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Performance Management of 3rd Generation Partnership Project Long Term Evolution

Master's Thesis submitted in partial fulfillment of the degree of Master of Science in Technology

Espoo, 27th September 2011

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Abstract

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Name off the Thesis:	Performance Management of 3rd Partnership Project Long Term Evolution
Date: 27 September 2011	**Number of pages:** 11 + 96 = 107
Department:	Department of Communications and Networking
Degree Programme:	Degree Programme in Communications Engineering
Supervisor:	Prof. Jyri Hämäläinen
Instructor:	M.Sc. Osman Yilmaz

Long Term Evolution (LTE) is the newest mobile network standard in the 3rd Generation Partnership Project (3GPP) evolution path, promising to considerably increase the performance of mobile networks. Building a mobile network is a huge investment for a network operator, and naturally operators try to maximize the revenue and minimize the operational expenditure created by their investment. This goal can be achieved by optimizing network performance and by minimizing the manual effort of network management.

This thesis introduces the most important key performance indicators (KPI) of LTE, which can be utilized to evaluate network performance. Self-Organizing-Networks (SON) concept designed to automate many of the network management tasks is also described. Furthermore, the feasibility, advantages and disadvantages of SON use cases are evaluated.

The final part of the thesis reports research carried out on the Cell Outage Compensation (COC), a SON use case designed to alleviate the effect of a network outage. The research, which was carried out using system level simulations, consisted of investigating the effects of a typical outage, selecting the most potential control parameters and developing a COC function. As a result, the developed COC function considerably alleviated the effects of the outage in the utilized simulation environment.

Key words: LTE, Optimization, Performance Management, SON, COC

AALTO-YLIOPISTO

Tiivistelmä

Tekijä:	Lasse Laine
Työn nimi:	3rd Generation Partnership Project Long Term Evolution -mobiiliverkon suorituskyvyn hallinta
Date: 27.09.2011	**Number of pages:** 11 + 96 = 107
Laitos:	Tietoliikenne ja tietoverkkotekniikan laitos
Tutkinto-ohjelma:	Tietoliikennetekniikan tutkinto-ohjelma
Työn valvoja:	Prof. Jyri Hämäläinen
Työn ohjaaja:	DI Osman Yilmaz

Long Term Evolution (LTE) on 3rd Generation Partnership Project:in (3GPP) uusin, suorituskyvyltään edeltäjiään huomattavasti kehittyneempi mobiiliverkkostandardi. Verkon rakentaminen on operaattorille aina valtava investointi, jonka vuoksi operaattorit luonnollisesti haluavat maksimoida verkon tuoton samalla minimoiden sen ylläpitämisen aiheuttamat kustannukset. Verkon tuottoa voidaan parantaa optimoimalla sen suorituskykyä ja verkon ylläpitokustannuksia pienentää automatisoimalla verkonhallinnan toimintoja.

Ratkaiseva vaihe verkon suorituskyvyn optimointiprosessissa on verkon suorituskyvyn arviointi. Tässä diplomityössä kuvataan LTE:n tärkeimmät verkon suorituskyvyn tunnusluvut, joiden avulla verkon toimintaa voidaan arvioida kokonaisvaltaisesti. Lisäksi diplomityössä esitellään verkonhallinnan toimintoja automatisoiva Self-Organizing-Networks (SON) -konsepti ja sen tyypilliset käyttösovellukset. Työssä arvioidaan myös näiden käyttösovellusten toteuttamiskelpoisuutta, vahvuuksia sekä heikkouksia.

Diplomityön viimeisessä osassa tutkitaan järjestelmätason simulaatioiden avulla SON -konseptin Cell Outage Compensation (COC) -käyttösovellusta, jonka tavoitteena on vähentää tukiasemien vikaantumisista verkon käyttäjille aiheutuvaa haittaa. Osiossa tutkitaan tyypillisen vikaantumisen vaikutuksia, valitaan kontrolliparametrit COC -algoritmille sekä kehitetään COC -funktio. Tehdyissä simulaatioissa kehitetty COC -funktio onnistui vähentämään vikaantumisen vaikutuksia merkittävästi.

Avainsanat: LTE, Optimointi, Suorituskyvyn hallinta, SON, COC

Preface

I would like to thank Professor Jyri Hämäläinen for the supervision of this thesis and for the thorough answers to my questions. Also my instructor, M.Sc. Osman Yilmaz, has my gratitude for his supporting comments and his enthusiasm towards the subject.

As this thesis was funded by Omnitele Ltd., I am grateful for both the opportunity and the resources provided for the thesis. It has been extremely educating and rewarding to work among the highly competent personnel of Omnitele and to investigate an extremely interesting subject. Especially, I would like to thank B.Sc. Jarkko Heikkinen for the time and effort he has used for aiding me during the thesis writing process.

I also would like to express my gratitude to all of my friends for helping me out during the writing process. Finally, I want to thank Ms. Heini Hyttinen for her unselfish aid during the thesis writing process. Her help has been invaluable for the success of the project and for the wellbeing of the writer.

Helsinki, 27 September 2011

Lasse Laine

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List of Abbreviations

3GPP	3rd Generation Partnership Project
ANR	Automated Neighbor Relations
APN	Access Point Name
ARP	Allocation and Retention Priority
CCO	Capacity and Coverage Optimization
CCU	Cell Center Users
CEU	Cell Edge Users
COC	Cell Outage Compensation
COD	Cell Outage Detection
COM	Cell Outage Management
CPICH	Common Pilot Channel
C-RNTI	Cell Radio Network Temporary Identifier
CSG	Closed Subscriber Group
DHCP	Dynamic Host Configuration Protocol
DL	Downlink
DM-RS	Demodulation Reference Symbol
EDGE	Enhance Data rates for Global Evolution
eNodeB	Evolved NodeB
EPC	Evolved Packet Core
E-RAB	E-UTRAN Radio Access Bearer
ESM	EPS Session Management
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access

GBR	Guaranteed Bit Rate
GERAN	GSM/EDGE Radio Access Network
GSM	Global System for Mobile Communications
HSDPA	High-Speed Downlink Packet Access
HSS	Home Subscriber Server
ICI	Inter-Carrier Interference
ICIC	Inter-Cell Interference Coordination
IP	Internet Protocol
ISI	Inter-Symbol Interference
KPI	Key Performance Indicator
LTE	Long Term Evolution
MBR	Maximum Bit Rate
MCS	Modulation and Coding Scheme
ME	Mobile Equipment
MHA	Mast Head Amplifier
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
NR	Neighbor Relation
NRT	Neighbor Relation Table
OFDMA	Orthogonal Frequency Division Multiple Access
O&M	Operation and Maintenance
PCI	Physical Cell Identity
PDN	Packet Data Network
P-GW	PDN Gateway
PLMN	Public Land Mobile Network
PTI	Procedure Transaction Identity

QAM	Quadrature Amplitude Modulation
QCI	QoS Class Identifier
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RLC	Radio Link Control
RLF	Radio Link Failure
RNC	Radio Network Controller
RRC	Radio Resource Control
RSCP	Received Signal Code Power
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SDF	Service Data Flow
S-GW	Serving Gateway
SINR	Signal-to-Interference-plus-Noise Ratio
SON	Self-Organizing-Networks
SRS	Sounding Reference Symbol
TCP	Transmission Control Protocol
TFT	Traffic Flow Template
TIBC	Time-In-Best-Cell
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink

UMTS	Universal Mobile Telecommunications System
USIM	Universal Subscriber Identity Module
UTRAN	Universal Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access

List of Symbols

$Thresh_{high}$	A threshold utilized in absolute priority based reselections when UE is moving into a higher priority layer
$T_{reselection}$	Cell reselection timer utilized in absolute priority based reselections
$Thresh_{low}$	A threshold utilized in absolute priority based reselections when UE is moving into a lower priority layer
Q_{target}	RSRP value the target cell
Q_{offset}	RSRP offset
$Q_{serving}$	RSRP value of the serving cell
Q_{hys}	RSRP hysteresis
$T_{trigger}$	Cell reselection timer utilized in equal priority reselections
E_c/N_0	Pilot signal energy of the CPICH within one chip duration divided with RSSI
Q_{in}	RSRQ threshold utilized in RLF detection when timer T300 is running
Q_{out}	RSRQ threshold utilized in RLF detection when timer T300 is not running
$Path\ loss$	Path loss
$k1$	Intercept parameter of the path loss
$k2$	Slope parameter of the path loss
d	Distance between two nodes
$k3$	UE antenna height correction factor
H_{ms}	UE antenna height above ground level
$k4$	UE antenna height correction factor
$k5$	Effective eNodeB height correction factor
H_{eff}	Effective eNodeB height

$k6$	Correction factor of effective eNodeB height and distance between UE and eNodeB
$k7$	Diffraction loss correction factor
L_{diff}	Diffraction loss
$L_{clutter}$	Clutter loss
S	UL MBR reduction step size
T decision	Amount of time the data is gathered for an optimization
D	Minimum acceptable average UL throughput
$\propto$	Intercept parameter of the UL SINR failure probability
β	UL interference correction factor
$Interference_{UL}$	UL interference
$Failures_{UL\ SINR}$	UL SINR failure probability
R^2	R-Squared
s	Simulated failure probability
e	Estimated failure probability
$\bar{s}$	Average of the simulated failure probabilities
F	F value
P	The number RSRP level changes per optimized cell
L	RSRP level reduction step size
x	Minimum improvement in the total failure rate to declare an optimization step successful

1 Introduction

Mobile networks are nowadays a significant part of our everyday life. Although the mobile networks have existed for a long time, the user requirements have changed radically in recent years. An increased number of users, new service types, smartphones and integrated laptop modem chips have introduced high capacity and service quality requirements for the mobile networks, forcing the operators to either constantly update their existing networks or to invest into new network technologies. The most widely utilized mobile network evolution path is based on the standards created by 3rd Generation Partnership Project (3GPP), which is a collaboration of multiple significant telecommunication associations. The newest mobile network standard in the 3GPP evolution path, promising to raise the performance of the mobile networks into a new level, is called the Long Term Evolution (LTE). Compared to previous 3GPP mobile network technologies, LTE offers multiple improvements, such as higher spectral efficiency, simpler network architecture and lower operational expenditure. The details of LTE are defined in 3GPP technical specification releases eight and nine, which can be freely downloaded from the 3GPP Internet site.

A mobile network is an enormous investment for a network operator. Similarly to any other company, operators try to maximize the revenue and minimize the operational expenditure created by their investment. Parameterization changes, software updates and hardware improvements are executed constantly to optimize the network performance, resulting in higher revenues. Naturally, the optimization of the network increases also the operational expenditure, and therefore operators must constantly estimate which optimization decisions are actually profitable and which are not. A concept of Self-Organizing-Networks (SON), which is seamlessly attached as a part of LTE, attempts to decrease the mobile network operational expenditure, by automating the network management tasks. A network which configures itself, optimizes itself and recovers automatically from failure situations is the ultimate goal of the SON.

The main goal of the thesis is to study: *How to improve the performance and the user experienced quality of service of an LTE network?* The thesis consists of six chapters, each having separate goals and significance in the overall structure. The first chapter describes the background, the basic concepts, the motivation and the structure of the thesis, giving a solid insight to the reader about the scope of the thesis. In the second chapter, LTE is investigated from a technical perspective. The network architecture and the radio access schemes, both in Uplink (UL) and Downlink (DL), are described and their advantages and disadvantages are evaluated. In addition, the basis of LTE Multiple-Input Multiple-Output (MIMO) and Inter-Cell Interference Coordination (ICIC) schemes are introduced. Furthermore, overviews concerning LTE bearer structures and the most significant processes are given. The goal of the second chapter is to familiarize the reader with LTE characteristics, advantages, disadvantages and differences compared to previous 3GPP mobile network technologies. Understanding the contents of the chapter two is crucial for the understanding of the subsequent chapters.

In the chapter three, basic optimization guidelines for LTE networks are described. The chapter introduces main LTE key performance indicators (KPI) and describes how network performance and user experienced quality of service can be evaluated based on the selected KPIs. In addition, for each KPI a comparison to UMTS (Universal Mobile Telecommunications System), a legacy 3GPP system, is executed to highlight the differences and the similarities between UMTS and LTE. The goal of the chapter three is to introduce the basics of LTE network performance evaluation/optimization and to familiarize the reader with the main KPIs of LTE.

In the chapter four, the SON concept is presented. Different architectural approaches are introduced and their advantages and disadvantages are evaluated. In addition, the most typical SON use cases are described and their usefulness and feasibility are investigated. Furthermore, an insight about the commonness of the SON features in real networks is given. The goal of the chapter four is to familiarize the reader with the SON concept and its typical use cases and to give an understanding about the possibilities and challenges related to SON.

In the chapter five, the feasibility and the potential of one of the SON use cases, the Cell Outage Compensation (COC), are investigated with network level simulations. The beginning of the chapter describes the goals of the COC, the simulation process and the simulation environment. In addition, the effects of a typical outage to the network performance and the user experienced quality of service are investigated. Based on these results, COC control parameters (parameters which are adjusted in an outage situation) are selected and their feasibility is tested utilizing network level simulations. Finally, a COC algorithm based on the selected control parameters is developed and tested utilizing the simulation environment described in the chapter five. Chapter six concludes the thesis and summarizes the most important findings.

2 Long Term Evolution

To fulfill the high capacity and service quality requirements of the mobile networks, LTE has many significant differences compared to the legacy mobile network technologies. This chapter introduces the main features, development decisions, advantages and disadvantages of LTE, and gives a solid basis for the reader to understand the subsequent chapters of the thesis.

2.1 Network Architecture

The main trend of reducing complexity of the network can be clearly seen in the LTE network architecture. Firstly, there is no circuit switched domain in LTE. All of the services are carried out using packet switched services, which simplifies the network greatly and allows more efficient optimization of the packet switched services. Secondly, the number of network elements is reduced compared to the legacy systems. Instead of centralized Radio Network Controllers (RNC), all radio related protocols are terminated straightly in Evolved NodeBs (eNodeB) enabling improvement on the latencies and optimizing the performance of the network. [1]

User Equipment (UE) consists of a mobile client device and a physical card, Universal Subscriber Identity Module (USIM), used to identify and authenticate a particular user. UEs are connected to Evolved Packet Core (EPC) via Evolved Universal Terrestrial Radio Access Network (E-UTRAN), which consists of multiple eNodeBs connected together via X2 interfaces. eNodeBs manage all the radio access related protocols and tasks, such as radio resource management, handover control, admission control and scheduling. As a comparison to UMTS system, eNodeBs handle similar tasks than NodeBs and RNCs in an UMTS network. [2] [3]

EPC delivers the user traffic between Packet Data Network (PDN) and E-UTRAN. EPC consists of three main elements: Mobility Management Entity (MME), Serving Gateway (S-GW) and PDN Gateway (P-GW). MME is the main control entity of EPC, and responsible for user authentication, mobility management, service tracking, subscription profile management and service connectivity. Functions requiring subscriber profile information are done by interacting with Home Subscriber Server (HSS). S-GW is responsible for forwarding and routing user packets and being a mobility anchor during handovers between LTE and other 3GPP networks. P-GW operates as an edge-router between EPC and PDN. It is typically the point of attachment for UEs and responsible for IP (Internet Protocol) address allocations. In addition, P-GW performs packet filtering and traffic shaping according to the active policies. The whole packet system consisting of EPC and E-UTRAN is denoted as Evolved Packet System (EPS). LTE system architecture and the related interfaces are illustrated in figure 1. [3]

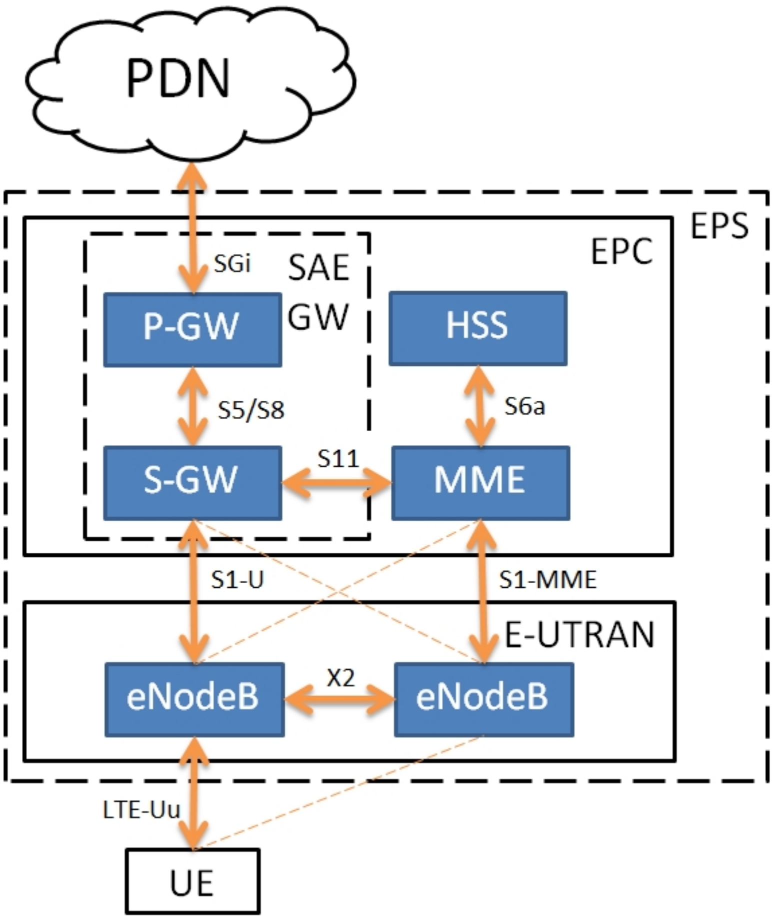


Figure 1. LTE system architecture.

2.2 Air Interface in LTE DL: Orthogonal Frequency Division Multiple Access

2.2.1 Carrier Structure and Inter-Carrier Interference

Frequency Division Multiple Access (FDMA) is a common multiple access method in cellular networks. One main problem of the traditional FDMA is the power leakage between adjacent subcarriers, which causes Inter-Carrier Interference (ICI). To tackle the signal degradation caused by ICI, guard bands must be introduced between subcarriers. Within these guard bands no information can be sent, and therefore they waste the capacity of the system. The insight behind the DL multiple access method of LTE, Orthogonal Frequency Division Multiple Access (OFDMA), is to use a subcarrier spacing, which makes the power of the neighboring subcarriers zero at the sampling instant of the desired subcarrier [1]. With this method, although the envelopes of the subcarriers reach the frequency band of the adjacent subcarriers, no ICI is created. Therefore, subcarriers can be packed close to each other and no guard bands are needed. As a downside, the orthogonality of the adjacent subcarriers depends highly on the accuracy of the frequency synchronization. Inaccurate synchronization introduces ICI and can be caused by, for example, inaccuracy of the local oscillators or the Doppler Effect. The subcarrier structure of OFDMA is illustrated in figure 2.

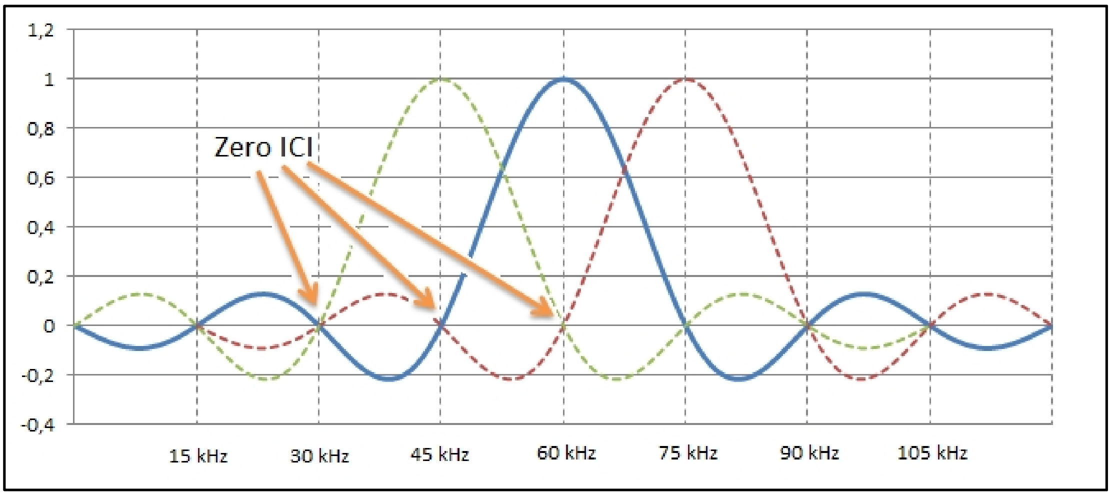


Figure 2. Subcarrier structure of OFDMA.

2.2.2 Frame Structure, Cyclic Prefix and Inter Symbol Interference

In the time domain, the transmissions of each subcarrier can be divided into frames with a length of 10 ms, which further can be divided into 1 ms subframes. Each subframe consists of two 0.5 ms time slots, which in turn build up from seven data symbols [4] [5]. In a typical radio environment, multiple delayed copies of the transmitted symbols are seen at the receiver as an effect of the multipath fading. These copies sum up causing Inter-Symbol Inference (ISI) between the symbols. To mitigate the effects of ISI, a cyclic prefix is added at the beginning of every symbol. The length of the cyclic prefix is determined by the delay characteristic of the radio channel. Ideally, all delayed copies of the transmitted symbol are received during the cyclic prefix, and therefore just by ignoring the cyclic prefix, the ISI can be mitigated. LTE introduces two different cyclic prefix lengths: normal and extended. In the normal mode, the cyclic prefix length of the first symbol in a time slot is 5.2 μs and for other six symbols 4.7 μs. In extended mode, the cyclic prefix length is 16.7 μs for all symbols [5]. The length of the cyclic prefix is a tradeoff between the capacity and the maximum tolerable delay variation of different radio paths between the transmitter and the receiver. If the delay variation of the radio paths exceeds the maximum allowed value, delayed signal components from the previous symbols will degrade the quality of the current symbol. The relations between the cyclic prefix length, the maximum allowed distance difference between the radio paths and the proportional capacity used for the cyclic prefix at the physical layer are illustrated in table 1. It should be noted, that the maximum cell size is typically much bigger than the maximum distance between radio paths, although these values are typically strongly correlated.

Table 1. The effects of the cyclic prefix length to the maximum allowed radio path difference and capacity utilized for the cyclic prefix.

Cyclic prefix length	Max. distance difference between the radio paths	Capacity used for the cyclic prefix
4.7 µs / 5.2 µs	1406 m	7 %
16.7 µs	5000 m	23 %

2.2.3 Resource Allocation and Reference Symbols

In OFDMA of LTE, subcarriers can be allocated to different users with a granularity of 12 subcarriers, resulting in the smallest possible allocation unit of 180 kHz in the frequency domain. In the time domain, resources can be allocated with an accuracy of a subframe, resulting in a smallest allocation time of 1 ms. Therefore, the basic allocation unit, denoted as a resource block, consists of 180 kHz bandwidth and 1 ms time. These resource blocks can basically be allocated to the users in an arbitrary manner, but the actual implementation of the resource scheduler can have some limitations.

As mentioned in sections 2.2.1 and 2.2.2, the orthogonality of the subcarriers diminishes the ICI and the use of the cyclic prefixes diminishes the ISI. However, even without ICI and ISI the symbols change during the transmission, since the radio channel between the transmitter and the receiver changes the phase and the amplitude of every symbol. In LTE, a part of the transmitted symbols are reference symbols, which original amplitude and phase are known to the receiver. With the help of these symbols, the receiver can estimate the original content of the received symbols. An example of the reference symbol structure is illustrated in figure 3. [1] [6]

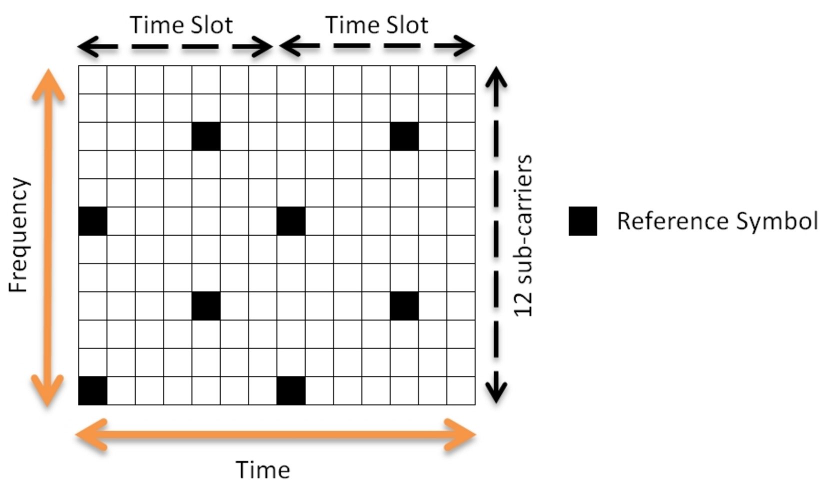


Figure 3. An illustration of the OFDMA reference symbol structure.

The accuracy of the channel estimation depends on the utilized number of reference symbols. Obviously, the denser the reference symbol grid is, the more accurately the channel can be estimated. On the other hand, reference symbols cannot be used to transmit user information, and therefore they are purely overhead traffic consuming the capacity of the system. The density of the reference symbol grid is determined by the assumed coherence time/frequency of the channel. If the channel changes rapidly as a function of time/frequency, a dense symbol grid is required. In contrast, with a slowly changing channel, much sparser symbol grid is adequate.

In addition to channel estimation, reference symbols are used for cell (re)selection and handover processes. UE measures constantly the average power of the reference symbols, denoted as Reference Signal Received Power (RSRP), from the serving and the adjacent cells. These measurements are used to determine the cell with the strongest signal. Furthermore, an estimate of the quality of the received signal, Reference Signal Received Quality (RSRQ), is calculated by dividing the RSRP value with a Received Signal Strength Indicator (RSSI). RSSI is a measure of the total received wideband power. [1]

2.2.4 OFDMA Advantages and Disadvantages

The multi-carrier transmission scheme of OFDMA enables multiple advantages compared to the legacy systems, particularly to WCDMA (Wideband Code Division Multiple Access) utilized in UMTS. Since in WCDMA all transmissions occupy the whole available bandwidth, the utilization of frequency diversity is impossible. Due to this fundamental restriction, even the latest technology improvement of UMTS, HSDPA (High-Speed Downlink Packet Access), can schedule the user transmissions only in time and code domain. In OFDMA, resource blocks can be allocated to the users in an arbitrary way, and therefore OFDMA can utilize both time and frequency diversity efficiently. This is a major reason for the higher spectral efficiency of LTE DL compared to UMTS DL, especially in frequency fading channels. Another main advantage of OFDMA is its capability to utilize flexibly various system bandwidths while keeping the receiver complexity at a rather low level. As a comparison in WCDMA, an increase in the system bandwidth increases drastically the complexity of the receiver due to the increased number of multipath components. [7] [8]

Main disadvantages of OFDMA are the sensitivity to the frequency synchronization errors and a high peak-to-average power ratio. In the time domain, the OFDMA transmissions consist of multiple sinusoidal signals, which are summed together. The resulting signal varies strongly, leading to a high difference between the average transmitted power and the highest transmitted power. In practice, high peak-to-average ratio increases the power consumption and the cost of the transmitter. However, these are not critical problems, since the transmitter lies in the eNodeB. [9]

2.3 Air Interface in LTE UL: Single-Carrier Frequency Division Multiple Access

2.3.1 Characteristic of SC-FDMA and Differences to OFDMA

High peak-to-average ratio, inevitably leading to poor power efficiency, was the main reason for not choosing OFDMA as the multiple access method for the LTE UL. Instead, a multiple access method called Single-Carrier Frequency Division Multiple Access (SC-FDMA) was selected. SC-FDMA has many desirable characteristics similar to OFDMA, but does not suffer from a high peak-to-average ratio. In SC-FDMA, the information of a user is sent utilizing only a single carrier. Similarly to OFDMA, the basic resource allocation unit is a resource block, consisting of a 180 kHz bandwidth and duration of 1 ms [1]. These resource blocks can be allocated to the users in an arbitrary way, as long as the allocated bandwidth is continuous. Therefore, SC-FDMA can utilize frequency diversity to achieve diversity gain; however, not as efficiently as OFDMA, since the degree of freedom in the resource block allocation is smaller. Similarly to OFDMA, there is no need to allocate guard bands between the carriers, since SC-FDMA carriers are based on a similar subcarrier structure than the subcarriers of OFDMA. The comparison between OFDMA and SC-FDMA carrier structure is illustrated in figure 4. [3] [8]

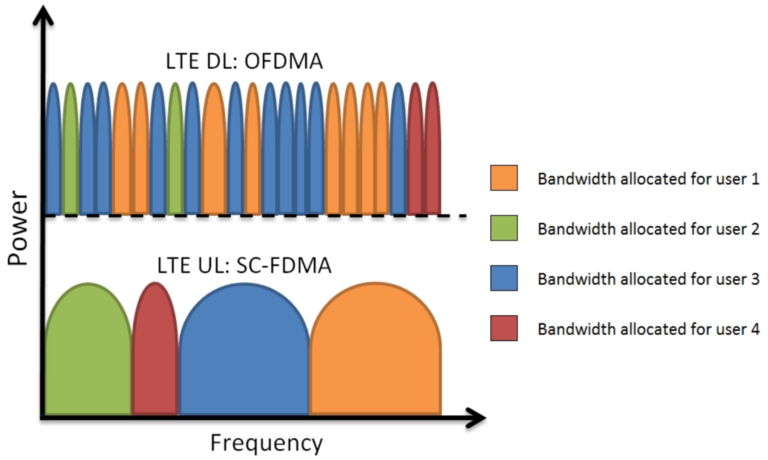


Figure 4. The difference between OFDMA and SC-FDMA carrier structures.

The symbol rate of SC-FDMA is much higher than the symbol rate of OFDMA, since the information of an individual user is sent via a single carrier instead of utilizing multiple carriers. Similarly to OFDMA, cyclic prefixes are added periodically to mitigate ISI. As a difference, cyclic prefixes are added only after a block of symbols, rather than after every symbol. As a result, only the ISI between the symbol blocks can be mitigated by ignoring the cyclic prefix at the receiver side and the ISI between adjacent symbols must be handled by the receiver. In practice, the receiver must be able to equalize the whole block of symbols, instead of just processing one symbol at a time [1]. This inevitably leads to a more complex receiver implementation than in OFDMA, which on the other hand is not a critical problem, since the receiver lies in the eNodeB. [8] [10]

Similarly to OFDMA, reference symbols are used in SC-FDMA to enable channel estimation. There are two reference symbol types in SC-FDMA: Demodulation Reference Symbols (DM-RS) and Sounding Reference Symbols (SRS). DM-RSs are used to enable coherent signal demodulation at the receiver side. DM-RSs are multiplexed in time domain into a SC-FDMA radio frame, similarly to any other symbols. Depending on the cyclic prefix length (normal or extended), third or fourth symbol of the frame is used. DM-RSs cannot be used for the purposes of frequency selective scheduling, because they are transmitted utilizing a bandwidth allocated to a particular user. To enable efficient frequency selective scheduling, SRSs can be sent periodically using a wider bandwidth. Using SRSs is not mandatory in the 3GPP specification of LTE, as they reduce the capacity of the cell by approximately 7 % [10]. However, SRSs do enable more efficient allocation of the bandwidth resources, which results in more efficient utilization of the frequency diversity. The reference symbol structure of LTE SC-FDMA is illustrated in figure 5. [11]

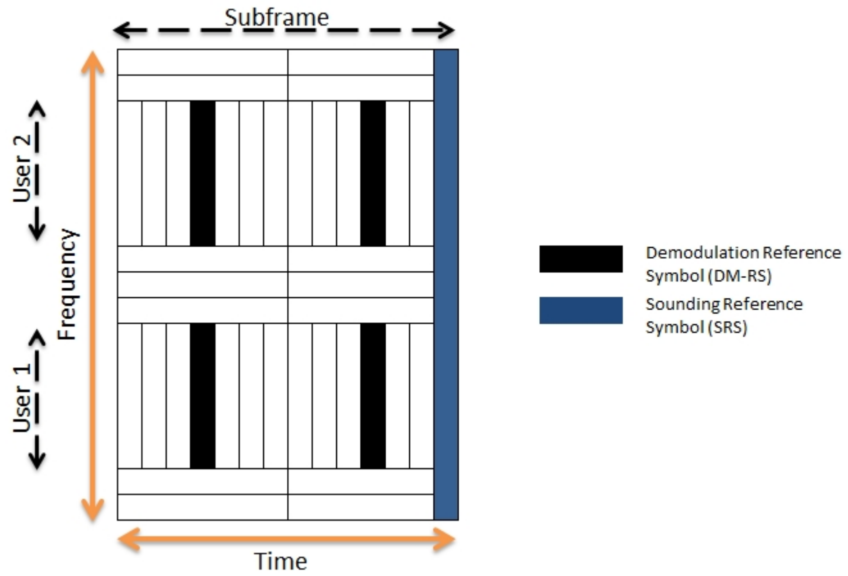


Figure 5. SC-FDMA reference symbol structure.

2.4 Multiple-Input Multiple-Output Schemes

MIMO schemes are one of the main innovations of LTE improving the spectral efficiency, the coverage and the peak rates of the network. MIMO technologies have been utilized also in legacy technologies, but in LTE the full support for MIMO features have been an essential design aspect from the beginning of the 3GPP standardization process. Different MIMO schemes, including spatial multiplexing, multi-user spatial multiplexing and transmit diversity can be used adaptively according to instantaneous channel conditions to boost the performance of the network. This section introduces the basic MIMO schemes utilized in LTE.

2.4.1 Spatial Multiplexing

Spatial multiplexing is used to create multiple parallel transmission channels between the receiver and the transmitter, without allocating any additional bandwidth resources. This is done by using multiple receiver and transmitter antennas. All transmitter antennas transmit different information, and with the means of signal processing, streams are separated at the receiver. Separation process is based on reference symbols described in section

2.2.3. At its best, spatial multiplexing doubles the peak rates when using two parallel streams (requires two receiver and two transmitter antennas) or increases the peak rates by a factor of four when using four parallel streams (requires four receiver and four transmitter antennas). [1]

In practice, spatial multiplexing can only be used relatively close to the cell center, because it requires high Signal-to-Interference-plus-Noise Ratio (SINR) to work properly. This is due to two main reasons. Firstly, the total transmission power is divided between the transmitter antennas. If two transmitter antennas are used, the transmitted power drops 3 dB and in the case of four transmitter antennas, the reduction in the transmitted power is 6 dB. Secondly, as the parallel data streams use the same physical resources, they also create interference to each other. As the MIMO stream separation is based on the channel response differences, strong correlation between the transmission channels leads to strong inter-stream interference, and weak correlation to weak inter-stream interference. [12]

As the UEs typically have only one transmission antenna, spatial multiplexing cannot be utilized in the UL direction. However, to enable a part of the spatial multiplexing benefits, a transmission method called multi-user spatial multiplexing can be used. The basic idea of the multi-user spatial multiplexing is to utilize normal spatial multiplexing principle with two different UEs. In contrast to normal spatial multiplexing, which increases the peak rates of individual users and the capacity of the network, multi-user spatial multiplexing increases only the overall network capacity. Multi-user spatial multiplexing principle is illustrated in figure 6. [13]

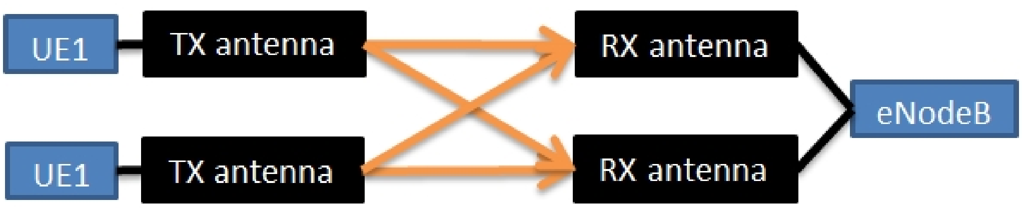


Figure 6. Multi-user spatial multiplexing principle.

2.4.2 Transmit and Receive Diversity

Macro diversity can be utilized either by sending the same signal via multiple transmitter antennas (transmit diversity) or by using multiple receive antennas for the signal reception (receive diversity). [14] By separating the antennas in space, the probability of deep fading dips in the received signal power can be reduced, since individual stream fade differently. The amount of gain depends on the correlation of the individual channels – more correlation exists, less gain can be achieved. Transmit/receive diversity is typically used for the cell edge users, whose achievable SINRs are relatively small. With the increase in SINR, cell range and capacity of the network can be increased.

2.5 Inter-Cell Interference Coordination

LTE network without any ICIC is basically a reuse one system, where every part of the available bandwidth is utilized equally. The main problem in this approach is the cell edge users experiencing heavy DL interference and also creating considerably amount of UL interference. As LTE is a multi-carrier technology, frequency utilization of adjacent cells can be easily coordinated to minimize the Inter-Cell Interference. The characteristics of four basic LTE ICIC methods are described in this section.

2.5.1 Hard Frequency Reuse

In hard frequency reuse, the available bandwidth is divided into exclusive segments allocated to individual cells in a way, that the adjacent cells do not utilize the same bandwidth segment. A parameter denoted as reuse factor defines the number of frequency segments [15]. With hard frequency reuse, the interference can be effectively diminished both in UL and DL, but at the cost of a major reduction in the system capacity, since only a part of the total bandwidth can be utilized in an individual cell. Since the system capacity drops with a factor equal to the reuse factor, hard frequency reuse cannot be seen as a practical ICIC scheme. In this thesis, it is only presented to provide a baseline when evaluating the more advanced ICIC schemes. Hard frequency reuse using reuse factor three is illustrated in figure 7.

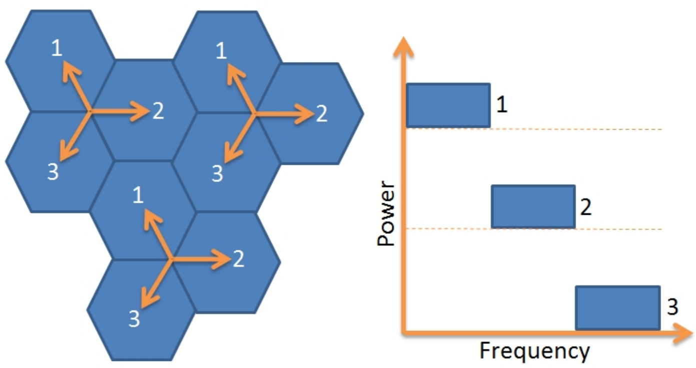


Figure 7. Hard frequency reuse scheme.

2.5.2 Prioritization

In prioritization scheme, the whole bandwidth can be utilized in all cells similarly to a network without any frequency coordination. As a difference, a prioritized bandwidth segment has been defined for each cell, into which the transmissions are prioritized over the rest of the bandwidth. The prioritization is done in a way, that the adjacent cells do not utilize the same bandwidth segments. [16] With prioritization, the probability of adjacent cells utilizing the same resource block is smaller than without prioritization, and therefore it can be used to diminish interference both in UL and DL. Prioritization works effectively with low network loads, but as the network load increases, the probability of adjacent cells utilizing the same resource blocks also increases. In a fully loaded network, prioritization does not offer any gain compared to a network without prioritization. Prioritization using three prioritization partitions is illustrated in figure 8.

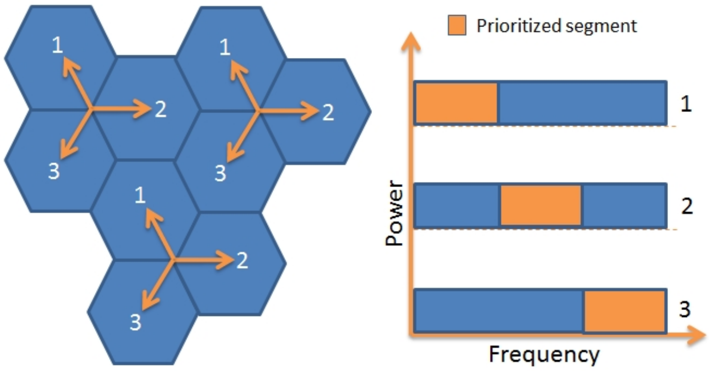


Figure 8. Prioritization scheme.

2.5.3 Fractional Frequency Reuse

In fractional frequency reuse, the available bandwidth is divided into segments, in which varying frequency reuse schemes can be utilized. Typically, the bandwidth is divided into two parts: the first part is allocated to the Cell Center Users (CCU) and the second part to the Cell Edge Users (CEU). As the CEU experience higher interference levels than the CCU, it is purposeful to use higher reuse factors for the CEUs than for the CCUs. In a typical fractional reuse scheme, reuse factors one and three are utilized in the cell center and the cell edge respectively. [17] If the utilized reuse factors are higher than one, fractional reuse decreases the spectral efficiency of the network; however, not as much as hard frequency reuse. Therefore, the performance of fractional reuse can be seen as a compromise between the spectral efficiency and the cell edge performance. Fractional frequency reuse principle is illustrated in figure 9.

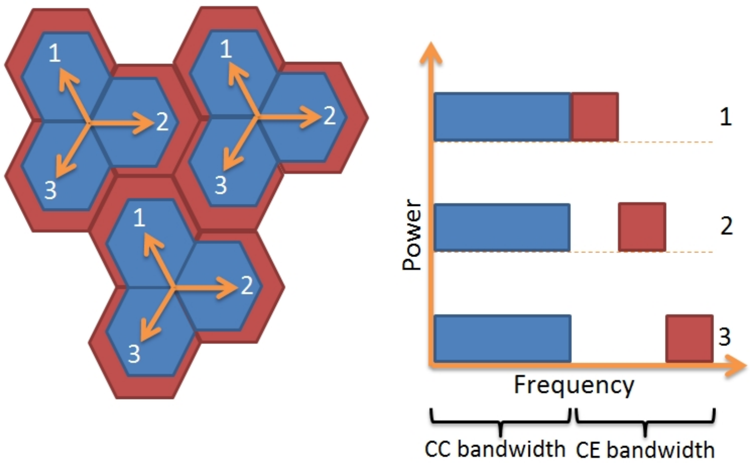


Figure 9. Fractional frequency reuse scheme.

2.5.4 Soft Frequency Reuse

In a basic soft frequency reuse scheme all cells can utilize the whole available bandwidth, but for each cell an individual power spectrum has been defined. The power spectrums are chosen in a way, where the probability of overlapping high power transmission is small. [17] With this method, the probability of adjacent cells utilizing the same resource block does not decrease, but the effects of a collision are smaller. As a result, the interference decreases effectively both in UL and DL. As a major benefit of the soft frequency reuse, the whole bandwidth can be utilized in all cells leading to a high spectral efficiency. Soft frequency reuse is illustrated in figure 10. In addition, combining the basic ICIC schemes described in this section is possible. As an example, an ICIC scheme utilizing prioritization, soft frequency reuse and fractional frequency reuse is illustrated in figure 11.

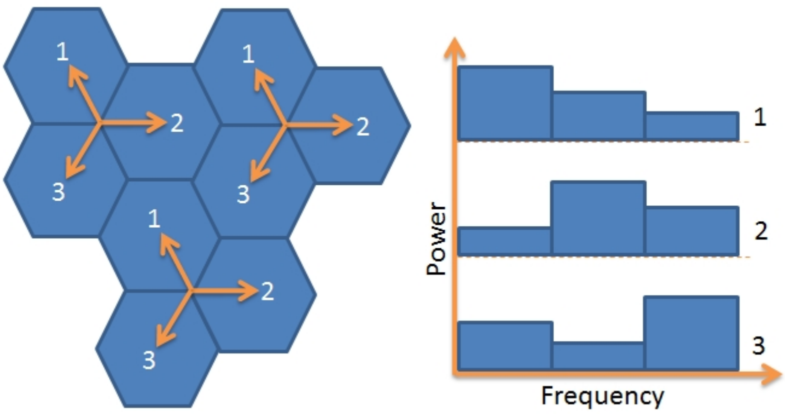


Figure 10. Soft frequency reuse scheme.

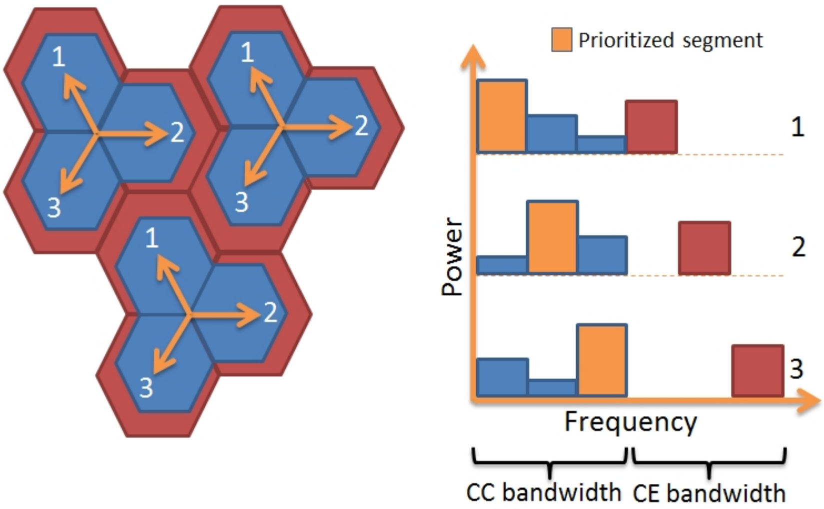


Figure 11. Combination of prioritization, soft frequency reuse and fractional frequency reuse schemes.

2.6 Bearers

A logical connection between two network elements defining the connection points, the traffic profile and the connection parameters is denoted as a bearer. In LTE, the user data is divided into Service Data Flows (SDF) by using Traffic Flow Templates (TFT). TFTs consist of one or multiple filters characterizing the packet types belonging to a particular SDF. TFT binds an SDF into an EPS bearer: a logical connection throughout the whole EPS (between the UE and the P-GW). There are two types of EPS bearers: a default EPS bearer and a dedicated EPS bearer. The default EPS bearer is established in the initial attach process, where the UE registers itself to the MME, and is maintained as long as the user detaches from the network. The main task of the default bearer is to provide IP level connectivity between the UE and the P-GW. All additional EPS bearers, which are established as needed basis, are called dedicated EPS bearers. Every EPS bearer is associated with a Quality of Service (QoS) profile, which includes the following parameters: QoS Class Identifier (QCI), Allocation and Retention Priority (ARP) and Maximum Bit Rate (MBR). In addition, for dedicated EPS bearers a Guaranteed Bit Rate (GBR) can be defined. EPS bearers have a one-to-one mapping to the lower layer bearers and consist of an E-UTRAN Radio Access Bearer (E-RAB) and a S5/S8 bearer. E-RAB is a composition of a radio bearer and a S1 bearer. The bearer architecture is illustrated in figure 12. [18]

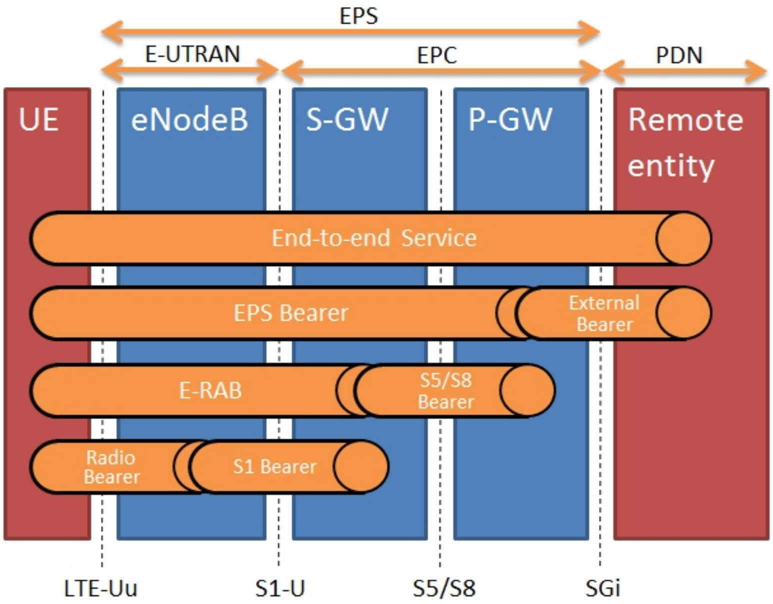


Figure 12. The bearer architecture of LTE.

2.7 Mobility

Mobility, a functionality providing continuous service to the users moving around in the network, is a fundamental feature of any mobile cellular system. This section introduces mobility principles utilized within E-UTRAN and from E-UTRAN to other Radio Access Technologies (RAT).

2.7.1 Absolute Priority Based Reselection

In a live network, LTE can utilize multiple different bandwidths simultaneously. In addition, operators might have other Radio Access Networks (RAN), such as Universal Terrestrial Radio Access Network (UTRAN) or GSM/EDGE Radio Access Network (GERAN). Each of these technologies/frequencies can be seen as an own layer, creating a layered cell structure to the network. For selecting the most suitable layer, a method known as absolute priority based reselection is implemented into LTE. In the absolute priority based reselection, each of the layers are given a priority, which from UE selects the highest priority layer assuming it can provide a decent level of service.

To determine if the target layer can provide an adequate service level, UE constantly measures the signal strength of the best cell in the target layer. Depending on the target RAT, different metrics are utilized. For example, in LTE the metric is RSRP and in UMTS the metric is the strength of the Common Pilot Channel (CPICH). If the measured value of the target layer fulfills a threshold $Thresh_{high}$ for a time of $T_{reselection}$, the reselection is executed. To make reselections to the lower priority layers, the measured value of the serving cell must be lower than $Thresh_{high}$ and the measured value of the target cell higher than $Thresh_{low}$. [1]

2.7.2 Equal Priority Reselection

The cell reselections between two equal priority E-UTRAN cells are executed with an algorithm called equal priority reselection, which is based on the RSRP measurements of the UEs. A reselection is executed to the target cell, if condition $Q_{target} + Q_{offset} > Q_{serving} + Q_{hys}$ is fulfilled for a time of $T_{trigger}$, where Q_{target} is the RSRP of the candidate target cell, $Q_{serving}$ is the RSRP of the serving cell, Q_{hys} is a hysteresis value used to avoid ping-pong handovers (back-and-forth handovers), $T_{trigger}$ is a time-to-trigger value used to avoid too frequent handovers and Q_{offset} is an offset value used to bias the handover process towards particular cells. [1] The equal priority reselection condition is illustrated in figure 13.

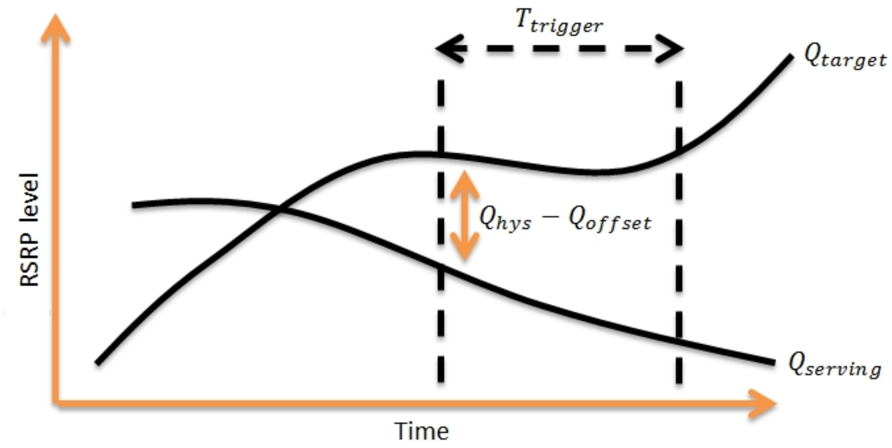


Figure 13. Equal priority reselection condition.

2.7.3 Handover

A transfer of an active UE connection from a cell to another cell is called a handover. All handovers initiated in LTE are hard, in which the connection between the UE and the RAN is broken for a while during the handover process. For intra-LTE handovers, a typical values for the detach delay (the time there is no connection between UE and RAN) are around 5-30 ms [19] [20]. For inter-RAT handovers, the detach delay depends highly on the target system, but for example, detach delays from E-UTRAN to UTRAN are typically over 50 ms. Intra-LTE handovers are lossless, in which no packets are lost in a successful handover. This is achieved by packet forwarding between the source and the target eNodeB during the handover process. In addition, inter-RAT handovers may be lossless if the target system supports packet forwarding. [1] Ensuring that no data is lost during the handover process is extremely important for many service types, for example, services based on Transmission Control Protocol (TCP), since even a small packet loss degrades the TCP performance greatly [21].

2.8 LTE Processes

Similarly to other mobile networks, the operations in LTE network are based on predefined processes. To understand the operation of LTE properly, these processes should be known and their significance to the overall performance of the network understood. This section introduces the most important LTE processes and evaluates their significance to the network performance. The descriptions of the timers related to LTE processes are described in appendix A.

2.8.1 Random Access

The random access process is initiated when the UE needs to establish UL time synchronization with the eNodeB [22]. In practice, the process is initiated in five different events:

- Radio Resource Control (RRC) connection establishment
- RRC connection re-establishment after a Radio Link Failure (RLF)
- Handover process
- DL data transmission with an unsynchronized UE
- UL data transmission with an unsynchronized UE [22]

There are two different random access process types in LTE. The first process type, contention based random access process, is illustrated in figure 14. Contention based random access process can be used in all five event types.

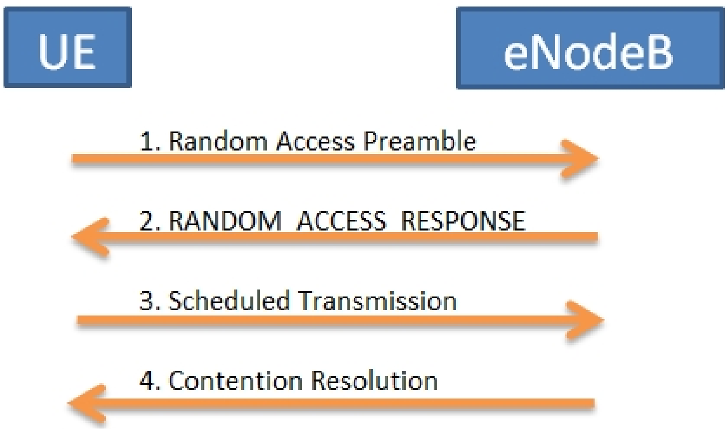


Figure 14. Contention based random access process.

1. The UE sends a randomly selected random access preamble towards the eNodeB via the random access channel. The preamble power is based on an estimation of the DL path loss. It should be noted, that the DL and UL path losses do not necessarily correlate, and therefore the UL path loss estimate can be rather inaccurate.

2. The eNodeB acknowledges the preamble with a RANDOM ACCESS RESPONSE message, which includes at least timing alignment data, information about the observed preambles and a Cell Radio Network Temporary Identifier (C-RNTI). Multiple preamble receptions (from multiple different UEs) can be acknowledged with one RANDOM ACCESS RESPONSE message.
3. The UE transmits a scheduled transmission using the UL shared channel. The identity of the UE is included in the message.
4. The eNodeB acknowledges the message and confirms that it has received the identity of the UE. [22]

If the UE does not receive an acknowledgment for its preamble (step 2) or for its identity (step 4), another preamble is transmitted with an increased transmit power. The random access process continues until it is successful or declared as failed. In case of UL/DL data transmission with an unsynchronized UE, the process is declared as failed if the maximum number of preambles is reached. In case of RRC connection establishment, RRC connection re-establishment and handover process, the RRC timer expiry declares the random access process failure. [1]

The second random access process type, non-contention based random access process, can be utilized only in handover processes and for synchronizing UE to initiate DL data transfer. The process is very similar to the contention based random access process. As a difference, instead of randomly selecting a preamble, eNodeB assigns a dedicated preamble to the UE. Since the identity of the UE is known to the eNobeB, messages 3 and 4 of the contention based process are not needed.

2.8.2 RRC Connection Establishment

In LTE, an UE can reside in two different activity states: RRC idle state or RRC connected state. In the RRC idle state, there is no RRC connection between the UE and the E-UTRAN. The UE monitors the paging channel for incoming calls, measures the neighboring cells, performs cell reselections and acquires system information. In the connected state, in addition to the idle state operations, the UE monitors shared/control channels, transmits channel quality information, performs measurement reporting and possibly sends application level data towards the eNodeB. The process of establishing a RRC connection is illustrated in figure 15. A rejected connection establishment is illustrated in figure 16. [1] [21]

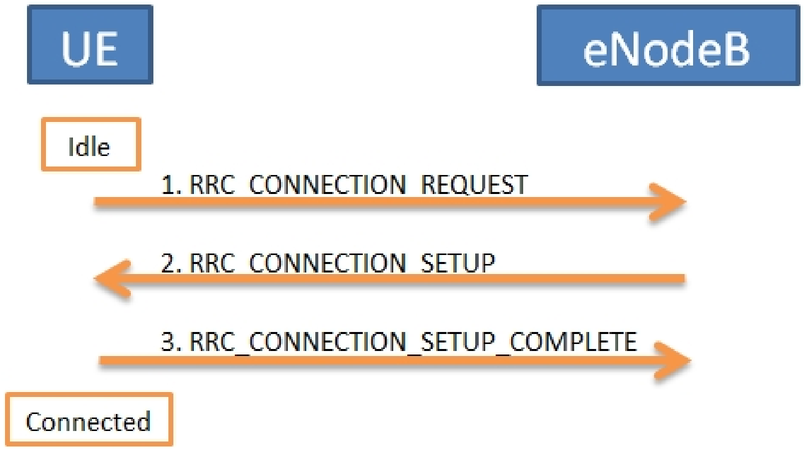


Figure 15. RRC connection establishment process.

1. The UE performs a random access process with the eNodeB, starts timer T300 and transmits a RRC CONNECTION REQUEST message towards the eNodeB.
2. If the eNodeB accepts the RRC connection establishment request, it answers with a RRC CONNECTION SETUP message. If timer T300 expires before the UE receives the RRC CONNECTION SETUP message, the process is declared as failed.
3. The UE acknowledges the establishment of the connection with a RRC CONNETION SETUP COMPLETE message. [23]

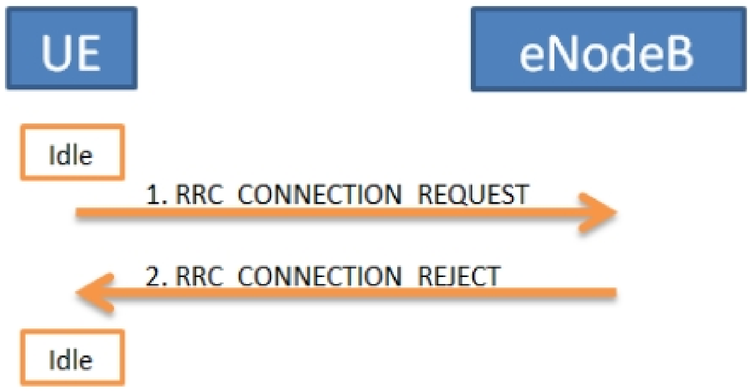


Figure 16. Rejected RRC connection establishment process.

1. The UE performs a random access process with the eNodeB, starts timer T300 and transmits a RRC CONNECTION REQUEST message towards the eNodeB.
2. The eNodeB rejects the connection request and sends a RRC CONNECTION REJECT message to the UE. The UE starts timer T302, remains in the idle state and is not allowed to send another RRC connection request until timer T302 expires. [23]

2.8.3 RRC Connection Reconfiguration

The RRC connection reconfiguration process is used to establish/modify/release radio bearers, perform handovers and setup/modify/release UE measurements. The process is initiated by the eNodeB, which sends a RRC CONNECTION RECONFIGURATION message towards the UE. If the UE can comply with the configuration changes, it responds with a RRC CONNECTION RECONFIGURATION COMPLETE message. On the other hand, if the UE cannot comply even with a part of the configuration changes, the UE initiates a RRC connection re-establishment process. No information about the failure cause is sent to the eNodeB. Successful and failed RRC connection reconfiguration processes are illustrated in figures 17 and 18 respectively.

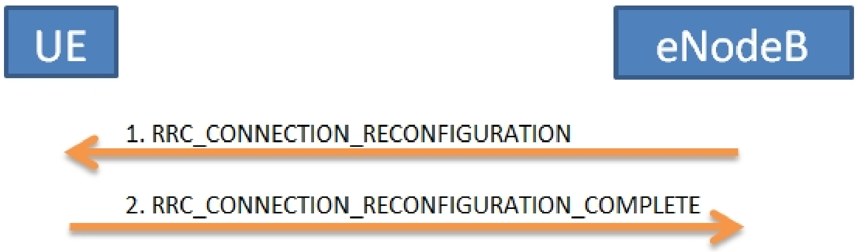


Figure 17. Successful RRC connection reconfiguration process.

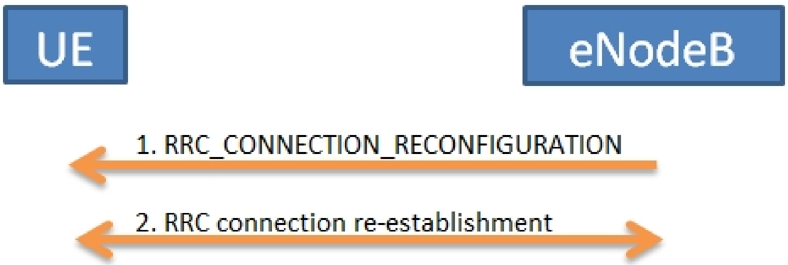


Figure 18. Failed RRC connection reconfiguration process.

2.8.4 Attach

In the attach process, the UE registers itself to the MME in order to receive the network services. During the attach process, a default EPS bearer is established enabling the always-on IP connectivity of LTE. The default bearer is maintained as long as the terminal is registered to the network. The UE context is created to the MME and an IP-address may be allocated to the UE during the attach process or with Dynamic Host Configuration Protocol (DHCP) after the default EPS bearer has been established. In addition, dedicated EPS bearer establishments may be triggered. [24] A successful attach process is illustrated in figure 19 and a rejected attach process in figure 20 [5].

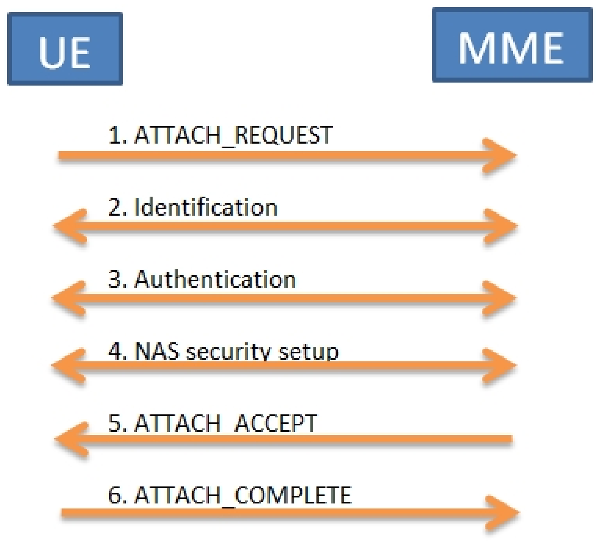


Figure 19. Successful attach process.

1. The UE performs a RRC connection establishment process towards the serving eNodeB and sends an ATTACH REQUEST message to the MME initiating the attach process. The attach message includes a PDN connectivity request which indicates the willingness to establish a default EPS bearer. Timer T3410 is started.

2-4. Identification, authentication and security processes may be initiated.

5. The MME responds to the ATTACH REQUEST with an ATTACH ACCEPT message. Timer T3410 is stopped.

6. The attach process is completed, as the UE sends an ATTACH COMPLETE message to the MME.

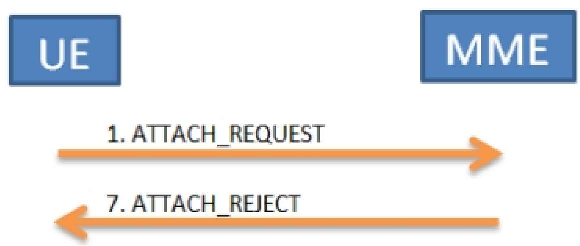


Figure 20. Rejected attach process.

7. The MME can reject the attach request by sending an ATTACH REJECT message to the UE. A reason code indicating the reason for the rejection is included in the message. Timer T3410 is stopped. [24]

2.8.5 Default EPS Bearer Establishment

The default EPS bearer establishment process is used to establish a default EPS bearer between the UE and the P-GW. The default EPS bearer is always established as a part of the attach process. In addition, to allow the UE to be connected to multiple PDNs simultaneously, additional default EPS bearers can be established. [25] The EPS bearer establishment process is illustrated in figure 21, the PDN connectivity rejection process in figure 22 and the default EPS bearer context activation rejection process in figure 23.

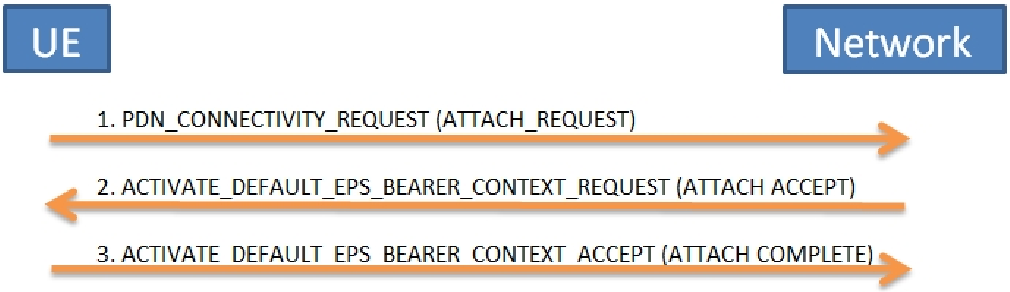


Figure 21. Default EPS bearer establishment process.

1. The UE requests a connection to the PDN by sending a PDN CONNECTIVITY REQUEST message towards the network. If the default EPS bearer establishment is done as a part of an attach process, the PDN CONNECTIVITY REQUEST is sent in an ATTACH REQUEST message. If the process is done apart from the attach process, the PDN CONNECTIVITY REQUEST is sent without the ATTACH REQUEST message and timer T3482 is started.
2. The network answers to the request by sending an ACTIVATE DEFAULT EPS BEARER CONTEXT REQUEST message. If the EPS bearer establishment is done as a part of the attach process, the ACTIVATE DEFAULT EPS BEARER CONTEXT REQUEST message is sent together with an ATTACH ACCEPT message. If the process is done apart from the attach process, the ACTIVATE DEFAULT EPS BEARER CONTEXT REQUEST is sent without the ATTACH ACCEPT message and timer T3485 is started. Timer T3482 is stopped if running.
3. The UE accepts the request and answers with an ACTIVATE DEFAULT EPS BEARER CONTEXT ACCEPT message. If the EPS bearer establishment is a part of an attach process, the message is sent together with an ATTACH COMPLETE message. After the network has received the message, the default EPS bearer is established and the timer T3485 is stopped if running.

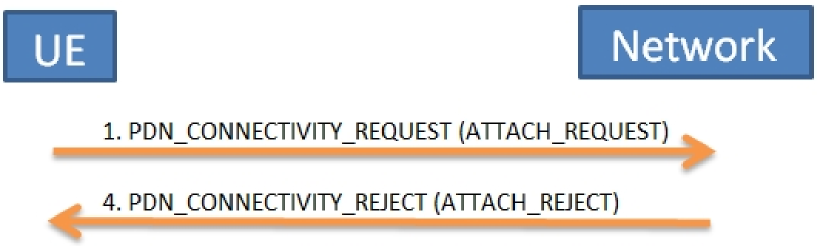


Figure 22. PDN connectivity rejection.

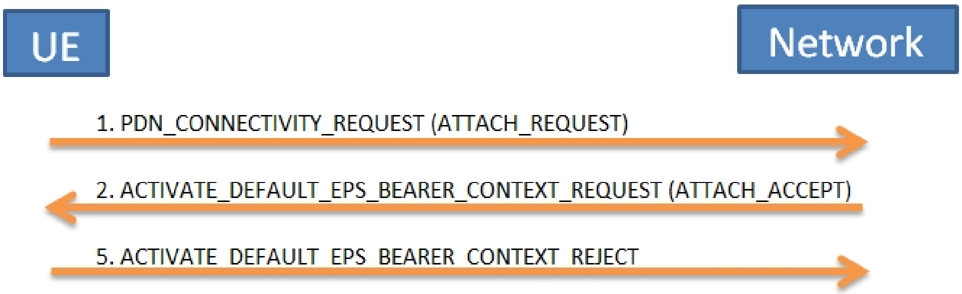


Figure 23. Default EPS bearer context activation rejection.

4. If the PDN CONNECTIVITY REQUEST is rejected by the network, the MME sends a PDN CONNECTIVITY REJECT message to the UE. The message contains a cause value, which indicates the reason for the rejection. Timer T3482 is stopped, as the UE receives the rejection message.
5. The UE can reject the default EPS bearer context activation of the network by sending an ACTIVATE DEFAULT EPS BEARER CONTEXT REJECT message towards the network. The message includes a cause value indicating the reason for the rejection. [25]

2.8.6 Dedicated EPS Bearer Establishment

The dedicated EPS bearer establishment process is used to establish a dedicated EPS bearer between the UE and the P-GW. Dedicated bearer establishment may be initiated as a part of the attach process or separately. The bearer establishment is initiated by the network, but also the UE can request the process by sending a BEARER RESOURCE ALLOCATION REQUEST message towards the network and by starting the timer T3480. If no answer to the request is received before T3480 expires, the UE tries to resend the message. After four failed retransmissions, the process is declared failed.

As the MME receives the BEARER RESOURCES ALLOCATION REQUEST message from the UE, it can either accept the request and respond with an ACTIVATE DEDICATED EPS BEARER CONTEXT REQUEST message (timer T3485 is started), reject the request and respond with a BEARER RESOURCE ALLOCATION REJECT message or request for a modification to the bearer parameters by responding with a MODIFY EPS BEARER CONTEXT REQUEST (timer T3486 is started). As the UE receives one of these three messages, it stops the timer T3480. If the UE accepts the context request, it responds with an ACTIVATE DEDICATED EPS BEARER CONTEXT ACCEPT message or with a MODIFY EPS BEARER CONTEXT ACCEPT message, depending on the MME request type. The UE might also reject the context request by sending an ACTIVE DEDICATED EPS BEARER CONTEXT REJECT or a MODIFY EPS BEARER CONTEXT REJECT message towards the network. After the network receives the UE response, timer T3485/T3486 is stopped. Different variations of the dedicated EPS bearer establishment process are illustrated in figure 24. [25]

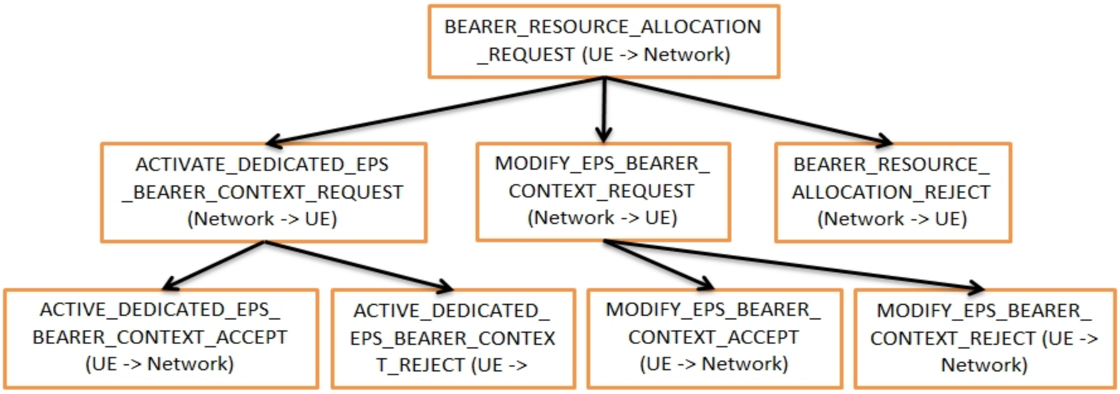


Figure 24. Different variations of the dedicated EPS bearer establishment process.

2.8.7 EPS Bearer Deactivation

The EPS bearer deactivation process is used to deactivate both default and dedicated EPS bearers. The process is initiated by the network, but also the UE might trigger it by requesting the deactivation. The deactivation signaling flow is illustrated in figure 25.

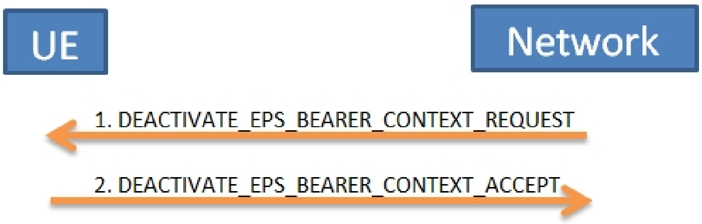


Figure 25. EPS bearer deactivation process.

1. The network sends a DEACTIVATE EPS BEARER CONTEXT REQUEST to the UE, which includes a cause value indicating the reason for the deactivation. As the request is sent, the MME starts timer T3495. If the UE does not answer to the message before timer T3495 expires, the request is resent. The retransmission is repeated four times. After the fifth expiry, the MME deactivates the EPS bearer locally.
2. UE deletes the EPS bearer context and responds with a DEACTIVATE EPS BEARER CONTEXT ACCEPT message after receiving the deactivation request. The UE has no option of refusing the deactivation. When the MME receives the deactivation accept message, timer T3495 is stopped and the process is finished.

2.8.8 Intra-LTE Handover

The intra-LTE handover process can be divided into three main phases: handover preparation, handover execution and handover completion. The handover preparation phase is illustrated in figure 26 and the handover execution phase in figure 27. The signaling flow of the handover completion phase is omitted, since it does not have much significance in the scope of this thesis. In the handover preparation phase, the network is prepared for the handover and the required resources are reserved. In the handover execution phase, the UE is informed about the handover, packet forwarding is started and the UE connection/state is transferred to the target eNodeB. In the last phase, the handover completion, the DL data path is switched from the source eNodeB to the target eNodeB and the packet forwarding is stopped.

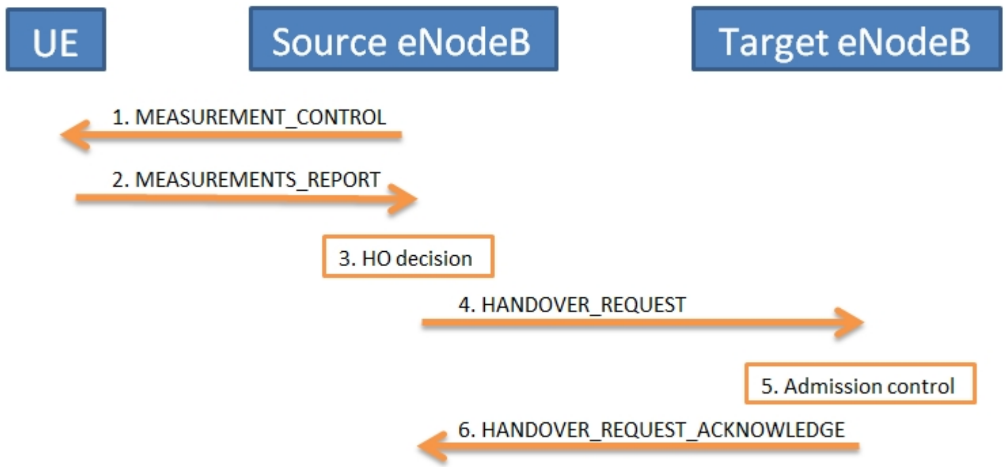


Figure 26. Intra-LTE handover preparation.

1. The eNodeB can specify different measurement reporting thresholds for the UEs with a MEASUREMENT CONTROL message. The measurement reporting can be either event based or periodic.

2. When the measurement reporting threshold is fulfilled, the UE sends a MEASUREMENTS REPORT message to the serving eNodeB. If the cell reselection condition is fulfilled, the handover process is initiated.

3. The source eNodeB makes a handover decision based on the contents of the MEASUREMENTS REPORT and cell reselection parameters.

4. The source eNodeB sends a HANDOVER REQUEST message to the target eNodeB.

5. Based on the amount of available resources, the admission control of the source cell decides if the incoming connection can be accepted. If the handover is accepted, target eNodeB reserves the necessary resources required for the connection.

6. Target eNodeB acknowledges the handover request. [1] [21]

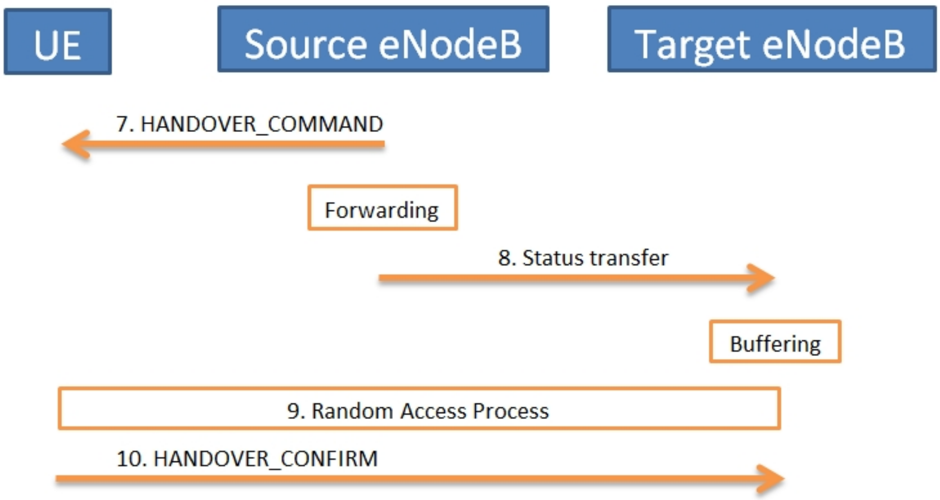


Figure 27. Intra-LTE handover execution.

7. The source eNodeB sends a HANDOVER COMMAND message to the UE and starts forwarding the DL user data to the target eNodeB. This is a critical point in the handover process. If the UE receives the HANDOVER COMMAND successfully, there is no more need for a radio connection between the UE and the source eNodeB.

8. The source eNodeB prepares the target eNodeB for the handover by transferring the UE context to it. The target eNodeB starts to buffer the traffic forwarded by the source eNodeB.

9. The UE starts the handover expiry timer T304 and establishes the connection to the target eNodeB by using the random access process. After successfully connecting the target cell, the UE stops timer T304.

10. After the completion of the handover process, the UE sends a HANDOVER CONFIRM message to target eNodeB. [1] [21] [23]

3 Optimization of the Long Term Evolution

The LTE optimization process is a complex and demanding task, in which the effects of multiple factors to the network performance must be considered simultaneously. This chapter introduces some basic KPIs of LTE, reasons for high and low values for the particular KPIs, KPI measurement methods and the significance of the KPIs to the network performance and the user experienced QoS. In addition, corresponding KPIs in UMTS are presented.

3.1 Integrity KPIs

3.1.1 RSRP Level of the Best Available Cell

Description: RSRP level of the cell with the highest RSRP.

Reasons for a low RSRP level: Basically, RSRP level distribution is determined by the number of cells in the network. However, many other factors also have a significant effect to the RSRP levels, such as antenna tilts, transmitted RSRP levels, antenna heights, antenna azimuths and the propagation environment.

Effects of a low RSRP level: The RSRP level of the best available cell can be seen as an excellent KPI for the network coverage, which is a fundamental requirement for any wireless network. Inadequate coverage causes many problems, such as RLFs, handover failures, low throughput levels and service unavailability.

How to measure the KPI: In practice, the RSRP levels are measured using drive testing, in which a special scanner or an UE measures and saves the RSRP levels constantly. In addition, a GPS module is typically used to pinpoint the RSRP measurements to specific locations. However, with standardized messages it is also possible to instruct the UEs to report periodically the RSRP measurements to their serving eNodeBs. The problem in this approach is the pinpointing of the measurement to specific locations accurately enough. Some proposals for solving this problem have been made, such as the X-Map estimation [26], but so far no commercial products are available.

Corresponding KPI in UMTS: A corresponding KPI in UMTS is Received Signal Code Power (RSCP).

3.1.2 RSRQ Level of the Best Available Cell

Description: RSRQ level of the cell with the highest RSRQ.

Reasons for a low RSRQ level: RSRQ level is affected by three factors: RSRP level, DL interference level (RSSI) and noise level. However, in a typical interference limited LTE network, the significance of the noise is relatively small.

Effects of a low RSRQ level: RSRQ level represents DL signal quality of the network. Basically, an inadequate RSRQ level creates problems similar to an inadequate RSRP level.

How to measure the KPI: RSRP measurement methodologies apply also to RSRQ measurements (see section 3.1.1).

Corresponding KPI in UMTS: A corresponding KPI in UMTS is E_c/N_0, defined as the pilot signal energy of the Common Pilot Channel (CPICH) within one chip duration divided with the RSSI [27].

3.1.3 Number of RRC Connection Establishments and Active RRC Connections

Description: The RRC connection establishment process is used to change the state of the UE from idle to connected, and thus enable the application level data exchange between the UE and the E-UTRAN [1].

Reasons for a low/high number of RRC connection establishment and active RRC connections: The number of RRC connection establishments and active RRC connections in a particular cell depends on the amount and behavior of users in the dominance area of the cell. For users utilizing data services constantly, the RRC connections remain active, even if the amount of sent data would be relatively small. If a majority of users behave similarly, the number of RRC connection establishments remains small, but the number of active RRC connections is high. On the other hand, for users having long pauses in their data utilization, the RRC connections are deactivated during the non-active periods and the user state is changed from connected to idle. Thus, in the next active period the RRC connection must be re-established via RRC connection establishment process. In a cell with a majority of users behaving this way, the number of RRC connection establishments is low and the number of active RRC connections high. In addition, the number of RRC connection establishment and the number of active RRC connections can be used to evaluate the balance of the network load. For example, a cell having significantly less RRC connection establishments and active RRC connections compared to the neighboring cells could indicate that the dominance area of the particular cell is too small. This can lead to a non-optimal network performance.

Effects of a low/high number of RRC connection establishment and active RRC connections: The RRC connection establishment process is based on the random access process, and therefore every connection establishment attempt consumes the random access resources. A high number of RRC connection establishments may cause delay in the random access process, random access failures and RRC connection establishment failures. In addition, eNodeBs have a limit for the maximum number of simultaneous active RRC connections. If the maximum number of RRC connections is exceeded, part of the connection must be dropped [1] resulting in a degraded QoS for some users.

How to measure the KPI: The KPI can be either measured using drive testing or obtained from the network statistics.

Corresponding KPI in UMTS: Also in UMTS, UE resides either in RRC idle state or RRC connected state, and the transition from the idle state to the connected is done using the RRC connection establishment process. However, in UMTS the connected state has several substates, in which UE moves depending on its activity. [27]

3.1.4 Cell-Specific Load

Description: There are two main resources in LTE: transmission power and capacity. The cell-specific load can be defined either as the ratio between the number of allocated resource blocks and the total number of resource blocks [30] or as the ratio of the average transmission power and the total available transmission power.

Reasons for a high cell-specific load: The load is basically determined from the number of users in the cell and the service types users are requesting. In addition, the average radio conditions of the users have an effect on the resource usage of the provided services. For example, more resources must be allocated to the cell-edge users to provide a particular service than to the users near the eNodeB.

Effects of a high cell-specific load: When a cell is highly loaded, admission and congestion control of the cell will start to deny new connections, downgrade the quality of existing ones and possibly even drop out some of the connections. This can lead to handover failures, RRC connection rejects, increased number of RRC connection establishments, RLFs, low user-specific throughput and general degradation of user QoS.

How to measure the KPI: The cell-specific load can be obtained from the network statistics.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network. However, due to the nature of the multiple access method of UMTS, the load is defined as the number of allocated codes rather than the number of allocated resource blocks.

3.1.5 Throughput

Description: The throughput of a particular user, a particular cell or the whole network.

Reasons for a low throughput: Low throughput can originate from multiple reasons. Low signal quality, high network load, terminal characteristics and subscription restrictions are the most typical reasons for low throughput levels. In addition, the transmission towards the core network may be a bottleneck, cutting the throughput levels even though the radio interface could support higher throughputs. Furthermore, mobility related problems may cause degradation in the throughput. I should also be noted, that a low number of users or low data rate requirements of the users may cause a low throughputs in a cell/network level.

Effects of a low throughput: An adequate user-specific throughput is essential for the quality of any service and has an immediate effect on the user satisfaction. The cell/network-specific throughput is an important metric when evaluating the overall performance of the cell/network.

How to measure the KPI: User-specific throughput can be obtained either using drive testing or from the network statistics. Cell/network specific throughput can obtained only from the network statistics.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.1.6 Modulation and Coding Scheme

Description: The utilized Modulation and Coding Scheme (MCS) in DL/UL.

Reasons for a utilization of low order MCSs: The utilized MCS is basically determined by the achievable SINR at the receiver end, which depends on the available transmit power, interference level, path loss and the magnitude of different hardware dependent gains and losses. In addition, mobility related problems can have a significant impact to the achievable SINR resulting in high proportion of low order MCS samples. Furthermore, the utilization of 64-Quadrature Amplitude Modulation (QAM) may be restricted without an additional license bought from the vendor. By enabling the support of the high order modulation schemes, the high SINRs can be utilized more effectively resulting in higher throughput levels.

Effects of the utilized MCS: The utilized MCS has a direct impact to the throughput both in UL and DL. The achievable throughputs may be very modest with the low order modulations and coding rates. In contrast, with more complex modulation schemes and higher coding rates, much higher throughput levels can be reached.

How to measure the KPI: The MCS distribution can be either measured using drive testing or obtained from the network statistics.

Corresponding KPI in UMTS: Adaptive MCS selection is utilized also in UMTS and has similar effects than in LTE.

3.1.7 User Plane Latency

Description: The user plane latency is typically measured as a Round Trip Time (RTT), defined as the time it takes for an IP packet to travel from the UE to a server in the PDN and back.

Reasons for a high user plane latency: Basically, the RTT of the user plane can be divided into six parts. Firstly, the processing delays of the UE and the eNodeB, depending on the amount of processing resources. Secondly, the transmission times in UL and DL. Thirdly, the scheduling delay consisting of a request time and a grant time. The request time is the delay for the UE to send a request of transmission opportunity and the grant time is the delay for the eNodeB to grant the request. Basically, the length of the scheduling delay depends on the load of the particular cell, the type of utilized service and the QoS parameters allocated to the particular EPS bearer. The fourth component is the additional delay caused by the retransmissions and the fifth component the latency of the core network. Core network latency mainly depends on the transport capacity of the S1-U interface and the processing capacity of the S-GW. The final component, the delay of the PDN can basically be affected only with the selection of the test server and its location. Typical proportions of the LTE RTT components are illustrated in figure 28. [1]

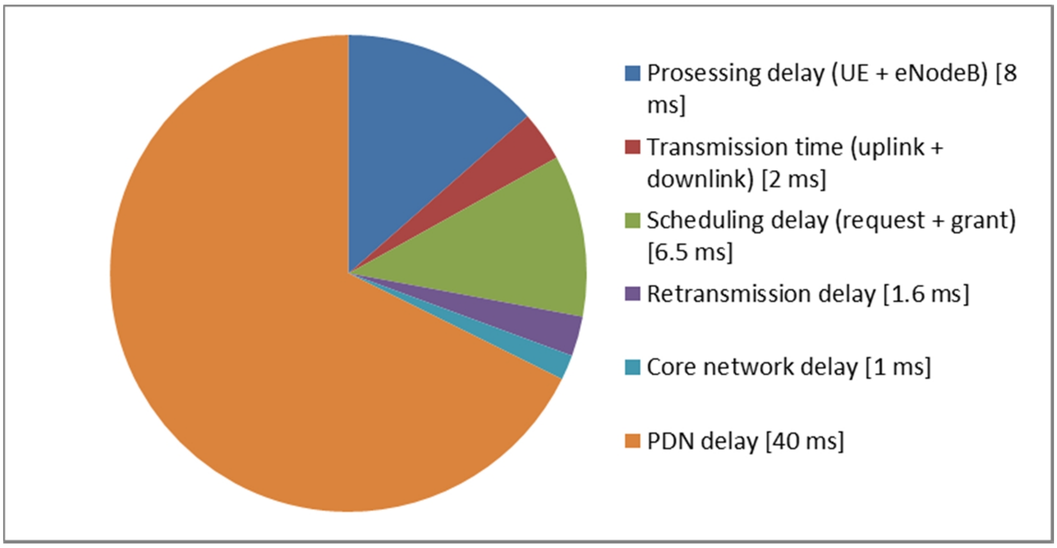


Figure 28. Components and typical proportions of LTE RTT.

Effects of a high user plane latency: Especially the real-time services can have strict delay requirements. If those requirements are not fulfilled, the QoS experienced by the users might degrade considerably.

How to measure the KPI: The RTT can be measured using drive testing.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.2 Accessibility KPIs

3.2.1 Attach Success Ratio

Description: The ratio between successful attach attempts and all attach attempts. Attach process may be unsuccessful due to two reasons: an attach failure or an attach reject. The process is declared as failed, if timer T3410 expires before the ATTACH

ACCEPT message is received, the process is rejected with an unknown cause or the lower layers indicate a failure. [25] Attach process is declared as rejected, if the MME answers to the attach request of the UE with an ATTACH REJECT message including a proper cause value.

Reasons for a low attach success ratio: The attach rejection reasons are included in the ATTACH REJECT message sent by the MME to the UE. The most typical attach reject cause values, listed in appendix B [25], are purely user subscription related and can be resolved by modifying the subscription of the user. Attach failures are typically related to problems in the lower layer processes, such as RRC connection establishment process or random access process.

Effects of a low attach success ratio: If the attach process is unsuccessful, UE is not able to register to the network and cannot utilize any network services.

How to measure the KPI: Basically, the attach success ratio can be either measured using drive testing or obtained from the network statistics. However, the network might not be aware of all attach attempts, and therefore drive testing is a much more preferable approach.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.2.2 RRC Connection Establishment Success Ratio

Description: The ratio between successful RRC connection establishment attempts and all RRC connection establishment attempts. RRC connection establishment process can be unsuccessful due to two reasons: the process is either failed or rejected. The process is declared as failed, if timer T300 expires during the RRC connection establishment process due to a failure in delivering the RRC CONNECTION REQUEST message or the RRC CONNECTION SETUP message [23]. In addition, the random access process may fail. The process is rejected when the eNodeB sends a RRC CONNECTION REJECT message towards the UE.

Reasons for a low RRC connection establishment success ratio: The admission control algorithm of the eNodeB decides about the rejection of the RRC connection requests. [5] The rejection decisions are based on an estimation that the QoS requirements of the old connections cannot be fulfilled if the new connections are allowed. The RRC connection establishment failures can be caused by many reasons, such as low signal strength, high UL/DL interference level or problems in the random access process.

Effects of a low RRC connection establishment success ratio: If the connection establishment request is unsuccessful, the UE remains in the idle state and does not get the requested service. If the attempt is rejected, the UE has to wait for a time defined by timer T302 before retrying to establish the RRC connection. In case of a failed process, there are no timers prohibiting an instant retry of the RRC connection establishment [23]. Therefore, the number of RRC connection establishments may increase rapidly when RRC connection failures start to occur.

How to measure the KPI: Basically, the RRC connection establishment success ratio can be either measured using drive testing or obtained from the network statistics. However, the network might not be aware of all RRC connection establishment attempts, and therefore drive testing is more preferable approach.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.2.3 Random Access Process Success Ratio

Description: The ratio between successful random access processes and all initiated random access processes. Random access process is declared as failed if the maximum number of preambles is reached (only when reason for the random access process is pending UL/DL data for an unsynchronized UE) or if one of timers T300, T301 or T304 expires during the random access process. [1] [22]

Reasons for a low random access process success ratio: The random access process may fail because of multiple reasons. Inadequate coverage, high interference level and mobility related problems are typical reasons for the random access failures. In addition, inadequate random access resources might create problems. For every cell, there are 64 orthogonal preamble sequences, which in typical situations lead to a collision probability of 1 % [1]. However, in a case of many simultaneous random access process initiations, the collision probability can increase to a level, which will start to cause a significant number of random access failures. For example, a train full of users in an edge of a tracking area can cause a huge amount of simultaneous tracking area updates, possibly causing a temporary depletion of the random access resources. Furthermore, non-optimal random access parameters can cause random access failures. For example, too low initial preamble power value, too small maximum number of preamble transmissions or too small increase in power between preambles can lead to failures in the random access process. Problems created by the depletion of the random access resources can be diminished with decreasing the cell size or utilizing the existing resources more efficiently by optimizing the random access parameters.

Effects of a low random access success ratio: Random access failures can lead to RRC connection failures, RRC connection re-establishment failures, handover failures or RLFs depending on the event initiating the random access process.

How to measure the KPI: Basically, random access success ratio can be either measured using drive testing or obtained from the network statistics. However, the network might not be aware of all initiated random access processes, and therefore drive testing is a much more preferable approach.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.2.4 Default EPS Bearer Establishment Success Ratio

Description: The ratio between successful default EPS bearer establishments and the total number of default EPS bearer establishment attempts. The default EPS bearer establishment can be unsuccessful due to two reasons: the establishment either fails or is rejected. The process is declared as failed if timer T3482 or T3485 expires during the process. The process is rejected if either the PDN connectivity request or the context activation request is rejected. [25]

Reasons for a low EPS bearer establishment success ratio: Typical causes for rejecting the PDN connectivity request and the EPS bearer context activation request are listed in appendixes C and D respectively. The default EPS bearer establishment failures might be caused by numerous reasons, such as random access process problems, RRC connection establishment problems, bad coverage, high UL/DL interference, problems in establishing the lower layer bearers or other lower layer problems.

Effects of a low EPS bearer establishment success ratio: As the default EPS bearer cannot be established, no IP-address can be allocated to the user and the user has no connection to the PDN. [25]

How to measure the KPI: Basically, the EPS bearer establishment success ratio can be either measured using drive testing or obtained from the network statistics. However, the network might not be aware of all initiated EPS bearer establishments, and therefore drive testing is a much more preferable approach.

Corresponding KPI in UMTS: In UMTS, the corresponding concept to the EPS bearer is the PDP context. However, the PDP context is established only when needed and has a QoS profile connected to it. Therefore, as the default EPS bearer is automatically created as a part of the attach process and has only a limited QoS profile, no corresponding KPI can be identified from the UMTS system.

3.2.5 Dedicated EPS Bearer Establishment Success Ratio

Description: The ratio between successful dedicated EPS bearer establishment attempts and the total number of dedicated EPS bearer establishment attempts. The dedicated EPS bearer establishment can be unsuccessful due to two reasons: the establishment either fails or is rejected. The process is declared as failed if one of the timers T3480, T3485 or T3486 expires four consecutive times. In addition, the bearer resource allocation request, the dedicated EPS bearer context activation request or the dedicated EPS bearer context modification request can be rejected resulting in a rejected dedicated EPS bearer establishment attempt. [25]

Reasons for a low dedicated EPS bearer success ratio: Typical reasons for rejecting the bearer resource allocation request, the dedicated EPS bearer context activation request and the dedicated EPS bearer context modification request are listed in appendixes E, F and G respectively. The dedicated EPS failures are caused by timer expiries, typically indicating a problem in the lower layer processes.

Effects of a low dedicated EPS bearer success ratio: If the establishment of the dedicated EPS bearer is not successful, the UE will not get the requested service. The UE remains connected to the PDN, if the default EPS bearer remains active, but without the dedicated EPS bearer the UE cannot request for any actual QoS guarantees for the data transfer.

How to measure the KPI: Basically, the EPS bearer establishment success ratio can be either measured using drive testing or obtained from the network statistics. However, the network might not be aware of all initiated EPS bearer establishments, and therefore drive testing is a much more preferable approach.

Corresponding KPI in UMTS: A corresponding KPI in UMTS is the PDP context establishment success ratio.

3.3 Retainability KPIs

3.3.1 Number of Radio Link Failures

Description: The UE monitors the DL RSRQ value of the serving cell periodically and compares the measured values to thresholds Q_{in} and Q_{out}. If the measured value is smaller than Q_{out} for a number of times defined by parameter N310, timer T310 is started. When the timer T310 expires, RLF is declared and the UE RRC state changes from connected to idle. However, if after starting the T310 timer (but before it expires), the measured RSRQ value exceeds the Q_{in} value for a number of times defined by parameter N311, timer T310 is stopped and no RLF occurs. In addition to T310 expiry, RLF is declared when the random access process is not successful (and timers T300, T301, T304 or T311 are not running) or if the Radio Link Control (RLC) indicates that the maximum number of retransmissions is reached. [23] [28]

Reasons for a high number of radio link failures: Reasons for a low RSRQ level of the best available cell are described in section 3.1.2. However, a low RSRQ level of the serving cell can be caused, in addition to the reasons mentioned in section 3.1.2, by problems related to mobility, such as missing neighbors or non-optimal handover parameters. In addition, problems in the random access process might be the cause of RLFs.

Effects of a high number of radio link failures: As the UE state is changed to idle, an interruption in the user place traffic is inevitable. Even if the RRC connection could be re-established immediately after the RLF, the quality of TCP based user data services is degraded considerably, real-time services are interrupted and generally the user experienced QoS is decreased. [29]

How to measure the KPI: KPI can be either measured using drive testing or obtained from the network statistics.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.3.2 EPS Bearer Cut-Off Ratio

Description: The ratio between the number of bearers deactivated without user request and the total number of established EPS bearers. The MME can signal the cause value of the deactivation to the UE or the deactivation can be done locally without any signaling. [25]

Reasons for a high EPS bearer cut-off ratio: When the network deactivates the EPS bearer, it sends a deactivation message with a cause value to the UE, indicating the reason for the deactivation. Typical reasons for the network initiated EPS bearer deactivations are listed in appendix H. Furthermore, the EPS bearer can be deactivated locally without specific signaling between the network and the UE in some special cases, such as the UE does not answer to five subsequent deactivation request messages before the expiry of timer T3495 or all radio bearers cannot be established during a handover process. [25]

Effects of a high EPS bearer cut-of ratio: When the dedicated EPS bearer is deactivated, the UE does not get the requested service anymore. Depending on the situation, user might be able to use the service with other dedicated EPS bearers or with the default EPS bearer. If the default EPS is deactivated, the UE loses the connection to the PDN altogether.

How to measure the KPI: The EPS bearer cut-off ratio can be either measured using drive testing or obtained from the network statistics.

Corresponding KPI in UMTS: A corresponding KPI in UMTS is the PDP context cut-off ratio.

3.4 Mobility KPIs

3.4.1 Number of Handovers

Description: The number of intra-system and inter-system handovers.

Reasons for a high number of handovers: The number of handovers depends on five main factors: cell sizes, strength of the cell dominance areas, mobility of the users, handover parameters and user activity factors.

Effect of a high number of handovers: All handovers initiated in LTE are hard, in which the connection between the UE and the RAN is broken for a while during the handover process. In addition, due to the possible packet forwarding in the handover process, the forwarded packets may arrive to the target UE parallel with the main data stream, causing the packets to arrive out-of-order and with varying delays. These effects may significantly reduce the user experienced QoS, especially for the TCP based services [19]. Effect of handovers to the real-time services, typically based on User Datagram Protocol (UDP), depends highly on the particular service type. Furthermore, handovers consume the network resources by introducing signaling load both to E-UTRAN and EPS.

How to measure the KPI: The KPI can be either measured using drive testing or obtained from the network statistics.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.4.2 Ping-Pong Handover Ratio

Description: The ratio between the number of ping-pong handovers and the total number of handovers. In a ping-pong handover, the UE performs a handover back-and-forth between two adjacent cells during a specific amount of time.

Reasons for a high ping-pong handover ratio: High ping-pong handover ratio is typically caused by too fast handover process, non-optimal neighbor lists and lack of cell dominance. If the handover process is too fast, the handovers are initiated too easily, and therefore varying signal strength levels cause ping-pong handovers. In case of non-optimal neighbor lists, the handovers may be performed into unwanted cell, for example, into a cell with only a small island of coverage in a particular area. Lack of cell dominance further worsens the situation, as the signal strength levels of different cells are close to each other.

Effects of a high ping-pong handover ratio: Ping-pong handovers degrade the quality of user services and consume the network resources similarly to ordinary handovers. As a difference, ping-pong handovers do not provide any gain.

How to measure the KPI: The KPI can be either measured using drive testing or obtained from the network statistics.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.4.3 Time In the Best Cell

Description: Time In the Best Cell (TIBC) is defined as the percentage of time the UE is connected to the best cell available based on the RSRP values.

Reasons for a low TIBC value: The TIBC value can be interpreted as a measurement of handover process efficiency. Slower the handover process is, lower the TIBC value becomes. Naturally, TIBC values also decreases if the mobility of the UEs increases [21].

Effects of a low TIBC value: As LTE typically uses reuse factor one, radio resources are not orthogonal between the cells. Because of this, user transmissions overlap and interfere with each other. To minimize the interference, users should be connected to the cell with a minimal path loss, since the additional path loss must be compensated with additional power causing additional interference. With low TIBC values, users are connected to non-optimal eNodeBs more often than with high TIBC values. Therefore, users with low TIBC values cause more interference to the network than users with high TIBC values. In addition, users with low TIBC values naturally experience higher path loss than users with high TIBC values.

How to measure the KPI: The TIBC values are calculated from the RSRP values of the serving cell and the best available cell. Obtaining RSRP level information from the network is described in section 3.1.1.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network.

3.4.4 Intra-LTE Handover Success Ratio

Description: The handover process can fail in multiple ways. Firstly, admission or congestion control of the target cell can reject the handover request. Secondly, the delivery of the MEASUREMENT REPORT or the HANDOVER COMMAND message may be unsuccessful. Thirdly, connecting to the target cell using the random access process may fail. [21]

Reasons for a high intra-LTE handover failure ratio: Admission and congestion control rejections are caused by a high load in the target cell. The MEASUREMENT REPORT or the HANDOVER COMMAND message delivery failures are typically caused by a too low signal quality, which is indicated by a low RSRQ-value. Connection to the target cell is declared as failed if timer T304 expires before the connection between the UE and the target eNodeB is successfully established [23].

Effects of a high intra-LTE handover failure ratio: In case of admission or congestion control rejections or failures in the delivery of the HANDOVER COMMAND message, the handover process halts and the connection between the UE and the source eNodeB persist. Although the connection of the UE is not affected by the handover failure, the handover process is initiated because the signal level of the target cell is higher than the signal level of the source cell. Therefore, it is likely that the service quality of the user is poor and the connection may fail, especially if the UE is moving towards the target cell [29]. In case of a failure in the random access process, the UE tries to re-establish the RRC connection [23]. If the re-establishment is successful, much smaller interruption in the connection occurs compared to a failed re-establishment. In case of a failure in the connection re-establishment, the UE changes its state to idle and performs a new RRC connection establishment. As a result, user data service quality is considerably degraded.

How to measure the KPI: The intra-LTE handover success ratio can be either measured using drive testing or obtained from the network statistics.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network. However, in UMTS two types of handovers should be distinguished: hard handovers, where UE can be connected only to one base station at time, and soft handovers, where UE can have multiple active connections into different base stations simultaneously. Most of the handovers within UMTS are soft, but as an exception, inter-frequency handovers and HSDPA handovers are always hard.

3.4.5 Handover Delay (Detach Delay)

Description: Handover delay is defined as the time the UE is not connected to the E-UTRAN during the handover process, i.e., the delay between starting and stopping timer T304.

Reasons for a high handover delay: Since the handover delay is dominated by the delay of the random access process [1], long detach delays are typically caused by random access process problems.

Effects of a high handover delay: The interruption in the connection causes degradation in the user experienced QoS. Obviously, the longer the interruption is, the more significant the degradation becomes. Effects of the detach time are considered in more detail in section 3.4.1.

How to measure the KPI: The detach delay can be measured using drive testing.

Corresponding KPI in UMTS: A similar KPI can be measured from UMTS network for the hard handovers. However, most of the handovers in UMTS are soft, in which no handover delay occurs.

4 Self-Organizing-Networks

Minimizing the effort of maintaining the network, thus reducing the operational expenditure, is one of the fundamental goals of any network operator. SON concept introduces functionalities which automatically configure, optimize and heal the network, helping the operators to achieve this goal. 3GPP specifications define a framework for the SON functionalities, but the actual implementations of the SON functions are vendor specific. The gains of different SON functions have been investigated in many scientific researches. However, only a little experience has been gathered from the live networks, since only a few SON functionalities have been actually utilized by the operators. This chapter introduces the possible SON architectures and the most significant SON use cases. In addition, the disadvantages, the advantages and the feasibility of each function are investigated.

4.1 SON Architectures

SON functionalities can be basically implemented utilizing four different architectural models: localized, distributed, centralized and hybrid. All of these approaches have their own advantages and disadvantages with respect to, for example, speed, complexity, database size and signaling load. This section introduces the four basic SON architectures and describes their main characteristics.

4.1.1 Localized Architecture

In a localized SON architecture, the SON functions are located in the eNodeBs. No SON related information is exchanged between the eNodeBs, and the optimization decisions are made based on local information only. Basically, the optimization decisions can only have an effect in the service area of the eNodeB running the algorithm, because the effects of the optimization decisions to the adjacent cells are unknown to the SON algorithm. The localized SON architecture has no restrictions about the scalability, because the SON functions operate independently and no signaling is required. The lack of signaling also makes the decision making extremely fast. In addition, introduction of the localized SON features is straightforward, since the features can be added to the eNodeBs one by one, and interactions between the network elements do not need to be considered. A typical use case for the localized SON architecture is the random access process optimization. Localized SON architecture is illustrated in figure 29.

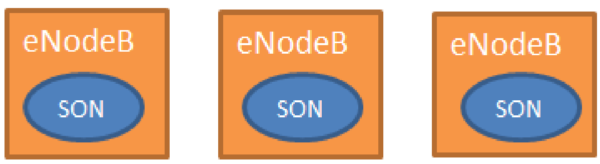


Figure 29. Localized SON architecture.

4.1.2 Distributed Architecture

In a distributed SON architecture, the SON functionality is distributed into the eNodeBs and the X2 interface is used to exchange SON related signaling between the adjacent eNodeBs. As the SON algorithm has knowledge about the effects of the optimization decisions to the adjacent cells, distributed architecture enables the implementation of more complex optimization functionalities compared to the localized architecture. However, the optimization decisions can be based on the information of only a few adjacent eNodeBs, since the signaling between two distant eNodeBs via the X2 interface is not feasible. Therefore, implementing complex optimization cases requiring the co-operation of many eNodeBs is difficult. In addition, as the optimization algorithms of the different eNodeBs interact with each other, the stability and the convergence must be ensured in local, regional and network level. The speed of the optimization decisions is much slower compared to the localized architecture, due to the X2 signaling delays. Although a single eNodeB can interact with only a few neighboring eNodeBs, distributed SON architecture can be used to create network wide SON functionalities. Typical use cases for the distributed SON architecture are the mobility robustness optimization and the load balancing. Distributed SON architecture is illustrated in figure 30.

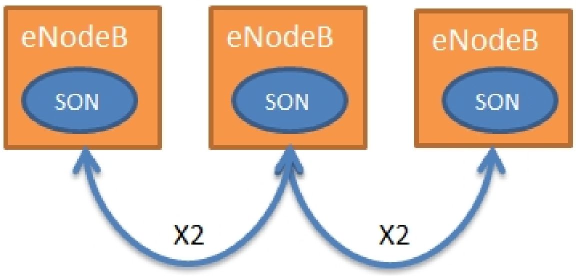


Figure 30. Distributed SON architecture.

4.1.3 Centralized Architecture

In a centralized SON architecture, the SON functionality resides in the Operation and Maintenance (O&M) system. The centralized architecture enables SON features, which utilize network wide information and allows the implementation of complex optimization scenarios. The actual optimization decisions are made in a centralized entity, which must be able to handle massive amounts of data. As the number of eNodeBs grows, the amount of signaling towards the centralized SON entity becomes too high to handle, and therefore, the centralized architecture does not scale well into large networks. Centralized SON functions react slowly to the changes of the network due to the delays in the signaling. Typical use cases for the centralized SON architecture are the Capacity and Coverage Optimization (CCO) and the Cell Outage Management (COM). Centralized SON architecture is illustrated in figure 31.

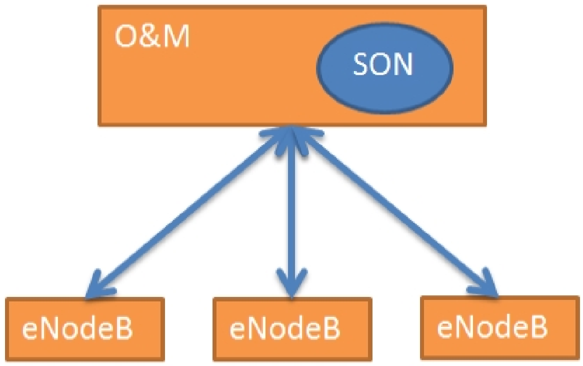


Figure 31. Centralized SON architecture.

4.1.4 Hybrid Architecture

Hybrid SON architecture is a mixture of localized, distributed and centralized architectures. Simple optimization tasks requiring only local information are executed in the eNodeBs. More complex tasks can be executed between a set of adjacent eNodeBs utilizing the signaling via the X2 interface, and the most complex tasks requiring network wide information in the O&M system. Hereby, hybrid SON architecture enables a flexible implementation of different SON algorithm types. Hybrid architecture also allows the interaction between the SON functions enabling, for example, the information gathered by a centralized function to be utilized by a distributed function. Hybrid SON architecture is illustrated in figure 32.

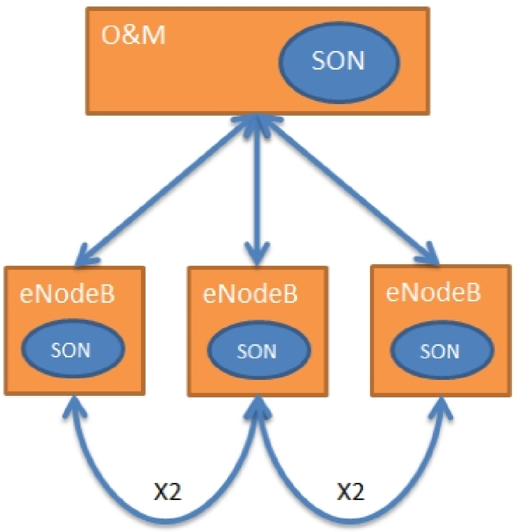


Figure 32. Hybrid SON architecture.

4.2 SON Use Cases

4.2.1 Automated Neighbor Relations

Imperfect neighbor lists degrade the performance of the network by creating many problems, such as RLFs, handover failures and unevenly distributed traffic load. Automated Neighbor Relations (ANR) is a SON functionality, which automatically maintains the Neighbor Relations (NR), and thus aims to reduce the operation and management efforts of the operator. A conceptual diagram of the ANR operation, defined by 3GPP [18], is illustrated in figure 33.

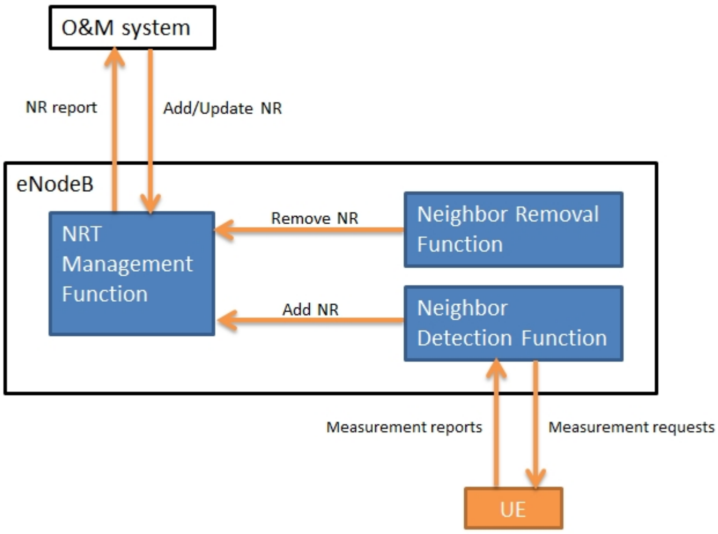


Figure 33. Functional operation principle of the ANR.

The actual ANR functionality resides in the eNodeB and basically no interaction with the adjacent eNodeBs is needed. The neighbor detection function adds NRs to the Neighbor Relation Table (NRT) of the eNodeB based on the UE measurements. Many different measurement policies can be defined, such as periodical or threshold based. The neighbor removal function deletes the outdated NRs. The implementation of both the neighbor removal function and the neighbor detection function are vendor specific. NRT management function maintains the NRT based on the messages of the neighbor removal and the neighbor detection functions. In addition, the NRT management function reports the NRT changes to the O&M system and allows the O&M system to update, add or delete NR entries. The following parameters, which can be controlled by the O&M system, provide some additional control for the operator: [18]

- **No Remove:** If active, the NR cannot be removed from the NRT by the neighbor removal function. This parameter can be used, for example, to ensure that critical NRs will not be removed.
- **No Handover:** If active, no handovers will be executed towards the particular NR. This parameter can be useful, for example, if a distant cell creates a small

island of coverage in the service area of the serving cell. Depending on the implementation of the neighbor detecting function, a NR can be created towards the distant cell causing unwanted handovers. To prevent this, "No Handover" –parameter can be checked.

- **No X2:** If active, the NR cannot use X2 interface to initiate processes towards the eNodeB of the target cell. [18]

Successfulness of the ANR function is determined by the implementation of the neighbor removal/detection functions and the measurement/reporting policies. If the measurement/reporting policies are chosen poorly, the information provided to the ANR function may be inadequate or biased. This may result in a non-optimal network performance. In addition, the neighbor detection/removal functions may not be able to utilize the given information properly, resulting in missing or unwanted NRs.

Major vendors, such as Ericsson [31], Nokia Siemens Networks [32] and Huawei [33] have developed their own ANR products. In addition, also the operators have utilized ANR in their networks [33] [31]. There are multiple reasons for the success of the ANR, such as the possibility to implement ANR basically with localized SON architecture; easily achievable stability and convergence; the possibility to introduce ANR into one eNodeB at time; accurate technical specification of the 3GPP; and the relatively simple relations between the reported signal levels and the neighbor lists.

4.2.2 Energy Saving

Energy costs compose a substantial part of the overall operating expenditures of a mobile network. To decrease the energy consumption, 3GPP has defined a SON energy saving use case for networks, where the cells providing additional capacity can be distinguished from the cells providing basic coverage. The idea is to deactivate the cells providing additional capacity when the capacity demand is low, and reactivate them again when the additional capacity is needed. The cell activation/deactivation decisions are based on the cell load information. The actual implementation of the energy saving functionality is vendor specific, but some common guidelines can be defined. [18]

SON energy saving algorithm monitors the load of the cells providing additional capacity, denoted as capacity boosters, and the loads of their adjacent cells. The function, in its simplest form, deactivates the capacity booster cells which load is under a certain threshold for long enough. The algorithm must ensure that the adjacent cells are loaded lightly enough to handle the traffic of the deactivated capacity boosters. The capacity booster cells are again reactivated if the load of the adjacent cells is raised over a predefined threshold for long enough. To prevent cells from activating and deactivating back-and-forth, the activation threshold must be considerably higher than the deactivation threshold and the time threshold should be long enough. In addition, in areas with multiple capacity booster cells, the activation/deactivation process must have a built-in randomness to decrease the probability of multiple cells activating/deactivating simultaneously.

The implementation of the energy saving algorithm should be based on a distributed architecture. The deactivation decisions are done in the eNodeBs owning the capacity booster cells. The X2 interface is used to signal the load information from the adjacent eNodeBs and to inform them about the deactivations. The activation commands are delivered by the adjacent eNodeBs via X2 interface. In addition, the O&M system must be able to adjust the deactivation and the activation policies.

The cell activation/deactivation concept has its limitations. Firstly, 3GPP specification basically just introduces the idea of saving energy with deactivations, leaving the whole design and implementation process of the functionality to the vendors. Secondly, the concept cannot be used to compensate for quick capacity demand changes. The distributed architecture can offer a rather fast response time, but the cell ramp up and ramp down processes typically take some time. In addition, cell activations and deactivations cause a considerable amount of handovers and rapid changes in the network interference level. These effects may have an effect on the user experienced QoS, especially if occurring constantly. Thirdly, the usage of the concept is restricted by the fundamental assumption of having separate cells for providing coverage and separate cells for boosting the capacity. As LTE is basically a reuse one system, overlapping coverage is avoided to minimize the inter-cell interference. Therefore, it is untypical to have a clear division of cells providing coverage and cells providing capacity. Obviously, by utilizing multiple frequency bands, a layered cell structure can be achieved, but especially in the deployment phase of a network, operators tend to utilize only a single frequency. The energy saving goal is visible in many SON related papers written by the vendors and the academic community, but 3GPP standard based live network implementations have not been publicly announced.

4.2.3 Load Balancing

In a typical cellular network, users with varying service requirements are unevenly scattered over the coverage area of the network, causing varying cell load levels. To maximize the user experienced QoS and the performance of the network, the load should be spread among the network as evenly as possible. To fulfill this goal, 3GPP has defined a SON load balancing use case, in which the handover parameters are dynamically adjusted to bias the handover process, thus balancing the load between the adjacent cells. [18] [34]

To enable load balancing, at least some level of overlapping coverage must exist. In case of intra-frequency cells, the overlapping areas are planned to be small to minimize the inter-cell interference. Therefore, load balancing between intra-frequency cells typically affects only the CEU. In case of inter-frequency cells, the overlapping areas may be considerably larger, and therefore the load balancing may affect users in all parts of the network. A functional architecture of the SON load balancing algorithm, defined by 3GPP, is illustrated in figure 34. The load reporting function exchanges cell specific load information with the adjacent eNodeBs via X2 interface. Based on the load information, the load balancing function may initiate handovers to the adjacent cells by using the handover function or request the adjacent eNodeBs to change their handover parameters by using the handover parameter adaptation function. In addition, the load balancing function may change the handover parameters of its own cells. The implementations of the functions are vendor specific, but some guidelines can be defined. [18]

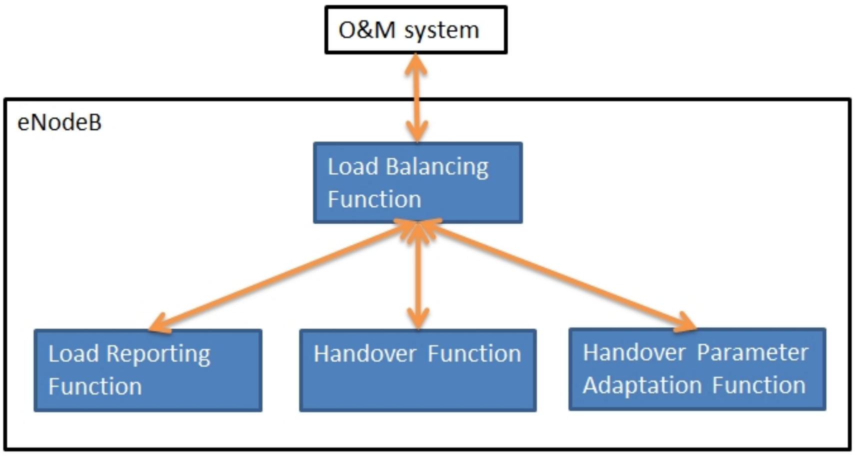


Figure 34. Functional operation principle of the load balancing.

Both load balancing mechanisms, adjusting the handover parameters and initiating load balancing handovers, can be used to distribute the load effectively. However, when using the handover parameter adjustment method, the cell selection parameters can be adjusted as well. If the cell selection parameters do not correspond with the handover parameters, the amount of handovers executed instantly after RRC connection establishment may be high. The load balancing handovers should be distinguished from the normal mobility handovers, whereupon appropriate admission control mechanisms can be applied. The actual load balancing algorithm running in the eNodeB should perform the following tasks: [34]

- Monitor the load of the own cells and exchange the cell load information with the adjacent eNodeBs via X2 interface.
- Determine the need to perform load balancing. In addition, determine the load balancing method and the load balancing target.
- If using load balancing handovers, initiate the handovers to the target cell with a 'load balancing' cause. If using handover parameter adjustment, determine the modified parameters, change own parameters or request the target eNodeB to modify its parameters.

Basically, the handover parameter adaptation function can modify any of the parameters used in the handover process. In practice though, some parameters are more feasible than others. In case of a layered cell structure, modifying the layer priorities is an efficient tool to bias the handover process towards particular cells. In addition, from the equal priority reselection parameters, the hysteresis value Q_{hys} and the offset value Q_{offset} can be modified. The actual implementation of the load balancing algorithm should be based on a distributed SON algorithm, in which the actual SON intelligence resides in the eNodeBs and O&M system is used only to make configuration changes to the algorithm parameters. To reduce the back-and-forth changes, the parameter changes should be based on averages over a relatively long time period [35]. In addition, rapid changes in the parameters should be avoided, which is achieved by modifying the parameters only in small steps [34].

A smoothly working load balancing function is particularly useful between inter-frequency cells, in which the cell overlapping is typically significant. Between intra-frequency cells, load balancing algorithm cannot typically make a major difference, since the overlapping coverage is relatively small. Adaptive load balancing is one of the main SON features, and the vendors seem to believe in its potential. However, no implementations in the live networks have been announced or publicly tested.

4.3.4 Cell Outage Management

As a cellular network consists of a major number of eNodeBs, it is common that a portion of cells is not operational at a given time. Cell outages can occur from multiple reasons, such as transmission faults, hardware faults, misconfigurations and power outages. Regardless of the reason, cell outages typically degrade the user experienced QoS, create coverage holes and decrease the overall network performance. The goal of the COM is to alleviate the effects of the outage by adaptively altering the parameterization of the cells surrounding the outage area. The COM function can be divided into two subfunctions: the Cell Outage Detection (COD) function and the COC function. The main task of the COD function is to detect the cell outages and deliver the outage information to the COC function. Basically, the COD function can utilize any available information, such as performance counters, network statistics, alarms or even subscriber complaints. The COC function, which makes the actual parameterization changes, can utilize information similar to the COD function to investigate the effects of the parameterization changes. A basic functionality of the COM is illustrated in figure 35.

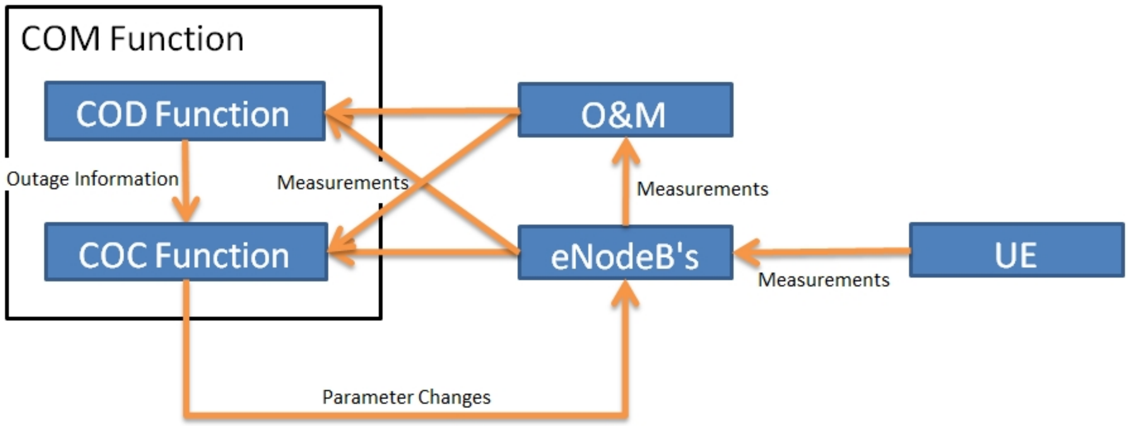


Figure 35. Operation principle of the COM functionality.

The actual compensation process is an iterative process, in which the selected control parameters are changed gradually based on the evolution of the selected KPIs. The selection and the weighting of the KPIs depend on the operator policy, i.e., which performance aspects the operator considers most important. The operator policy can be, for example, capacity, quality or coverage driven. Typical examples for investigated KPIs are throughput, number of RLFs, cell load, interference level and RSRP level. For the control parameters, there are numerous candidates. Basically, any parameter which can be adjusted without human intervention and has an effect to the radio network behavior can be seen as a potential control parameter. In practice thought, other parameters are more feasible than others. Typically, the best control parameters affect either the coverage and/or the interference level. Examples of possible control parameters are:

- Transmitted RSRP level. The cell dominance area can be modified by adjusting the power of the reference signals. The size of the dominance area has a direct impact to the cell load.
- Overall transmit power. In UL, increasing the transmit power in an outage situation is not feasible due to strict maximum power limitations. In DL, the possibility to increase the transmit power in an outage situation requires that a portion of the total power is not used in normal operation.
- Antenna parameters. Antenna tilt, antenna azimuth and antenna radiation pattern are effective parameters for adjusting the cell footprint and managing the network interference level. Modern antennas allow the adjustment of the antenna parameters remotely, making the antenna parameters excellent COC control parameter candidates.
- ICIC parameters. ICIC parameter can be used to modify the interference level of the network effectively both in UL and DL.
- Cell load. Reducing the cell load reduces the network interference level.

The actual COM implementation can be either centralized or distributed solution based. The main drawbacks of the centralized SON architecture, slow decision speed and poor scalability, are not issues in the COM. This is because the cell outage frequency is typically rather small, the outages typically last relatively long time (hours instead of seconds) and the SON functionality has to simultaneously interact with only a few eNodeBs. In addition, the benefits of the centralized solution, such as simple implementation, can be fully utilized making the centralized approach the best option for most COM optimization schemes. COM is a central part of the SON framework and many papers have been written concerning the subject, for example, research done as a part of the SOCRATES project [36]. However, live network implementations have not been seen.

4.3.5 Mobility Robustness Optimization

The goal of the mobility robustness optimization is to optimize the parameters utilized in the handover and the cell (re)selection processes. Suboptimal mobility parameters create many unwanted effects, such as RLFs, handover failures and ping-pong handovers. All of these problems degrade the network performance and the user experienced QoS, but the handover problems leading to RLFs cause the most considerable degradation. Therefore, the reduction of RLFs can be seen as the primary goal of the mobility robustness optimization and the mitigation of other mobility problems as the secondary goal. 3GPP has defined a basic framework for identifying the cause of the handover problems. The basic idea is to divide handover problems into three exclusive categories: [18] [34]

- Handover failures caused by too slow handover process
- Handover failures caused by too fast handover process
- Handover failures caused by handovers to unwanted target cells

The identification process is based on two subprocesses: the RLF indication process and the handover reporting process. Using the RLF indication process, the target eNodeB can inform the source eNodeB about an RRC connection re-establishment, in which the serving cell before the RLF belonged to the source eNodeB [37]. Using the handover reporting process, the target eNodeB can inform the source eNodeB about a RLF that occurred instantly after a handover from the source eNodeB to the target eNodeB [37].

In case of failures caused by a too slow handover process, the handover parameters are not aggressive enough. Therefore, the connection between the UE and the source eNodeB breaks during the handover process or before it is initiated. Too slow handover process is characterized by a RRC connection re-establishment to the target cell after a RLF in the source cell. To inform the source eNodeB about the RRC connection re-establishment of the UE, the target eNodeB utilizes the RLF indication process over the X2 interface. The destination for the RLF indication message is acquired from the RRC connection re-establishment message. To summarize, a RLF and reception of a RLF indication message concerning the same UE shortly after the RLF, indicates that the handover process might be too slow. The signaling flow of too slow handover is illustrated in figure 36.

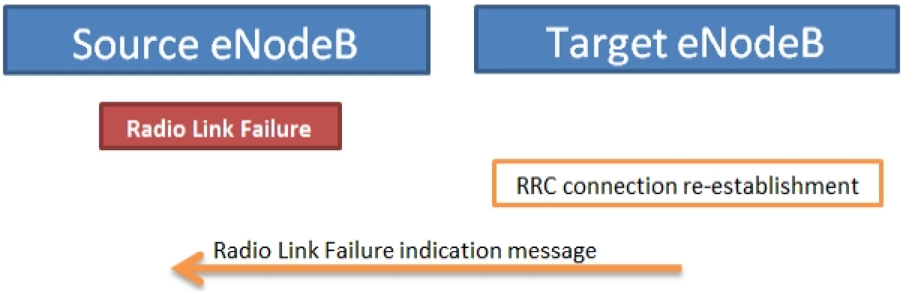


Figure 36. Signaling flow of too slow handover.

In case of a failure caused by too fast handover process, the handover parameters are too aggressive, which causes the connection between the UE and the target eNodeB to disrupt during the handover process or immediately after it. Too fast handover process is characterized by a RRC connection re-establishment to the source cell after a RLF in the target cell. Similarly to too slow handovers, the source eNodeB indicates the RRC connection re-establishment to the target eNodeB by using the RLF indication process. However, since the UE has performed a handover from the source cell to the target cell recently, the target eNodeB should inform this to the source eNodeB with a handover report message. To summarize, reception of a handover report message (with problem type "too early handover") indicates that the handover process is too fast. The signaling flow of too fast handover is illustrated in figure 37.

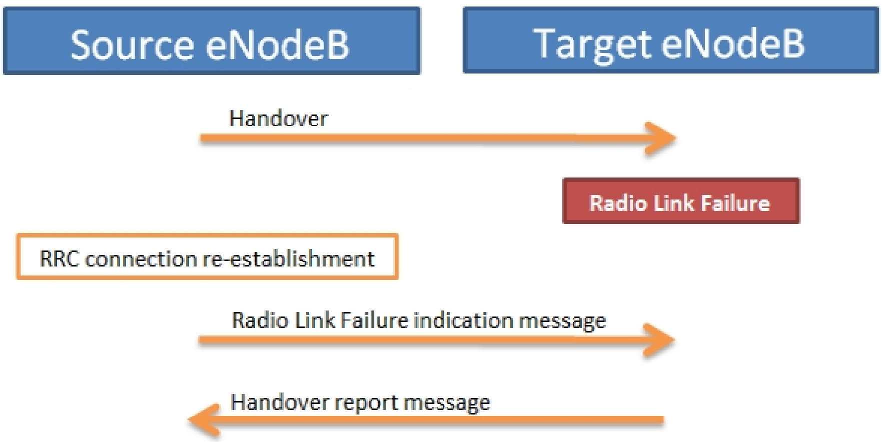


Figure 37. Signaling flow of too fast handover.

In case of a failure caused by a handover to an unwanted target cell, the connection is disrupted during the handover process or immediately after it. The UE re-establishes the connection to a cell, which is not owned either by the target eNodeB or the source eNodeB. The eNodeB into which the UE re-establishes the connection, informs the target eNodeB about the re-establishment. Since the UE has executed a handover into the target cell within a time threshold, the target eNodeB informs this to the source eNodeB by sending a handover report message. [34] To summarize, reception of a handover report message (with problem type "handover to wrong cell") indicates that the handover parameter and/or the neighbor lists might not be optimal. The signaling flow of handover to unwanted cell is illustrated in figure 38.

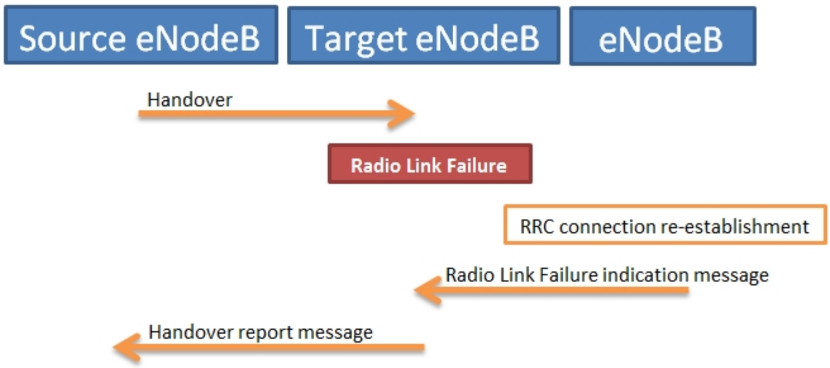


Figure 38. Signaling flow of a handover to unwanted cell.

The signaling mechanisms described in this section give a solid basis for the implementation of a mobility robustness SON algorithm. A natural choice for the SON architecture type is distributed, since all the required information can be easily delivered via X2 interface. The actual feasibility and the effectivity of the mobility robustness optimization depend greatly on the actual implementation of the developed algorithm. In addition, many implementation decisions have a significant impact on the overall performance of the algorithm, such as how easily the mobility parameters are altered, how big variation is allowed on the parameters and how the convergence of the algorithm is ensured. A mobility robustness optimization algorithm based on 3GPP signaling framework could diminish the number of handover related RLFs considerably, but as a downside, it cannot be used to alleviate the effects of any other handover related problems.

4.3.6 Capacity and Coverage Optimization

Providing both adequate coverage and capacity is a fundamental requirement for any mobile network. The goal of the CCO is to fulfill the coverage and capacity requirements by altering the radio parameters automatically based on the information gathered from the network. 3GPP has defined the CCO as one of the SON use cases, but solutions to implement the CCO functionality has not been developed. In the Release 10 SON requirements [38], 3GPP defines four simple scenarios, in which the CCO should be able to identify and fix the capacity/coverage related problems. The simplicity of the 3GPP scenarios and the lack of implementation guidelines reflect the fact that optimizing the network coverage and capacity is an extremely difficult task. However, some solutions to implement CCO functionality have been researched, for example, a solution utilizing Adaptive Antenna Systems [39]. Basically, the CCO can be seen as a general case of the COC, and therefore similar control parameter and functionality could be applied. As a difference, the COC algorithm has more a priori information than the CCO algorithm, since it is executed only when an outage occurs. At the moment, the CCO is only a concept and it will probably take some time before the vendors have their implementations ready.

4.3.7 Self-Configuration

The goal of the SON self-configuration use case is to decrease the manual effort of adding a new eNodeB to the network, by automatizing the eNodeB configuration process. The installation of a totally self-configuring eNodeB could be done without the presence of a radio-expert just by powering up and plugging in the eNodeB. As a result, the cost of the installation and the probability of configuration errors would decrease since the amount of manual work would be minimized. According to the 3GPP standards, eNodeB should move to a pre-operational state after it is powered up and the transmission cable is connected. In the pre-operational state, eNodeB configures itself by performing the following tasks: [18]

- Perform self-testing including detection of transport type, hardware configuration, antenna configuration, antenna cable lengths and Mast Head Amplifiers (MHA).
- Establish IP level connectivity to the EPC
- Establish required O&M, X2 and S1 connections
- Authenticate with the network
- Load required software and licenses
- Load radio parameters
- Load neighbor list information

It should be noted, that the radio parameters, the transmission parameters and the neighbor lists must be planned beforehand to enable the automatic configuration. Obviously, when the actual optimization solutions are mature enough, a basic set of parameters could be utilized in the self-configuring and the parameters could be optimized when the eNodeB is in the operational state. The SON self-configuration use case does not renew the eNodeB deployment process significantly compared to the processes utilized nowadays. At the moment, base stations are typically configured with configuration files exported from the network design or management systems. As the configuration files include all the required information for the base station operation, basically no manual configuration work is required on-site. In addition, automatic software/license loading is widely utilized.

5 Cell Outage Compensation

5.1 Introduction

As the COC is a promising part of the SON concept, a simulation study was performed to evaluate the potential and the possible gains of the COC principle. The simulations were performed using ASSET 7.0, a multi-technology radio network planning and optimization tool developed and maintained by Aircom International. ASSET, which is a part of bigger software family called Enterprise suite, is widely used by many operators and companies in the telecommunication business.

The actual simulations were done by investigating two different scenarios: a small failure with two nonoperational eNodeBs and a major failure with 12 nonoperational eNodeBs. The nonoperational eNodeBs were adjacent to each other, forming a continuous outage area. In both scenarios, the effects of the outage were investigated to understand the factors degrading the user experienced QoS and the network performance. Based on the observed effects, two COC control parameters were selected and their feasibility was investigated. In addition, a simple algorithm, based on the selected control parameters, was developed and the performance of the algorithm was evaluated in both outage scenarios.

5.2 Cell Outage Compensation Objectives

As discussed in section 4.3.4, the goal of a COC algorithm is to alleviate the effects of an outage. Depending on the operator policy, this goal can be pursued using different methods, such as maximizing the network throughput or trying to offer at least basic level of service to all users. However, regardless of the operator policy, the fundamental purpose of any mobile network is to make profit, and a key tool to make profit is to keep the users satisfied. Therefore, in this thesis the goal of the COC is seen as maximizing the number of satisfied users. A satisfied user is defined as a user fulfilling the following requirements:

- RSRP and RSRQ levels are adequate
- Achievable UL/DL SINRs are adequate
- The serving cell has enough capacity to support a bit rate equal or higher than the GBR defined in QoS profile of the user

Naturally, this kind of approach requires some level of QoS classification implemented to the network, which is not generally done nowadays. However, as the LTE has only a packet switched domain and operators likely wish to support also services having GBR requirements, QoS mechanisms will probably be widely implemented into LTE networks.

5.3 Simulation Environment

5.3.1 Network Parameters and eNodeB Grid

The simulations were performed in Frequency Division Duplexing (FDD) mode, with a carrier frequency of 1800 Mhz and a frequency band of 10 Mhz both in UL and DL. In addition, normal cyclic prefix length was used and no ICIC schemes were utilized. The actual simulation environment was a typical Finnish suburban area of 57 km^2 consisting of forest, open areas, fields, residential areas, industrial areas and commercial areas. The whole simulation area was relatively hilly with altitude differences up to 90 m. The base station grid was built up from 38 eNodeBs distributed to the simulation area according to typical network planning criteria, such as user distribution and land shapes. The simulations were executed in the whole 57 km^2 simulation area, but to highlight the differences between the simulation runs, the simulation results were gathered only around the actual outage areas.

5.3.2 Cells

Each eNodeB in the simulation area had 1-3 cells, resulting in total number of 109 cells. The maximum transmit power of every cell was set to 43 dBm, according to typical LTE eNodeB performance. Each cell had two receive and two transmit elements. The antenna parameters, such as antenna radiation pattern and antenna gain were derived from the antenna data specification of a typical 1800 Mhz capable LTE antenna. Antenna azimuths and antenna tilts varied between the cells similarly to live networks. In addition, every cell was defined as MIMO capable, providing both spatial multiplexing and transmit diversity in DL. In UL, only receive diversity was supported.

5.3.3 Clutters

A category type denoted as a clutter was defined for each point in the simulation area. Clutters specify the characteristics of a particular area. Totally ten different clutter types were defined, including forest, high-rise building area, water, detached house area and industrial area. The clutter types were utilized for two different purposes: calculating the signal attenuations (more information in 5.3.4) and defining the terminal distribution (more information in 5.3.5). The clutter map of the simulation area is illustrated in figure 39.

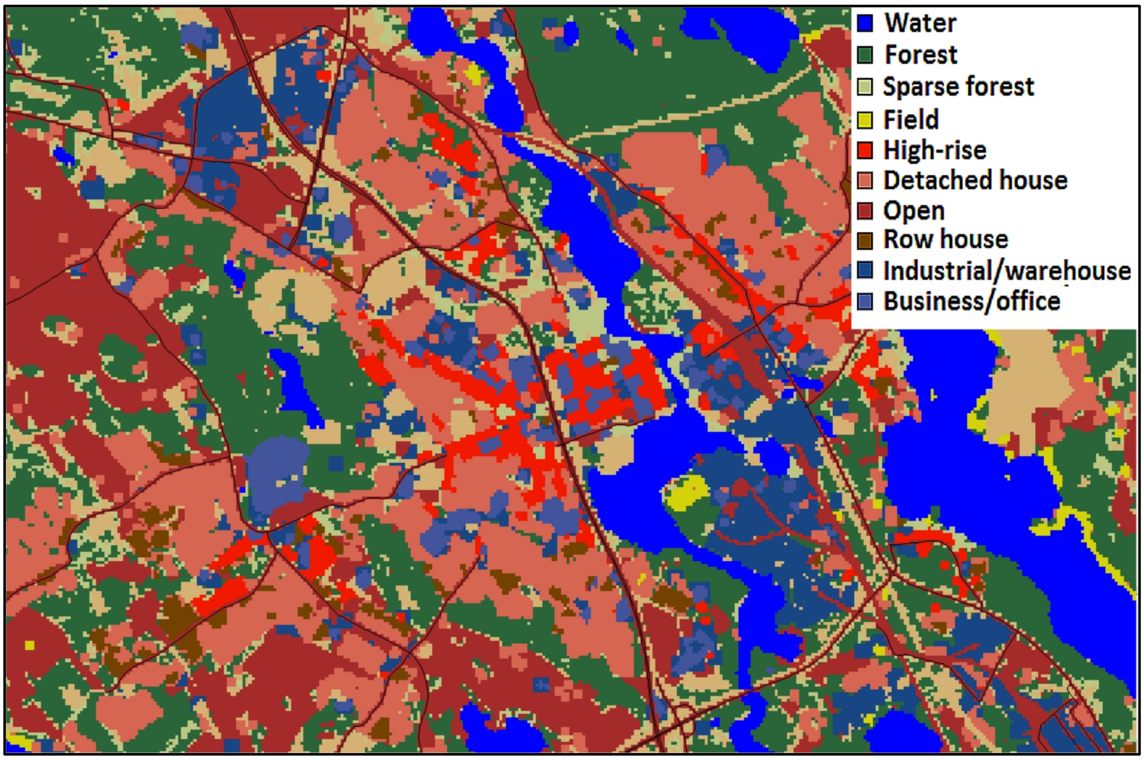


Figure 39. Clutter map of the simulation area.

5.3.4 Propagation Model

The propagation model, which is used to estimate the signal attenuation between the transmitter and the receiver, is extremely important for the reliability of the simulation results. The utilized propagation model is presented in an analytical form in equation 1, where k1/k2 are the factors defining the intercept and the slope of the distance dependent path loss, d is the distance between two nodes, k3/k4 are the correction factors for the UE antenna height gain, H_{ms} is the UE antenna height above ground level, k5/k6 are the correction factors for the effective eNodeB height, H_{eff} is the effective eNodeB height, k7 is the correction factor for the diffraction loss, L_{diff} is the diffraction loss and $L_{clutter}$ is the clutter loss.

$$
\begin{aligned}
Path\ loss = \ & k1 + k2 * \log_{10}(d) + k3 * H_{ms} + k4 * log_{10}(H_{ms}) + \\
& k5 * log_{10}(H_{eff}) + k6 * log_{10}(H_{eff}) * log_{10}(d) + \\
& k7 * L_{diff} + L_{clutter} \qquad (1)
\end{aligned}
$$

Parameters k1, k2, k3, k4, k5, k6 and k7 are used for tuning the propagation model for the simulated network environment. H_{eff}, describing the relative height of the eNodeB compared to the UE height, is defined as a subtraction between the eNodeB height and the UE height above sea level. L_{diff} is calculated using Epstein-Peterson method [40] and $L_{clutter}$ is calculated utilizing clutter information of the areas between the UE and the eNodeB. For each clutter type, four parameters have been defined: through-loss, through-loss distance, offset-loss and indoor loss. The first parameter, through-loss, defines the amount of additional signal attenuation caused by the clutter type when the signal propagates through the particular area. The second parameter, offset-loss, defines how much the signal attenuates when arriving at a particular clutter type. The third parameter, through-loss distance, defines which points between the UE and the eNodeB are taken into account in the total clutter loss calculation. The fourth clutter parameter, indoor loss, defines the additional signal attenuation for the indoor terminals.

5.3.5 Terminals

A weight illustrating the terminal density was defined for each clutter type. Based on these weights, totally 1200 terminals were distributed to the simulation area. This approach models the fact that in some areas the average number of users is higher than in other areas. For example, in a forest clutter the typical number of users is considerably lower than in a high-rise building clutter. In addition, a terminal indoor probability was defined for each clutter.

All terminals had two receive elements and one transmit element. In DL, spatial multiplexing and receive/transmit diversity were supported. Only receive diversity was utilized in UL, due to one receive element of the UE. All DL and UL modulation types were supported, excluding UL 64-QAM. The maximum UL transmit power was set to 24 dBm and the minimum RSRP and RSRQ values to -125 dBm and -19 dB respectively.

5.3.6 Services and Bearers

Two different service types were introduced: a VOIP service and a best effort service. Half of the users were set to use the VOIP service and the other half the best effort service. The VOIP service had a GBR and a MBR requirement of 32 Kbit/s both in UL and DL. As the MBR was very low, terminals running the VOIP service did not utilize any extra capacity, even if it would be available. In contrast, the best effort service did not have any GBR requirements. The MBR of the best effort service was initially set to unlimited both for UL and DL, and therefore the best effort services utilized as much capacity as available.

The scheduler, which divides the available resources between the individual users, had a primary goal of guaranteeing the GBR requirements of the terminals using the VOIP service. If additional resources were left over, the extra resources were divided between the best effort users utilizing a proportional fair [41] scheduling algorithm. The proportional fair scheduler allocates the resources rather equally between the terminals, still taking into account the instantaneous channel conditions of the individual users.

5.4 Simulation Process

The simulation process, consisting of multiple subsequent steps, is illustrated in figure 40. The process begins with defining the initial simulation parameters, such as the eNodeB locations, the number of users, the clutters, the UE service types, the power parameters and the propagation environment information. After once defining the initial parameters for both scenarios, the parameters are loaded from a configuration file in the beginning of each simulation run. After starting the simulation and defining the initial parameters, the path loss predictions are calculated between every site and every point of the simulation area. The path loss prediction calculations are based on the propagation model defined in 5.3.4.

In the next step, the Monte Carlo simulation, multiple static simulations denoted as snapshots are executed subsequently. In each snapshot, the terminals are distributed to the simulation area randomly based on the user-defined distribution. After defining the locations of the terminals, iterative radio condition and resource sharing calculations are executed to determine an estimation of the network state with given parameters. In addition, multiple failure conditions for each terminal are tested, such as testing of RSRQ and RSRP levels. The number of snapshots is a user defined variable, depending on the required accuracy of the results. Obviously, increasing the number of snapshots also increases the simulation time linearly. In this thesis, as a compromise between the accuracy and the required time 500 snapshots were used in all simulation runs. After the completion of every snapshot, average results are calculated from the snapshot values and the results are saved. In addition, the investigated control parameter values are altered according to the simulation plan and the simulation cycle is restarted from the path loss prediction phase. After the simulation of all control parameter combinations of interest, the simulation results are post-processed with various tools.

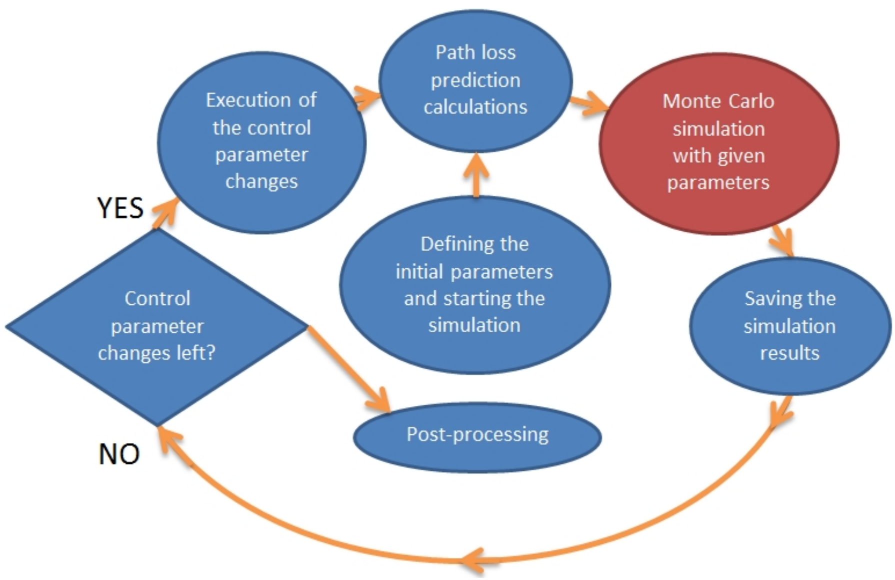


Figure 40. An illustration of the simulation process.

5.5 Effects of an Outage

This section investigated the effects of both failure scenarios on the network performance and the user experienced QoS. The results of this section are utilized in the latter sections to select the most feasible control parameters for a COC algorithm. The effects of the outage on the network performance are evaluated based on five KPIs:

- RSRP of the best cell
- RSSI level
- RSRQ of the best cell
- Required UL transmit power
- UL interference level

The objective of these KPIs is to describe the performance of the network objectively and from all aspects of interest. The outage effects on the coverage and the DL interference level can be evaluated investigating the RSRP, the RSSI and the RSRQ levels. Similar analysis can be done in UL based on the required UL transmit power and the UL interference level. These KPIs can be seen as tools to understand the performance of the network. However, as they do not actually describe the effect of the outage from the user point of view, they can be seen as secondary KPIs. The selected primary KPIs, trying to measure the actual user experienced QoS, are:

- Percentage of unsatisfied users
- Average best effort user UL throughput
- Average best effort user DL throughput

The percentage of unsatisfied users describes the actual number of unsatisfied users based on the definitions in section 5.2. In addition, for the best effort users the average DL/UL throughputs are used to evaluate their level of satisfaction. It should be noted, that the RSRP, the RSSI, the RSRQ and the required UL transmit power values are simulated separately for each point of the simulation area, and the KPI distributions are calculated based on these simulations. In contrast, the UL interference level is simulated only in points where the eNodeBs are located. The average throughput values are calculated over every best effort user. For the users failing to get service, the average throughput both in UL and DL is set to zero.

5.5.1 Scenario I: Outage of Two eNodeBs

5.5.1.1 Downlink Performance in Scenario I

As expected, the outage decreases the RSRP levels around the outage area, since the path loss between the UEs and the eNodeBs increases. However, as the number of malfunctioning eNodeBs is only two and the eNodeB grid is rather dense, the RSRP values remain at a fair level even in the middle of the outage area. Also the RSSI levels decrease due to the outage. In the simulated network, most of the DL power resources are utilized constantly, similarly to a typical mobile network with high load. Therefore, no additional power resources can be utilized to diminish the effects of the outage, and as the number of transmitting eNodeBs decreases, also the average RSSI decreases. The RSRQ distribution remains unaffected by the outage, since the RSRQ levels near the outage area decreases and the RSRQ levels further away increases. The RSRP, the RSSI and the RSRQ distributions before and after the outage are illustrated in appendix I.

Table 2 represents the percentages of failures caused by DL problems before and after the outage. The results indicate that the number of unsatisfied users does not increase significantly due to the degradation of DL performance. In an outage situation, the eNodeBs surrounding the outage area start to serve the users previously served by the malfunctioning eNodeBs. Therefore, the number of users per cell ratio increases and the amount of capacity/power resources available per user decreases. In addition, as the number of CEU increase, the average path loss becomes higher, and more power resources are needed to maintain an acceptable SINR level at the receiver. This is especially true for the VOIP users, whose data rates must be kept at a fixed level to fulfill their strict GBR requirements. As a result, the amount of power and capacity resources for an individual best effort user decreases significantly. This results in much lower average throughput. The average DL throughput distribution for the best effort users before and after the outage is illustrated in figure *41*.

Table 2. Percentage of failures caused by problems in DL.

	VOIP users (before/after)	**Best effort users (before/after)**
Too low RSRP	0.04 % / 0.04 %	0.04 % / 0.06 %
Too low RSRQ	0 % / 0 %	0 % / 0 %
Too low DL SINR	0 % / 0 %	0 % / 0 %
Inadequate DL capacity	0 % / 0.01 %	0.02 % / 0.01 %
Total	**0.04 % / 0.05 %**	**0.05 % / 0.07 %**

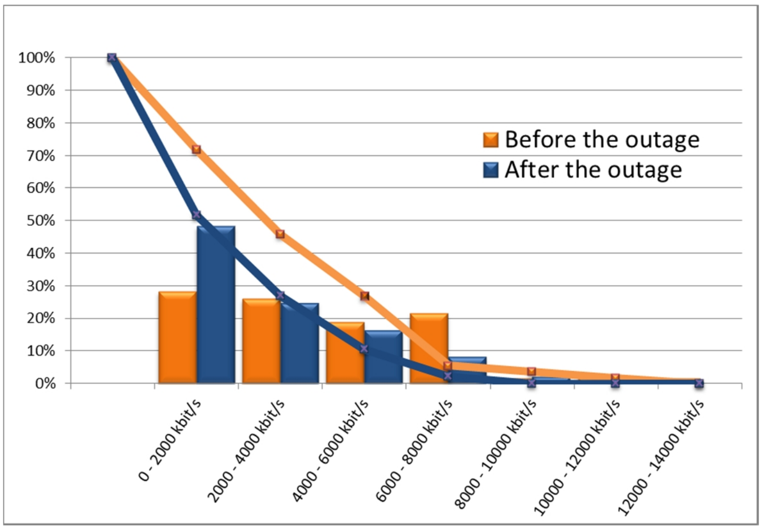


Figure 41. Average best effort user DL throughput distribution before and after the outage.

5.5.1.2 Uplink Performance in Scenario I

The UL performance in an outage situation differs from the DL performance due to different transmission principles: UL transmissions occur from multiple UEs to one eNodeB and DL transmissions from one eNodeB to multiple UEs. The outage causes an increase in the average path loss between the UEs and the eNodeBs. To maintain the SINR at an adequate level, UEs must compensate this additional path loss by increasing their transmission power. Obviously, this increases also the UL interference level. The required transmission power and the UL interference level distributions before and after the outage are illustrated in appendix J. Since the maximum UL transmission power has a strict upper limit, part of the users cannot anymore overcome the increased path loss and interference, resulting in a failures. The percentage of failures caused by UL problems are described in table 3 before and after the outage. For the VOIP users, the number of failures due to insufficient UL SINR increases 89 % (2.42 percentage points) and for the best effort users 85 % (2.27 percentage points). In addition, the higher interference level, the higher average path loss and the smaller amount of capacity per user (due to the smaller number of serving cells) decrease the best effort average throughputs significantly. This is illustrated in figure 42.

Table 3. Percentage of failures caused by problems in UL.

	VOIP users (before/after)	**Best effort users (before/after)**
Too low UL SINR	2.71 % / 5.13 %	2.64 % / 4.91 %
Inadequate UL capacity	0 % / 0 %	0 % / 0 %
Total	2.71 % / 5.13 %	2.64 % / 4.91 %

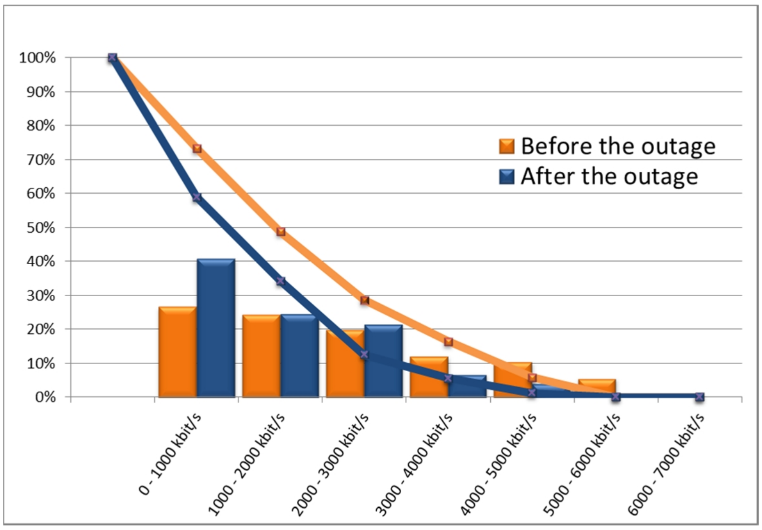


Figure 42. Average best effort user UL throughput distribution before and after the outage.

5.5.2 Scenario II: Outage of Multiple eNodeBs

5.5.2.1 Downlink Performance in Scenario II

In the executed simulations for the scenario II, similar outage effects were observed than in scenario I. As expected, both the RSRP and the RSSI levels decreases considerably, as the number of serving cells decreases. The RSRP and the RSSI distributions are illustrated in appendix K. It should be noted that the distributions are plotted for an outdoor terminal. Indoors, the both RSRP and RSSI levels are 7 – 23 dB lower depending on the clutter type. Similarly to scenario I, the RSRQ distribution did not considerably change due to the outage, since as the number of serving cells decreases, both the RSRP and the RSSI levels diminish. However, in contrast to scenario I, a small change in the RSRQ distribution can be seen. Since the outage area is relatively large, the RSRP levels are extremely low especially in the center of the outage area. This results in a relatively small difference between the noise level and the RSRP level. Therefore, the noise power starts to have an effect to the RSRQ values. The RSRQ distribution before and after the outage is also illustrated in appendix K.

Table 4 illustrates the percentage of failures caused by problems in DL performance. The results indicate that even in a major outage the number of failures caused by DL performance is not significant. Similarly to scenario I, the power and the capacity resources can be efficiently divided between the users ensuring the fulfillment of the QoS requirements of most users. Obviously, as the number of users per cell ratio and the average path loss increase, the amount of resources left for the best effort users decreases considerably. As a result, the DL throughput decreases massively, which is illustrated in figure 43.

Table 4. Percentage of failures caused by DL problems.

	VOIP users (before/after)	Best effort users (before/after)
Too low RSRP	0.07 % / 0.65 %	0.07 % / 0.63 %
Too low RSRQ	0.01 % / 0.05 %	0.01 % / 0.08 %
Too low DL SINR	0 % / 0.06 %	0 % / 0.06 %
Inadequate DL capacity	0 % / 0.43 %	0 % / 1.93 %
Total	**0.08 % / 1.19 %**	**0.08 % / 2.7 %**

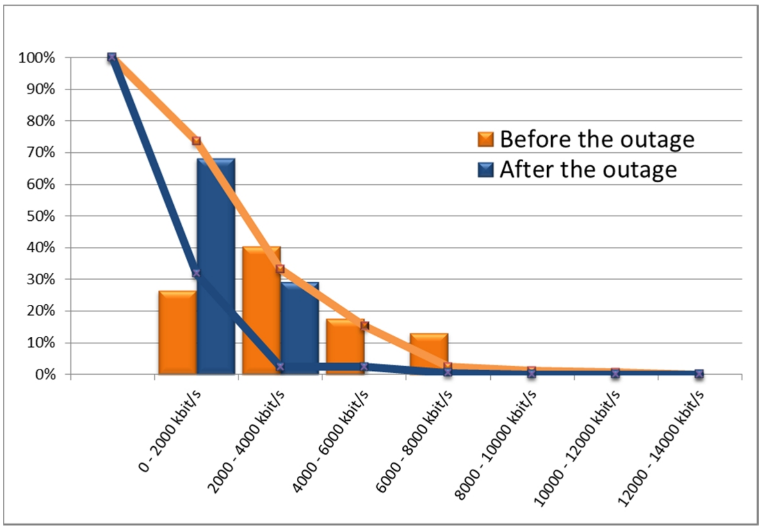


Figure 43. Average best effort user DL throughput distribution before and after the outage.

5.5.2.2 Uplink Performance in Scenario II

Similar effect in the UL performance than in the scenario I can be observed. To compensate the additional attenuation of the signal, the active UEs must increase their transmission powers. If the required transmission power exceeds the maximum allowed value, the UE cannot achieve high enough UL SINR: this result in a failure. As the average UL transmission power increases, the amount of interference created per UE also increases. However, in the utilized simulation model failed UEs do not create interference at all and the number of failed UEs due to the problems in UL performance is significant. Thus, the total UL interference level actually decreases due to the outage. The required transmission power and the UL interference level distribution before and after the outage are illustrated in appendix L.

As the average path loss increases, the number of users experiencing inadequate UL SINR increases significantly. As can be seen from table 5, the increase in the number of failures of both the VOIP and the best effort users is 482 % (14.3 percentage points). Similarly to scenario I, the decreased amount of resources per user and the increased path loss decrease the UL throughput, which is illustrated in figure 44.

Table 5. Percentage of failures caused by UL problems.

	VOIP users (before/after)	Best effort users (before/after)
Too low UL SINR	3.74 % / 18.01 %	3.75 % / 18.07 %
Inadequate UL capacity	0 % / 0 %	0 % / 0 %
Total	3.74 % / 18.01 %	3.75 % / 18.07 %

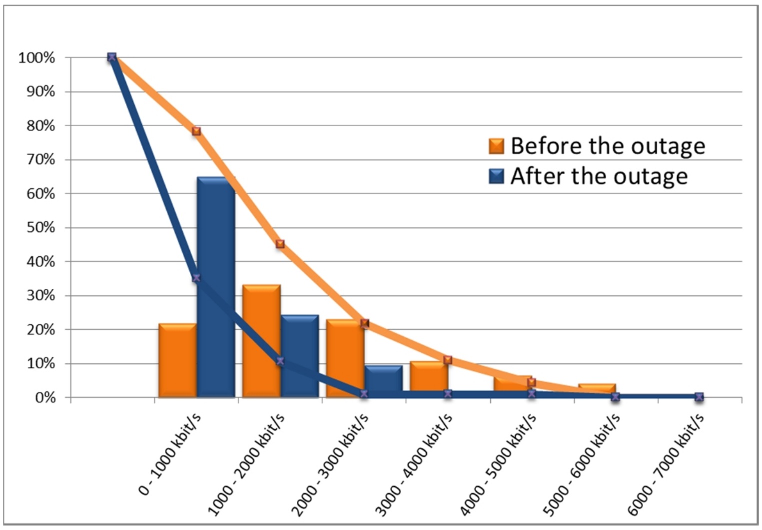


Figure 44. Average best effort user UL throughput distribution before and after the outage.

5.6 Cell Outage Compensation Group and Control Parameters

Selection of the parameters changed in an outage situation to alleviate the effect of the outage, denoted as control parameters, is a challenging task. In this section, based on the simulations of section 5.5, two control parameters are selected and their feasibility is tested. In addition, methods for selecting the group of cells participating in the outage compensation, denoted as the Cell Outage Compensation Group (COCG), are described.

5.6.1 Cell Outage Compensation Group

Selection of the cells belonging to the COCG is a vital component of a successful COC function. The COCG forming can be done using multiple different methods, such as manual forming, based on the NRs or based on the executed handovers. The manual forming of the COCGs is extremely time consuming, but on the other hand, the results are very reliable. Using the neighbor or the handover based COCG forming, the process can be made fully automatic, but the results might not be optimal. For example, missing or unwanted NRs might result in non-optimal COCGs. Due to the restrictions of the simulation environment, in this thesis the COCGs are formed manually.

5.6.2 Control Parameters

Basically, any network parameter affecting the behavior of the network is a potential COC control parameter. However, in practice some parameters are more feasible than others. A good parameter can be altered without any human interaction and has a desirable, predictable and consistent effect to the network performance.

The simulations conducted in section 5.5 indicate, that the DL QoS requirements of most users can be fulfilled even in a major outage due to an efficient reallocation of the power and the capacity resources. Obviously, this requires that all resources are not utilized before the outage or alternatively, part of the users can tolerate a decrease in the amount of resources allocated to them. In practice, before the outage part of the users must be served with higher bit rate than their GBR or they should not have a GBR requirement at all. In UL, the capacity resources can be reallocated similarly to DL, but due to the "many-to-one" nature of UL, the reallocation of power resources is not possible. Therefore, the increased path loss and the possibly increased interference cause failures for the CEUs whose signals are not strong enough to reach the eNodeB with an adequate SINR. The average bit rates of the users without strict GBR requirements decrease both in UL and DL considerably due to decreased number of serving cells and increased average path loss.

As the most significant failure cause after the outage is inadequate UL SINR, the selected control parameters should either increase the UL signal strength or decrease the UL interference level. As the UL transmission power is strictly regulated, the obvious choice is the reduction of the UL interference. The UL interference can be diminished in many ways, but altering the QoS parameters and especially the MBR value, provides a straightforward and flexible way to do it. Since, in this thesis, only the bit rates of the best effort users can be reduced without creating unsatisfied users, the first investigated control parameter is the UL MBR of the best effort users. In DL, altering the QoS parameter to diminish the interference is not necessary due to the efficient reallocation of the power and the capacity resources.

The number of failures caused by an inadequate capacity was relatively small in the simulations conducted in section 5.5. However, if adjusting the UL MBR of the best effort users increases the number of satisfied users as expected, also the depletion of capacity resources might start to increase the number of failures. In addition, in a more crowded network the number of failures caused by inadequate capacity resources would likely be higher. In a real network, the users are distributed extremely unevenly. Although the user distribution is considered in the design process of the network, in practice some cells are always more loaded than others. This is especially true after an outage changing the layout of the network considerably. A straightforward way to balance the load differences, is to bias the cell (re)selection process. This can be achieved using two different methods: adjusting the cell (re)selection parameters or adjusting the RSRP levels. Decreasing the RSRP levels of the most loaded cells is investigated as a second control parameter. Decreasing the RSRP levels have one advantage over the cell reselection parameter adjustment: the additional power can be allocated to the user plane transmissions.

5.6.3 Control Parameter Feasibility

In this section, the feasibility of the selected control parameters is investigated. The purpose of the section is to research the effect of the control parameter changes on the network performance and the user experienced QoS. To achieve this goal, a set of simulations were conducted in two parts. The first part investigates the best effort user UL MBR and the second part the RSRP level.

5.6.3.1 Best Effort UL MBR

To investigate the effects of the best effort UL MBR on the network performance, the UL MBR was decreased in steps from 10000 kbit/s to 500 kbit/s. For each step a simulation run was executed and the average values of each KPI were calculated. With the average values, the dependency between the control parameter and the KPIs could be evaluated. The UL interference level as a function of the best effort UL MBR is illustrated in figure 45. In both scenarios, decreasing the best effort UL MBR clearly diminishes the network interference level. In scenario I, the slope of the curve is more constant than in scenario II, since in scenario I the user data rates before the compensation are more evenly distributed. In scenario II, most of the user data rates are between 500 kbit/s and 2000 kbit/s, and therefore the effects of the UL MBR deduction are highest on that particular area.

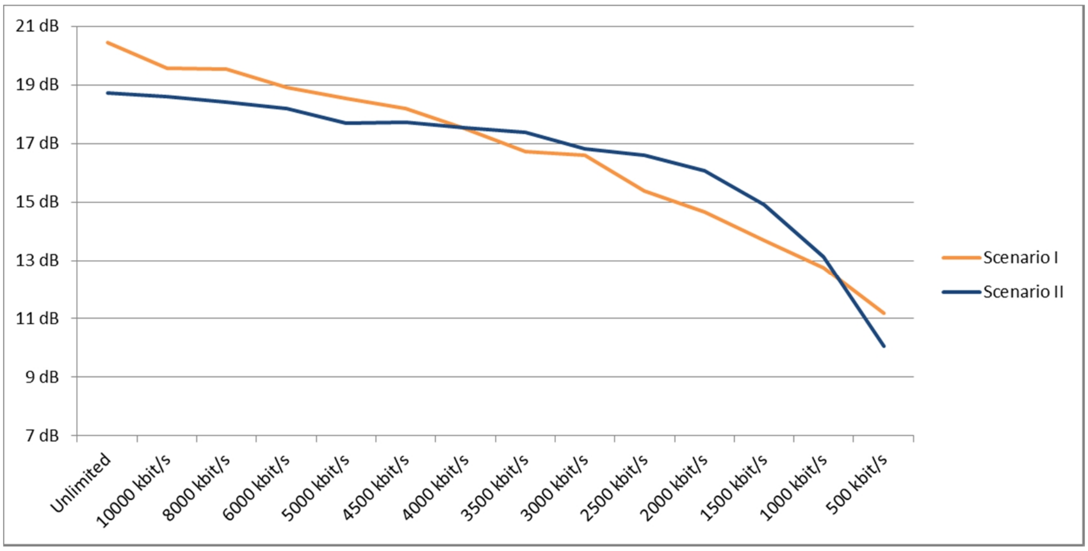


Figure 45. UL interference level as a function of best effort UL MBR.

As the interference level decreases, an adequate UL SINR can be reached using lower transmission powers. Therefore, the number of UL SINR failures decreases in both scenarios with waveforms similar to the UL interference levels in figure 45. The decreased number of UL SINR failures naturally increases the number of active users. Since in the scenario II the number of serving cells after the outage is very low, the capacity of the network is not adequate to serve the additional users, and therefore the number of failures due to the inadequate capacity increases. In scenario I, a similar effect cannot be observed, since only two eNodeBs are non-operational, and the capacity of the network is adequate even after the outage. The failure probabilities as a function of the best effort UL MBR are illustrated in figure 46. In addition, decreasing the best effort UL MBR diminishes the average UL throughput of the best effort users in both scenarios. The dependency between the best effort UL MBR and the average UL throughput of the best effort users is illustrated in figure 47.

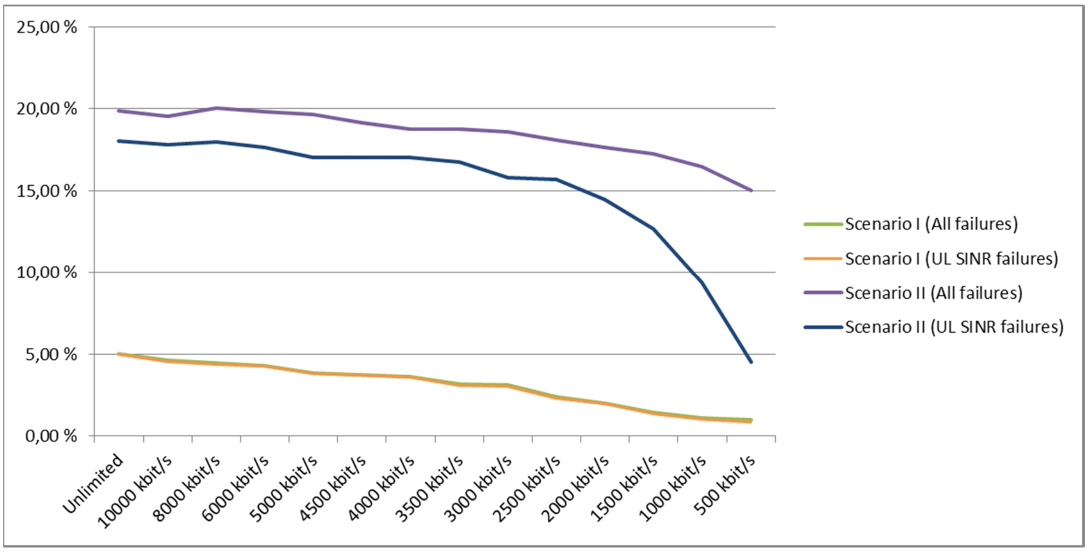


Figure 46. Failure probabilities as a function of best effort UL MBR.

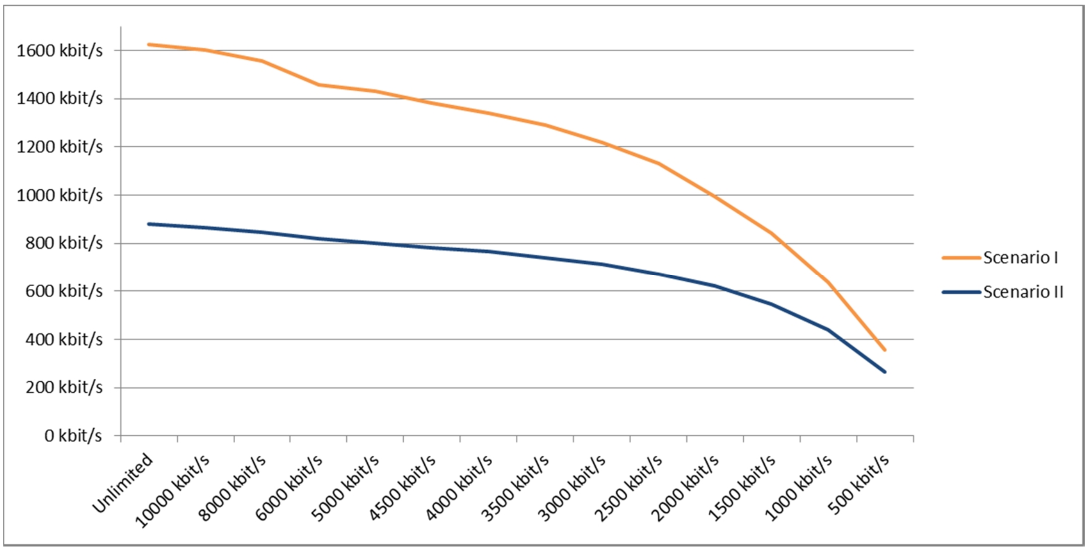


Figure 47. Average best effort user UL throughput as a function of best effort UL MBR.

5.6.3.2 RSRP level

The RSRP level feasibility simulations were performed only for the scenario II, since in the scenario I the depletion of capacity did not cause any failures. In the simulation, the UL best effort MBR was fixed to 300 kbit/s to maximize the failures created by inadequate capacity, and thus to emphasize the effects of the RSRP level adjustments. Since the number of different RSRP variations is huge, a simple RSRP tuning algorithm was developed instead of a brute-force solution. The developed algorithm decreases the RSRP level of the most heavily loaded cells in steps of 0.25 dB. After each RSRP reduction, the algorithm evaluates the effects of the adjustment on the network performance based on the total number of failures. An improvement of 0.3 percentage points was required to declare the RSRP change as successful due to the variance of the simulation results. The principle of the algorithm is illustrated in figure 48.

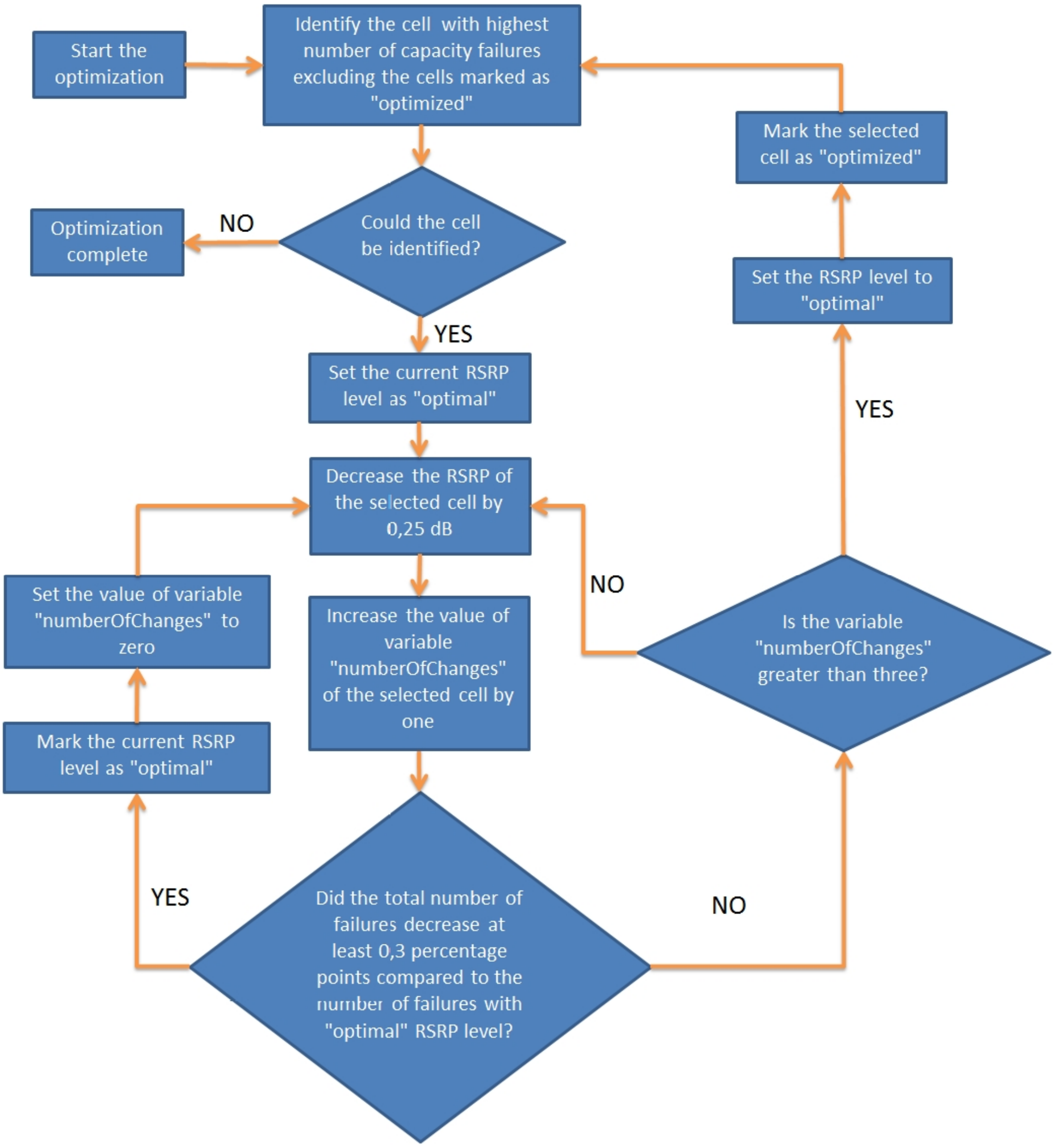


Figure 48. RSRP tuning algorithm utilized in the RSRP feasibility testing.

The RSRP tuning algorithm performed 24 RSRP level changes, from which four resulted in a significant improvement in the failure rates. As the RSRP level adjustments bias the cell (re)selection process, the average path loss increases. Therefore, UL average transmission power also increases, which for one increases the UL interference level. In DL, all eNodeBs typically utilize most of the available power all the time, and therefore the RSRP adjustments do not affect the DL interference level. The changes in UL and DL interference levels as a function of the level RSRP changes are illustrated in figure 49.

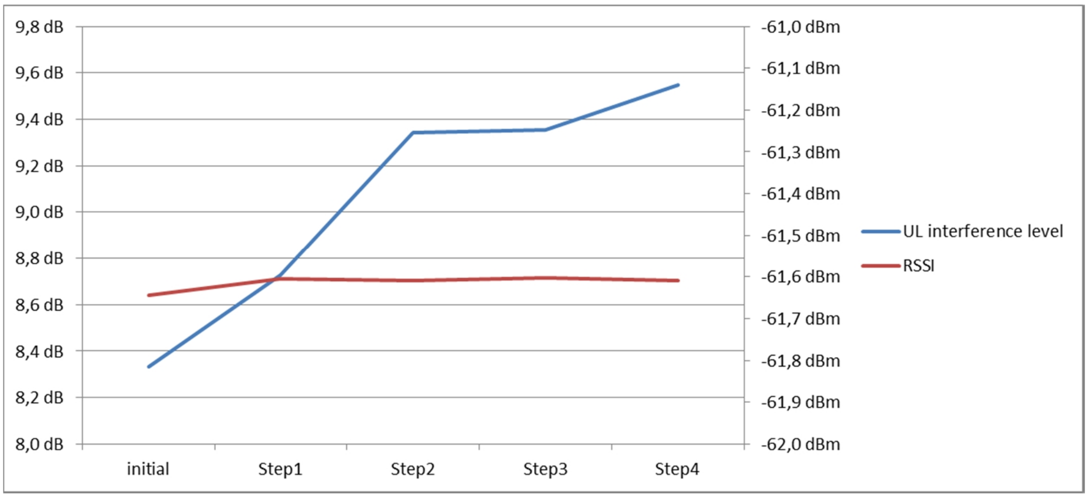


Figure 49. The effects of RSRP level adjustments on the network interference level.

The effect of RSRP adjustments on the failure probabilities are illustrated in figure 50. The total number of failures decreases slightly less compared to the number of failures caused by inadequate capacity. Reason for this is the increased UL interference level resulting in slightly increased number of UL SINR failures. Nevertheless, the increase in UL SINR failures is considerably smaller than the decrease in capacity failures, resulting in a decrease in the total number of failures.

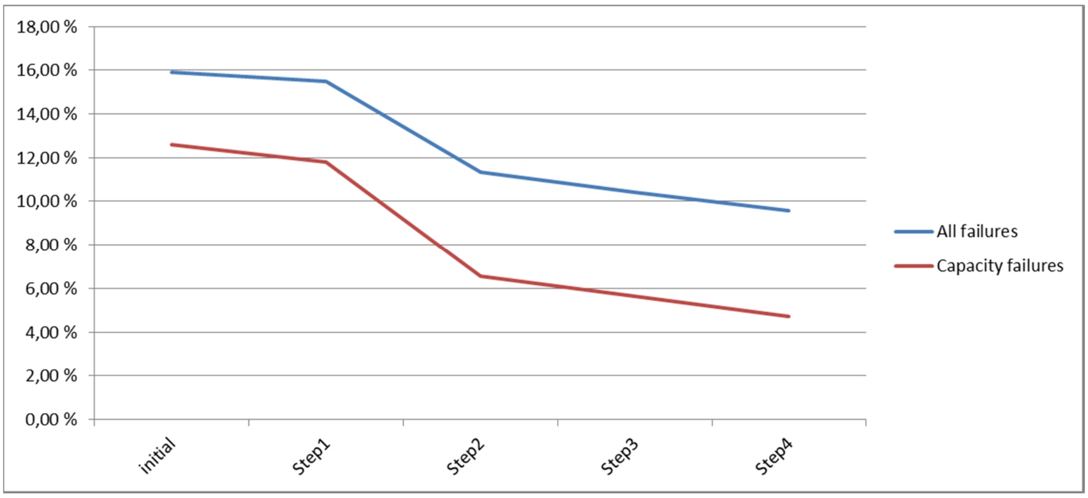


Figure 50. The effects of RSRP level adjustments on the failure probabilities.

As mentioned, the RSRP adjustments cause increase in the UL interference and the average path loss between the UEs and the serving eNodeBs. This obviously should decrease the average best effort user throughput both in UL and DL. However, as can be seen in figure 51, according to simulations only DL throughput actually decreases. The reason for this is the low best effort UL MBR used in the simulations. As the UL MBR limits the achievable bit rates for most of the users (instead of the achievable UL SINR), the bit rates are not affected by either the increased UL interference level or the increased path loss. In addition, as the average throughput is constrained at extremely low level, the additional users are likely to get throughputs higher than the average. With higher UL MBR values, the UL throughput would decrease as the RSRP levels are biased similarly to the DL throughput.

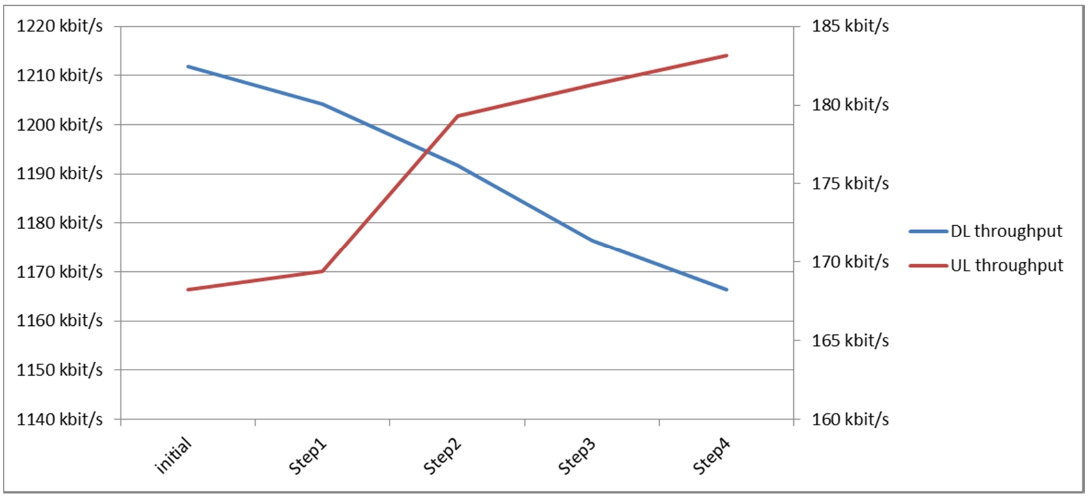


Figure 51. The effects of RSRP level adjustments on the best effort user throughput.

5.6.3.3 Summary

The best effort UL MBR and the RSRP level were determined as potential COC control parameters. Decreasing the best effort UL MBR diminishes the UL interference level resulting in a smaller number of unsatisfied users. As a downside, the average best effort UL throughput decreases significantly. By decreasing the RSRP levels of the most loaded cells, the network resources can be utilized more effectively, which increases the number of satisfied users. As a downside, the increased UL interference creates some amount of UL SINR failures.

5.7 Algorithmic Approach

In this section, a simple COC function is developed based on the simulation results of sections 5.5 and 5.6. In addition, the potential of the developed algorithm is evaluated in failure scenarios I and II. The developed COC function consists of two subsequently executed sub functions: UL MBR based compensation function and RSRP level based compensation function. The UL MBR based compensation function decreases the UL MBR values of the users whose UL MBR values are higher than their UL GBR values. The RSRP level based compensation function reduces the RSRP level of the most congested cells belonging to the COCG defined for the particular outage.

5.7.1 COC Functionality and Architecture

The implementation of the COC function is based on a centralized SON architecture. The main problem of the centralized SON architecture, the scalability, is not an issue since the number of eNodeBs participating in the compensation process is relatively low. Furthermore, the delays caused by the signaling will not make the overall speed of the functionality much slower, since the time required for gathering enough data for the decision making after each optimization step is dominant. When using a centralized architecture, the convergence and the stability are easy to achieve. In addition, the implementation is typically simpler compared to, for example, a distributed architecture.

The COC function is a part of the centralized O&M system. The firstly executed part of the COC function, the UL MBR based compensation function, requests the MME to decrease the UL MBRs of the users based on UL throughput measurements signaled from the eNodeBs. The MME utilizes the EPS bearer context modification process to modify the EPS profiles [25]. After the convergence of the UL MBR based compensation function, the RSRP level based compensation function starts to adjust the RSRP levels of the network based on the UL interference levels and the capacity failure measurements. As the RSRP level compensation function finishes the optimization, a convergence has been reached and the execution of the COC function is ready. The architecture of the developed COC function is illustrated in figure 52.

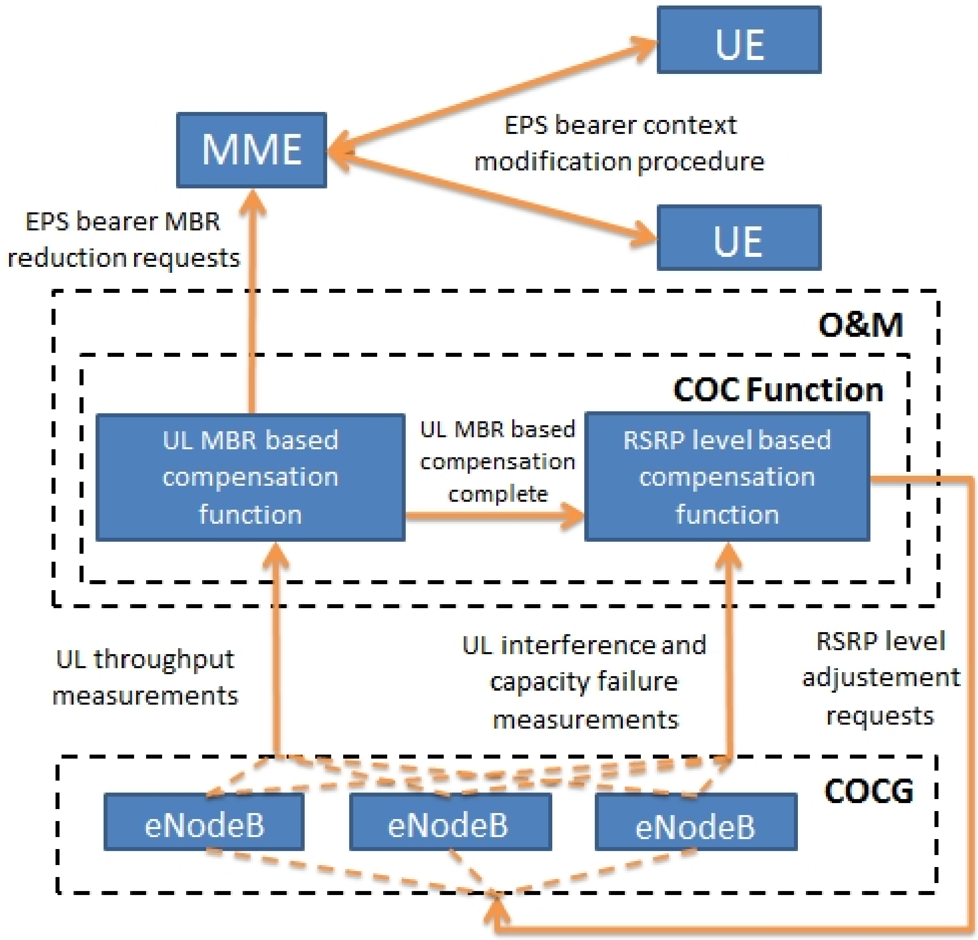


Figure 52. The architecture and the interfaces of the COC function.

5.7.2 UL MBR Based Compensation Function

In the feasibility testing performed for UL MBR reduction in section 5.6.3.1, the total number of satisfied users was used as a KPI. Although the number of satisfied users is an excellent KPI to describe the user experienced QoS, it is extremely hard to estimate reliably in a real network. Therefore, an approach based on using capacity related failures as a KPI and utilizing the average UL throughput as a boundary condition was implemented. The algorithm reduces the UL MBR of the best effort users in steps of S. After every reduction, UL throughput data is gathered a time defined by variable T. If the average UL throughput calculated from the gathered data is greater than minimum acceptable average UL throughput, denoted as D, the UL MBR is again reduced. The execution of the algorithm continues until smallest UL MBR value fulfilling the minimum UL throughput requirement is found. The principle of the algorithm is illustrated in figure 53.

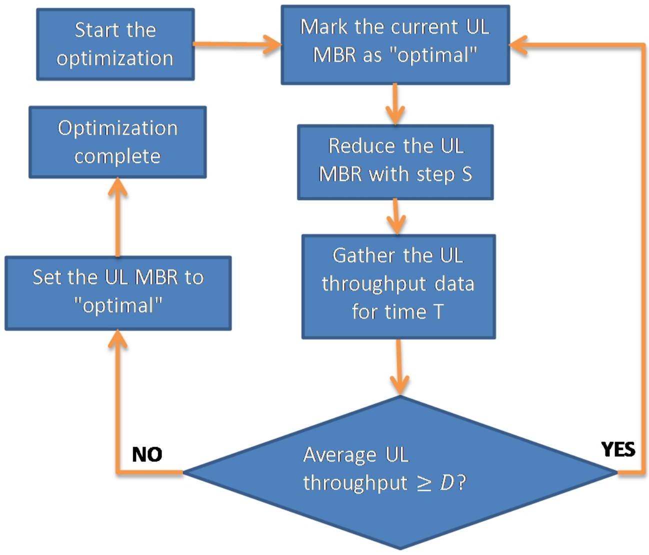


Figure 53. Functional operation principle of UL MBR based compensation function.

The selection of the parameter D can be seen as a compromise between the number of satisfied users and the QoS experienced by the best effort users. Basically, D represents the operator policy: how major bit rate reductions are acceptable for particular user groups. However, regardless of the operator policy, D should be based on the UL average throughput before the outage and the scale of the outage: in a major outage the data rates are expected to be much lower compared to a minor outage. With parameter S, the speed and accuracy of the algorithm can be modified. With high S values, the algorithm reaches convergence quickly but the final UL MBR value might be further away from the optimal solution compared to low S values. Parameter T can be used to adjust the reliability of the optimization decisions. With high T values, the probability of making an unbeneficial optimization decision is small but the algorithm convergence time is long and vice versa. In this thesis, for the scenario I, D was set to 900 kbit/s and for the scenario II to 300 kbit/s. Parameter S was set to 500 kbit/s when the best effort UL MBR was between 10000 kbit/s and 1000 kbit/s and to 200 kbit/s when the UL MBR was between 1000 kbit/s and 0 kbit/s. Due to the nature of the simulation environment, parameter T was not included in the simulation.

5.7.3 RSRP Level Based Compensation Function

Similarly to UL MBR based compensation function, the total failure rate could not be used as a KPI in the RSRP level based compensation function. Based on the simulations done in section 5.6, the RSRP adjustments decrease the number of capacity failures and increase the number of UL SINR failures. Basically, the number of capacity failures in the network is known, but the number of UL SINR failures is unknown. Therefore, the number of UL SINR failures needs to be estimated. In figure 54, the number of UL SINR failures is plotted as a function of the UL interference level in both scenarios. The figure is based on the simulation results of the UL MBR feasibility testing done in section 5.6.3.1.

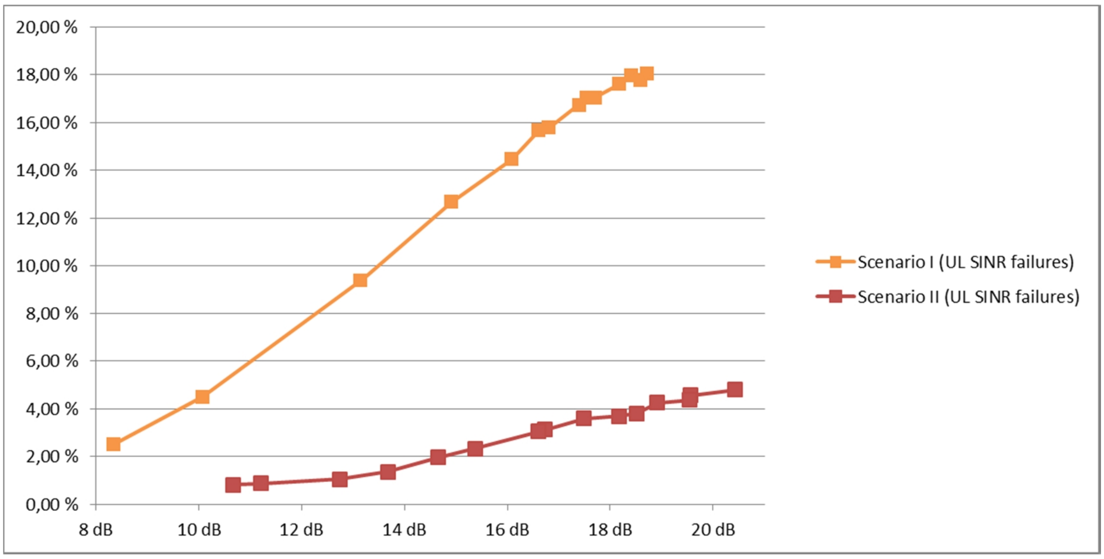


Figure 54. The UL SINR failure probability as a function of UL interference level.

A clear linear dependency between the UL interference level and the UL SINR failure rate can be seen in the figure 54. Therefore, a method for estimating the UL SINR failure rate by utilizing the UL interference level and linear regression was investigated. The linear dependency between the UL SINR and the UL interference level is illustrated in equation 2, where parameters $\propto$ and β are constants, $Interference_{UL}$ is the UL interference level and $Failures_{UL\ SINR}$ is the proportion of unsatisfied users due to inadequate UL SINR.

$$Failures_{UL\ SINR} = \propto\ + \beta \cdot Interference_{UL} \qquad (2)$$

The coefficients $\propto$ and β were estimated using the least squares method [42]. The estimation results are gathered in table 6. R^2-value, defined in equation 3, represents the percentage of variable $Failures_{UL\ SINR}$ variation explained with the changes of the variable $Interference_{UL}$. The calculated R^2-values are 0,9761 for scenario I and 0,9993 for scenario II, indicating that the model explains the UL SINR failure changes extremely well. In equation 3, s is the simulated failure rate, e is the estimated failure rate and $\bar{s}$ is the average of the simulated failure rates. To further evaluate the developed model, an F test was conducted [32]. The overall F values, calculated by using equation 4, were 531 for scenario I and 19651 for scenario II. This indicates that the model is statistically significant with all commonly utilized significance levels. The developed RSRP level based compensation function, which utilizes the developed failure estimation model, is based on the RSRP tuning algorithm described in section 5.6.3.2. The operation of the function is illustrated in figure 55.

Table 6. Coefficients utilized in the UL SINR failure estimation.

	Scenario I	Scenario II
$\propto$	-0,04229	-0,1086
β	0,00437	0,01571

$$R^2 = 1 - \frac{\sum_i (s_i - e_i)^2}{\sum_i (s_i - \bar{s})^2} \tag{3}$$

$$F = (n-2)\frac{R^2}{1-R^2} \tag{4}$$

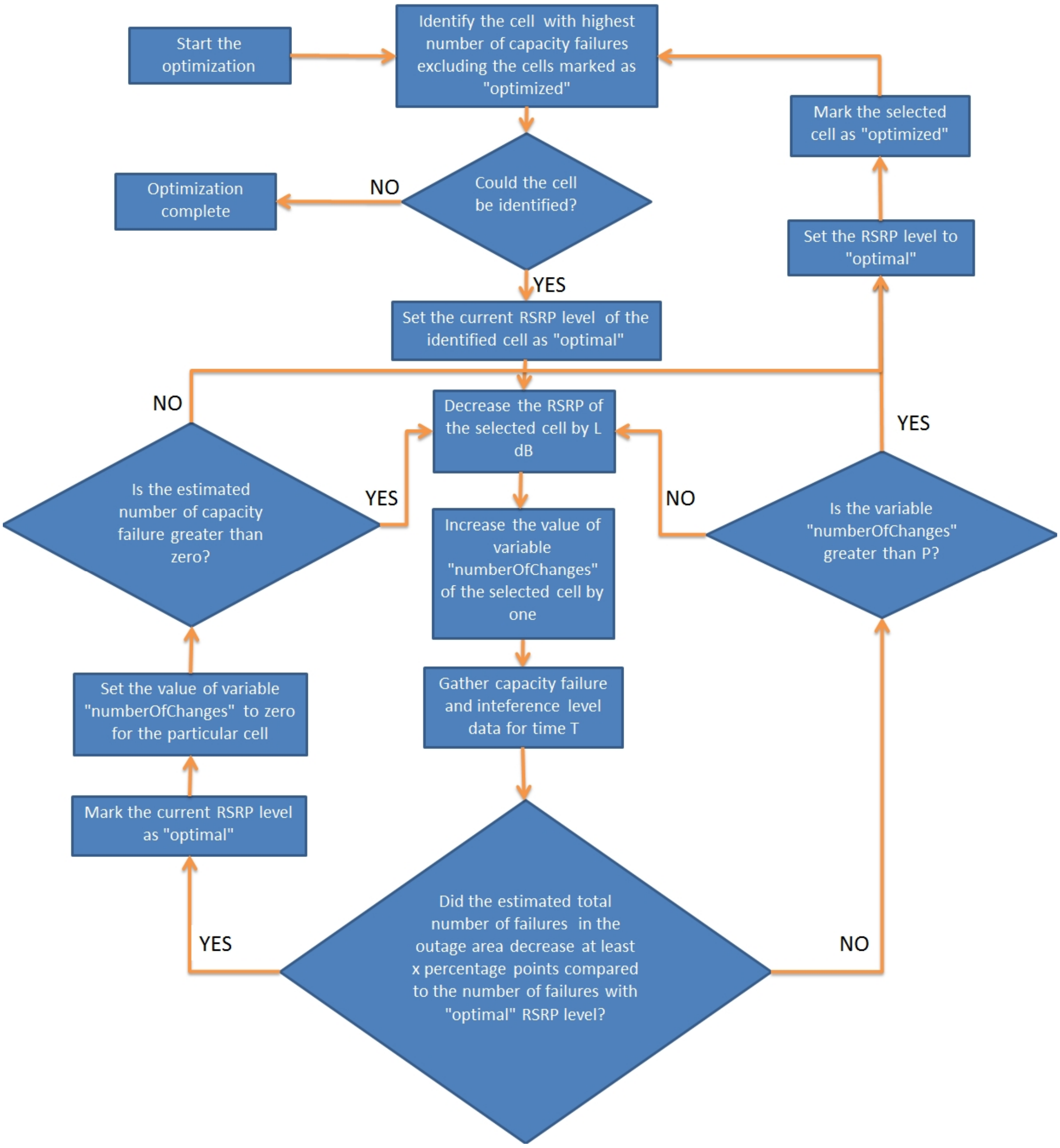


Figure 55. Functional operation principle of RSRP level based compensation function.

Parameters T, P, L and x can be used to modify the behavior of the algorithm. Similarly to the UL MBR based compensation function, choosing the parameter T is a compromise between the algorithm convergence speed and the accuracy of the failure rate estimation. With a combination of parameters P and L the algorithm behavior can be modified to match the network environment. Parameter P specifies how many times the RSRP level is changed for each optimized cell and parameter L specifies the step size. Basically, with small L and high P values the number of optimization steps is high and the convergence time is long, but the accuracy of the results is high. Obviously, high L and small P values have an opposite effect. The final parameter, x, defines the minimum improvement in the total failure rate to declare the optimization step successful. With high parameter x values, the probability of making a wrong interpretation about the effects of the RSRP level change is small, but the probability of denoting a beneficial step as unsuccessful is high. With low x values, opposite algorithm behavior can be expected. For this thesis, parameter P was set to three, parameter L to 0,25 dB and parameter x to 0,50 percentage point. Due to the nature of the simulation environment, parameter T was not included in the simulation.

5.7.4 Results

In this section, the performance of the developed COC function is evaluated based on the selected KPIs. In scenario I, the outage increases the number of unsatisfied users from 3 % to 5 % and decreases the best effort user UL/DL throughput levels considerably. After the detection of the outage, the UL MBR based compensation function starts to reduce the UL interference level, thus reducing the number of unsatisfied users to 2 %. The failure rates of scenario I are illustrated in figure 56. As expected, the best effort user DL throughput is not significantly affected by the compensation, but in the UL throughput a major reduction can be seen. However, the best UL throughput stays over the predefined low limit. The UL and DL best effort user throughputs are illustrated in figure 57. The RSRP level based compensation function does not perform any RSRP level changes, since no capacity failures occur. Altogether, the COC function manages to alleviate the effects of the outage and improve the user experienced QoS in an outage situation.

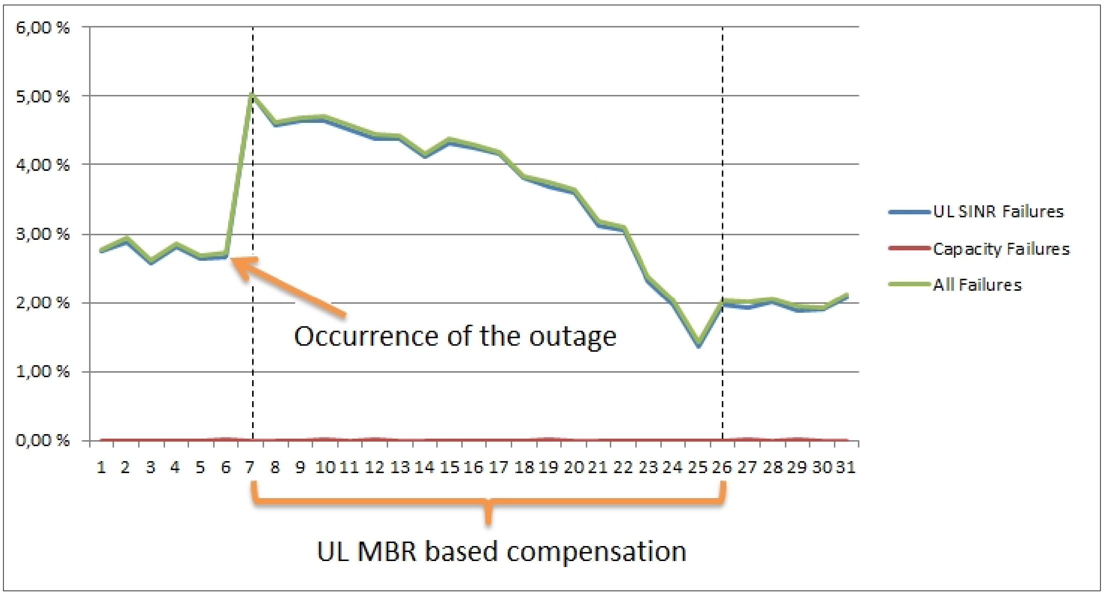


Figure 56. The effects of the COC function on the user failure probabilities in scenario I.

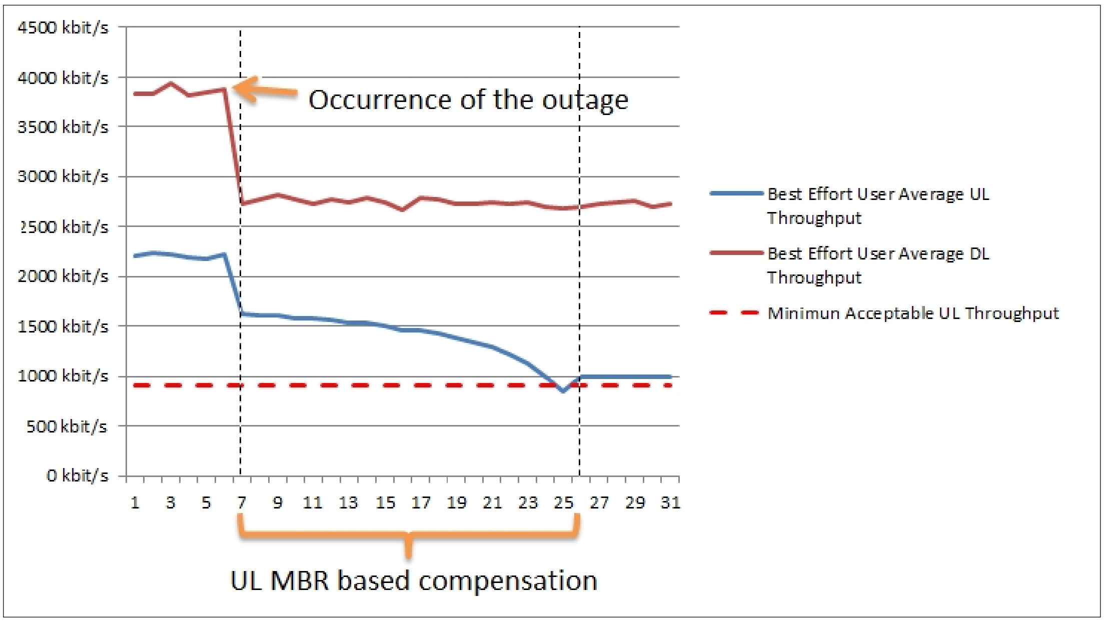


Figure 57. The effects of the COC function on the best effort throughputs in scenario I.

In scenario II, the outage increases the number of unsatisfied users from 4% to 20 % and reduces the best effort user UL/DL throughput levels considerably. The UL MBR based compensation function manages to reduce the number of unsatisfied users to 15 %. As a downside, also the best effort UL throughput reduces significantly. After the completion of UL MBR based compensation, the RSRP level based compensation function starts to balance the network load by adjusting the utilized RSRP levels. As a result, the number of capacity failures reduces significantly. However, the changes in RSRP levels increase the UL interference level, and therefore also the number of UL SINR failures increases slightly. The increase in the UL SINR failures is thus much smaller than the reduction of the capacity failures. Therefore, the total number of unsatisfied users decreases. Altogether, the COC function manages to alleviate the effects of the outage and improve the user experienced QoS also in scenario II. The failure rates in scenario II are illustrated in figure 58 and the best effort average throughputs in figure 59.

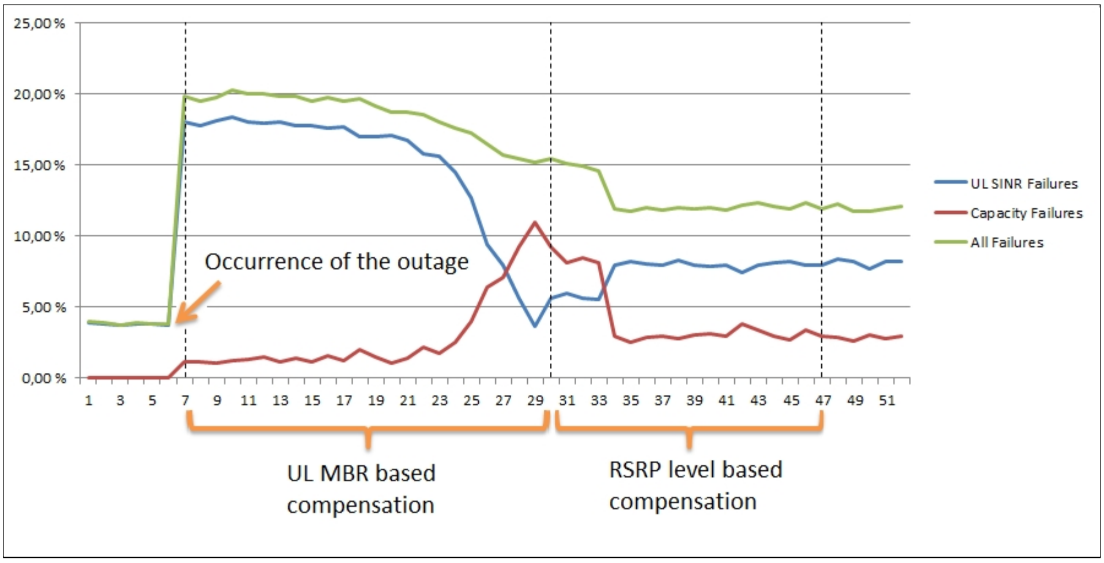


Figure 58. The effects of the COC function on the user failure probabilities in scenario II.

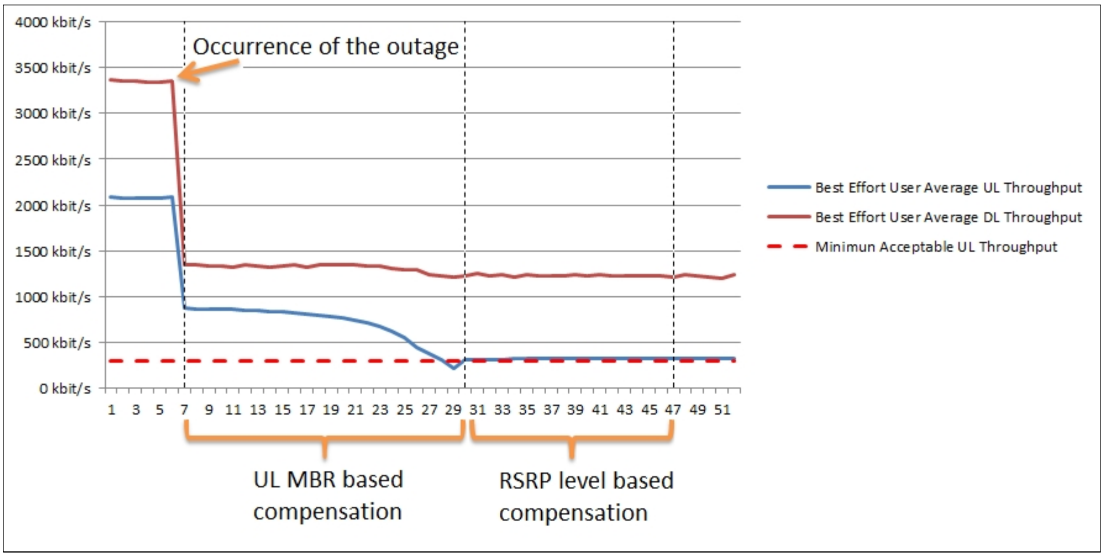


Figure 59. The effects of the COC function on the best effort throughput in scenario II.

6 Conclusions

The thesis described the most important KPIs of LTE and enlightens how the KPIs should be interpreted to understand the network behavior. In addition, the LTE KPIs are compared to corresponding UMTS KPIs to illustrate the differences and the similarities between UMTS and LTE.

The thesis also introduced the SON concept, the SON architectures and the SON use cases defined by 3GPP. In practice, the SON concept is still at a concept level, with only few applications utilized or tested in the live networks. The main problem of SON seems to be the complex relations between the control parameters and the network performance: it is extremely difficult to develop an algorithm capable of making good optimization decisions in many different network environments with varying user distributions. However, significant amount of resources is allocated to the development of SON and many stakeholders are anticipating major gains from it.

The COC use case of SON was selected to more throughout investigation. According to the system level simulations, in a typical outage situation UL performance problems cause much more user unsatisfaction compared to DL problems: since the distance between the UEs and the eNodeBs increases, some UEs do not have enough power to reach an adequate UL SINR level. In addition, the capacity of the network might not be adequate in case of a major outage. Based on the simulated effect of a typical outage, two parameters were selected as the COC function control parameters: UL MBR utilized to decrease the UL interference level and RSRP level utilized to balance the load of the network. Both control parameters were discovered to be feasible COC control parameters having a desirable and predictable effect to the network performance.

In the final part of the thesis, a developed COC function was introduced. The function is based on the selected control parameters and consists of two sub functions: UL MBR based compensation function and RSRP level based compensation function. The UL MBR based compensation function decreases the UL interference level of the network by altering the UL MBR values. The optimization decisions are based on UL throughput measurements. The RSRP level based compensation function decreases the RSRP level of the most congested eNodeBs based on UL interference and capacity failure measurements. The performance of the developed COC function was simulated in two different outage scenarios, in which the COC function managed to alleviate the effects of the outage considerably.

References

[1] H. Holma and A. Toskala, *LTE for UMTS OFDMA and SC-FDMA Based Radio Access,* 1st edition, John Wiley & Sons Ltd., 2009.

[2] Motorola, *Long Term Evolution (LTE): A Technical Overview,* white paper, 2007.

[3] T. Karjalainen, *Long Term Evolution – A Study on Deployment Strategies,* Master of Science Thesis, 2010.

[4] 3GPP Technical Specification 36.201 v.8.3.0, *LTE Physical Layer – General Description (Release 8)*, 2009.

[5] M. Rumney, *LTE and the Evolution to 4G Wireless - Design and Measurement Challenges,* 1st edition, John Wiley & Sons Ltd., 2009.

[6] Motorola, *Long Term Evolution (LTE): Overview of LTE Air-Interface,* white paper, 2007.

[7] H. Holma and A. Toskala, *WCDMA FOR UMTS – HSPA EVOLUTION AND LTE,* 5th edition, John Wiley & Sons Ltd., 2010.

[8] Ixia, *SC-FDMA – Single Carrier FDMA in LTE*, white paper, 2009.

[9] J. Zyren, *Overview of the 3GPP Long Term Evolution Physical Layer,* white paper, 2007.

[10] Telesystem Innovations Inc., *LTE in a Nutshell: The Physical Layer*, white paper, 2010.

[11] F. Rayal, *The essential aspects of LTE's PHY (Part 2),* 2010.

[12] 3G Americas, *MIMO Transmission Schemes for LTE and HSPA Networks*, white paper, 2009.

[13] Rohde & Schwarz, *UMTS Long Term Evolution (LTE) Technology Introduction,* application note, 2007.

[14] S. Sesia, I. Toufik and M. Baker, *The UMTS Long Term Evolution – From Theory to Practice,* John Wiley & Sons Ltd., 2009.

[15] V. Pauli, J. D. Naranjo and E. Seidel, *Heterogenous LTE Networks and Inter-Cell Interference Coordination,* Nomor Recearch GmbH, 2010.

[16] AIRCOM International, *Asset 7.0 User Reference Guide*, edition 1, 2010.

[17] K. Doppler, C. Wijting and K. Valkealahti, *Interference Aware Scheduling for Soft Frequency Reuse,* Nokia Research Center, 2009.

[18] 3GPP Technical Specification 36.300 v.9.6.0, *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (Release 9),* 2010.

[19] D. Pacifico, M. Pacifico, C. Fischione, H. Hjalrmasson and K. H. Johansson, *Improving TCP Performance During the Intra LTE Handover*, 2009.

[20] L. Bajzik, P. Horvath, L. Korossy and C. Vulkan, *Impact of Intra-LTE Handover with Forwarding on the User Connections,* 2007.

[21] Y. Yang, *Optimization of Handover Algorithm in 3GPP LTE,* Master of Science Thesis, 2009.

[22] M. Amirijoo, P. Frenger, F. Gunnarsson and J. Moe, K. Zetterberg, *On Self-Optimization of the Random Access Procedure in 3G Long Term Evolution,* white paper, 2009.

[23] 3GPP Technical Specification 36.331 v.9.5.0, *Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (Release 9)*, 2010.

[24] 3GPP Technical Specification 23.401 v.9.7.0, *General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (Release 9)*, 2010.

[25] 3GPP Technical Specification 24.301 v.9.5.0, *Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3 (Release 9),* 2010.

[26] Socrates Project, *Final Report on Self-Organization and its implications in Wireless Access Networks,* 2010.

[27] H. Holma and A. Toskala, *WCDMA FOR UMTS,* 3rd edition, John Wiley & Sons Ltd., 2004.

[28] 3GPP Technical Specification 36.213 v.9.3.0, *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 9),* 2010.

[29] Qualcomm, *LTE Mobility Enhancements,* white paper, 2010.

[30] Socrates Projects, *Review of use cases and framework,* v.1.0, 2009.

[31] Ericsson, *Self-Organizing Network solution tested in live LTE Network,* press release, 2010. Available: http://www.ericsson.com/news/101119_lte_network_244218599_c. Referred 2.8.2011.

[32] Nokia Siemens Networks, *Self-Organizing Networks (SON) – Introducing the Nokia Siemens Networks SON Suite – an efficient, future-proof platform for SON,* white paper, 2010.

[33] Huawei, *T-Mobile and Huawei Complete Testing on World's First LTE Self-Organizing Network,* press release, 2010. Available: http://www.huawei.com/ilink/en/about-huawei/newsroom/press-release/HW_062655?KeyTemps=4G,China%20Mobile. Referred 2.8.2011.

[34] 3GPP Technical Report 36.902 v.9.3.0, *Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Self-configuring and self-optimizing network (SON) use cases and solution (Release 9),* 2010.

[35] A. Lobinger, S. Stefanski, T. Jansen and I. Balan, *Load Balancing in Downlink LTE Self-Optimizing Networks,* Socrates project, 2010.

[36] Socrates Project, *Cell Outage Management in LTE Networks*, 2010.

[37] 3GPP Technical Specification 36.423 v.9.5.0, Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 application protocol (X2AP) (Release 9), *2010.*

[38] 3GPP Technical Specification 32.521 v10.1.0, *Self-Organizing Networks (SON) Policy Network Resource Model (NRM) Integration Reference Point (IRP); Requirements (Release 10),* 2010.

[39] O. N. C. Yilmaz, *Self-Optimization of Coverage and Capacity in LTE using Adaptive Antenna Systems*, Master of Science Thesis, 2010.

[40] EnVision Wireless, *Propagation Model Optimization,* 2005.

[41] G. Horvath, C. Vulkan, *Throughput Analysis of the Proportional Fair Scheduler in HSDPA,* 14th European Wireless Conference, 2008.

[42] M. Blackwell, *Multiple Hypothesis Testing: The F-test,* Harvard University, 2008.

[43] 3GPP Technical Specification 23.060 v.9.7.0, *General Packet Radio Service (GPRS); Service description; Stage 2 (Release 9),* 2010.

Appendix A - Timers

Timer	Description
T300	Defines the time UE waits for a response to the RRC CONNECTION REQUEST message before declaring the RRC connection establishment process as failed.
T301/T311	Defines the time UE tries to re-establish the RRC connection before the RRC connection re-establishment process is declared as failed.
T302	Defines the time UE has to wait in the idle state after receiving the RRC CONNECTION REJECT message.
T304	Defines the time UE tries to establish a connection to the target cell before the handover process is declared as failed.
T310	Defines the time UE waits before declaring a RLF when UE has measured smaller RSRQ values than Q_{out} for a number of times defined by parameter N310.
T3410	Defines the time UE waits for a response to the ATTACH REQUEST message before declaring the attach process as failed.
T3480	Timer utilized in declaring a bearer resource allocation process as failed.
T3482	Timer utilized in declaring a PDN connection establishment process, which is not combined to an attach request, as failed.
T3485	Timer utilized in declaring a dedicated EPS bearer context establishment as failed.
T3486	Timer utilized in declaring an EPS bearer context modification as failed.
T3495	Timer utilized in declaring an EPS bearer deactivation as failed.

Appendix B - Typical causes for attach rejections

Cause	Description
#3 - Illegal UE	The identity of the UE is not acceptable or the UE does not pass the authentication check
#6 - Illegal ME (Mobile Equipment)	The ME is not acceptable (for example blacklisted)
#7 - EPS services not allowed	The UE is not allowed to utilize the EPS services
#8 - EPS services and non-EPS services not allowed	The UE is not allowed to utilize either the EPS services or the non-EPS services
#11 – PLMN (Public Land Mobile Network) not allowed	The UE is not allowed to operate, due to the subscription or a barring, in the particular PLMN
#12 - Tracking area not allowed	The UE is not allowed to operate, due to the subscription, in the particular tracking area
#13 - Roaming not allowed in this tracking area	The UE is not allowed to roam in the particular tracking area
#14 - EPS services not allowed in this PLMN	The UE is not allowed to roam in the particular PLMN
#15 - No suitable cells in tracking area	The UE is not allowed to operate, due to the subscription, in the particular tracking area
#25 - Not authorized for this CSG (Closed Subscriber Group)	The UE is not allowed to operate, due to the subscription, in the particular CSG cell

Appendix C - Typical causes for PDN connectivity request rejections

Cause	Description
#8 - Operator determined barring	The MME rejected the request due to an operator determined barring
#26 - Insufficient resources	The request cannot be accepted due to insufficient resources
#27 - Missing or unknown APN (Access Point Name)	The request was rejected, because the access point name is unknown
#28 - Unknown PDN type	The request was rejected because the PDN type could not be recognized
#29 - User authentication failed	The request was rejected because the authentication of the user failed
#30 - Request rejected by S-GW or P-GW	The S-GW or the P-GW rejected the request
#31 - Request rejected, unspecified	The request was rejected due to an unspecified reason
#32 - Service option not supported	The requested service is not supported by the PLMN
#33 - Requested service option not subscribed	The request was rejected because the UE has no subscription for the service
#34 - Service option temporarily out of order	The request was rejected because one or more functions required for the service are not available
#35 - PTI (Procedure Transaction Identity) already in use	The request was rejected because the PTI is already in use
#38 - Network failure	The request was rejected due to an error situation in the network
#50 - PDN type IPv4 only allowed	Only IPv4 is allowed for the requested PDN connectivity
#51 - PDN type IPv6 only allowed	Only IPv6 is allowed for the requested PDN connectivity
#53 - ESM (EPS Session Management) information not received	The request was rejected because no ESM information was received
#54 - PDN connection does not exist	In handovers from non-3GPP access networks, network uses this ESM cause to indicate that the MME has no information about the requested PDN connection
#55 - Multiple PDN connections for a given APN not allowed	The request was rejected, because the APN does not allow multiple PDN connections
#95-111 - protocol error	More details in [25]

#112 - APN restriction value incompatible with active EPS bearer context	This ESM cause is used by the network to indicate that the EPS bearer context(s) have an APN restriction value that is not allowed in combination with the currently active EPS bearer context. More information on [43]

Appendix D - Typical causes for default EPS bearer context activation request rejections

Cause	Description
#26 - Insufficient resources	The request cannot be accepted due to insufficient resources
#31 - Request rejected, unspecified	The request was rejected due to an unspecified reason
#95-111 - Protocol error	More details in [25]

Appendix E - Typical causes for bearer resource allocation request rejections

Cause	Description
#26 - Insufficient resources	The request cannot be accepted due to insufficient resources
#30 - Request rejected by S-GW or P-GW	The S-GW or the P-GW rejected the request
#31 - Request rejected, unspecified	The request was rejected due to an unspecified reason
#32 - Service option not supported	The requested service is not supported by the PLMN
#33 - Requested service option not subscribed	The request was rejected because the UE has no subscription for the service
#34 - Service option temporarily out of order	The request was rejected because one or more functions required for the service are not available
#35 - PTI already in use	The request was rejected because the PTI is already in use
#37 - EPS QoS not accepted	The QoS requirements of the UE cannot be accepted
#41 - Semantic error in the TFT operation	The request was rejected because of a semantic error in the TFT operation of the request
#42 - Syntactical error in the TFT operation	The request was rejected because of a syntactical error in the TFT operation of the request
#43 - Invalid EPS bearer identity	The EPS bearer identity number is not valid or the EPS bearer context identified by the linked EPS bearer identity is not active
#44 - Semantic errors in packet filter(s)	The request was rejected because of one or more semantic errors in the packet filter(s) utilized in the TFT of the request
#45 - Syntactical error in packet filter	The request was rejected because of one or more syntactical errors in the packet filter(s) utilized in the TFT of the request
#56 - Collision with network initiated request	The network has already initiated activation, modification or deactivation for the bearer of the request
#59 - Unsupported QCI value	The requested QCI value is not supported
#95-111 - Protocol error	More details in [25]

Appendix F - Typical causes for dedicated EPS bearer context activation request rejections

Cause	Description
#26 - Insufficient resources	The request cannot be accepted due to insufficient resources
#31 - Request rejected, unspecified	The request was rejected due to an unspecified reason
#41 - Semantic error in the TFT operation	The request was rejected because of a semantic error in the TFT operation of the request
#42 - Syntactical error in the TFT operation	The request was rejected because of a syntactical error in the TFT operation of the request
#43 - Invalid EPS bearer identity	The EPS bearer identity number is not valid or the EPS bearer context identified by the linked EPS bearer identity is not active
#44 - Semantic errors in packet filter(s)	The request was rejected because of one or more semantic errors in the packet filter(s) utilized in the TFT of the request
#45 - Syntactical error in packet filter	The request was rejected because of one or more syntactical errors in the packet filter(s) utilized in the TFT of the request
#95-111 - Protocol error	More details in [25]

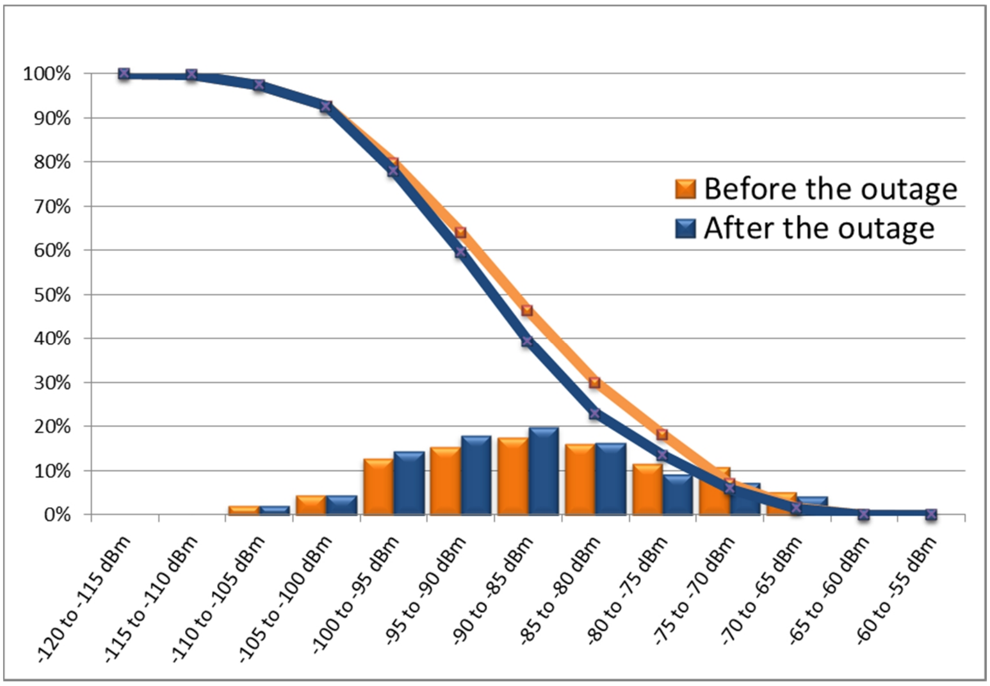
Appendix G - Typical causes for dedicated EPS bearer context modification request rejections

Cause	Description
#26 - Insufficient resources	The request cannot be accepted due to insufficient resources
#41 - Semantic error in the TFT operation	The request was rejected because of a semantic error in the TFT operation of the request
#42 - Syntactical error in the TFT operation	The request was rejected because of a syntactical error in the TFT operation of the request
#43 - Invalid EPS bearer identity	The EPS bearer identity number is not valid or the EPS bearer context identified by the linked EPS bearer identity is not active
#44 - Semantic errors in packet filter(s)	The request was rejected because of one or more semantic errors in the packet filter(s) utilized in the TFT of the request
#45 - Syntactical error in packet filter	The request was rejected because of one or more syntactical errors in the packet filter(s) utilized in the TFT of the request
#46 - EPS bearer context without TFT already activated	The EPS bearer has already been activated without TFT
#95-111 - Protocol error	More details in [25]

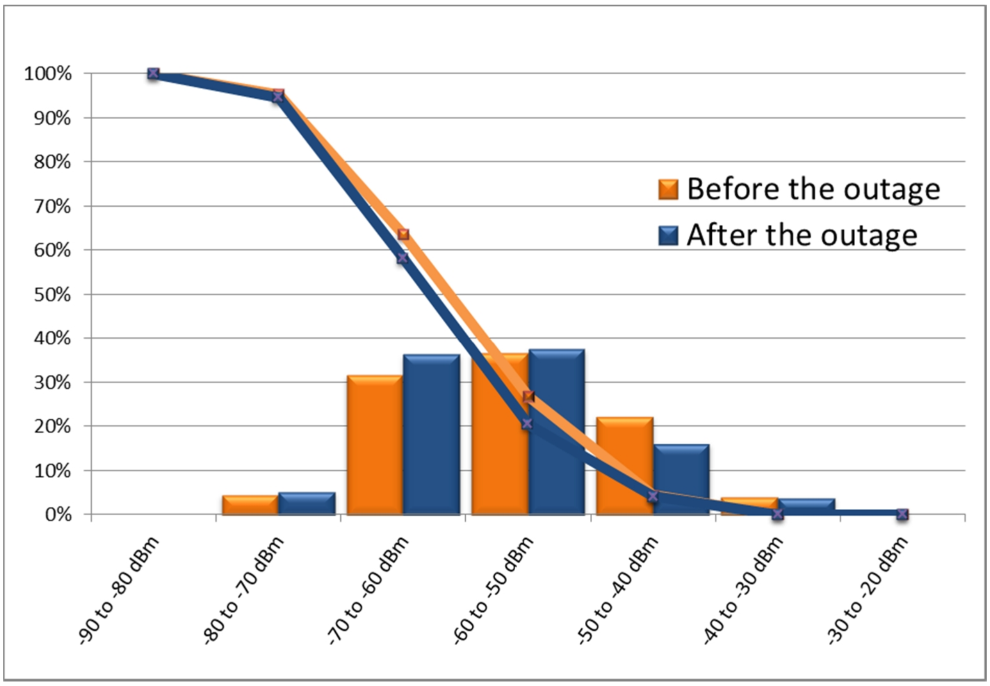
Appendix H - Typical causes for EPS bearer deactivations

Cause	Description
#8 - Operator determined barring	The MME rejected the request due to an operator determined barring
#36 - Regular deactivation	A regular EPS bearer deactivation initiated by either the UE or the network
#38 - Network failure	The request was rejected due to an error situation in the network
#39 - Reactivation requested	The network requests an EPS bearer reactivation from the UE
#112 - APN restriction value incompatible with active EPS bearer context	This ESM cause is used by the network to indicate that the EPS bearer context(s) have an APN restriction value that is not allowed in combination with the currently active EPS bearer context. More information on [43]

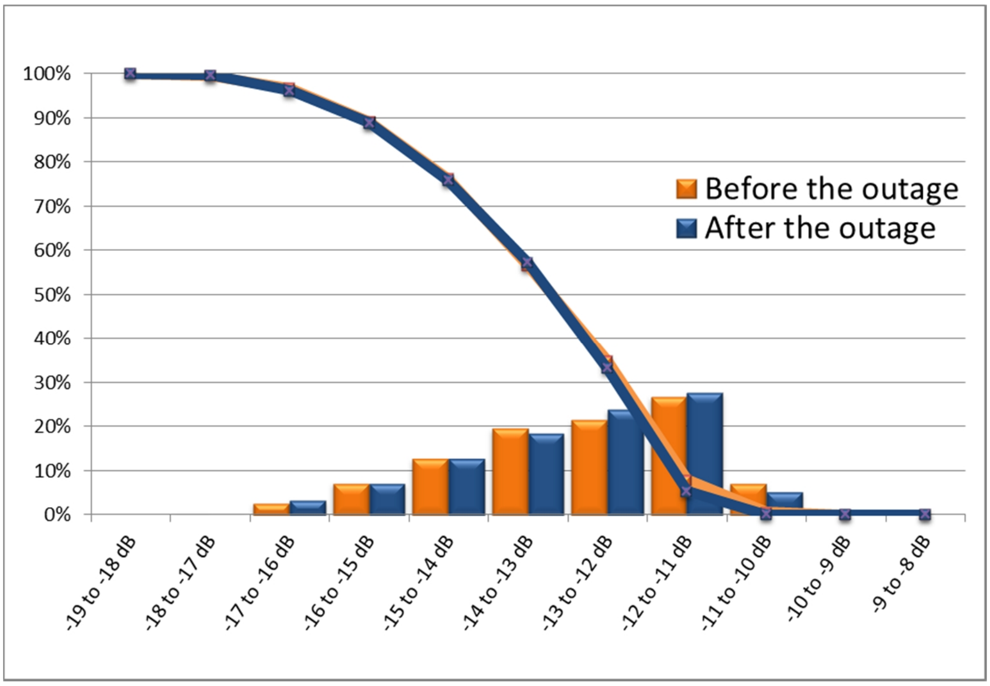
Appendix I - Effects of the outage to the DL performance in scenario I



RSRP distribution for an outdoor terminal before and after the outage.

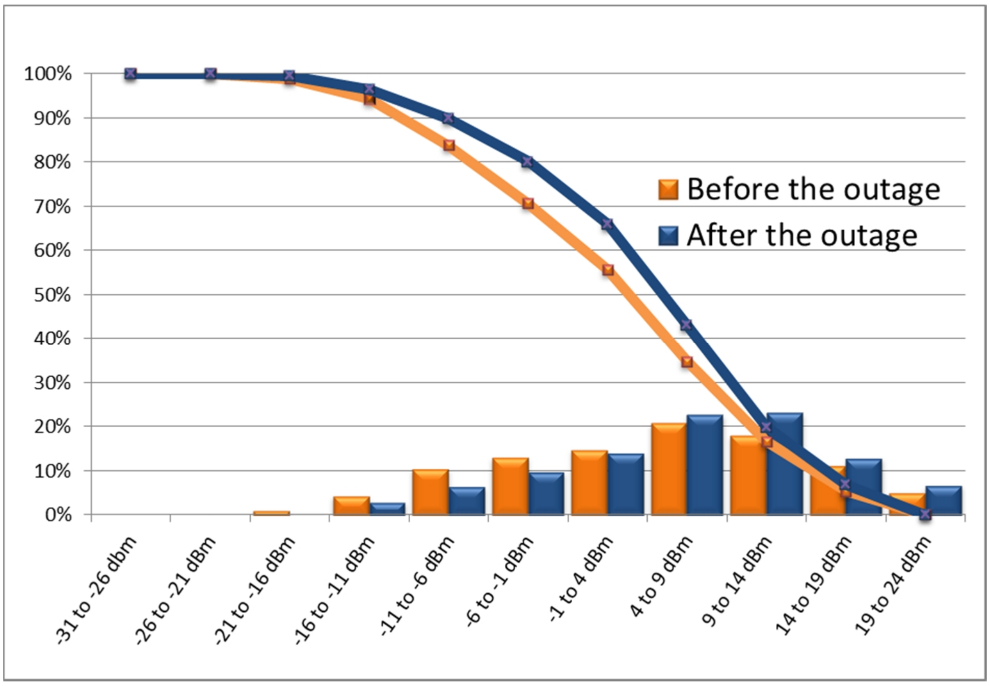


RSSI distribution for an outdoor terminal before and after the outage.

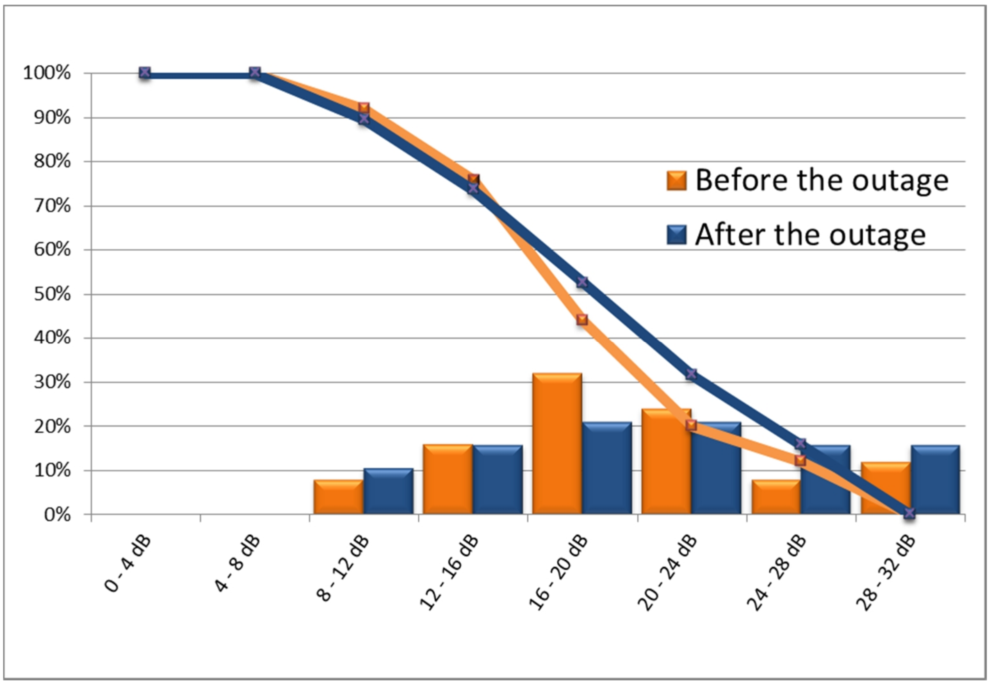


RSRQ distribution for an outdoor terminal before and after the outage.

Appendix J - Effects of the outage to the UL performance in scenario I

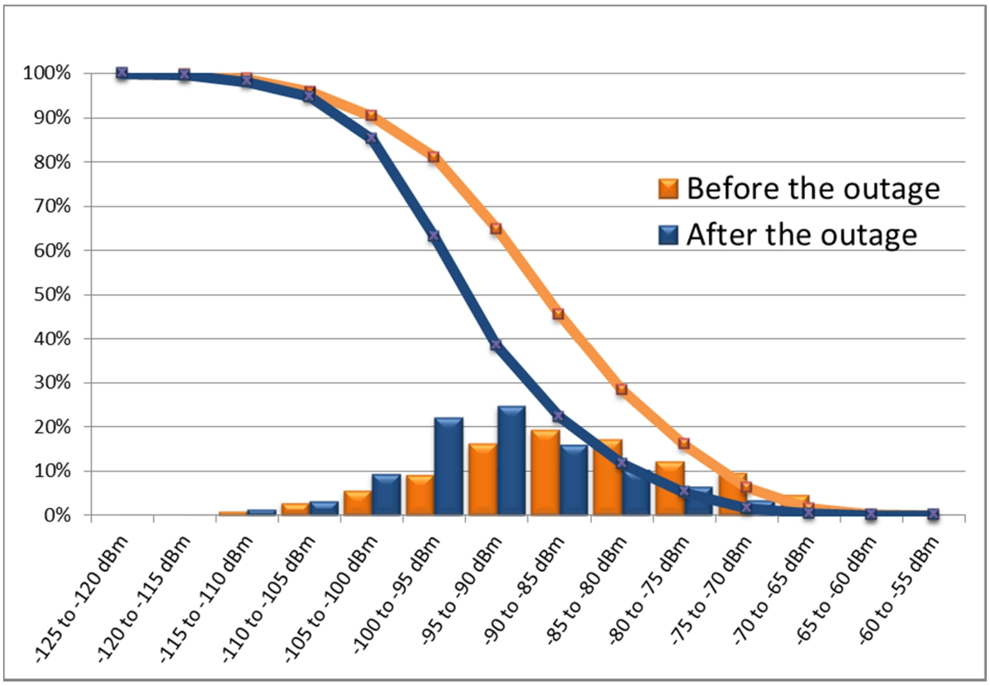


Required UL transmit power for an outdoor terminal before and after the outage.

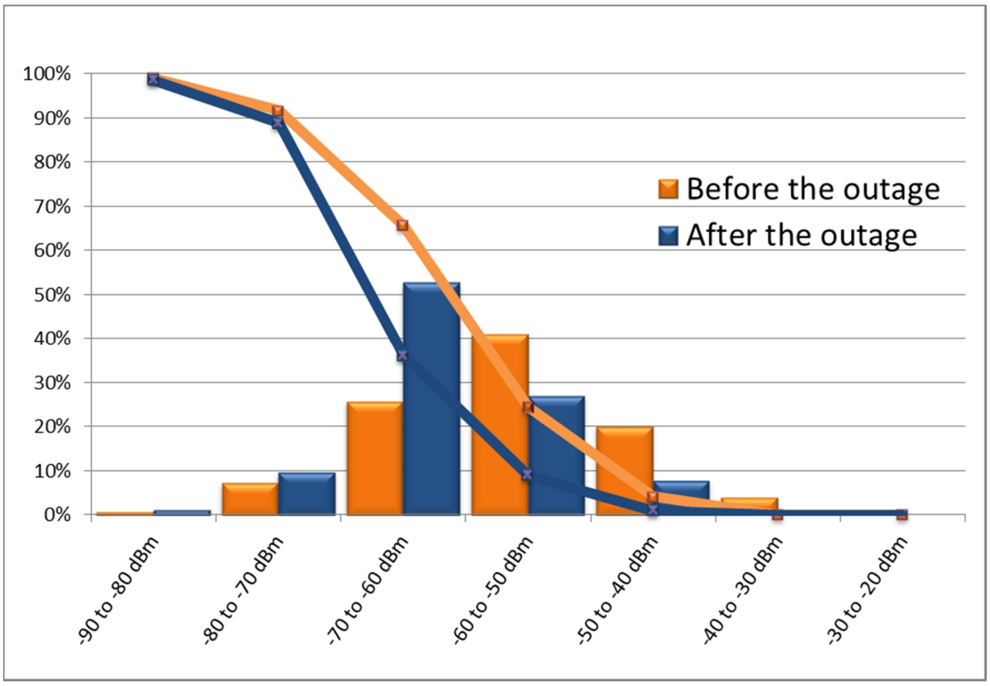


UL interference distribution before and after the outage.

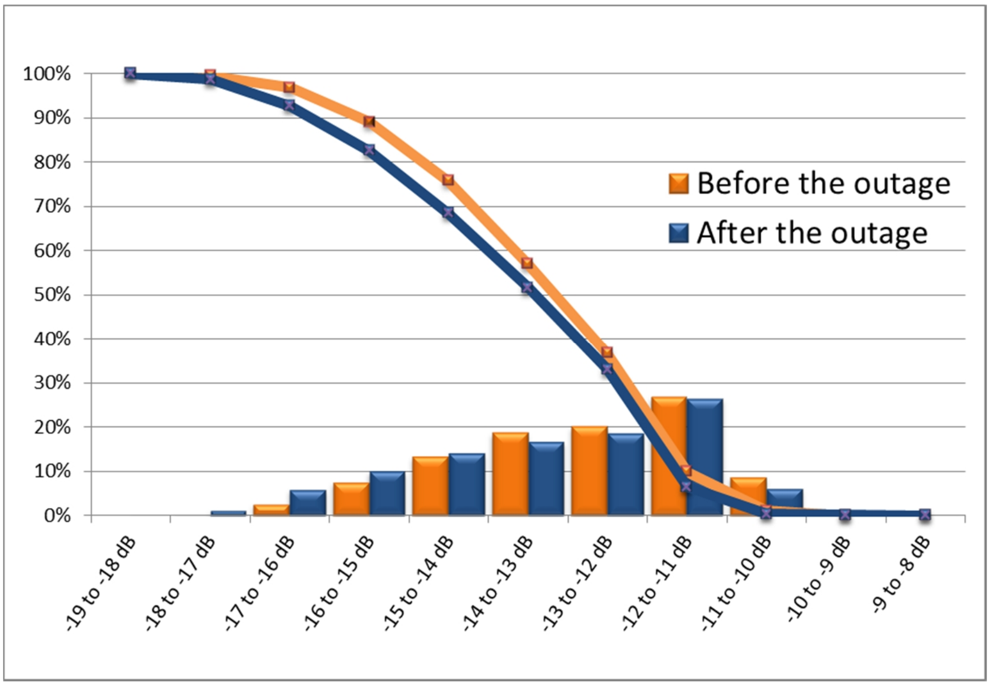
Appendix K - Effect of the outage to the DL performance in scenario II



RSRP distribution for an outdoor terminal before and after the outage.

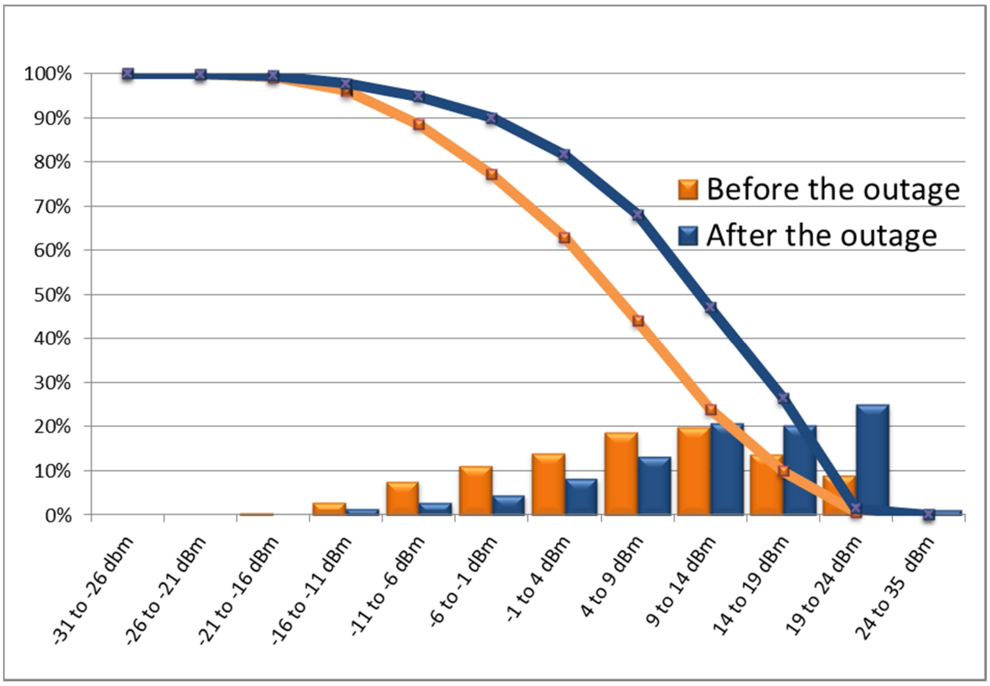


RSSI distribution for an outdoor terminal before and after the outage.

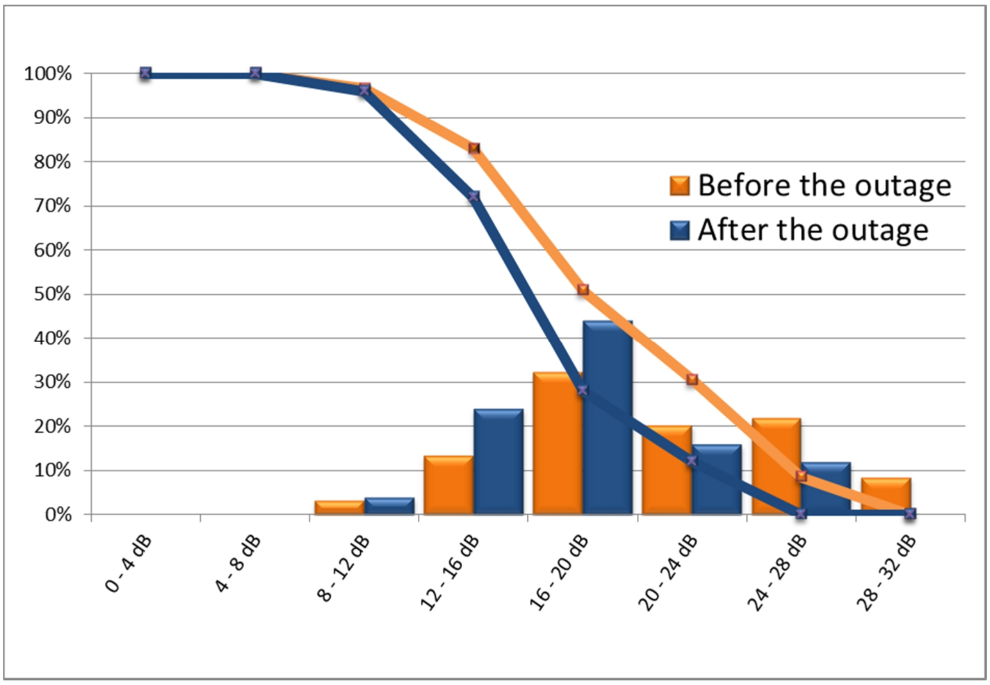


RSRQ distribution for an outdoor terminal before and after the outage.

Appendix L - Effect of the outage to the UL performance in scenario II



Required UL transmit power for an outdoor terminal before and after the outage.



UL interference distribution before and after the outage.