of (neighbouring) cells whose pilot channel $E_c/I_0$ is continuously measured but not strong enough to be added to the active set.

- Measurements

Accurate measurements of the $E_c/I_0$ of the pilot channel (CPICH) form the main input for obtaining the RRC measurement report, necessary for making handover decisions. Mainly three parameters can be measured. Besides the $E_c/I_0$ of the CPICH also the received signal code power (RSCP) and the received signal strength indicator (RSSI) are measured. RSCP is the power carried by the decoded pilot channel and RSSI is the total wideband received power within the channel bandwidth. $E_c/I_0$ is defined as:

$$\frac{E_c}{I_0} = \frac{RSCP}{RSSI}$$  \hspace{1cm} (2.1)

It is important to apply filtering on the handover measurements to average out the effect of fast fading. Measurement errors can lead to unnecessary handovers. Appropriate filtering can increase the performance significantly. As long filtering periods can cause delays in the handovers\(^{13}\), the length of the filtering period has to be chosen as a trade-off between measurement accuracy and handover delay. Also the speed of the user matters, the slower the user equipment is moving the harder it is to average out the effects of fast fading. Often a filtering time of 200ms is chosen.

Other essential information needed during the so-called intra-mode handovers – soft and softer handover – is timing information. As the WCDMA network is of asynchronous nature there exist relative timing differences between the cells. To
allow easy combining in the Rake receiver and avoid delays in the power control loops, the transmissions have to be adjusted in time. After the UE has measured the timing difference between the CPICH channels of the serving cell and the target cell, the RNC sends DCH timing adjustment info to the target cell.

- The soft handover algorithm
The WCDMA soft handover algorithm as described in the 3GPP TR 25.922 specifications differs slightly from the IS 95A algorithm as used in cdmaOne, the standard for North American cellular systems also based on CDMA. Even though the significance of the latter cannot be ignored this discussion is restricted to the analysis of the WCDMA algorithm only.

Based on the $E_c/I_0$ measurements of the set of cells monitored, the mobile station decides which of three basic actions to perform; it is possible to add, remove or replace a node B in the active cell. These tasks are respectively called Radio Link Addition and Radio Link Removal, while the latter is Combined Radio Link Addition and Removal. The example below is directly taken from the original 3GPP specifications. Discussing this scenario gives a good insight into the algorithm itself and forms an introduction to the illustrating simulations included in the next paragraph. This scenario can be based on a user following a trajectory as shown below.

Figure 18: soft handover scenario

13 Delays in handovers can cause a user to penetrate deeply in an adjacent cell and generate harmful interference before the cell is added to the active cell.
Figure 19 shows how the pilot signal strengths of the different cells evolve in time.

At the start of the scenario the user is connected to cell number 1 which has the strongest pilot signal. Due to the user moving or to slow fading the perception of the signal strengths to the mobile user can change and following actions are taken:

- Event A: cell 2 is added
- Event B: cell 1 is replaced with cell 3
- Event C: Cell 3 is removed from the active set

This example could be based on a mobile user following a path similar to the picture below.

The main parameter in the soft handover algorithm is the threshold for soft handover As,Th. As will be shown in the following chapters the value of this figure is a crucial design parameter, it determines the amount of users being in soft handover mode and hence influences the system capacity and coverage. Roughly stated it is the maximum difference in SIR two pilot signals can have so their cells can coexist in the active set. As,Th_Hyst is the hysteresis for the As,Th threshold and As,Rep_Hyst is the replacement hysteresis.
The actual algorithm is as follows:

- Adding: If Meas_Sign is greater than (Best_Ss – As_Th + As_Th_Hyst) for a period of \( \Delta T \) and the Active Set is not full, the Best cell outside the Active Set is added to the Active Set.

- Removing: If Meas_Sign is below (Best_Ss – As_Th – As_Th_Hyst) for a period of \( \Delta T \) remove Worst cell in the Active Set.

- Replacing: If Active Set is full and Best_Cand_Ss is greater than (Worst_Old_Ss + As_Rep_Hyst) for a period of \( \Delta T \) add the Best cell outside the Active Set and Remove the Worst cell in the Active Set.

Where:

- Best_Ss: the best measured cell present in the Active Set;
- Worst_Old_Ss: the worst measured cell present in the Active Set
- Best_Cand_Set: the best measured cell present in the monitored set
- Meas_Sign: the measured and filtered \( \text{Ec/Io} \) of the pilot channel of the monitored cell

In Appendix C a flowchart of this vital algorithm is included.

- Signalling

Depending on which type of soft handover is performed, the signalling load will differ. In case of handover between base stations controlled by the same RNC the situation is quite simple. When a handover is performed between two base stations controlled by different RNC’s, the situation is more complicated. This requires signalling between the so-called drift and serving RNC using the Iur interface (see figure 10). But in all cases the signalling sequence between the UE and the RNC starts with the transmission of a measurement report from the UE to the RNC and ends with an “Active Cell Update Complete” message in the opposite direction.

- Soft handover gain

Enabling soft and softer handovers can result in a reduction of the interference present in the system and improve the performance due to the macro diversity principle. Macro diversity provides a gain in the system when multiple signals are combined. This phenomenon is also referred to as the soft handover gain. The macro diversity gain highlights the importance of soft handover. Not only is soft handover necessary
to provide mobility to the users and control the system load, it also enables a more efficient use of the radio resources available and hence improves the overall system capacity and coverage.

The soft handover gain can be easily illustrated using the following example. As a radio connection is supported by two or more radio links during the soft handover, it is possible to use links with lower quality as long as the combined effect is sufficient to provide the requested quality of the radio connection. Imagine a desired BLER of 1/10000. When using two bearers with a BLER of only 1/100 this can be achieved, as a block error will only occur if both links fail. This will happen with a probability of 
\[
\frac{1}{100} \times \frac{1}{100} = \frac{1}{10000}.
\]
Lowering the link quality enables the transmission power to be kept at lower levels resulting in less interference in the system.

On the other hand there is an increase in interference in the system when base stations and mobile terminals are transmitting additional signals over the air interface compared to situations where every radio network connection consists of one link – as is the case in systems using only hard handovers. For efficient resource usage it is therefore necessary to allow the appropriate amount of soft handovers in the system to maximise the soft handover gain while keeping the increase in interference due to multiple link connections below acceptable levels.

In the graph below the average in uplink direction transmitted power, as obtained during one of our simulations, is plotted. The first data series represents this statistic plotted as function of the soft handover thresholds. These values are compared with the uplink-transmitted power in an identical network where soft handovers are disabled. For the lower handover threshold values soft handovers improve the power budget compared to networks with only hard handovers. From threshold values higher than 7dB the situation worsens significantly compared to the hard handover situation. The multiple connections consume substantial additional power; hence the macro diversity gain is largely outstripped by the power loss caused by the increase in interference. From this point soft handovers are no longer favourable for network performance.
Figure 20: average UL transmission power compared for soft and hard handovers

Table 1: parameters used for simulation of Figure 20

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>2 km</td>
</tr>
<tr>
<td>Node B spacing</td>
<td>3.5 km</td>
</tr>
<tr>
<td>Traffic type</td>
<td>Conversational sample load, One-way</td>
</tr>
<tr>
<td>User speed</td>
<td>60 km/h</td>
</tr>
<tr>
<td>Model</td>
<td>SIM 2</td>
</tr>
<tr>
<td>Pathloss model</td>
<td>Vehicular</td>
</tr>
</tbody>
</table>

It has to be noted that the values in the picture above are not representative for real systems for several reasons. Firstly this graph is based on the results of a fictive network model with 3 Node B’s and only one moving user. Besides that the mobile station is in soft handover during only a fraction of the time considered to calculate the average transmitted power. This picture merely illustrates the effect of the two above described mechanisms on the transmitted power in a system. Exact figures obtained for real network situations are displayed in the picture below. This graph shows the soft handover gain for the downlink transmission power compared to the relative path loss to two base stations. As shown in [14], the situation in the uplink direction is similar although the gain and especially the loss have lower absolute values.
As can be seen there is a power gain of several dB when combining two signals with a relative path loss lower than approximately 5dB. As the total transmitted power in the air interface is reduced, the capacity and coverage of the system will clearly benefit from soft handovers. When the relative path loss difference between two cells exceeds 5dB it is favourable to disable soft handovers as the transmitted power increases significantly. Setting the soft handover threshold to an appropriate level of around 4-5dB implements this. In the following chapters the importance of the choice of the soft handover margin is illustrated.

2.2.4 Demo simulation

In this paragraph some of the results gathered during initial simulations in OPNET® are presented. The goal is to give a deeper insight in the soft handover mechanism and demonstrate the effect on the signals in the physical layer. But also building and simulating these simple models offered the chance to get familiar with the OPNET® simulation tool.

During this demo the signal strengths of different signals and some soft handover parameters is evaluated while the mobile station follows a trajectory between 3 Node B’s as shown on the picture below.
As can be seen on the pictures below somewhere between the Node B’s, the mobile station has two simultaneous connections – which is soft handover.

The functions to which the transmitted power varies can be easily explained using the applied propagation loss model. During the simulations carried out, the ITU Vehicular outdoor path loss model has been used, as will be discussed in chapter 3. For a base station antenna height of 40m and carrier frequency of 1940 MHz, the signal strength decreases from the Node B towards the mobile station following this relation:

$$L_{PMax} = 33,6 \cdot \log_{10} R + 120,2$$

(2.2)

where $L_{PMax}$ is the calculated path loss and $R$ the distance to the Node B in kilometres. As the goal of the power control algorithms is to equalise the power received at the Node B in order to overcome the near-far effect, the mobile station has to compensate for the power lost due to the path loss between the Node B and the mobile station as represented by the shaded area in the picture below.
Below the received power at the Node B is shown. Whereas the transmitted power values range over almost 50dBm, the received power at the base station is equalised within a narrow range of 2dBm. This is due to the different power control algorithms implemented in the UTRAN network part.

**Table 2:** parameters used for simulation of DEMO1 model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>1 km</td>
</tr>
<tr>
<td>Node B spacing</td>
<td>1.73 km</td>
</tr>
<tr>
<td>Traffic type</td>
<td>Conversational sample load, One-way</td>
</tr>
<tr>
<td>User speed</td>
<td>5 km/h</td>
</tr>
<tr>
<td>Time elapsed</td>
<td>1h23m</td>
</tr>
<tr>
<td>Model</td>
<td>SIM4</td>
</tr>
<tr>
<td>Soft handover threshold</td>
<td>8 dB</td>
</tr>
<tr>
<td>Pathloss model</td>
<td>Indoor to outdoor pedestrian</td>
</tr>
</tbody>
</table>
2.3 Summary

In this chapter the UMTS technology as specified in the 3GPP specifications has been described. The first section dealt with the network architecture. Also special attention has been given to the reasons why some technology choices have been made.

One of the primary choices that have been made during the creation of the UMTS system, was implementing WCDMA as the multiple access scheme for the radio access network. Before being transmitted the data is first encoded with OVSF codes during the channelization process. As a fixed chip rate of 3.84Mcps is used, varying the spreading factor results in connections with different data rates available for the user. After channelization the data is scrambled using Gold codes. The distinctive codes enable user, sector or channel separation.

A consequence of choosing CDMA as the multiple access scheme is the need for sophisticated power control algorithms to overcome the near-far effect. Open loop power control is needed during connection setup. The fast closed loop power control algorithm makes it possible to overcome the effects of fast fading in the air interface channel. The closed loop power control algorithm is carried out in the Node B at a frequency of 1500Hz. The third power control method is the outer loop power control; it sets the target value for the fast power control algorithm.

Other characteristic aspects of the radio access network are the duplexing method used. In UMTS systems TDD and FDD mode coexist. Multi-path signals are processed using maximum ratio combining in the Rake receiver. Concerning the radio interface channels it is important to remark that logical channels are mapped into transport channels, which are in turn mapped into the physical channels. The cell structure of UMTS is mixed as it consists of different cell types. Also different user profiles and mobility profiles are supported.

In a following section the main network elements have been described. The user equipment contains the hard- and software necessary to provide security & authentication, terminate the end-to-end connection and perform the radio transmission. The Node B or base station performs all the tasks necessary to establish
the connection with the user terminal. In this context it is very similar to its GSM counterpart. Other tasks include fast power control and softer handovers. The third network element discussed is the Radio Network Controller. The so-called RNC – which forms the interface to the core network – has all the control functionality implemented related to handovers and performs other tasks as load control and open loop power control. In case one UE-UTRAN connection occupies resources from at least two RNC’s, the RNC can fulfil two logical roles: drift and serving RNC.

The early releases of the core network architecture have not changed as significantly from its GSM counterpart as the radio access part has. One of the key requirements for the future core network as specified in Releases 4 and 5, was the creation of a core network backwards compatible with older technologies as GSM and upgradeable to a core network able to serve as backbone for future technologies. Functionally it can be seen as the combination of a home network, serving network and transit network part.

The second part of this chapter discusses handovers and especially soft and softer handover in detail. Handovers take place when mobile users roam from cell to cell in a cellular telecommunications network. But handovers can also be used to balance the load in a communication network and in the case of soft handovers it enhances the system capacity and the coverage.

Hard handovers are the type of handover where the connection is broken before a new connection is set up. They are used to change the system frequency when multiple carriers are used. Also in cases where no macro diversity is supported and to change between FDD and TDD mode, hard handovers are applied.

Inter-system handovers are necessary for enabling compatibility between UMTS and other system architectures, e.g. GSM. Characteristic for this handover type is that the necessary measurements preceding the handover are done using slotted mode. This is due to the fact that the measurements take place at another frequency. From technical point of view this handover type belongs to the hard handovers.

The last part of this chapter discusses CDMA-specific handovers types in detail; soft or softer handovers occur when the mobile station is in the overlapping coverage area
of two cells. In the case of softer handover the cells belong to the same base station. The two simultaneous signals are combined in the node B using Rake processing. During soft handover the two signals received from two different base stations are routed to the RNC where they are compared on a frame-by-frame basis.

The WCDMA soft handover algorithm as specified in 3GPP TR 25.922 implements guidelines for measurements of handover parameters and the soft handover algorithm itself. Filtered measurements of the $E_c/I_0$ of the different pilot channels combined with timing information form the inputs for executing the soft handover algorithm. Basically three actions can be performed on cells in the system. They can be added to, removed from or replaced in the active set of a mobile user.

The soft handover gain is the gain provided by combining multiple signals. This is also called macro diversity gain. When the appropriate soft handover margin is used, this soft handover gain enhances the system performance significantly.
References

[1] Carl Andren “A Comparison Of Frequency Hopping And Direct Sequence Spread Spectrum Modulation, A Comparison For IEEE 802.11 Applications At 2.4 Ghz”, Harris Semiconductor


[12] Peter Chong “WCDMA physical layer” – lecture slides Wideband CDMA systems, Helsinki University of Technology


[14] Harri Holma, “Physical Layer Performance” – lecture slides Wideband CDMA systems, Helsinki University of Technology


Chapter 3

Network modelling

The previous chapter introduced the UMTS system technology described in the 3GPP specifications as also the soft handover process and its implications on the system performance. The goal of this research is to analyse the soft handover process with simulations, draw some conclusions on the probability a user is in soft handover and the impact of soft handover on issues as network capacity and coverage. In order to draw valuable conclusions, efficient network modelling is a vital aspect of this project.

The first part of this chapter gives a walkthrough of the OPNET® network optimisation software that was used for these simulations. This software package enables network modelling on different levels of detail; the logical network configuration can be edited in the network editor, the node level provides facilities to define the structure and internal configuration of the network elements and the process layer enables configuration of processes inside the node and direct implementation of communication protocols. Another advantage of OPNET is that it has a specific UMTS model built in, based on the 3GPP specifications.

The following sections of this chapter present considerations around network modelling. For this research as series of six simulations and three case studies have been created. The six simulations – referred to as SIM1 to SIM6 – present simple network models useful for studying the probability a user is in soft handover. The
three case studies – CASE1 to CASE3 – reflect more the network reality. Those models are more complex due to the higher number of users present and the application-specific traffic generated by the network nodes. The chapter concludes by discussing the iterative process of setting goals, modelling, simulating and analysing results, as has been used during this research. Some specific choices are motivated and discussed in more detail.

### 3.1 OPNET® Modeler

OPNET® Modeler provides a graphical user interface, which enables modelling and simulating networks. The modelling environment consists of different hierarchical layers for developing communication structures. OPNET® provides the flexibility to build very detailed customized models as well to perform general system analysis. Systems are built up in an object oriented way, compiling the models automatically generates discrete event simulations in C language [1]. After simulation it is possible to gather and analyze results with some of the built-in performance statistics features provided by this package.

#### 3.1.1 Network layer

The network layer enables to define the network topology on a logical or geographical map. It is possible to place network elements – called nodes – and interconnect them with different types of links; both fixed and radio links. Users having a radio link connection can be assigned trajectories to simulate their mobility. This being particularly useful in this context where it is necessary to be able to simulate mobile UMTS users and their effect on the network resources used.

In the network layer it is possible to nest subnetworks to configure complex hierarchical networks. Imagine a pan-European network, consisting of different
national networks, formed by interconnection of different ring networks, which can in turn be connected to LAN entities…

![Network Editor Screenshot](image)

**Figure 26:** screenshot of the network editor

A network project can be built up using the network editor. OPNET® contains an extensive library of node models of different technologies ranging from Ethernet, ATM, UMTS, wireless and IP networks as also equipment models of specific manufacturers as Cisco, 3Com and others.

### 3.1.2 Node layer

The node layer provides functionality to build node – or network element – models to be used and interconnected on network level. In the node editor the nodes are built up out of processors, queues, transmitters and receivers. These building blocks called *modules* allow implementing node specific characteristics. Different modules are interconnected with packet streams, statistic wires or logical associations between them. Modules act as information sources and sinks or simply process the packets sent between them.
The picture below shows the node level implementation of a UMTS workstation (umts_wkstn_adv) as included in the OPNET® UMTS model. Notice the presence of the full TCP/IP stack.

![Node representation of UMTS workstation](image)

**Figure 27:** node representation of UMTS workstation

### 3.1.3 Process layer

To further increase the level of detail used in the network model, the process layer makes it possible to program the different modules used in the node layer in order to implement specific protocols or desired behavior of the nodes. The processes carried out by the nodes are very similar to executable programs. Again OPNET® contains an extensive kernel of standard procedures commonly used in communication networks but it is also possible to include user specific functions by writing C++ code. The process editor makes use of a programming language called *proto-C*, which combines graphical State Transition Diagrams (STD) and C/C++ programming language. A STD consists of states with transitions between them. Both forced and unforced states
exist. Whereas a system can wait in an unforced state, it has to leave the forced state immediately after executing the executives of that state. The state executives are actions to be performed right after entering – enter executives – or right before leaving a state – exit executives. Whether a transition should be traversed or not is decided by the transition conditions. These statements expressed in C/C++ language respond to interrupts or combinations of state variables.

![State Transition Diagram (STD) of umts_gmm process in UE GMM layer](image)

Figure 28: State Transition Diagram (STD) of umts_gmm process in UE GMM layer

### 3.1.4 OPNET® UMTS model

OPNET® Modeler offers specialized models that address the specific needs for modeling and simulating networks focused on a certain area of technology. One of those specialized models is the UMTS model based on the 3GPP specifications\(^\text{14}\). This model follows closely the UE-UTRAN-CN system architecture as described in the previous chapter. The UE model offers functionality related to terminal equipment and mobile termination, responsible for terminating the radio link. The UTRAN part consists of models for the Node B and the RNC. The Core Network architecture is not fully implemented. The SGSN and the GGSN are implemented but the MSC/VLR

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\(^{14}\) The UMTS model incorporated in OPNET® Modeler 9.0 – as used for the simulations of this research – is based on Release 99 of the 3GPP specs.
and the HLR are currently not included in the UMTS model. The graphical representation of the architecture is shown on the picture below.

**Figure 29: OPNET® UMTS architecture representation**

Below an overview of the features of the UMTS model as used for the modelling, will be given beside a discussion of the implementation of the different node models.

The UMTS specialised model supports a wide range of features resembling real network characteristics. Four different traffic classes have been defined: streaming, conversational, interactive and background. With each traffic class a QoS profile has been associated. This allows studying the effect of error or delay sensitive traffic in the system.

Also the following channels (as further described in Appendix B) are supported in the model: DCH, DSCH and FACH&RACH. Hence also the Cell DCH and the Cell FACH state as mentioned in the previous chapter are supported. To simulate soft handovers it is essential to model users in the Cell DCH state as only dedicated transport channels support soft handovers [2].

Additional features of the UMTS model are the supported mobility of users, power control and TCP/IP functionality.

Although the UMTS model is very extended and reflects real networks to high detail it has significant limitations. One limitation is that only the UMTS FDD mode is supported. As initially pointed out not to evaluate the TDD mode this shortcoming is not limiting. Several other limitations are related to attaching procedures between the mobile device and the network. GMM idle mode and the GPRS detach procedure are not included. Also mobility of the mobile terminal prior to the attachment to the network is impossible. These aspects of the model are not limiting the simulation work done, as the aim is to evaluate the effect of handovers on the network performance rather than to study the specific signalling procedures preceding
communications. In the following paragraph some of the primary modelling choices made during this research are presented and motivated.

3.2 Network modelling

During this project a total of 10 simulation series were build and run in order to obtain the desired results. To draw the conclusions about the effect of the distance to the Node B and the soft handover threshold on the soft handover probability SIM1 to SIM6 was developed. The first four model moving mobile stations whereas the latter two model a static user distribution. Analysis of coverage and capacity-related issues is done using more sophisticated structures including multiple base stations and users generating application-specific traffic: CASE1 until CASE3.

3.2.1 SIM1–SIM4: Moving user

The first four models consist of three Node B’s and one moving user following a straight-line trajectory in the coverage area of the three base stations.

\[ \text{Figure 30: SIM1, SIM2 and SIM3 model – three-cell scenario with three chosen trajectories} \]

For SIM1, 2 and 3 the three Node B’s are placed in a triangle; the model of SIM4 represents three base stations aligned along the straight-line path the mobile user follows. Although the path followed in SIM 3 and the trajectory shown on the picture
below for SIM4 are very similar, it is interesting to analyse the impact on the soft handover probabilities of the presence of an additional base station at a distance of 1.5 times the cell radius R from the followed path.

![Figure 31: SIM4 model – mobile user moving along three Node B’s](image)

In these simple models generic not application-based traffic is used, as the goal is to evaluate the effect of raw traffic on signals in the radio layer, rather than to analyse the performance of different traffic patterns and packet types in the system. This results in a significantly shorter runtime. Besides this, these four simple models also hold the advantage that they quickly provide an insight in the soft handover mechanism and produce similar results as obtained by simulation of more complex or real networks models. It is also justified to assume that there are no capacity constraints as the few users present in the system occupy only a limited number of channels. Hence the soft handover algorithm can be executed with sufficient radio resources available.

3.2.2 SIM5 & SIM6: Static model

The last two series of simulations analysing the soft handover probabilities in a UMTS network, model a high number of non-moving users randomly distributed in a cell surrounded by six other cells. Determining the number of connections there exists between each UE and the UTRA network corresponds to taking a snapshot of a real network. Hence the soft handover probability can be determined and reliable conclusions can be drawn on the effect of the soft handover threshold and the distance to the Node B.

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15 The OPNET® UMTS model requires that each Node B has at least one UE attached to it at simulation start time for complete initialization. Therefore each model contains three fixed UE’s and one mobile UE.
The model used in SIM5 and SIM6 contains approximately 50 users, each having 12.2kbps voice connections. By choosing this number of users it is possible to obtain a sufficient level of detail in each simulation with a resolution of 2% on the soft handover probability for a perfectly randomly distributed user population. Still no blocked calls due to insufficient capacity are experienced. Also the OPNET® UMTS model does not support more than 62 mobile nodes assigned per Node B.

### 3.2.3 CASE1–CASE3: Capacity & Coverage Constraints

The goal of the simulations included in chapter 5 of this research, is to load the system and examine effects as system outage and capacity constraints in the network. Those phenomena that were considered as undesired behaviour in the previous simulation sets, now form the starting point for giving a deeper insight in the mechanisms determining coverage and capacity in the UMTS network studied. The models CASE1 to CASE3 consist of, reflect the network reality to a higher extent. The amount of users in general and more specifically the amount of mobile users is significantly larger than in the above-described simulations. Besides application specific traffic types such as high bit rate video conferencing and interactive traffic are applied to the nodes in the system. These factors increase the running time for these simulations significantly.
CASE1 represents a mobile user moving out of the cell coverage area of one Node B. This model makes it possible to determine the point the moving user has no longer a connection to the UTRA network. The maximum path loss between the Node B and the UE while they are still connected is a good measurement parameter for the coverage. Varying the load on the network enables to analyse the relation between these two important system parameters studied in chapter 5.

![Figure 33: CASE1 – user moving out of the cell coverage area of one Node B](image)

The next case studies are intended to evaluate the impact of the amount of soft handover users on the available coverage and the supportable traffic load in a system. By analysing a set of system parameters in a model resembling a real network it is possible to acquire results about coverage and capacity issues. The goal of the CASE2 series is not to gather general results applicable to real networks; rather the figures obtained can be indicative for several trends and mechanisms affecting these system performance parameters in realistic systems. Some of the variable parameters include user speed, the type of application traffic and the amount of soft handovers in the system.

![Figure 34: CASE2 – seven-cell realistic network situation](image)

CASE3 has been designed to study the soft capacity. As soft capacity means that the available capacity per cell is not hard limited by the number of channels but
determined by the total amount of interference in the system the load in the adjacent cells will influence the capacity in the system. Especially a loaded cell can borrow capacity from adjacent cells with lower traffic density. This scenario is modelled in CASE3. In one loaded cell the required capacity increases due to users moving into the cell area from the neighbouring cells. The effect of this scenario on the distribution of the load is examined for different traffic types.

![Figure 35: CASE3 – users moving into loaded central cell](image)

### 3.2.4 General

During the modelling phase of this report it was important to analyse the trade-off between building simple models and simulating real network cases. Simple network models as used in the “SIM-series” may produce results in a reasonable amount of time but they should provide reliable information applicable to real network situations and reflect characteristics recognizable in real life systems. Simulation of real networks on the other hand results in accurate results but the issue is if the increase in complexity and computing time is worthwhile.

The following iterative process has been used to obtain the end-results:

1. Define goals:
   The scope of this project is to study the overall impact of soft handovers on the system performance. During the early stages of this research it has been decided that mainly two aspects of soft handovers are to be examined: the
probability a user is in soft handover and the effect of soft handovers on coverage and capacity in the system.

2. Build model:

For the study of the soft handover probability the soft handover algorithm serves as the starting point. As this algorithm has the characteristics of signals present in the system as input, simple models have been built making it possible to study the variation of signal strengths in the network. Generic, non-application based traffic is applied to the nodes. Hence the capacity of the system is not taken into account, as the main output results of these models are path loss values of different signals in the system, rather than data rates.

The models built to evaluate capacity and coverage-specific aspects of the UMTS network need to be more complex. Loading a network and evaluating events as capacity saturation and a limited coverage area, demand realistic network situations with a high number of users. Hence the runtime for the simulations increases.

In all the models built, the core network was either abstracted or aggregated as a compound object as the exact knowledge of the mechanisms affected in this part of the network are not considered relevant in the scope of this project.

For all the modelling and simulating work carried out, OPNET® Modeller 9.0 was used. The modelling has been restricted to the network layer of OPNET®. Early in the modelling process the decision has been made to use the process and node models included in the UMTS specialized library without modifying proto-C source code in the process editor or designing new node models using the node editor. This enables fast configuration of network models in the network editor using the included models of Node B’s, RNC’s and mobile workstations based on Release 99 of the 3GPP specifications. To model mobile users the UMTS model was used in combination with the Wireless module of OPNET®. This additional module enables assigning three-dimensional trajectories to mobile objects and includes terrain effects in the network editor. This first feature being especially useful for simulating the non-static models built for this project.
3. Simulate
The simulations are discrete event, continuous time simulations and are run in OPNET®. The runtime varied from 10 seconds to some minutes for the simple models used in the “SIM series” up to some hours for the “CASES”.

4. Analyse results
The results on the soft handover probability are presented in chapter 4, while chapter 5 focuses on capacity and coverage in the UMTS network.

Some UTRAN-specific modelling choices made are listed below:

- Cell state:
As the dedicated channels are the only transport channels supporting soft handovers only users in Cell DCH state have been modelled.

- Path loss model:
In dimensioning the target coverage of a cellular system it is essential to have reliable information about the propagation of the signal in the air interface. Therefore different path loss models for wireless communications have been developed throughout the years. A commonly used model for UMTS systems is the Okumura-Hata model which is especially useful when simulating urban or suburban environments. This model and other models built on formulas specified by the International Telecommunications Union are included in the OPNET® UMTS specialized model. For all the simulations carried out the Vehicular Outdoor environment as specified by the ITU [3] was chosen. The vehicular model is generally applicable for the user speeds and the cell sizes used in the simulations carried out. Besides setting one path loss model for all the models makes it more reliable to compare results.

The formula on which the model is based is as follows:

\[ L_{\text{path}} = 40.(1 - 4.10^{-3} \Delta h_B \log_{10} R - 18.\log_{10} \Delta h_B + 21.\log_{10} freq + 80 \]  

(3.1)

16 It is possible to define the environment simulated by setting the value of the UMTS Cell Pathloss attribute object in the Node B model.
where $R$ is the distance between mobile station and base station in kilometres, $\Delta h_b$ is the base station antenna height in meters and $freq$ is the carrier frequency in MHz. For an antenna height of 40 meters and carrier frequency of 1940 MHz – which is the middle of the in Europe allocated UMTS uplink transmission band – the formula becomes:

$$L_{P_{Max}} = 33.6 \log_{10} R + 120.2$$  \hspace{1cm} (3.2)

A plot of the formula for cell radius values up to 6 kilometres is shown below.

![Figure 36: ITU Outdoor Vehicular path loss model](image)

- **Cell structure:**
  In each simulation carried out, only one cell size has been applied. The Node B’s are located in the centre of hexagonal cells that cover the simulation area.

![Figure 37: UMTS cell structure used for simulations](image)
This follows the in OPNET® suggested architecture and differs from the traditionally used architecture in UMTS networks where each Node B contains three directional antennas covering three areas of each approximately 120 degrees horizontal angle. The picture above shows how the two architectures can be associated with each other. The grey shaded cells in the picture above represent the UMTS cell structure to be used in real networks. On top of this structure the hexagonal cell structure as used in OPNET® is drawn. The OPNET® Node B model has one antenna with uniform radiation pattern in the horizontal plane resulting in the structure of one base station covering one hexagonal cell, as has been used in the simulations carried out. As can be seen on the picture the relative Node B positions remain the same for the two cell architectures.

A consequence of following this OPNET® architecture is that it becomes impossible to simulate softer handovers. As each Node B covers only one sector – i.e. the total hexagonal cell coverage area – users being in the overlapping coverage area of two sectors belonging to one Node B cannot be modelled. In order to present a complete study of CDMA-specific handover types, inclusion of softer handovers would be desirable. The fact that softer handovers are not included in the OPNET® UMTS specified model limits the simulation work done in this research to only soft handovers.

3.3 Summary

This short chapter consists of two main parts. The first part discusses the OPNET® Modeler used for this project. The second section presents the models built for the several simulations and case studies used and includes some general considerations around the network modelling done.

OPNET® Modeler is a modular software package that enables intelligent network management by providing the environment to model, simulate and analyse networks consisting of hierarchical layers. OPNET® supports three different layers in a network which enable specifying the desired level of detail to be used in the model. Each layer
is built up using a specific editor. The network layer – edited in the network editor – makes it possible to place network nodes on a geographical or logical map and interconnect them. In the network layer itself different sub networks can be nested to configure complex hierarchical networks. The node layer provides functionality to configure network nodes by interconnecting so-called modules with packet streams, statistic wires or logical associations between them. The lowest level of detail can be specified using the process layer. The behaviour of the nodes or the implementation of specific communication protocols can be done using proto-C which combines state transition diagrams and C/C++ programming language.

OPNET® contains specialised models that address the specific needs of networks covering a certain area of technology. The UMTS model based on the 3GPP specifications was used for this research. The UE and the UTRAN model are very extended and reflect reality to high extent. Some useful features of the UMTS module are the implementation of different traffic classes, different channels and cell states and WCDMA-specific features as soft handover and power control.

The second section of this chapter covers some general issues on network modelling. First the different models built during this research have been presented. To study the soft handover probability six different simulation series have been created. SIM1 to SIM3 consist of three Node B’s placed in a triangle and one mobile user moving at constant speed along a straight-line track. SIM4 models a user moving at constant speed along a straight-line trajectory with Node B’s placed alongside the followed path. The first four simulation series with mobile users were conceived to study the mechanisms determining the soft handover probability. SIM5 and SIM6 model static users in a loaded cell. These models are built to study the value of the soft handover probability for users in a real system and get insight in the influence of the distance between the mobile and the Node B on the soft handover probability. Whereas the models built to study the soft handover probability reflect fairly simply network situations, the models built for obtaining the results in chapter 5 are more complicated and resemble real systems. To study the relation between capacity and coverage CASE1 has been conceived. The model used during this simulation represents a user moving out of the cell coverage area of one Node B. By applying different load situations in the cell it is possible to study the relation between the
capacity and the coverage. The latter parameter can be expressed by measuring the maximum allowable path loss between Node B and mobile station. Due to the increased number of network parameters gathered and the higher complexity present in the last two models they are called case studies. CASE2 represents a real network consisting of 7 cells and one mobile user and a high number of fixed users randomly distributed in the system. All users have been assigned realistic traffic profiles containing different applications. CASE3 models a number of users moving into a cell supporting a substantially large user population. This case study was carried out to examine the amount of capacity users in the central cell borrow from neighbouring cells.

This chapter concludes with summing up some general modelling aspects. In this research project the iterative process of setting goals, building models, simulating and analysing results has been used. For studying the soft handover probability the focus is primarily on the signal levels in the UTRAN air interface and the models do not take into account effects as limited capacity. This in contrary to the more complex models built to study the system parameters load and coverage in chapter 5. Also the core network has been abstracted or aggregated in most of the models, as the scope of this project is to study mechanisms in the UTRAN network part. The simulation and modelling has been done using the network layer of OPNET®. The UMTS specialised model contains the models of the UMTS network elements used and the Wireless Module has been included to simulate mobile users by assigning trajectories to nodes in the network layer.

UTRAN-specific modelling choices made are:
- All the users have been modelled in the CELL DCH state.
- The path loss model used is based on the ITU Vehicular Outdoor environment and given by \( L_{\text{path}} = 33.6 \log_{10} R + 120.2 \).
- The cell structure used does not reflect the traditional UMTS cell structure where each Node B has one base station with three directional antennas covering three sectors of 120 degrees. Instead the OPNET® architecture has been followed; each base station contains one isotropic antenna centred in the hexagonal coverage area. It has been shown that the two topologies are similar although the latter does not allow the simulation of softer handovers.
References

[1] OPNET® modeller online documentation, “Modelling Concepts – Chapter 1: Modelling Overview”


Chapter 4

Soft handover probability

The probability a user is in soft handover mode is an important parameter for radio network planning. As an excessive amount of soft handovers causes an overhead on system resources used, it is important to be able to set system parameters to an appropriate level resulting in a number of handovers that optimizes network performance. In this chapter the effect of mainly two parameters is investigated. The first system design parameter analyzed is the soft handover threshold or soft handover margin. This figure has been described in chapter two in the part dealing with the soft handover algorithm and determines the soft handover probability significantly. Secondly the relation between the distance a user is from the base station and the soft handover probability is analyzed.

The goal of this chapter is to first analyze the effect of both parameters separately and then draw conclusions about the combined effect of distance to the Node B and the setting of the soft handover threshold. To perform this a series of models was created. Simulating mobile users in a simple network consisting of three Node B’s forms the starting point before simulating more enhanced models reflecting more realistic network situations. Varying system parameters, using different traffic types and different user profiles gives insight into the mechanisms that control the soft handover probability.
The organisation of the chapter is as follows; first the soft handover probability is introduced and its importance in a planning UMTS network is motivated. The following paragraphs present the results of the simulations studying the SHO probability. Paragraph 4.2 discusses the influence of the soft handover threshold by analysing the results of simulation series SIM1 to SIM4. Paragraph 4.3 presents SIM5 and SIM6 as also the conclusions drawn on the influence of the distance between the mobile station and the Node B. The chapter concludes with giving indicative figures of the soft handover probability in a real system.

4.1 Soft Handover probabilities

The macro diversity gain as introduced in paragraph 2.2.3 is responsible for the increase in system performance caused by soft handovers. On the other hand every soft handover results in one or more extra connections in the radio network layer, consuming additional resources and causing interference. In the downlink direction an additional base station transmitting at relatively high power levels causes the total amount of power present in the system to rise significantly. In the uplink direction a mobile station in soft handover also transmits two or more signals – which are received by two or more different Node B’s. Hence the interference present in the system increases although not as significantly as in the downlink direction. This is due to the higher power levels used by the transmitter in the base station. Typically in the downlink data is transmitted at values up to some Watts whereas mobile terminals transmit at around 125mW. For this reasons special care should be taken to avoid that the increased interference does not exceed the diversity gain offered by soft handover.

Soft handovers do not only consume extra radio resources but multiple-link connections require also more orthogonal codes and consume extra resources in the Node B and the RNC. Also the signalling capacity over the Iub interface between the Node B and the RNC in the UTRA network part is more extensively used when multiple links are allowed.
These arguments plea for a good knowledge of the probability that a soft handover will occur in the network in order to ensure reliable network management. The soft handover probability is the amount of users having multiple link connections relative to the total user population. In the simulations below the soft handover probabilities have been measured using two different methods. Either this ratio was calculated directly by dividing numbers of users or time ratios were used. Indeed, for users moving at constant speeds, the ratio of the time they are in soft handover to the total time they are moving in the system is a good measure for the soft handover probability. When relevant paths in the network are simulated, reliable probabilities can be achieved, as will be shown in the next paragraphs.

4.2 Soft Handover Threshold and Cell Size

To study the above mentioned soft handover probabilities six simulation series have been developed. SIM1 to SIM4 focus on the relation between the soft handover probability and the soft handover threshold. The cell size is a variable parameter. The soft handover threshold is the parameter $A_{\text{Th}}$ used in the WCDMA soft handover algorithm and is also commonly referred to as the soft handover margin. In OPNET® this parameter is incorporated as an attribute of the RNC model and is called the macro-diversity margin. In the soft handover algorithm this threshold value determines the maximum difference in measured quality there can exist between the two pilot signals of cells in the active set of one mobile station. When this value increases it is clear that for one given cell a larger population of candidate signals will exist as the constraints for the signal quality of the cells to be added to the active set become less strict when a larger difference in $E_b/N_0$ is allowed.

In the following sections the results of the simulations carried out are presented separately for each series of models. SIM1 to SIM4 consist of three-cell systems with one user moving along a straight-line path at a constant speed. In the first three simulations the user path is situated in the triangular area formed by the three Node B’s. In the model in SIM 4 the user is moving along the straight line path the three
Node B’s are placed on. This model has already been used to obtain the results of DEMO1 presented in chapter 2.

For the simulations SIM1 till SIM4 the numerous sequences have been run using the parameters below:

**Table 3: parameters used for SIM 1-4**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SIM 1</th>
<th>SIM 2</th>
<th>SIM 3</th>
<th>SIM 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile station speed</td>
<td>5 km/h</td>
<td>60 km/h</td>
<td>120 km/h</td>
<td></td>
</tr>
<tr>
<td>Soft handover threshold</td>
<td>From 1 to 12, step 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell radius</td>
<td>500 m</td>
<td>1000 m</td>
<td>1500 m</td>
<td>2000 m</td>
</tr>
<tr>
<td></td>
<td>2500 m</td>
<td>3000 m</td>
<td>4000 m</td>
<td>5000 m</td>
</tr>
<tr>
<td></td>
<td>6000 m</td>
<td>8000 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic type</td>
<td>Conversational sample load, One-way</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– max. bit rate 12.2 kbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Path loss model</td>
<td>Vehicular</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It has been experienced that the user speed does not have any influence on the soft handover probability; hence the simulation results for a mobile station speed equal to 60 km/h have been used.

**4.2.1 SIM 1**

The first series of simulations models a user moving from the cell centre in a straight line towards the vertex and continuing its way along the edge of the two neighbouring cells.
The picture below shows the uplink-transmitted power by the mobile station. While moving closer towards Node B no. 1, the transmitted power decreases. When the UE approaches the base station, the power decreases following an inverted logarithmic function – similarly as in Figure 23 – showing the UL transmitted power for DEMO 1. As explained in paragraph 2.2.4 this is due to the fact the power control algorithm forces the mobile terminal to make up for the path loss between the mobile station and the Node B.

As the user reaches the gravitation point of the triangle formed by the three base stations, the power necessary to connect to the initial Node B increases and soft handovers become more probable. Once the user reached the gravitation point itself, the distance to each of the three Node B’s becomes equal to one cell radius. In this symmetrical situation, connecting to each of the base stations is as favourable for the mobile user and three simultaneous connections are present. Depending on the soft handover threshold used in the system and the distance to the gravitation point, the active set size will remain three for some time.
Table 4: SIM 1 – parameters used for obtaining Figure 39

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>1500m</td>
</tr>
<tr>
<td>Node B spacing</td>
<td>2600m</td>
</tr>
<tr>
<td>Traffic type</td>
<td>Conversational sample load, One-way – max. bit rate 12.2 kbps</td>
</tr>
<tr>
<td>User speed</td>
<td>60 km/h</td>
</tr>
<tr>
<td>Time elapsed</td>
<td>6min</td>
</tr>
<tr>
<td>Soft handover threshold</td>
<td>7 dB</td>
</tr>
<tr>
<td>Path loss model</td>
<td>Vehicular environment</td>
</tr>
</tbody>
</table>

While moving along the cell edge between cell 2 and cell 3, two identical simultaneous connections should theoretically exist as the position of the mobile is defined to be exactly symmetric towards Node B 3 and 2. As can be seen on the picture above this is not the case. The uplink transmission power differs for the two simultaneous connections established during the second half of the trajectory. This is due to the fact that points on the defined path are not exactly equidistant to the two node B’s at every time. As simulations carried out on a model representing the exceptional situation where a user is equidistant to two base stations for a considerably long time, the results would not be representative for general network situations. Hence roughly defined trajectories are used resulting in more useful results. For the same reason it occurs that for lower threshold values no second connection is made during this second half of the trajectory as will show on the results of this simulation series.

For the handover probabilities, the following results have been obtained:

Figure 40: SIM1: influence of SHO threshold on SHO probability for different cell sizes

71
The graphs for different cell sizes have similar shapes. The graph area can be divided in two zones. In the first zone for low threshold values the handover probability increases with a more or less constant slope that is similar for the three simulations series. At a certain threshold value the soft handover probability suddenly increases discontinuously to significantly higher values above 50 percent. From that point on the probability increases further with a slightly lower slope than in zone 1. Again the slope has similar values for the three cell sizes.

In the pages above it has been explained that – due to the fact that the trajectory does not follow the cell edge exactly – for lower threshold values the mobile station will have only one connection to the Node B as it moves along the cell edge. This is due to the fact that there exists a difference in path loss towards the two Node B’s that is higher than the threshold value, hence the user is not in soft handover. In zone 2 the threshold value is higher than the difference in path loss to the Node B’s and the mobile station will be continuously in soft handover as it moves along the cell edge. In zone 1 on the other hand, the probabilities to be in handover are still low as the mobile user has only multiple link connections at the moment he is close to the point where the three cells meet – the gravitational point of the triangle formed by the three base stations. This phenomenon causes the discontinuity in the graph above.

It is remarkable that the breakpoint in the curve moves towards higher threshold values for smaller cells. This is due to the fact that the power transmitted by the Node B decreases much faster close to the Node B. To discuss this situation it is necessary to introduce the concept of the soft handoff window. The handoff window is the zone in the network where soft handovers are possible. This implies that in this zone the strengths of the pilot signals from the two Node B’s differ less than the soft handover threshold used in the system. When the Node B’s are placed closer to each other, the so-called handoff window becomes smaller for the same threshold value. This is shown on the picture below. Hence the soft handover probability for users in the cell edge area decreases with the cell size.
Figure 41: comparison of handoff windows for different Node B spacing

That the soft handover probabilities have equal values for threshold values below 3 and above 9 is a consequence of the fact that for all the threshold values higher than 9, the trajectory is located in the handoff window for all cell sizes. Similarly the trajectory falls not within the handoff window for threshold values lower than 3, also for all cell sizes.

4.2.2 SIM 2,3&4

- SIM2:
The second trajectory is orthogonal to the one used in the first simulation. The followed track also coincides with the gravitation point of the imaginary triangle formed by the three node B’s but it makes a right angle with the cell edge crossed.

Figure 42: SIM2 - triangular three-cell scenario with trajectory coinciding with three-cell point

As the user comes near to base station no. 2 and 3, the uplink transmitted power decreases but the lowest levels are still significantly higher than the levels reached when the path of the mobile coincides with the location of the Node B. When passing the gravitational point of the triangle – the point where the three hexagonal cells meet
the mobile station is in soft handover, having three simultaneous connections with the UTRAN network. The reason that the transmitted power levels on the picture below are not equal on the moment the active set size is three, is that the graphically defined trajectory does not coincide exactly with the above-described point.

![Figure 43: SIM 2 – transmitted power in uplink direction](image)

**Table 5: SIM 2 – parameters used for simulation of Figure 43**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>2000m</td>
</tr>
<tr>
<td>Node B spacing</td>
<td>3460m</td>
</tr>
<tr>
<td>Traffic type</td>
<td>Conversational sample load, One-way</td>
</tr>
<tr>
<td>User speed</td>
<td>60 km/h</td>
</tr>
<tr>
<td>Time elapsed</td>
<td>8min</td>
</tr>
<tr>
<td>Soft handover threshold</td>
<td>6 dB</td>
</tr>
<tr>
<td>Pathloss model</td>
<td>Vehicular environment</td>
</tr>
</tbody>
</table>

For the handover probabilities compared to the soft handover threshold used in each simulation, the following results have been obtained:

![Figure 44: SIM2: influence of SHO threshold on SHO probability for different cell sizes](image)
• SIM3:
The last simulation of the ‘triangular series’ models a user moving on the virtual connection line between two node B’s.

![Figure 45: SIM3 – triangular three-cell scenario with trajectory between two Node B’s](image)

The graph below represents the uplink transmitted power by the mobile station. The inverted logarithmic path loss curves are easy recognisable. At the Node B the mobile station reaches its absolute minimal transmission power.

![Figure 46: SIM 3 – transmitted power in uplink direction](image)

**Table 6: SIM 3 – parameters used for simulation of Figure 46**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>1500m</td>
</tr>
<tr>
<td>Node B spacing</td>
<td>2600m</td>
</tr>
<tr>
<td>Traffic type</td>
<td>Conversational sample load, One-way</td>
</tr>
<tr>
<td>User speed</td>
<td>60km/h</td>
</tr>
<tr>
<td>Time elapsed</td>
<td>6min</td>
</tr>
<tr>
<td>Soft handover threshold</td>
<td>5 dB</td>
</tr>
<tr>
<td>Path loss model</td>
<td>Vehicular environment</td>
</tr>
</tbody>
</table>
For the handover probabilities, the following results have been obtained:

![Figure 47: SIM3: influence of SHO threshold on SHO probability for different cell sizes](image)

**Figure 47:** SIM3: influence of SHO threshold on SHO probability for different cell sizes

- **SIM4:**
  To verify the results obtained in SIM3 a fourth series of simulations was run. SIM4 is an extension to DEMO 1 presented in chapter 2. A mover follows a trajectory along 3 Node B’s in a network with hexagonal cells. This simple model reflects the real network situation where a mobile user travels on a highway with radio towers placed alongside the transportation route. The only difference with SIM3 is that the mobile user can have maximum two connections to the UTRA network as there are only base stations placed on and not next to the trajectory in this scenario.

![Figure 48: SIM 4 – three-cell scenario with trajectory along three Node B’s](image)

**Figure 48:** SIM 4 – three-cell scenario with trajectory along three Node B’s

A graph of the uplink-transmitted power can be found in chapter 2 in the section discussing DEMO 1.
For the handover probabilities, the following results have been obtained:

![Figure 49: SIM4: influence of SHO threshold on SHO probability for different cell sizes](image)

Figure 49: SIM4: influence of SHO threshold on SHO probability for different cell sizes

These results are very similar to those obtained from simulating SIM3. The fact that there are other base stations in the vicinity of the trajectory clearly does not influence the overall handover probability. When the mobile user is in the middle between Node B no.1 and no.3 (figure 45) he is at his closest point to Node B no.2, which is at a distance of \( \frac{3R}{2} \). As the maximum distance to the other two base station is never higher than \( \frac{\sqrt{3}}{2}R \) the UE will have established two connections already before a third connection is set up with Node B no.2. This does not affect the handover probability. It has to be noted that the values for the soft handover probabilities are significantly lower than those obtained in the two previous simulation series. This is due to the fact that the trajectory used in SIM3 does not coincide with the gravitational point of the triangle formed by the three Node B’s. Instead of crossing this point where three simultaneous connections are likely to occur – the user passes two base stations on its way, which will decrease the number of soft handovers significantly as near to the Node B antenna the mobile will have only one connection whatever the value of the soft handover threshold is. Still the figures obtained from these four simple series of simulations are valuable as these models allow drawing important conclusions on the overall probability as shown blow:
For the SIM2, SIM3 and SIM4 series carried out, the soft handover probability increases for higher threshold values. This can be explained as follows. The soft handover algorithm uses the signal with the lowest radio link attenuation as a reference to determine the handover state. The probability to find the signal with the second lowest radio attenuation is higher when the signal quality can be up to 12dB lower than when the two signals can only differ 3dB. The mathematical analysis of the soft handover probability is given below. Why there exists a linear relation between the threshold and the probability will be shown as also the reason why the soft handover probability is independent of the cell size – as can be noted in figure 44 figure 47 and figure 49.

As mentioned in the beginning of this chapter two methods have been used to calculate the soft handover probability. The first method is by determining the amount of users in soft handover. Dividing this figure by the total amount of users in the system gives the soft handover probability. This method will be used in the static simulations in the next paragraphs – SIM5 and SIM6. The second method relies on time ratios. Indeed, if the amount of time a user is in handover is divided by the total time he is present in the system the soft handover probability is obtained on condition that the user is moving at constant speed. This is the method used for the first four simulation series of this chapter. Hence the soft handover probability $SHO\_PROB$ can be written as:

$$SHO\_PROB = \frac{\Delta t_{SHO}}{\Delta t_{total}} = \frac{\Delta x_{SHO}}{\Delta x_{total}} = \frac{\Delta x_{SHO}}{v}$$  \hspace{1cm} (4.1)$$

where $\Delta t_{SHO}$ is the time the user is in soft handover and $\Delta t_{total}$ the total time simulated. Analogous to this $\Delta x_{SHO}$ is the distance of the trajectory crossed in handover mode and $\Delta x_{total}$ the total length of the trajectory. $v$ is the velocity of the mobile user. For the model used in SIM3 this probability can also be written as:

$$SHO\_PROB = \frac{W}{\sqrt{3}.R}$$  \hspace{1cm} (4.2)$$

where $W$ represents the width of the handoff window and $R$ is the cell radius\(^{17}\).

---

\(^{17}\) It is common to define the cell radius of hexagonal cellular architectures as used in this study, as the distance from the cell centre to the vertex.
The picture below represents the in downlink direction received power at the mobile station for the trajectory between two Node B’s as modelled in SIM3. The node B’s are placed at \( x = 0 \) and at \( x = \sqrt{3}R \). The transmitted power \( f(x) \) of the Node B placed in \( x = 0 \) follows this relation:

\[
f(x) = f(0) - \text{pathloss}(x) = P_0 - (33.6 \log_{10} x + 120.2)
\]  \hspace{1cm} (4.3)

\( P_0 \) is the transmitted power at the base station and the path loss is given by the ITU vehicular path loss model described at the end of chapter 3. Between the two base stations, near the cell edge around \( x = \frac{\sqrt{3}R}{2} \) the ratio \( \frac{\text{SHO}_\text{TH}}{W} \) can be rewritten using this linear approximation:

\[
\frac{\text{SHO}_\text{TH}}{W} \approx \left| \frac{df(x)}{dx} \right|_{x = \frac{\sqrt{3}R}{2}} = \frac{33.6}{\ln 10} \left| \frac{1}{x} \right|_{x = \frac{\sqrt{3}R}{2}} = A \frac{1}{R}
\]  \hspace{1cm} (4.4)

Hence \( W = A \cdot \text{SHO}_\text{TH} \). Substituting this value in equation (4.2) gives a valuable expression for the soft handover probability:

\[
\text{SHO}_\text{PROB} = \frac{R \cdot \text{SHO}_\text{TH}}{\sqrt{3}A} = \frac{1}{\sqrt{3}A} \text{SHO}_\text{TH}
\]  \hspace{1cm} (4.5)

**Figure 50:** mathematical model used for calculation of formula (4.6)
For the Vehicular path loss model used, this formula becomes:

\[ SHO\_PROB = \frac{1}{29.2} SHO\_TH \]  

(4.6)

The picture below compares the soft handover probabilities obtained with the model and the values obtained through simulation of model SIM4, as this is the model the formula is based on.

![Comparison between simulation values and analytical model](image)

**Figure 51**: comparison between simulation values and analytical model

In the picture above it can be seen that the model gives similar values to the ones obtained through simulation. For higher threshold values the model becomes less accurate. This is due to the fact that the handoff window becomes larger for high threshold values; hence the linear approximation used in formula (4.4) becomes less accurate, resulting in a slight overestimation of the soft handover probability.

This formula is important as it proves the linear relation between the soft handover probability and the soft handover threshold as can be seen on the shape of the curves obtained during the performed simulations. It is essential to remark that the cell radius is not present in equation (4.5). Whatever the value of the cell size, the soft handover probabilities will remain the same for a given threshold value. The soft handover probability for a user being located between two base stations is calculated taking the ratio between the length of the handoff window and the cell size. As the handoff window increases proportionally with the cell size this probability is independent of the cell size used. In paragraph 4.4 an analytical model will be presented to calculate the overall handover probability in one cell instead of the soft handover probability for a user being situated between two Node B’s.
4.3 Distance to Node B: SIM5

The last 2 simulations of this chapter model static users in a cell surrounded by 6 adjacent cells. For SIM5 a high number of users was distributed in the hexagonal cell coverage area of one Node B. As other cells surround the central cell it is very likely that users in the loaded cell – especially those located near the cell edge area – will have connections with base stations from the adjacent cells. Whereas the above-described models analyse the overall handover probability of one or more cells, SIM5 analyses the soft handover probability distribution inside on cell. In order to analyse the effect of the distance between the mobile terminal and the Node B on the soft handover probability, the central cell area was divided in a number of concentric rings centred on the Node B.

![Diagram of a cell network with Node B and adjacent cells]

**Figure 52: SIM 5**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>2000m</td>
</tr>
<tr>
<td>Node B spacing</td>
<td>3460m</td>
</tr>
<tr>
<td>Model type</td>
<td>Static</td>
</tr>
<tr>
<td>Traffic type</td>
<td>VoIP call (GSM quality)</td>
</tr>
<tr>
<td>Soft handover threshold</td>
<td>From 3dB to 12dB, step 3dB</td>
</tr>
<tr>
<td>Number of users</td>
<td>48</td>
</tr>
<tr>
<td>Path loss model</td>
<td>Vehicular environment</td>
</tr>
</tbody>
</table>

**Table 7: parameters used for SIM5**
The results obtained after simulation of the system above are shown in the picture:

Figure 53: impact of the distance to the Node B on the SHO probability for different threshold values

As it has been showed in the previous section, the soft handover probability is independent of the cell size used. Hence these results for a cell with radius 2000m are generally applicable for smaller and larger cells. Several remarks can be drawn from the graph:

- The intuitive notion that users close to the cell edge have higher handover probabilities is confirmed by this graph. Also it can be seen that – whatever the handover margin used – users at the cell edge are in soft handover with a probability of 100%. This does not show clearly for the series with threshold value 3, as the handoff window is very narrow in this case and only users placed on the cell edge or in its very near vicinity will have connections to multiple Node B’s.

- The curves also show that the probability to be in soft handover increases with the soft handover threshold in the system, a result obtained in the previous paragraphs already.

- When the distance over which the transition form zero handover probability to 100% probability is made, is compared between the higher threshold values and the case where SHO_TH = 3, it can be seen that the transition to maximum probability is much faster for the higher threshold values. This is again due to the fact that the
probabilities to find the cell pilot signal with second lowest radio attenuation are higher for higher handover thresholds.

4.4 Probability over one cell

SIM 6 is similar to SIM5 as this sequence is also carried out on a model of one loaded cell surrounded by six other cells. The users are static and have continuous Voice over IP connections with GSM quality, resulting in bit rates of 12,2kbps. The goal of this simulation is to verify the soft handover probabilities obtained during the analysis of simple models in SIM 1-4.

![Figure 54: SIM6](image)

**Table 8:** parameters used for SIM6

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>2000m and 4000m</td>
</tr>
<tr>
<td>Node B spacing</td>
<td>3460m and 7000m</td>
</tr>
<tr>
<td>Model type</td>
<td>Static</td>
</tr>
<tr>
<td>Traffic type</td>
<td>VoIP call (GSM quality)</td>
</tr>
<tr>
<td>Soft handover threshold</td>
<td>From 1dB to 12dB, step 1dB</td>
</tr>
<tr>
<td>Number of users</td>
<td>50</td>
</tr>
<tr>
<td>Path loss model</td>
<td>Vehicular environment</td>
</tr>
</tbody>
</table>
Figure 55: SIM6: influence of SHO threshold on SHO probability for different cell sizes

Although the previous models have been really useful in determining the mechanisms that affect the soft handover probability in a system, they are not very well suited for drawing conclusions on the absolute values of this probability in the network. Therefore the model of a high number of users randomly distributed in a cell – as used in SIM5 and SIM6 – is particularly useful as it allows drawing conclusions on the soft handover probabilities in a real system. As can be seen on the picture above the conclusions drawn in the previous paragraphs about the shape of the curves still hold. The handover probability increases towards higher threshold values and the cell size has no influence on the probabilities. The fact that the curve shows slight variations to the imaginary regression curve is a consequence of the limited number of mobiles used at a hence limited number of locations. In order to average out this ‘sampling’ effect and obtain smoother curves, the mobiles could be assigned random trajectories in the cell. This simulation was not carried out, as the run time would increase significantly. Generally it can be said that the soft handover probability varies from 5% for a threshold value of 1dB to 35% for 6dB and reaching up to 60% for a threshold value equal to 12dB.

The picture below presents the same results as in figure 55 for cell size 2000m, but in this case the number of users having double and triple link connections is shown separately.
Figure 56: SIM6: number of users having double and triple link connections relative to total number of users

The following remarks can be made on this graph:
- The percentage of double link connections – users having active set size equal to two – does not show a clear upward trend when related to the soft handover threshold. For most threshold values 10 to 20% of the user population is connected to two different Node B’s.
- This is not the case for users with active set size equal to three. The number of triple link connections increases significantly towards higher threshold values. For soft handover threshold value equal to 12 the users having three simultaneous connections in the UTRA part of the network make out half of the population. As those connections cause more overhead on the system it is favourable to set the handover threshold not to very high values as this will cause capacity shortage due to the high number of connections established in the system caused by those so-called triple link connections.
4.4.1 Mathematical model

To verify the results obtained by simulation, the following section introduces a mathematical model that makes it possible to calculate the average soft handover probability in a cell for a given threshold. This probability can be calculated by taking the ratio of the surface area of the part of the network where soft handovers are possible, relative to the total network surface. Using the picture below, due to the symmetry present in the network this can be simplified to:

\[ SHO \_ PROB = \frac{A_{\text{shaded \_ area}}}{A_{\text{triangle}}} \]  \hspace{1cm} (4.7)

where \( A_{\text{shaded \_ area}} \) is the surface of the shaded area in the picture below and \( A_{\text{triangle}} \) is the surface of the red triangle.

![Diagram showing calculation of soft handover probability using surface ratios](image)

The shaded area is formed by the edges of the triangle and the curve for which this relation holds:

\[ path \_ loss \_ 1 - TH = path \_ loss \_ 2 \]  \hspace{1cm} (4.8)

Using the vehicular path loss model this can be transformed to:

\[ 33.6 \log_{10} x_1 + 120.2 - TH = 33.6 \log_{10} x_2 + 120.2 \]  \hspace{1cm} (4.9)

where \( x_1 \) and \( x_2 \) represent the distance to NodeB1 and NodeB2 respectively. Simplifying this equation gives:

\[ \frac{x_1}{x_2} = 10^{\frac{TH}{33.6}} = k \]  \hspace{1cm} (4.10)
Using the so-called circle of Apollonius it can be proven that the locus of the points in
the plane, for which the ratio of the distances to two fixed points – in this case the two
Node B’s – is constant, is a circle [1]. Using the intuitive notion of the shape of the
handoff area the following situation from which the surface of the shaded area can be
calculated is obtained:

![Figure 58: mathematical model used for calculation of formula (4.15)](image)

Expressing the relation $\frac{x_1}{x_2} = k$ in the two points where the x-axis and the circle
intercept – the points A and B on figure 58 – the following two relations are obtained:

$$\frac{\sqrt{3}R - (r - t)}{r - t} = k \quad (4.11)$$
$$\frac{\sqrt{3}R + (t + r)}{t + r} = k$$

where $R$ represents the cell radius. Solving this for $r$ gives:

$$r = \frac{\sqrt{3}Rk}{k^2 - 1} \quad (4.12)$$

The surface of the handoff window is given by the surface of the grey plus the red
shaded area on the picture below. Seen the fact that the values obtained for $r$ are
significantly higher than the cell radius$^{18}$, the handoff area can be approximated by the surface of the grey area.

This surface can be integrated as follows:

$$2\int_{0}^{[OA]} y \, dx = \int_{0}^{(R - \frac{2x}{\sqrt{3}})} (R - \frac{2x}{\sqrt{3}}) \, dx = \int_{0}^{(R - \frac{2x}{\sqrt{3}})} dx$$

(4.13)

where $|OA|$ represents the distance from point O to A as shown on the picture above and $y$ is given by the equation of the edge of the red triangle. Calculating this integral gives for the surface of the shaded area:

$$R^2 \left( \frac{\sqrt{3}}{4} - \frac{\sqrt{3}}{(k+1)^2} \right).$$

(4.14)

The soft handover probability is given by the ratio of this surface area with the surface of the triangle:

$$SHO \_ PROB = \frac{R^2 \left( \frac{\sqrt{3}}{4} - \frac{\sqrt{3}}{(k+1)^2} \right)}{\frac{\sqrt{3}R^2}{4}} = 1 - \frac{4}{(k+1)^2}$$

(4.15)

Substitution of the value for $k$ gives:

$$SHO \_ PROB = 1 - \frac{4}{\left( \frac{TH}{10^{33.6} + 1} \right)^2}$$

(4.16)

Similarly to (4.6), this relation shows again that the soft handover probability in a UMTS network is independent of the cell size used. The number of handover increases no longer linearly although a linear approximation would give good results.

In the graph below the good correspondence between the analytical model and the simulation results is shown. The relation found between the soft handover threshold and the soft handover probability is not linear although the approximation with a linear model would introduce very few inaccuracies.

$^{18}$ For $SHO\_TH = 5$, $r = 2.48R$
4.5 Conclusions

In this chapter a thorough analysis of the soft handover probability in a UMTS network has been presented. First the importance of a reliable prediction of the amount of soft handovers in a system has been discussed. The overhead caused by soft handovers on both radio resources occupied, signalling performed and the number of codes used should not exceed the gain in system performance achieved by soft handovers. Two methods are used to define the soft handover probability. The most commonly used method is to take the ratio of the size of the handover population relative to the total amount of users in the system. Besides this direct approach this project makes presents a method of calculating the probabilities by dividing the time spent in handover situation to the total time the user is connected to the network. When users moving at constant speeds are modelled, this ratio gives representative figures on the handover probability in the system.

The rest of this chapter presents and analyses the results of the simulation work carried out. Six series of models have been simulated. SIM1 to SIM4 contain network situations built up of three Node B’s and one mobile user moving at a constant speed following a straight-line trajectory. SIM5 and SIM6 present static models of loaded cells. The first four simulation series have been carried out to study the mechanisms
determining the soft handover probability in a UMTS network. The last two simulation series of this chapter have been conceived to study the effect of the distance to the Node B on the handover probability and to give representative values for the soft handover probabilities in a real system respectively.

SIM1 – the situation where the mobile user moves along the cell edge between two adjacent cells for a considerable time – showed the importance of the handoff window in a system. The handoff window is the area over which the received strengths of the pilot signal differ less than the handover threshold. Otherwise stated, the handoff window is the area of the network where soft handovers are possible for a given threshold value. The simulations carried out clearly showed that for low threshold values the handoff window becomes narrower than when high threshold values are used.

The results of SIM3 and SIM4 clearly showed the linear relation there exists between the soft handover threshold and the total amount of soft handovers in the system. The intuitive explanation for this phenomenon is that the higher the threshold value is, the more candidates there will be to be combined with the monitored signal using macro-diversity combining. Hence the soft handover probability will increase towards higher threshold values. This paragraph also analyses the overall soft handover probability in a system mathematically. Starting from the one-dimensional situation of a user being located between two Node B’s as present in SIM3 and SIM4 an expression for the soft handover probability was derived. It can be shown that this relation holds:

$$SHO\_PROB = \frac{2}{\sqrt{3A}}SHO\_TH$$

where A is a constant parameter, only determined by parameters used in the path loss model. This relation expresses the linearity between the soft handover algorithm parameter SHO_TH and the soft handover probability for the situation where a mobile is located between two Node B’s. As A is a constant value, the soft handover probability is also be proven to be independent of the cell size used in the system as can be seen in the simulation results.

As the above-described models analyse the overall handover probability of one or more cells, SIM5 analyses the soft handover probability distribution inside on cell. By
randomly distributing a high number of users in a loaded cell the handover probability was evaluated. It showed that near the cell centre very few users are in soft handover. In the cell edge area a soft handover probability of 100% is achieved. Concerning the effect of the handover threshold it is shown that the lower the value of this parameter, the slower the transition from 0% to 100% is made. For threshold values of 3dB and below, only users located on or very near the cell edge have 100% probability to be connected to multiple base stations.

SIM6 has been carried out in order to obtain reliable handover probabilities for a real system. The first four simulation series model exceptional network situations and hence their value is merely to show general behaviour of handover systems rather than to give indicative values for handover probabilities. A randomly distributed user population loading a cell showed handover probabilities linearly increasing with the handover threshold value. The acquired values range from probabilities of 5% for a soft handover threshold of 1dB to 35% for 6dB and reaching probabilities of 60% in systems where the threshold value is set to 12dB. From the results obtained during SIM6 the probabilities to have either a double link connection or a triple link connection are plotted. The users with active set size equal to 2 make out 10-20% of the total user population for different threshold values. Users having three connections to different Node B’s are rare for low threshold values. Towards higher thresholds the users with active set size equal to three are responsible for the further increase in soft handover probability.

This chapter concludes with introducing a mathematical model that makes it possible to calculate the soft handover probability. By taking the ratio between the cell area where soft handovers are enabled and the total cell area this relation has been derived:

\[ SHO\_PROB = 1 - \frac{4}{\left(10^{\frac{TH}{3.6}} + 1\right)^2} \]

This relation shows that the soft handover probability is independent of the cell size used in the system and is only determined by the soft handover threshold. Plotting the formula for different threshold values gives a curve that can be easily linearly approximated.
References

Chapter 5

Capacity & Coverage

After dimensioning the rough number of required base stations and sites in a first dimensioning step, the next step in the radio network planning process is to dimension the amount of traffic to be supported. In this chapter the network capacity and coverage are analysed in more detail, as these are vital parameters to measure network performance. As will be shown, the traffic load per base station – the capacity – is strongly correlated with the coverage provided by the system.

In the first paragraph some general issues around capacity and coverage are presented. This section of the report discusses mechanisms influencing the values of these system characteristics and studies the relation between these two parameters. These considerations form the starting point for an analysis coverage and capacity individually in paragraphs 5.2 and 5.3 respectively. Also the impact of soft handovers in the network is studied. As in a soft handover-enabled network a considerable fraction of the total user population has established two or more simultaneous link connections with the Node B’s using the WCDMA air interface, the total amount of resources used will increase rapidly and the network could get overloaded if no special care is taken to keep the number of soft handovers to an acceptable level. On the other hand it has been shown in chapter 2 that soft handover results in a decrease of the average power used per link. Hence it will be analysed to which extent the overall network coverage will benefit from this.
The last section of the paragraph on capacity in soft handover networks introduces the soft capacity principle. As mentioned earlier CDMA networks are not hard capacity limited. This means that additional users cannot be hard blocked due to a lack of timeslots or shortage in the number of copper wires available, as is the case in for example GSM and POTS networks respectively. Instead of being hardware limited, CDMA networks are interference limited. This means that every additional user will gradually degrade the noise figure in the system until the network is fully loaded. The interference-determined behaviour of soft handover networks makes it possible for loaded cells to borrow capacity from surrounding cells with lower traffic density. These and other phenomena will be analysed and illustrated with simulation examples.

To obtain the results included in this chapter a set of three case studies has been simulated. As described in chapter 3, CASE1, 2 and 3 represent loaded network situations with mobile terminals transmitting and receiving application-specific traffic. Besides comparing different load situations other methods are used to compare the network performance. CDF plots (Cumulative Distribution Function) of the power transmitted in the system make it possible to draw conclusions about coverage issues. Also the amount of interference present in the system can be compared using this technique. Another figure by which capacity and coverage issues can be studied is the system outage. During different simulations the capacity is increased until at some point the user suffers a quality decrease in order to comply with the power restriction. The point at which communication is no longer possible is often referred to as “system outage”. By doing this a good measure for the system coverage is obtained.

5.1 Capacity vs. Coverage

Intuitively it can be seen that capacity and coverage are not independent parameters in a UMTS system. Imagine the situation where a lot of users are concentrated in the central cell area. As the users are sending and receiving more and more application traffic over the WCDMA air interface, the total amount of noise present in the system
will increase. Hence a user near the cell edge will be ordered by the power control algorithm to power up in order to overcome the increase in noise and still reach the Node B with a power level similar to the users in cell centre. The remote mobile station will be transmitting at increasing power levels and will soon reach its maximum transmission power as the traffic load generated in the network keeps increasing. The other users “overshout” the user near the cell edge area, as the high power transmitted is not sufficient to reach the Node B. The user will no longer be able to establish communication with this Node B. Otherwise stated, the area covered by the Node B becomes smaller. This phenomenon is characteristic for CDMA networks; the coverage decreases with increasing traffic load.

The above-described scenario also causes the effect of breathing cells, which means that the coverage area of a cell is not strictly defined but can move depending on the load present in the system. A particular example of this phenomenon are so-called pulsing cells. When a user far away from the cell centre tries to establish a high bit rate connection with the network – e.g. a streaming video connection – the load will increase. Following the above-described load-controlled mechanism, this will result in a decrease of the coverage area. If the remote user is located in the area of coverage that gets lost due to the increased load he will lose the connection right after establishing it. Hence the load will decrease again and the coverage area will get bigger. As the user will now be again located in the coverage area of the Node B a new attempt will be made to connect and the scenario will repeat itself. This situation of increasing and decreasing coverage is referred to as the pulsing of a cell as the cell coverage area expands and shrinks like a beating hearth.

Seen the importance of the relation between coverage and capacity, a series of simulations was carried out comparing the maximum allowable path loss with the traffic load in the system. The maximum path loss before the mobile station can no longer connect to the Node B is directly related to the distance between the UE and the Node B as determined by the path loss model used. The value of this parameter was examined while varying the load.

To determine the maximum allowable path loss before communication become no longer possible, a user moving out of the cell coverage area has been modelled. At a
given point the mobile station reaches its maximum transmission power and due to continuous retransmissions without communication the connection will be broken. At this outage point the path loss to the Node B is measured. Hence a good measure for the system coverage is obtained. The CASE1 simulation series model a cell loaded with a number of static users. The mobile user that moves out of the cell coverage area is assigned the same traffic profile as the rest of the user population. The picture below show the network situation modelled.

![Figure 60: CASE1 – user moving out of cell coverage area](image)

The following simulation parameters have been used to obtain the results. The number of fixed users in the central cell is gradually increased, resulting in higher load values. The application traffic profile reflects realistic user behaviour.

<table>
<thead>
<tr>
<th><strong>Table 9</strong>: parameters used for CASE1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>User speed</strong></td>
</tr>
<tr>
<td><strong>Number of static users</strong></td>
</tr>
<tr>
<td><strong>Application traffic profile</strong></td>
</tr>
<tr>
<td>FTP: inter-request time: exponential $\frac{1}{\lambda} = 3600s$, file size: constant size = 1kB</td>
</tr>
<tr>
<td>Email: send/receive inter-arrival time: exponential $\frac{1}{\lambda} = 3600s$, email size: constant size = 0,5kB</td>
</tr>
<tr>
<td>Video conferencing: low resolution video, repeatability: once per simulation</td>
</tr>
<tr>
<td>Voice: voice over IP (GSM quality), repeatability: once per simulation</td>
</tr>
<tr>
<td><strong>Path loss model</strong></td>
</tr>
<tr>
<td><strong>Cell size</strong></td>
</tr>
</tbody>
</table>

The maximum path loss is calculated by taking the difference between the transmitted signal strength in the uplink direction at the mobile station and the received signal strength at the Node B. The moment where communication between Node B and
mobile station becomes impossible is the reference outage point where this maximum path loss difference is measured. The method is shown on the picture below:

![Figure 61: method for determining maximum path loss](image)

The results obtained with CASE1 show the relation between the maximum path loss and load in a network. As has been stated above, the maximum path loss at which communications are still possible is a good measure for the coverage in the system.

![Figure 62: example of coverage vs. capacity in uplink](image)

Several remarks can be made on the figure:
- There exists a clear trend towards lower maximum allowable path loss values for an increasing load. This means that for higher traffic density in the cell, the coverage area will shrink.
- A high variance is present on the path loss values obtained. This is due to the fact that a user profile containing diverse applications was used. As will be shown below – the maximum path loss value differs for video and voice traffic. Hence if the
mobile user has a video connection at the outage point, the path loss will be different from the situation in which he is having a voice conversation, even when the load distribution in the rest of the network is similar.

- The load values in the picture above are fairly low when compared to the often advertised 2Mbps a UMTS system will be able to support. This is due to the fact that the Node B model used in OPNET contains only one transceiver pair. According to [1], depending on the parameter values used, the planned transceiver capacity ranges typically from 400 kbps to 700 kbps per transceiver. In real systems one Node B antenna pole contains multiple transceivers resulting in higher data rates available\textsuperscript{19}.

The picture below is based on the same data series as figure 62. Only the path loss values have been transformed to distances using the inverted vehicular path loss formula (3.2):

\[
R = 10^{\frac{L_{\text{path}} - 120.2}{33.6}}
\]  
(5.1)

![Graph showing capacity in the uplink related to the distance](image)

\textbf{Figure 63:} capacity in the uplink related to the distance

This graph displays clearly how the cell coverage area shrinks when the cell load increases. When planning the UMTS network graphs similar to the one shown above can be used to determine the cell size. Indeed, if traffic studies show a certain foreseeable demand of bandwidth (kbps) in a given area it is possible to determine the appropriate cell size.

\textsuperscript{19}The first operational UMTS networks will support peak downlink rates of 384kbps but in later UMTS networks it will be technically feasible to offer 2Mbps to one user.
5.2 Coverage

As mentioned in the previous paragraph the coverage is determined by the maximum allowed path loss in a system. It has also been shown that the available coverage in a system is related to the total capacity. This is due to the fact that both the capacity and the coverage are limited by the interference in the system.

Besides the amount of interference a range of other factors influences the coverage [2]:

- Characteristics of the receivers and the antennas used in the system
  Receivers with a higher sensitivity or antennas providing a better gain increase the maximum path loss there can exist between a Node B and the mobile terminal. Hence the coverage is better if these elaborate techniques are used.

- The mobile transmission power in case of the uplink capacity.
  Higher transmission values used in the mobile station better the coverage situation significantly although the generated interference in the system increases proportionally.

- The bit rate used
  The influence of the bit rate used in the system is twofold. The first factor is that high bit rate connections require slightly lower $E_b/N_0$ values. [2] suggests a difference of 2dB between a connection with a bit rate of 8kbps and a connection of 256kbps.
The second factor is the processing gain. As mentioned in chapter 2 the robustness against interference of coded data provides a gain given by the formula below.

\[
Gain = 10\log_{10}\left(\frac{\text{chiprate}}{\text{datarate}}\right)
\]  

(5.2)

The higher the data rate is, the lower the resulting gain will be as a fixed chip rate of 3.84Mcps is used in UMTS systems. Hence the coverage will be smaller for high data rate connections. Applying this formula on the bit rates used in the example above gives a difference of $10\log_{10}\left(\frac{256\text{kbps}}{8\text{kbps}}\right) = 15dB$. In
real systems the second factor outweighs the first one largely. Hence the transmitted power is higher for high bit rate connections.

- The multi-path diversity gain

The gain provided by combining multi-path signals using the Maximum Ratio Combining (MRC) technique improves the coverage situation in the system.

- The macro diversity gain

The influence on the coverage of the macro diversity gain or the gain obtained by combining different signals during soft handover is important in the scope of this chapter. As has been explained at the end of chapter 2, the gain provided by soft handovers allows for the *per link* average power transmitted in the system to drop some dB. On the other hand the interference in the system will increase due to a higher number of present in the system.

To illustrate the factors determining the system coverage some results of the following case study are included. The realistic network model used is CASE2 as introduced in chapter 3 and shown in the picture below.

![Figure 64: CASE2 – mobile user in realistic network situation](image)

The same network is compared when soft handovers are supported and when only hard handovers are enabled. The simulation parameters used are:

**Table 10: simulation parameters used for case study CASE2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>User speed</td>
<td>50kmh</td>
</tr>
<tr>
<td>Handover type</td>
<td>- Run1: Soft handover enabled: soft handover threshold = 6dB</td>
</tr>
<tr>
<td></td>
<td>- Run2: Only hard handovers</td>
</tr>
<tr>
<td>Application traffic profile</td>
<td>- Video conferencing: low resolution video, repeatability: once per simulation</td>
</tr>
<tr>
<td></td>
<td>- Voice: voice over IP (GSM quality), repeatability, once per simulation</td>
</tr>
</tbody>
</table>
As the user crosses the network he establishes traffic connections supporting voice and video conversations. The goal is to study the Cumulative Distribution Function (CDF) of the powers transmitted in the uplink direction.

![Figure 65: example of Cumulative Distribution Functions of uplink required transmission power for video and voice connections in a system with soft handovers and a system with hard handovers](image)

As can be seen on the graph two of the above listed factors determining the coverage show clearly.
- Video connections require higher power. Due to the higher bit rate present in video traffic, the processing gain is significantly lower and hence the required power per link higher. This graph shows values of around 8dB.
- Enabling soft handovers requires slightly lower power levels to establish a connection:

This graph represents the power for one physical channel used by a fixed user. It can be seen that although there is only one mobile user in the system the average interference is lower in the soft handover enabled system, resulting in lower overall power levels. This is due to the fact that the soft handover or macro diversity gain allows the average power required per link to be lower. Even though the graph above reflects the general trend that proves the soft handover situation as favourable
concerning the power required per link, some of the results gathered from CASE2 show higher power levels in soft handover situations. It is indeed possible that the increase in interference due to a high number of additional links will outweigh the macro diversity gain. Hence the hard handover situation offers lower average powers. This phenomenon occurs more frequently towards higher handover thresholds.

The parameters described above are included in the so-called link budget calculations which give the cell edge propagation loss in dB. Once this maximum allowed path loss has been calculated, the propagation environment model makes it possible to map the dB values for the path loss to distances to the Node B in kilometres as shown in figure 36 in chapter 3. When planning radio networks also figures of coverage probabilities are provided by the national regulator or by studies on the economical feasibility of the project. When combining these figures with the information obtained from the path loss model as given by formula (3.2), the system cell range can be determined. This follows the same method used to obtain Figure 63 from the data series displayed in Figure 62.

The method below shows how setting the maximum power per radio link affects the coverage probabilities for a system. The two curves represent the cumulative distribution function of the average uplink transmission power required to establish a voice and a video connection respectively\(^{20}\).

![Figure 66: relation between target coverage probability and the maximum transmitted power per radio link](image)

\(^{20}\) The values used in this graph are not representative for all real systems.
This example shows that in order to guarantee a target coverage probability of 95% for voice conversations, the limit for the uplink-transmitted power should be set at 28dBm. Setting the maximum transmission power to support video conversations at 33dBm results in coverage of still only 72%.

5.2.1 Uplink-Downlink

When the uplink and the downlink coverage are compared it can be said that the main coverage constraint lies in the uplink direction. This is because the transmission powers used in the mobile station are significantly lower than those used in the Node B. Typical values for the mobile are 21dBm (=125mW) compared to values up to 40 or 46dBm (=10 to 40W) for macro cell base stations. The picture below shows that for a mobile station moving out of the cell coverage area the connection is first broken in the uplink direction:

![Figure 67: UL vs. DL coverage for user having video connection](image_url)
5.3 Capacity and soft handovers

The possibility to offer new attractive high bit rate services to the end-user will be determining in making the consumer population decide to use the UMTS system. By using CDMA as the multiple access scheme it is possible to offer a substantially higher capacity than any other mobile communication system designed to provide global coverage could at this moment\(^{21}\). The choice to use CDMA makes it also possible to offer different data rates to the user. By varying the spreading factor used and multiplexing channels together, speeds ranging from low data rates suited for voice conversations up to 2Mbps can be offered to the user.

As more connections are established in the system the total amount of noise will rise. Increasing the transmission power of Node B’s and mobile terminals to still meet the \(E_b/N_0\) requirement as noise rises is not recommended for several reasons. For the mobile station the battery capacity limits the usable transmission power values. Increasing the power in the Node B can result in higher available data rates in the cell controlled by that Node B but the interference in the adjacent cells would increase proportionally, so this practice is not able to increase the overall capacity of the network. Hence CDMA systems are interference limited, assumed that enough codes are available to prevent users from being blocked due to code shortage.

The picture on the next page shows the uplink noise as a function of the total uplink data throughput in a cell. The total received wideband power at the Node B is measured for different loads in the system. This figure represents the interference experienced by the users in the cell controlled by the Node B. The situation for load equal to 207kbps and interference level of \(-106.8\)dBm at the Node B, is taken as reference point. The results are taken from simulation of CASE1.

\(^{21}\) Wireless LANs for example are able to offer higher data rates than UMTS but are designed to offer coverage in limited area. The UMTS specification effort aims at setting a global standard for a high bit rate mobile network as the UMTS abbreviation suggests.
5.3.1 Soft Capacity

The phenomenon where the capacity is limited by the amount of interference in the air interface, it is called soft capacity. This is due to the fact that the capacity can no longer be easily predicted using the Erlang B formula. This formula gives too pessimistic results on the blocking probabilities because the capacity is not hard blocked, i.e. limited by the number of channels in a cell [2]. Because the interference in a cell is shared with the adjacent cells, it is possible to share capacity between cells. If a central cell is highly loaded it is possible to borrow capacity from one of the lightly loaded adjacent cells.

Figure 68: uplink noise rise for increased uplink data throughput

Figure 69: soft capacity between WCDMA cells (picture based on [2])
Some sources refer to soft capacity as the interference-limited nature of the capacity in the network itself, whereas in this report soft capacity is defined as the measurable additional amount of capacity available on top of the capacity given by the Erlang B formula used to calculate the hard-blocked capacity.

As OPNET® does not enable load calculations using Erlangs unless a specialised extra module is used, the above-defined soft capacity is calculated by comparing the additional capacity that becomes available in a system using soft handovers when compared to a hard handover system. Indeed, when soft handovers are enabled a user will be able to establish an additional connection in a neighbouring cell while still having a connection with the cell he was originally connected to. This makes it possible to use a connection with lower quality in the first cell, hence the interference present will drop and the capacity will increase.

The example below illustrates the borrowing of capacity from neighbouring cells. The model used in CASE3 represents a population of users moving towards a loaded cell.

![CASE3 - users moving into a loaded cell](image.png)

**Figure 70:** CASE3 – users moving into a loaded cell

The users moving into the central cell area will increase the demanded capacity. As the number of users is calculated to maximise the transported load in the central cell for a given application, some of the users at the cell edge area are expected to be handed over into a neighbouring cell.

On the graph on the next page; the active set size, the uplink transmission power and the total transmitted load of one user terminal in the central cell are shown. The last data series represents the total uplink throughput of the Node B in the central cell.
Some events can be watched on the picture:

- The user having a 12.2kbps voice connection establishes an additional connection in a neighbouring cell during the period that the load in the central cell is the highest.
- In the second graph – showing the uplink transmitted power – it can be seen that the power level of the mobile terminal increases as the load in the central cell increases. The link to the central Node B is the connection with the lowest power levels as the mobile terminal is located in the central cell. This confirms the fact that the interference increases as the total cell load becomes higher.

The same simulation has been run for users having connections supporting video conferencing in a network with and without soft handovers enabled.
Table 11: simulation parameters used for CASE3

<table>
<thead>
<tr>
<th></th>
<th>Voice Communication</th>
<th>Video Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>1500m</td>
<td>1500m</td>
</tr>
<tr>
<td># of moving users</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Speed of moving users</td>
<td>20km/h</td>
<td>20km/h</td>
</tr>
<tr>
<td># of fixed users</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Application traffic profile</td>
<td>Voice over IP (GSM quality): 12.2 kbps</td>
<td>Low resolution video: 64kbps</td>
</tr>
<tr>
<td>Handover type</td>
<td>- Run1: soft handover enabled: soft handover threshold = 7dB - Run2: only hard handovers</td>
<td>- Run1: soft handover enabled: soft handover threshold = 7dB - Run2: only hard handovers</td>
</tr>
</tbody>
</table>

Voice and video communication have been simulated in two separate simulation runs. For each model the soft and the hard handover case is examined. The following results are obtained:

Table 12: soft capacity in uplink

<table>
<thead>
<tr>
<th></th>
<th>Hard handover System load (kbps)</th>
<th>Soft handover system load (kbps)</th>
<th>Extra capacity due to soft handover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice 12.2kbps</td>
<td>205</td>
<td>256</td>
<td>25%</td>
</tr>
<tr>
<td>Video 60kbps</td>
<td>143</td>
<td>227</td>
<td>59%</td>
</tr>
</tbody>
</table>

Several remarks can be made about these results:

- When comparing a system with only hard handovers and a system with soft handovers enabled, the latter system allows higher loads in a loaded cell surrounded by lightly loaded cells as modelled in CASE3.
- A system with one traffic type is more efficiently loaded when low bit rates are used. The higher the granularity of the traffic the lower the maximum load in the network is.
- The relative increase in capacity when soft handovers are enabled is higher for high data rates.

The first remark has been intuitively explained above. A user having an additional connection with another cell makes it possible to reduce the quality of the link used in
the central cell and hence the overall cell capacity will increase. The two other phenomena can be explained as follows. In capacity analysis studies the trunking efficiency is defined to express the percentage of utilisation of the existing capacity. This figure can be calculated by dividing the hard blocked capacity with the total number of channels in the system. The hard blocked capacity can be calculated using the Erlang traffic model for a given number of channels.

The Erlang model above shows that for a low number of channels in the system the blocking probability is higher for the same relative load. Otherwise stated the available capacity will be used less efficient and the trunking efficiency will be lower. When high data rate traffic is present in the network, the number of available channels in the system with a given maximum capacity, is smaller and hence the efficiency lower. This explains the lower load values for the 60kbps video connections in the table above.

When soft handovers with other cells are permitted the capacity increases in the central cell. This corresponds to a higher number of available channels in the system. As the efficiency for the voice signals is already high in the system using only hard handovers, the increase in capacity is not as substantial as for the video connections that experienced low trunking efficiency.

The values in table 12 for the extra capacity due to soft handover are high. A soft capacity study presented in [2] gives 5% soft capacity for a 12.2kbps bit rate and 17%
additional capacity at a bit rate of 64kbps. The reason that the values obtained during the study of CASE3 are significantly higher is that the network is evaluated for a loaded central cell surrounded by six neighbouring cells without users in the coverage area. In these six adjacent cells there is only capacity consumed by the users that are handed over from the central cell and hence the extra capacity that becomes available in the central cell is substantially higher than in real systems.

Although soft handovers improve the soft capacity significantly due to the soft capacity principle, other soft handover-related factors influence the overall system capacity as is discussed in the following two sections.

5.3.2 Soft Handover Overhead

An increasing number of soft handovers results in more connections established in the system, more system resources are consumed and hence a part of the capacity will be occupied by the overhead of extra connections caused by soft handovers. As shown on figure 56; towards high handover thresholds or high handover probabilities especially the number of users having three simultaneous connections in the UTRAN part of the network increases significantly. Therefore it is recommended to set the soft handover threshold value at around 5dB. This will result in a soft handover probability of around 30% and will control the number of users having active set size higher than three.

To illustrate the effect of the overhead on the used capacity in the network caused by soft handovers, the results of CASE2 are presented in the table below. The soft handover overhead is calculated by comparing the load in the network with only hard handovers enabled and in the same system supporting soft handovers.
The simulation sequences have been run for the model CASE2, shown in figure 64, with the parameters from in table 10.

From the values in table 13 it can be remarked that the soft handover overhead shows similar results as the soft handover probabilities obtained in chapter 4. The fact that the overhead value for soft handover threshold equal to 9dB is slightly higher than would be expected can be caused by the higher number of users having three simultaneous connections with Node B’s, consuming excessive network resources.

![Figure 73: comparison between soft handover overhead and soft handover probability for different thresholds](image)

5.3.3 Average interference per cell

It has been shown at the end of chapter 2 that the average power needed per link decreases when soft handovers are enabled. The picture below compares the total wideband received power at the central Node B in CASE1 for a network with only

| Only hard HO | 773kbps | Soft HO: SHO_TH = 3dB | 879kbps | 13.7% |
| Soft HO: SHO_TH = 6dB | 956kbps | 23.7% |
| Soft HO: SHO_TH = 9dB | 1080kbps | 39.7% |

Table 13: Soft handover overhead values for different handover threshold values
hard handovers and three network situations with soft handovers and threshold value varying from 3 to 9 with step3.

Figure 74: total received wideband power at Node B for hard and soft handover situations

The total received wideband power is a good measure for the total interference experienced by the users in a cell. As can be seen on the picture the situation with soft handover threshold equal to 3 shows the lowest interference values and hence the highest capacity. The situation with only hard handovers enabled is less favourable. For high threshold values the macro diversity gain no longer compensates for the increased interference caused by multiple connections in the system and the overall interference is higher. The amount of interference present in the cell reaches even higher values than in a system with only hard handovers enabled.
5.3.1 Uplink-Downlink

Different research results show that the downlink air interface capacity in WCDMA systems is less than the uplink capacity. According to [2] the main reason is “the use of better receiver techniques in the base station than in the mobile station”. Additionally, a user’s traffic profile showing asymmetric download behaviour with high loads towards the user, turns the downlink capacity – more than the uplink capacity – into one of the key constraints to offer a high performance broadband network. During the numerous case studies and models simulated for this chapter it was observed that in loaded cells where capacity constraints become apparent, the total downlink load was always lower than the uplink load.
5.4 Summary

This chapter consists of three main parts. First the relation between the capacity and the coverage in a system has been analysed. In the following two sections those two system parameters have been examined separately and the effect of soft handovers on the coverage and the capacity has been further discussed.

To study the relation between capacity and coverage CASE1 was built. The model of a user moving out of the coverage area of one Node B allows determining the maximum allowable path loss before communications become no longer possible. This maximum allowable path loss is a good measure for the coverage in a cellular system. The results of this simulation series show that the coverage decreases as the load present in the system increases. A shrinking coverage area for increasing load can be experienced by a user at the cell edge transmitting at maximum power levels. When the load in the cell and hence the interference increases, the mobile station will lose connection as it cannot execute further power-up commands received from the Node B. The load-controlled nature of the coverage area results in breathing or pulsing cells as the coverage dynamically varies.

Besides the amount of load in the system the coverage depends on other factors. The characteristics of the antennas and receivers used in the system, the mobile transmission power and the multi-path diversity gain directly influence the maximum allowable path loss in the system and hence the system coverage. Two other factors affecting coverage have been analysed and illustrated with simulation results: the macro diversity gain provided by soft handovers and the bit rate of a given connection.

The macro diversity gain provided by soft handovers reduces the average power transmitted per link with some dB. This affects the coverage in a positive way. This effect shows in the result of CASE8. For networks using high handover values on the other hand the coverage can worsen slightly when soft handovers are enabled. This is due to the increased interference level present in the system caused by the extra links established in the system.
Two mechanisms influence the maximum allowable path loss for different bit rate connections in an opposite way. Firstly high bit rate connections require lower powers. On the other hand low bit rate connections benefit from a higher processing gain provided by the coding. In real systems the effect of the second factor will largely outweigh the first one and hence the average transmitted power is higher for high bit rate connections and the coverage will be worse. Given the cumulative distribution function for the power transmitted per link for a certain traffic type connection, the coverage probability determines the maximum transmitted power per radio link and vice-versa. In real systems the maximum power per radio link is higher and the coverage area is smaller for high bit rate connections.

When the coverage is compared between uplink and downlink, the coverage will be better in the downlink direction. This is due to the higher transmission powers used in the Node B compared to the mobile terminal.

The capacity supported in the UMTS network is of prime importance as improved capacity provision has been one of the main driving factors behind the development of the UMTS system. The results gathered from the simulation of CASE1 show that as the network load increases the noise present in the system rises proportionally. If it can be assumed that sufficient codes are available in the system, the capacity is limited by the noise in the system. The higher the load of the network the more interference the users cause each other. This phenomenon is called graceful degradation of the capacity and eventually results in blocked calls.

As interference in CDMA systems is shared between cells it is possible to borrow capacity from neighbouring cells. The additional capacity that hence becomes available on top of the capacity calculated with the Erlang B formula is called the soft capacity.

To study the effect of soft capacity combined with soft handovers CASE2 has been studies. This model simulates users moving from the adjacent cells into the coverage area of a Node B supporting high traffic loads. It can be observed that users in the central cell establish an additional connection in one of the surrounding lightly loaded cells at moments when the peak capacity is reached in the central cell. From the results obtained during this case study the following conclusions have been drawn:

- In a loaded cell surrounded by lightly loaded cells, soft handovers allow a higher overall data throughput because users in the central cell can be given an
additional connection in a neighbouring cell. This results in connections with lower powers, which decreases the interference and increases the load in the central cell.

- The higher the granularity of the traffic, the lower is the maximum load in the network. This is due to the Erlang traffic model that suggests that if fewer channels are available for a given relative load, the blocking probabilities will be higher. As this is the case for high bit rate connections, the network efficiency will be lower.

- The soft capacity is higher for high data rates. The additional capacity that becomes available when capacity can be borrowed from other cells betters the low efficiency of systems with high data rate connections more significantly than the efficiency of systems with low data rate connections. The latter enjoy a fairly high efficiency without soft capacity.

On the further influence of soft handovers on the system capacity several remarks have been made. The results of CASE1 show a proportionally increasing soft handover overhead for an increasing number of soft handovers. Especially for high handover thresholds the overhead increases rapidly due to the high number of users having triple link connections. When the soft handover overhead is compared with the soft handover probabilities very similar results are obtained.

The results of CASE1 also show that the total amount of interference present in the system is minimal for networks with soft handovers enabled when considerably low threshold values are used.

Due to better receiver techniques in the Node B and an asymmetric traffic profile with higher bandwidth towards the user; the main constraint for the capacity lies in the downlink direction.
References

[1] www.umtsworld.com

Chapter 6

Conclusions

This research presents beside a thorough dissertation of the UMTS technology, issues around network modelling and the main findings of the simulations carried out. The probability a user is in soft handover has been analysed using six different simulation series. To study capacity and coverage in a system and the correlation between those two network parameters, three cases have been carried out.

6.1 UMTS

The first part of this report describes the UMTS technology as specified in the 3GPP specifications. WCDMA has been implemented as the multiple access scheme, resulting in a more efficient use of the available bandwidth and enabling multiple users with different data rates to coexist in the same air interface. Sophisticated power control algorithms and soft and softer handover algorithms are consequences of implementing CDMA.

The network architecture consists of the User Equipment, the UTRAN part and the Core Network part. The RNC and the Node B are part of the UTRAN network and are responsible for network control and establishing the radio communication
respectively. Early releases of the 3GPP specifications suggest few modifications on the UMTS core network. Following the later standards, the ultimate goal is to create a universal core for various technologies.

As in every cellular system, in UMTS handovers have been implemented to allow roaming between cells. The UMTS system supports basically three types of handovers. Hard handovers are the type of handover where the connection is broken before a new connection is set up. Inter-system handovers are necessary for enabling compatibility between UMTS and other system architectures, e.g. GSM. The CDMA-specific handover types – soft and softer handover – occur when the user is in the overlapping cell coverage area of two sectors belonging to two or one Node B’s respectively. The WCDMA soft handover algorithm is described in 3GPP TR 25.922 and specifies three actions that can be performed on cells in the system. They can be added to, removed from or replaced in the active set of a mobile user. The macro diversity gain provided by combining multiple signals enhances the system performance significantly.

6.2 Network Modelling

For the simulations done during this research OPNET® Modeler has been used. OPNET® enables network modelling in hierarchical layers. Each layer is built up in the specific editor offering the desired level of detail. The network layer consists of interconnected nodes placed on a logical or geographical map. These nodes are built up of modules in the node layer. Specific behaviour of the modules can be modelled in the process editor using Proto-C programming language. OPNET® offers a specialised UMTS model that contains libraries of models and processes based on the 3GPP specifications.

To obtain the results presented in this chapter six simulation series and three case studies have been carried out. To study the soft handover probability six different
simulation series have been created. The first four simulation series model mobile users in three-cell systems and have been conceived to study the mechanisms determining the soft handover probability. SIM5 and SIM6 model static users in a loaded cell. These models are built to study the value of the soft handover probability for users in a real system and get insight in the influence of the distance between the mobile and the Node B on the soft handover probability. The models created to study coverage and capacity related issues are more complicated. To study the relation between capacity and coverage the model of a user moving out of the coverage area of one Node B has been created, named CASE1. CASE2 and CASE3 represent real networks and have been used to illustrate different aspects about capacity and coverage individually.

In this research project the iterative process of setting goals, building models, simulating and analysing results has been used. The focus has been mainly on parameters in the UTRAN part of the network while the Core Network has been abstracted in an effort to simplify the models as much as possible.

6.3 Soft handover Probabilities

The overhead caused by soft handovers on both radio resources occupied, signalling performed and the number of codes used should not exceed the gain in system performance achieved by soft handovers. In this research two methods are used to define this soft handover probability. The first one makes use of ratios of user populations; the second method calculates the probabilities by dividing the time spent in handover to the total time the user is connected to the network.

SIM1 – the situation where the mobile user moves along the cell edge between two adjacent cells for a considerable time – shows the importance of the handoff window in a system. The handoff window is the area over which the received strengths of the pilot signal differ less than the handover threshold. The simulations carried out show that for higher threshold values the handoff window becomes wider.
The results of SIM2, SIM3 and SIM4 show the linear relation there exists between the soft handover threshold and the total amount of soft handovers in the system. Starting from the one-dimensional situation of a user being located between two Node B’s as present in SIM3 and SIM4 an expression for the soft handover probability was derived. It can be shown that this relation holds:

\[ SHO\_PROB = \frac{1}{\sqrt{3A}} \cdot SHO\_TH \]

where A is a constant parameter. This relation expresses the linearity between the soft handover algorithm parameter SHO_TH and the overall soft handover probability in the system. As A is a constant value, the soft handover probability is also proven to be independent of the cell size used in the system as can be seen in the simulation results.

SIM5 analyses the soft handover probability distribution inside one cell. It shows that near the cell centre very few users are in soft handover. In the cell edge area a soft handover probability of 100% is achieved. Concerning the effect of the handover threshold it is shown that the lower the value of this parameter, the slower the transition from 0% to 100% is made.

SIM6 is carried out in order to obtain reliable handover probabilities for a real system. The acquired values range from probabilities of 5% for a soft handover threshold of 1dB to 35% for 6dB and reaching probabilities of 60% in systems where the threshold value is set to 12dB. Concerning the double and triple link connections in a system it has been found that the users with active set size equal to 2 make out 10-20% of the total user population for different threshold values. Users having three connections to different Node B’s are rare for low threshold values but their number rapidly increases towards higher threshold values.

Chapter 4 concludes with introducing a mathematical model that makes it possible to calculate the soft handover probability. By taking the ratio between the cell area where soft handovers are enabled and the total cell area this relation has been derived:

\[ SHO\_PROB = 1 - \frac{4}{\left( \frac{TH}{10^{33.6}} + 1 \right)^2} \]
This relation shows that the soft handover probability is independent of the cell size used in the system and is only determined by the soft handover threshold. Plotting the formula for different threshold values gives a curve that can be easily linearly approximated.

6.4 Capacity & Coverage

To study the relation between capacity and coverage CASE1 was studied. The maximum allowable path loss for a user moving out of the coverage area of one Node B is a good measure for the coverage in a cellular system. The results of this case study show that the coverage decreases as the load present in the system increases. The load-controlled nature of the coverage area results in breathing or pulsing cells as the coverage dynamically varies.

Besides the amount of traffic in the system, the maximum allowable path loss and hence the coverage are controlled by other factors. The characteristics of the antennas and receivers used in the system, the mobile transmission power and the multi-path diversity gain directly influence the system coverage. The macro diversity gain provided by soft handovers reduces the average power transmitted per link with some dB. This affects the coverage in a positive way.

The effect on the coverage of connections supporting different data rates is mainly determined by the larger processing gain for low bit rate connections. Hence, low data connections have a better coverage. Due to the higher transmission powers used in the Node B compared to the mobile terminal, the coverage will be better in the downlink direction.

The capacity in the UMTS networks is limited by the interference as the noise rises proportionally with increasing loads. The higher the load of the network the more interference the users cause each other. This phenomenon is called graceful degradation and eventually results in blocked calls. As interference in CDMA systems is shared between cells it is possible to borrow capacity from neighbouring cells. The
additional capacity that hence becomes available on top of the capacity calculated with the Erlang B formula is called the soft capacity.

To study the effect of soft capacity CASE3 has been studied. This model simulates users moving from the adjacent cells into the coverage area of a Node B supporting high traffic loads. It can be observed that users are handed over to the surrounding lightly loaded cells at moments when the peak capacity is reached in the central cell. When the capacity supported in the central cell is compared for the same network having voice and video connections, it shows that the loading is lower for high data rates and systems with only hard handovers enabled. When soft handovers are enabled, the additional capacity that becomes available – the soft capacity – is relatively higher for high data rate connections.

Soft handovers in the system also influence the capacity by increasing the traffic load due to the overhead in connections made during soft handovers. The results of CASE1 show a proportionally increasing soft handover overhead for an increasing number of soft handovers.

Also the total amount of interference present in the system is minimal for networks with soft handovers enabled when considerably low threshold values are used. Due to better receiver techniques in the Node B and an asymmetric traffic profile with higher bandwidth towards the user the main capacity constraint lies in the downlink direction.

### 6.5 Future work

Although this research tried to give an impression of the main factors affecting the impact of soft handovers on the overall network capacity, many aspects have not been covered in this report. For future research more attention has to be drawn to quality of service requirements in the system. As the implementation of QoS is essential for offering for example real time services, this is a vital aspect of the UMTS system. Studying the effect of soft handovers on parameters as the end-to-end delay for a
given connection or the block error rate could provide interesting results on the
system performance for each of the four UMTS QoS classes.

Although most of the results obtained from the simulations and case studies carried
out have been very useful to illustrate mechanisms influencing the network
performance parameters, it has not always been possible to generate figures and
values generally applicable for real systems. This has various reasons. Some
uncertainties and inaccuracies have been introduced during the modelling step.
Limitations of the OPNET® tool and assumptions and approximations made when
building the models affect the degree to which the reality is reflected.
In order to obtain results applicable to real networks more simulations with more
variable parameters have to be carried out. Also testing on the emerging commercial
UMTS networks and knowledge gathered from operation and management of these
real networks could provide a rich source of information for future research.
In future research also more attention could be drawn to the aspects of different
channels in the system and the way in which their characteristics affect the capacity of
the system.

Finally it should be studied in which way the different handover and power control
algorithms present in the system can be further optimised.
Appendix A

Coding

When coding a string of data bits, every bit is represented by a number of chips. The number of chips used per bit is called the spreading factor. The data bits are multiplied with the spreading code – every bit with the same chip sequence. After modulation, this spread signal is sent out. At the receiver side, all the received signals are demodulated and again multiplied with the used code. The decision which of the received signals to choose is made by integrating the different de-spread signals. As can be seen in the picture below, multiplying the received signal with the own code followed by integration increases the amplitude of the data signal. The result of multiplying an interfering signal with the code of the desired signal followed by integration, results in a signal with low power levels, close to zero. This effect is called ‘processing gain’ and is responsible for the high robustness of CDMA systems against interference and noise. The processing gain can be defined as follows:

\[ 10 \log_{10} \left( \frac{\text{chiprate}}{\text{datarate}} \right) = 10 \log_{10} (SF), \tag{A.1} \]

where SF represents the spreading factor. Due to the processing gain it is also possible to identify separate users and treat them equally by assigning them different codes instead of different slices of spectrum or timeslots in FDMA/TDMA systems.
In UMTS systems Orthogonal Variable Spreading Factor (OVSF) codes are used for the channelization coding process. The codes are derived from a hierarchical code tree. OVSF coding allows combination of different spreading factors while maintaining orthogonality. The only requirement is that codes from different branches are used.

![Channelization Code Tree]

**Figure 75:** spreading and detection

**Figure 76:** channelization code tree
Appendix B

UTRA Channels

The UTRA layer has three types of channels, which are mapped into each other: logical into transport channels, the transport channels are in turn mapped into the physical channels.

- **Logical Channels:**
  - BCCH: Broadcast Control Channel
  - PCCH: Paging Control Channel
  - DCCH: Dedicated Control Channel
  - CCCH: Common Control Channel
  - DTCH: Dedicated Traffic Channel
  - CTCH: Common Traffic Channel

- **Transport Channels:**
  There are two types of transport channels – the common channels and the dedicated channels.

  DCH: Dedicated Transport Channel
  The DCH carries user specific information; user data as well as control information for layers above the physical layer. This channel supports features as fast power control and soft handover.

  The six other transport channels are common channels; they do not support soft handover, some have fast power control.
BCH: Broadcast Channel
This channel, broadcasted from the node B, carries information intended for the whole cell and is hence sent out at fairly high power levels.

FACH: Forward Access Channel
The FACH channel carries control data in the downlink direction, but it is also suited for sending packet data. A system can have multiple FACH channels.

PCH: Paging Channel
This downlink channel contains paging information. Paging is the procedure in which the network notifies a terminal it wants to initiate communication [Ref 3-Chapter2].

RACH: Random Access Channel
The RACH channel is designed to carry control information but it is also possible to send small data amounts on it.

CPCH: Uplink Common Packet Channel
This channel is similar to the RACH channel. It is used to send data in the uplink direction but transmission can last longer than in the RACH structure. Together with the RACH channel it forms the uplink opponent of the FACH channel.

DSCH: Downlink Shared Channel
The DSCH carries user data and/or control information. The main feature is a variable bit rate on a frame-by-frame basis. The DSCH is associated with one or more DL dedicated channels.

- Physical Channels:
  - PCCPCH: Primary Common Control Physical Channel
  - SCCPCH: Secondary Common Control Physical Channel
  - PRACH: Physical Random Access Channel
  - DPDCH: Dedicated Physical Data Channel
  - DPCCH: Dedicated Physical Control Channel
  - PDSCH: Physical Downlink Shared Channel
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCPCH</td>
<td>Physical Common Packet Channel</td>
</tr>
<tr>
<td>SCH</td>
<td>Synchronisation Channel</td>
</tr>
<tr>
<td>CPICH</td>
<td>Common Pilot Channel</td>
</tr>
<tr>
<td>AICH</td>
<td>Acquisition Indication Channel</td>
</tr>
<tr>
<td>PICH</td>
<td>Paging Indication Channel</td>
</tr>
<tr>
<td>CSICH</td>
<td>CPCH Status Indication Channel</td>
</tr>
<tr>
<td>CD/CAICH</td>
<td>Collision Detection/Channel Assignment Indicator Channel</td>
</tr>
</tbody>
</table>
Appendix C

Flowchart of WCDMA soft handover algorithm

This flowchart is taken from the 3GPP TR 25.922 specifications:

![Flowchart of WCDMA soft handover algorithm](image)

Figure 77: flowchart of the soft handover algorithm