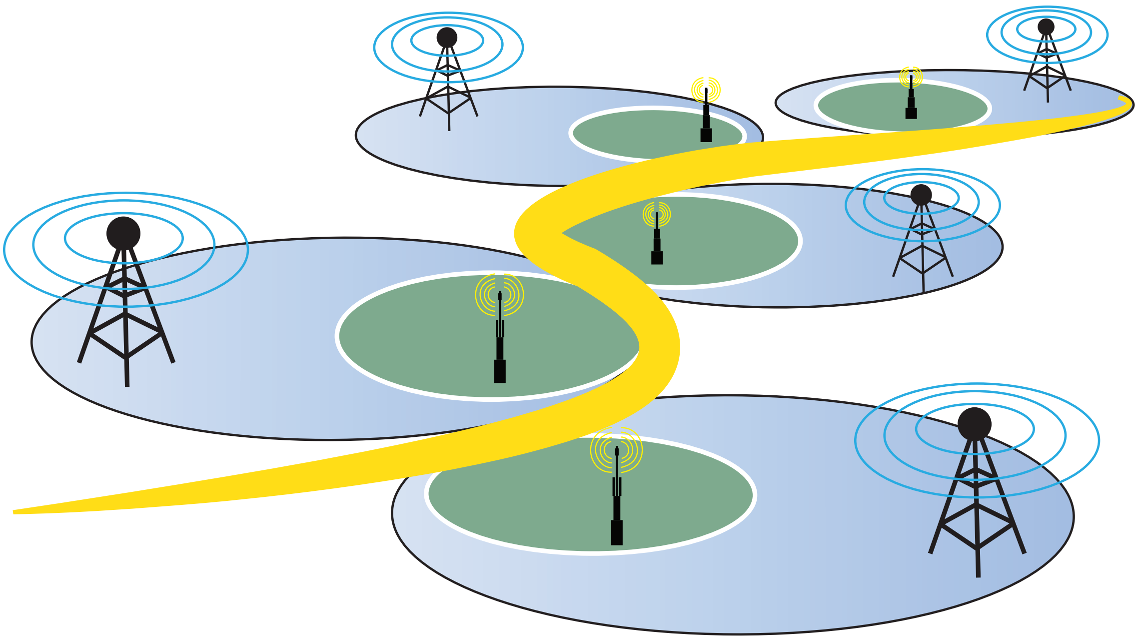
Design of optimized mobility capabilities in future 5G systems



Aalborg University

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Group 1053 - Wireless Communication Systems

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Abstract:

The focus for this thesis is improving the mobility performance in high speed and achieving high data rate. The study departs from analysing the existing LTE cellular system both at low and high speeds by means of real field measurements. Simulation scenarios have been created for the LTE system in order to check if the generated results are reliable compared to the real measurements. From these it is found that LTE cannot support a thousandfold increase in data rate. Thus, an additional 5G network layer to the existing LTE aims to support this data rate increase.

In this project the 5G network deployment is based on high frequency, ultra dense small cells and high bandwidth. The mobility study is based on dual connectivity between different radio access technologies: LTE and 5G. Results from simulations show that the time-to-trigger has a major impact in the mobility performance and that high connectivity to the 5G small cells improves the throughput experienced by the users in the scenario.

Preface

This report written by group 1053 who are 10th semester students at the department of Wireless Communication under the institute of Electronics Systems, Aalborg University. The theme for this project is *" Design of optimized mobility capabilities in future 5G systems"*. The project has been devised in the period September, 1. 2014 to June, 3. 2015.

Reading Instructions

This report is addressed to supervisors, students and others who are interested in the field of Wireless Communication. By extension the report presumes the reader to have a basic knowledge within this field.

The report contains references following the Harvard-method; [Surname,Year]. These references point to a bibliography in chapter 8 (p. 70). The bibliography contains information about the source like author, title, year of release etc.

Figures and tables are numbered according to their location in the report. Lists of figures and tables can be found in chapter 8 (p. 70). Unless otherwise specified, the figures and tables in the report have been produced by the project group. References to these will be followed by a page number unless they are on the current page.

Formulas and calculations will also be numbered according to their location. The presentation of these are inspired by the ISO-31 standard for technical communication which, amongst other things, means that the SI-unit system will be used.

Appendices and Annex CD

Throughout the report, references to annex and appendix will occur. All material contained in the appendix is made by the project group unless otherwise specified. The annex CD contains other material relevant for the report. This includes relevant literature such as articles and notes. An overview of the annex can be found in Chapter 9 and the annex itself is placed on the CD attached to the report. The appendix is placed in the back of the report. References to these will occur when they are relevant.

Contents

Abbreviations and Nomenclature

BS	Base Station
CDF	Cumulative Distribution Function
DL	Downlink
EPC	Evolved Packet Core Network
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
CDF	Cumulative Distribution Function
FTP	File Transfer Protocol
GSM	Global System for Mobile Communications
NetNet	Heterogeneous Network
HO	Handover
HOF	Handover Failure
HSPA	High-Speed Packet Access
ISD	Inter Site Distance
LOS	Line Of Sight
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
NLOS	Non-Line-Of-Sight
P-GW	Packet Data Network Gateway
RACH	Random Access Procedure
RAT	Radio Access Technology
RLF	Radio Link Faileure
RRC	Radio Resource Control
RSRP	Reference Signal Recieved Power
RSRQ	Reference Signal Recieved Quality
RSSI	Received Signal Strength Indication
S-GW	Serving Gateway
SINR	Singnal to Interference Plus Noise Ratio
TTT	Time to trigger
UDN	Ultra Dense Network
UE	User Equipment
WCDMA	Wideband Code Division Multiple Access

Chapter 1

Introduction

In the recent years, the mobile technology evolution has been achieved thanks to different factors: for instance, the cost of the devices has become accessible to everyone compared to the past. The remarkably increasing number of mobile subscribers in the recent years has developed the need for ubiquitous coverage and high capacity. Nowadays terminals are not only used for phone calls, but they can also be connected to internet and provide a wide range of services. For example, with the introduction of streaming services like Netflix or Video-on-Demand (VOD) the demand of traffic is growing exponentially as well as the media quality. If the traffic growth continues, the actual capacity will not be able to support the demand [Holma and Toskala, 2009]. For this reason, a major effort has been spent in the recent years in the development of next-generation wireless communication systems that will bring higher data rate and system capacity.

One of the crucial challenges nowadays is to ensure a reliable connectivity and, at the same time, a high data rate when a user is travelling at high speed. When the User Equipment (UE) is moving towards one cell, before the radio link signal of the actual serving cell beomes weak, it is necessary to move the connection to the cell from which the UE receives a better signal level. This operation is called **handover** and it becomes extremely difficult when the UE speed increases. In fact, if the handover fails, the UE loses the connection and experiences a so called connection dropping. Therefore, choosing the right condition that triggers the handover event is essential. All these factors determine the performance of the mobility.

The researchers started to investigate a new technology beyond the actual Long-Term Evolution (LTE). In fact, projects like "*Mobile and wireless communications Enablers for the Twenty-twenty Information Society*" (METIS) have the objective of laying the foundation for the next-generation technology named 5G. Even though there is not a clear idea of what the 5G will be, the main assumptions are related with the very high carrier frequency, a large bandwidth, ultra dense network (small cells) and massive MIMO [Jeffrey G. Andrews et al., 2014]. With these configurations a higher data rate can be reached but, at the same time, the mobility has to be redefined especially when high speed is involved. The 5G technology aims to reach at least 10 Mbps in any kind of environment [Ericsson, 2015].

For these reasons, with this work is wanted to investigate the mobility performance in a high speed scenario where small cells are involved, as well as the throughput experienced by the UE.

Several field tests in the existing LTE cellular system are performed. Simulations are created for these tests based on operator and measurement information. The reason for performing simulations is to evaluate if the model used to generate the results is reliable. Furthermore, these simulations will be used as a baseline for introducing 5G elements in the scenario. The steps for the study are as follows:

- LTE field measurements in the city center of Aalborg at low speed (15 km/h) for evaluating the LTE performance
- simulation of the LTE system in low speed used to validate the implemented model
- LTE field measurements on the highway in Aalborg at high speed (100 km/h) also for LTE performance evaluation
- simulation of the LTE system in high speed in order to verify if the LTE system can support an increase in data demand. It is expected that the data rate should increase 1000 times more for the traffic demand [Jeffrey G. Andrews et al., 2014].
- addition of a 5G network to the existing high speed scenario with the aim of achieving high throughput for the UE. The additional network consists of densely deployed small cells along the path followed in the field measurements.

The 4G network layout for the highway is used as a layer of macro cells while along the highway small cells are deployed, constituting a HetNet. A new feature from LTE is used, called *carrier aggregation*, that combines different carrier frequencies in order to increase the bandwidth and therefore the data rate.

The presented work has been carried out focusing on the theoretical background of LTE, on its real performance in the real network and on the implementation and testing of the proposed HetNet scenario where 5G is also involved.

Together with high data rate another aim of this study is the optimization of the mobility performance in the scenario that contains 5G. For this study, concepts like Ultra Dense Networks (UDN), increased frequency and dual connectivity will be implemented and their impact on the developed system will be investigated. High data rate is difficult to achieve in high mobility in a very dense heterogeneous network. Therefore, it is assumed that deploying small cells operating at high frequency and high bandwidth play an important part in achieving high data rate at the user end. Given the deployment of the scenario consisting of two layers operating at different carrier frequencies that belong to different Radio Access Technologies (RAT), the mobility performance will be analysed. Furthermore, methods to improve this mobility performance and enhance the dual connectivity between base stations belonging to different RATs will be studied.

The mobility performance radio parameters such as Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Received Signal Strength Indication (RSSI), throughput are some of the Key Performance Indicators (KPI) that will be used to evaluate the performance of both the existing LTE system and the newly implemented scenario. Other KPIs that are discussed relate to radio link failures, handover failures and ping-pong effect.

The delimitations for the scenario consisting on LTE and 5G are as follows:

- use of carrier aggregation and HetNet
- having a minimum of 10 Mbps throughput satisfaction for a high percentage of the users in the system
- constant user speed of 120 km/h
- carrier frequency of the 5G layer of cells in the range of 6-20 GHz
- inter site distance for the small cells of 100 meters
- overall bandwidth for the small cells of 100 MHz for 10 Physical Resource Blocks (PRB)

The parameters for creating the network of small cells are chosen according to the 3GPP standard ([TR36.814,]) and METIS tests ([METIS et al., 2015]).

The thesis is organized as follows: *Chapter 2* gives an overview of the LTE in terms of system architecture, mobility and carrier aggregation. *Chapter 3* illustrates the results from the measurements performed in Aalborg city center on 4G network as well as the comparisons with the simulations. *Chapter 4* highlights the performance from the measurements done in the highway on the area of Aalborg and presents the basis and motivation for the new technology (5G). *Chapter 5* explains the developed scenario in terms of propagation models and mobility. It also describes the simulation results and the performance. *Chapter 6* presents the enhancements brought to the previous implementation by redefining some of the parameters. Their impact on the scenario is analysed and the obtained results can give an insight of what parameters and network deployment can be utilized while advancing towards 5G.

Chapter 2

LTE Overview

In order to have a good overview of the mobile system, this chapter explains the history evolution of the mobile communications from the first generation (1G) to the latest version of LTE (Long Term Evolution), the latest version of mobile telecommunication systems. The purpose of this introduction is to give an overview of the LTE system and its advantages compared to the previous technologies. The following topics will include the architecture of LTE, the mobility functionality in LTE and methods that can enhance user association.

The first mobile communication system arrived in 1980 named *"First Generation"* (**1G**) which was using an analogue technology with bulky equipment and comprise a number of independently developed systems worldwide.

The *"Second Generation"* (**2G**) also known as GSM (Global System for Mobile communications), arrived with the introduction of digital system communication. GSM was mainly designed for voice traffic while data appeared later with the introduction of GPRS/EDGE. All these technologies were based on Time- and Frequency- Division Multiple Access (TDMA/FDMA).

Later the data usage became more remarkable, thus a *"Third Generation"* (**3G**) was developed in order to satisfy the market demand. This was possible thanks to the introduction of CDMA (Code Division Multiple Access) in U.S. and WCDMA (Wideband Code Division Multiple Access) in Europe.

In December 1998, the ***Third Generation Partnership Project*** (**3GPP**) was created; 3GPP was formed by standards-developing organizations from all regions of the world that had the aim of *"co-operate in the production of globally applicable Technical Specification and Technical Report for a 3rd Generation Mobile System based on evolved GSM core network and the radio access technology that they support"* [3GPP Agreement 4 December 1998, www.3gpp.org].

In the following years various upgrades have been made to 3G, such as High Speed Downlink Packet Access (HSDPA) in 2002, High Speed Uplink Packet Access (HSUPA) in 2004 and HSPA+ in 2007. During 2009, 3GPP initiated the work on 3GPP Long-Term Evolution (4G), aiming to take a step forward in terms of system performance and service capabilities.

In the Figure 2.1 (p. 5) it is shown the evolution of the mobile communications standards landscape from the GSM technology up to latest version of LTE.

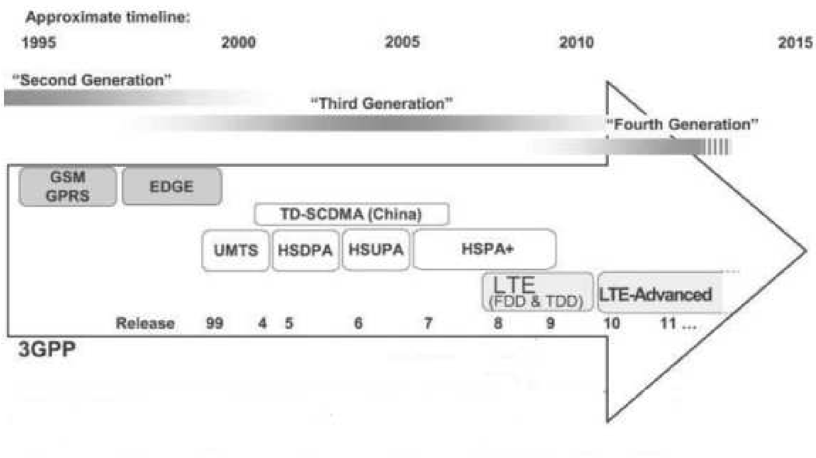

Figure 2.1: Timeline of the mobile communications standards landscape [Stefania Sesia and Baker, 2011]

The next in the 3GPP standardization is LTE Release 8, providing improved data performance compared to the previous systems. Afterwards, Release 9 introduces new elements in the architecture. This is followed by LTE-Advanced, specified in 3GPP Release 10, which allows the use of carrier aggregation in heterogeneous networks and aims to improve the performance of the users at the cell edge.

With the introduction of every new technology it has been also possible to gradually increase the data traffic. The evolution of the data rate is shown in Figure 2.2.

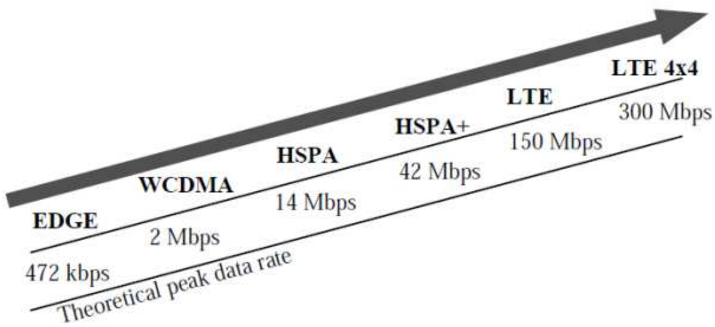

Figure 2.2: Evolution peak data rate [Holma and Toskala, 2009]

LTE-Advanced is designed to improve the capabilities of LTE in terms of data rate, capacity and coverage. Thus, this technology will be used for the purpose of this project. Further on, the following chapter will give an insight in the LTE architecture, mobility procedure and the carrier aggregation technique, since these will be the main topics covered in the following study.

2.1 LTE System Architecture

This section will give an insight in the architecture and protocols of the LTE System, underlying the basic functions and utilities of the system components.

LTE was designed to provide seamless connectivity between the User Equipment (UE) and the Packet Data Network (PDN), without the UE experiencing any disruption in its applications. The user is able to access the Internet at the same time is makes a voice call for example (VoIP), while the network ensures the user keeps it security and privacy.

The basic architecture of the LTE Release 8 can be depicted in Figure 2.3. It consists of four main levels: User Equipment (UE), Evolved Universal Terrestrial Radio Access Network (E-UTRAN), Evolved Packet Core Network (EPC) and the Services domain. The first three layers in the architecture scheme, UE, E-UTRAN and EPC, represent the Evolved Packet System (EPS) whose main function is to provide IP connectivity [Holma and Toskala, 2009].

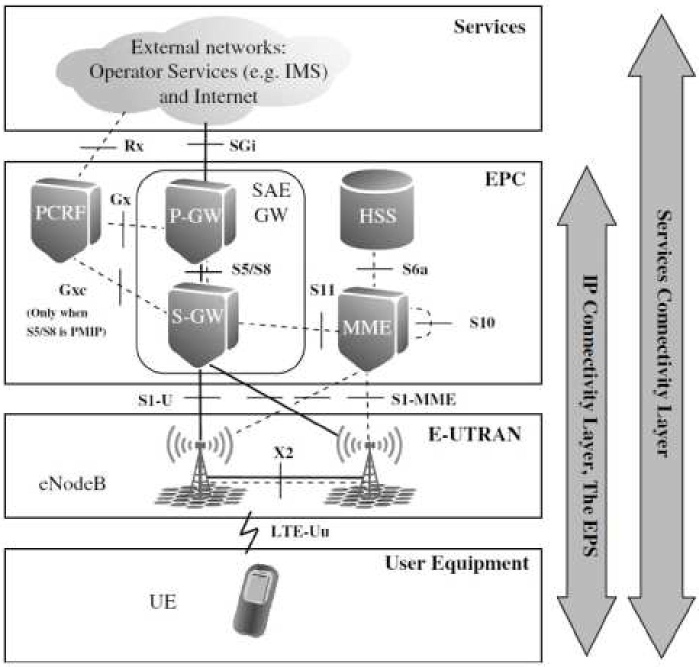

Figure 2.3: Basic System Architecture Overview [Holma and Toskala, 2009]

The development in the E-UTRAN LTE architecture is related to the evolved NodeB (eNodeB), also known as the base station. E-UTRAN is a mesh of eNodeBs connected to each other through the X2 interface. All radio related protocols are terminated in the eNodeB. Its role is to avoid sending the same data IP header repeatedly. It needs to be connected to the neighboring eNodeBs to which the handover may be made. As it can be seen in Figure 2.3, the eNodeB acts as a bridge between the UE and the EPC, connecting the eNodeBs to other logical functions of the EPC. The eNodeB relays the data between the radio connectivity and the IP connectivity towards the EPC. It also monitorizes the resource usage and makes handover decisions for the UE. This connection can also be depicted in figure 2.3 (p. 6) [Holma and Toskala, 2009].

Within the EPC, MME, S-GW and P-GW can be found:

- **The Mobility Management Entity (MME)** in EPC keeps track of the users location in the Tracking Area and is the main control function of EPC. It also controls the signaling in the handoveror cell change between eNodeBs, S-GW and MMEs, when the UE is in connected mode. If the UE is idle, then it will report its location periodically or when it moves to another Tracking Area [Holma and Toskala, 2009]. The protocols running between the UE and EPC are known as Non Access Stratum (NAS), which establishes the connection and security between the UE and the network [Stefania Sesia and Baker, 2011].

- Another component of the EPC is the **Packet Data Network Gateway (P-GW)**. It allocated IP adresses to the UE when it requests a Packet Data Network (PDN) connection. Therefore, the P-GW acts as a router between the EPS and external packet data networks. P-GW is the highest level mobility anchor in the system. When a UE moves from one S-GW to another, the bearers have to be switched in the P-GW. The P-GW will receive an indication to switch the flows from the new S-GW [Holma and Toskala, 2009].

- The **Serving Gateway (S-GW)** is used to transfer the IP packets when the UE moves between eNodeBs. Its main role is to control the user plane tunnels by routing and forwarding user data packets. It receives commands from the MME to switch tunnels between eNodeBs [Stefania Sesia and Baker, 2011].

- Communication is protected by eavesdropping using the authentication function in the **Home Subscriber Server (HSS)**. This function assures that the user is who it claims to be. It also stores the identities of the used P-GWs

The purpose of this section was to give an overview of the main LTE architecture components and their main functionalities, as they play an important role in the mobility process, which will be described in the next section.

2.2 Mobility

This chapter gives an insight in the LTE mobility procedure, which is useful for the purpose of this project and will make the subject for measurements that will be presented in the next chapter. Describing the mobility in LTE is essential for understanding the procedure and parameters used to make it work, being able afterwards to analyse the outcome of the performed measurements.

2.2.1 Mobility Overview

To get information about the available channels in the selected area, the UE sends a random request over the medium, also known as *random access procedure (RACH)* which will be detailed further in section 2.2.5 (p. 15).

There are two mobility procedures in LTE: **RRC idle** and **RRC connected** [Stefania Sesia and Baker, 2011]. RRC stands for Radio Resource Control protocol, which is in charge of the signalling between the user and the eNodeB. First of all the idle mode procedure will be described, then the connected mode and how the handover is performed. The main focus will be on the connected mode procedure, since this is the main topic for this thesis.

- **Idle mode Mobility Procedure**

  In **idle mode**, the mobility is controlled by the UE, which decides and performs cell selection and reselection based on its measurements. First, the UE selects a suitable cell for camping from a selected network, according to radio measurements.

  After the cell *selection*, the UE will keep checking if there are better cells. This process is known as *reselection*. During the idle periods, the UE measures the signal quality of the neighbours it can receive, then it decides the best connection based on different parameters(e.g. signal quality, priorities). If the UE does not manage to find a suitable cell for selection, it will look for a cell in another network [Holma and Toskala, 2009].

  In LTE, *priority* is a new parameter. The eNodeB can provide a priority per LTE frequency and per RAT. In case the UE camps on a cell with the highest priority frequency, the UE doesn't need to measure other cells as long as the signal strength is above a certain threshold. Otherwise, if it camps on a low cell priority, it should do regular measurements for other cells with high priority frequency/RAT [Holma and Toskala, 2009].

  In 3GPP Release 9, the cell reselection rule is based on cell absolute priority. This means that the cells operating on the same carrier frequency have equal priority and the cell selection is based on the signal level and quality. In case the reselection process is between different radio access technologies (RAT) or inter-frequency reselection (layers), each layer is assigned a different priority. The reselection is then made towards the highest priority

RAT/frequency that can provide good service to the UE [Salo, 2013].

- **Connected mode Mobility Procedure**

  The transition to RRC **connected mode** is done as long as there is an active data session or call setup. In cellular communication systems, a cell has limited coverage area. When a UE is connected to a cell, it is possible to move out of a cell's coverage while being in a call session. The process by which the session is transferred to another cell is called **handover**. This is done in order to avoid the interruption when the UE gets outside the coverage of the first cell.

  The handovers are performed while the UE is in connected mode and they are based on radio measurements. The handovers are controlled by the network, which decides to which cell a UE should connect in order to maintain the radio link quality. In the early releases of LTE, the UE can connect to one cell, meaning that before connecting to the second cell, it breaks the connection to the first one. This is the concept of *hard handover*. With the Release 10 of LTE, it is possible to establish dual connectivity with cells operating on different frequencies. This concept is known as *carrier aggregation*. Hard handover still happens in Release 10 due to the use of OFDM. The carrier aggregation technique will be the subject for the next section [Holma and Toskala, 2012].

During this switching of the UE from one eNodeB to another, some packet transmission issues may occur. In the downlink direction, the retransmission of unnecessary packets by the target eNodeB happens if the source does not acknowledge their reception at the UE. It is the UE which identifies and removes the duplicate packets. It may also happen that the same packets are sent twice in the uplink direction, this problem is then being solved in the packet core [Holma and Toskala, 2009].

2.2.2 Measurements in LTE

The topic for this section is to present the measured quantities in an LTE system. Whenever the UE sends a measurement report, it also reports the measured quantities. The most used quantities are the Reference Signal Received Power (RSRP) and the Reference Signal Received Quality (RSRQ). Their definitions will be further described in this subsection, as well as the relation of RSRQ with the signal-to-noise-plus-interference ratio (SINR).

The RSRP that the UE experience is an average of all the Resource Elements that contain cell-specific Reference Signal over the entire measured bandwidth [TR36.214, 2011]. The RSRP takes only into account the reference signal and omits the interference power and the noise. The reporting range of the RSRP is between -140 dBm and -44 dBm. The RSRP is defined in

Equation 2.1 [Salo, 2013].

$$RSRP = \frac{1}{K}\sum_{k=1}^{K} P_{rs,k} \qquad [W] \quad (2.1)$$

Where $P_{rs,k}$ is the estimated received power for the k^{th} Reference Signal Resource Element.

The RSRQ definition can be found in Equation 2.2 [Salo, 2013], which is the ratio between the RSRP and the total received power and noise normalized to 1 PRB (corresponding to one slot in time domain (1 ms) and 180 MHz in frequency domain [TR36.211, 2007]). The RSRQ indicates the quality of the received signal.

$$\begin{aligned} RSRQ &= N_{prb}\frac{RSRP}{RSSI} \\ &= N_{prb}\frac{\frac{1}{K}\sum_{k=1}^{K} P_{rs,k}}{\sum_{n=1}^{N_{re}} P_n} \end{aligned} \qquad (2.2)$$

The RSSI (Received Signal Strength Indicator) term in the equation denotes the power from the serving cell, the interference and the thermal noise. It contains the total power P_n observed in the n^{th} resource element that containing the reference signal. The total number of resource blocks is $N_{re} = 12 \cdot N_{prb}$, where N_{prb} is the number of physical resource blocks in the measurements bandwidth and 12 is the number of the sub-carriers. The range where the RSRQ operates is between -19.5 dB and -3 dB [Salo, 2013].

The RSSI definition can be expressed in Equation 2.3, over the whole measurement bandwidth.

$$RSSI = S_{tot} + I_{tot} + N_{tot} = \sum_{n=1}^{N_{re}} P_n \qquad [dB] \quad (2.3)$$

Where S stands for received signal power measured over the $12N_{prb}$ subcarriers of the measurement bandwidth, I for interference and N for noise [Salo, 2013].

In contrast with the RSRP, RSRQ is not a suitable quantity for triggering an intra-frequency handover. This is due to the fact that the ratio between the RSRQ of the serving cell and the RSRQ of a neighbouring cell will only depend on the ratio of the RSRPs of these cells.

Network quality can be analysed by the SINR. It can be defined in terms of RSRP, average interference power(I) and thermal noise power (N), as in Equation 2.4.

$$SINR = \frac{RSRP}{I + N} \qquad (2.4)$$

2.2.3 Layer 1 and Layer 3 Filtering

The UE can perform inter-frequency measurements (between cells operating on two different carrier frequencies) or intra-frequency measurements (between cells on the same carrier frequency). The UE perform measurements at the physical layer, Layer 1, (3GPP TS 36.214) and it reports them to the Layer 3 (network) (3GPP TS 36.331). The 3GPP specifications contain information about the accuracy of the measurements. Intra-frequency RSRP measurement difference between a serving and a target cell should not have more that 3 dB error. In the case of inter-frequency measurements, the difference between serving cell RSRP and the target cell RSRP can be at most 6 dB. Therefore, the accuracy for the intra-frequency measurements is better than for the inter-frequency. These accuracy specifications are part of the Layer 1 filtering of the measurements [Salo, 2013].

In order to improve the measurements accuracy and mitigate the effects of fading , Layer 3 filtering is applied to the physical layer measurements. The raw measurements from Layer 1 are filtered at Layer 3. The updated filtered measurement result is used for evaluating the reporting criteria or for measurement reporting [Salo, 2013].
The Equation 2.5 shows how the filtering is done at the network layer .

$$F_n = (1-\alpha) \cdot F_{n-1} + \alpha M_n \tag{2.5}$$

Where:

- M_n is the latest received result from the L1 layer
- F_n is the updated filtered measurement result
- F_{n-1} is the old filtered measurement result
- k is the filter coefficient for the corresponding measurement quantity
- $\alpha = \left(\frac{1}{2}\right)^{\frac{k}{4}}$

For inter-frequency measurements, *measurement gaps* can be assigned to the UE for the time periods where no uplink or downlink transmissions are scheduled. In inter-frequency measurements, when the UE has less opportunity to detect a cell, *measurement gaps* are configured. Two possible measurement gaps can be configured by the network, each gap having a length of 6 ms: in the first gap, measurements are performed every 40 ms, while in the second one they are performed every 80 ms. The filtering at the two layers (1 and 3) is shown in Figure 2.4 (p. 12). The advantage of using short measurement gap is the identification delay of a cell is shorter, but there can be bigger interruptions in data transmission or reception [Stefania Sesia and Baker, 2011].

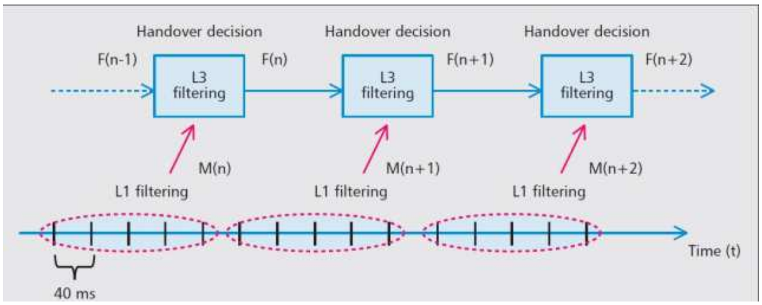

Figure 2.4: Filtering at Physical and Network Layers [Lopez-Perez et al., 2012]

2.2.4 The Handover Procedure

A detailed description of the handover procedure will be covered in this subsection, showing the message exchange at every entity level in the LTE architecture.

There are three steps for the handover. The first one is the *handover preparation*, which can be depicted in Figure 2.5. First, the eNodeB configures the UE measurements (1).

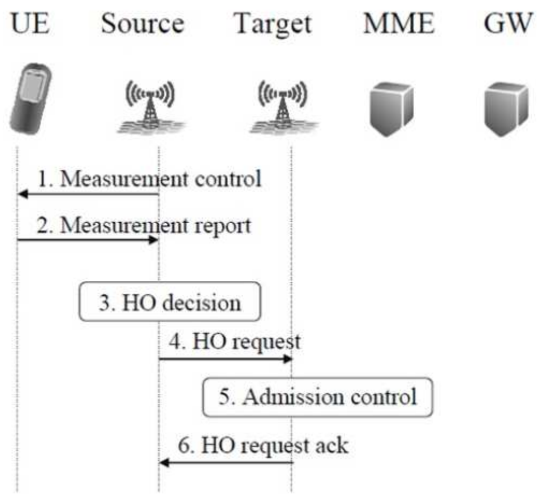

Figure 2.5: Handover Preparation [Holma and Toskala, 2009]

The *decision for performing the handover* is based on UE measurements and it is done by the network. The report towards the source eNodeB is made when the measurement from the target eNodeB has fulfilled a specific threshold condition (2). In case of intra-frequency handovers, the UE is normally connected to the cell with the lowest path loss value because this indicates better signal strength and lower uplink interference. The UEs that are not connected to the cell with minimum path loss use unnecessary high transmit power, therefore they create uplink interference. The handover request is sent from source to target eNodeB (4). An admission control method is used for the network to check if there are enough resources for the target cell (5). If so, the handover towards the target cell is ready to be performed, otherwise the connection will be dropped in order to avoid high interference. The last step in the preparation of the handover is sending an acknowledge request from the target to the source, which means that the target is ready to be handed over the connection (6) [Holma and Toskala, 2009].

The second step in the handover procedure is the *handover execution* and it is represented in Figure 2.6. After having received the acknowledge from the target, the source eNodeB sends the handover command to the UE (7) and transfers the packets acknowledged by the UE to the target through the X2 downlink interface (8). These packets are then buffered by the target eNodeB. Using the RACH procedure (Section 2.2.5 (p. 15)) the UE synchronizes and accesses

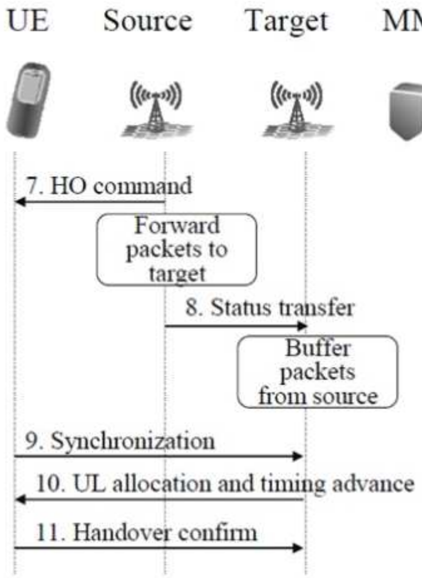

Figure 2.6: Handover Execution [Holma and Toskala, 2009]

the target cell (9). After receiving the uplink information from the target, the UE confirms the handover to the target, which can now send data to the UE (11).

The last part of the handover is called *handover completion*. Its main steps can be seen in Figure 2.7 (p. 14). The target eNodeB has received the confirmation message from the UE and now it informs the MME about the change of the cell. It also requests an update for the User Plane (UP) from the S-GW, which switches the downlink data to the target. The UP update has to be confirmed by the MME. Afterwards, the target eNodeB requests the source to release the radio and control plane resources associated to the UE.

The reporting criteria for the measurements and the format are contained in the reporting configuration. The criteria are for the UE to trigger a measurement report and they can be event triggered or periodic. This includes quantities that are shown in the measurement report (number of cells, serving cells, listed cells). For handover measurements, it is usually the RSRP estimation over the cells included in the list. This RSRP estimation is done at Layer 1, where handover measurements are filtered (Section 2.2.2 (p. 9)).

A handover is triggered if the Layer 3 filtered handover measurements meets a handover event

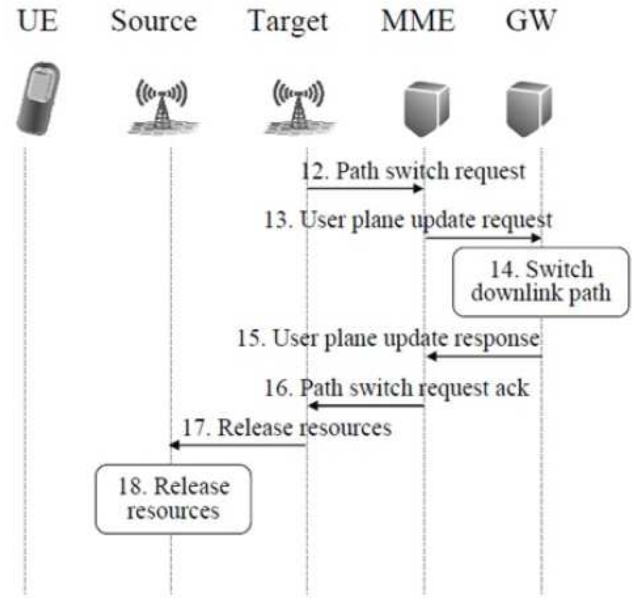

Figure 2.7: Handover Completion [Holma and Toskala, 2009]

Event A1	Serving cell becomes better than absolute threshold
Event A2	Serving cell becomes worse than absolute threshold
Event A3	Neighbour cell becomes better than an offset relative to the serving cell
Event A4	Neighbour cell becomes better than absolute threshold
Event A5	Serving cell becomes worse than one absolute threshold and neighbour cell becomes better than another absolute threshold
Event B1	Neighbour cell becomes better than absolute threshold
Event B2	Serving cell becomes worse than one absolute threshold and neighbour cell becomes better than another absolute threshold

Table 2.1: Event-Triggered Reporting Criteria for LTE and Inter-RAT Mobility [Stefania Sesia and Baker, 2011]

entry condition [Lopez-Perez et al., 2012]. The types of handover event entry conditions are presented in Table 2.1.

The eNodeB can influence the entry condition by setting the value of some parameters used in the triggering event. These parameters are configurable and they can be one/more threshlods, an offset and a hysteresis, depending on the event used for triggering. The parameter called time-to-trigger is the minimum time period for which the entry condition must be satisfied in order for an event to be triggered. [Stefania Sesia and Baker, 2011]

Figure 2.8 (p. 15) shows the triggering of the A3 event (most commonly used for handover triggering), where the *Offset* and *Time To Trigger* are configured as threshold values. The reporting condition is met when the signal of the neighbouring cell becomes better than the signal of the serving cell by a certain offset. If so, the handover preparation will be performed to the neighbouring cell after the Time To Trigger has expired and the reporting condition is still fulfilled. The Time To Trigger value is set in case the serving cell signal becomes better than the neighbouring during this time. If this happens the handover will not be performed [Stefania Sesia and Baker, 2011].

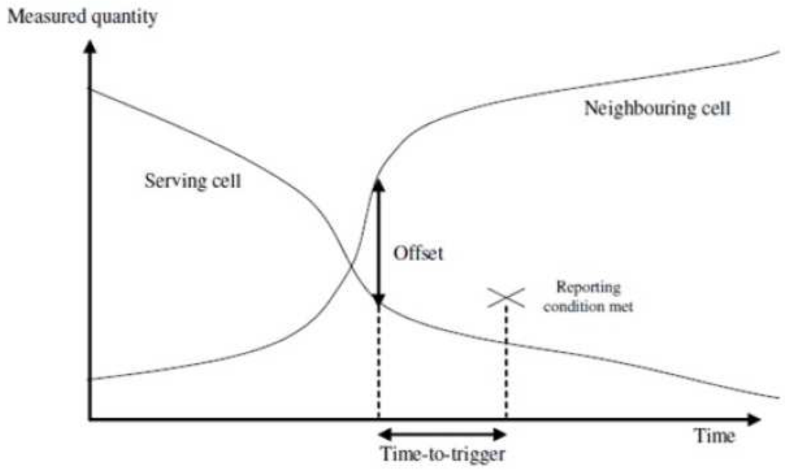

Figure 2.8: Triggering conditions for handover in connected mode [Stefania Sesia and Baker, 2011]

The values of the configured parameters have an important role in the handover performance. If the TTT value is too small, this may lead to handovers being performed too early, or if the TTT is too big the handover may be performed too late. This may result in system failures [Lopez-Perez et al., 2012].

2.2.5 The RACH Procedure

The random access procedure is used for initial network access by the UE and also in the handover process. It can be *contention-free* (no collision with requests from other users in the requested cell) or *contention-based*. When the UE wishes to connect to a network for the first time, it sends a request over the medium containing the UE's specific signature, also known as *RACH preamble*. Therefore, different UEs will have different preambles, though it is possible that two UE attempt a connection using the same preamble. In this case, there will be a collision. There are 64 available preambles for initial UE access and they are assigned differently according to the type of RACH used: contention-based (the preamble is randomly chosen by the UE) or contention-free (the decisions upon the preamble are made by the network) [Stefania Sesia and Baker, 2011].

When the RACH procedure is contention-free, some resources are reserved and the UE is assigned specific resources by the eNodeB. RACH procedure is used during the handover process and the message exchange between the UE and the target eNodeB can be seen in Figure 2.9 (p. 16). In this case, the assignment of the preambles is signalled via a *handover* command from a source to a target eNodeB, since it is the eNodeB that controls the handovers.

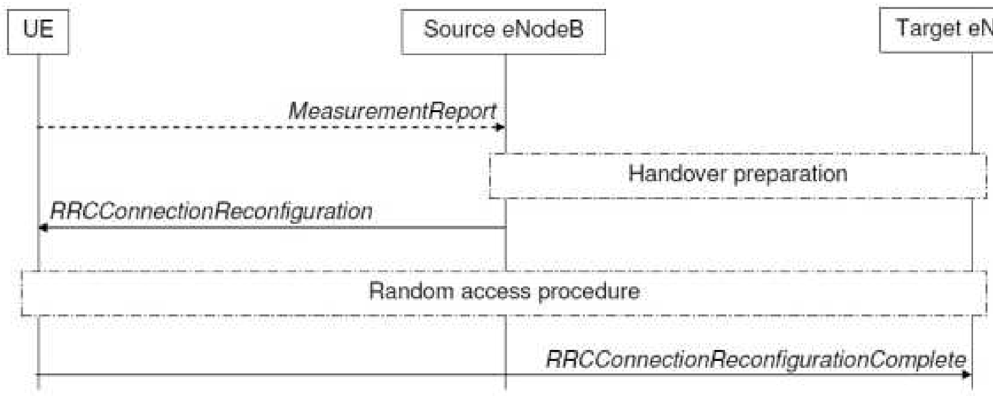

Figure 2.9: RACH Procedure in the Handover Process [Stefania Sesia and Baker, 2011]

The eNodeB requests for the target cell to prepare for the handover before sending the command to the UE in *handover preparation*. This can contain information about UE capabilities. The handover command is sent from the eNodeB to the UE in the *RRCConnectionReconfiguration* message. In this messages it is included information about the cell ID, frequency and the radio resource configuration. The measurement configuration may also be included in this RRCConnectionReconfiguration message, but in order to avoid the message being too large, the eNodeB can send another reconfiguration message with the measurement configuration [Stefania Sesia and Baker, 2011].

If the UE is able to comply with this configuration, then it starts a timer, T304, and the *random access* procedure is initiated towards the target cell. When the RACH procedure has been successfully completed, the timer T304 stops [Stefania Sesia and Baker, 2011].

In the early releases of LTE, the handover can result in delay plus interruption time. The interruption time is defined as the time from the end of the handover command from the serving cell to the moment the UE starts transmitting in the uplink channel to the target cell. This process is shown in Figure 2.10 (p. 17).

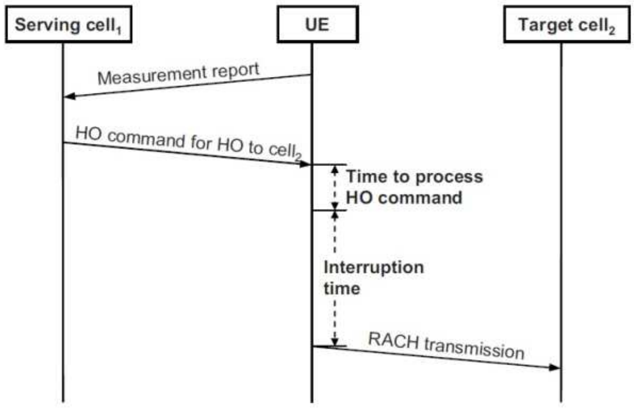

Figure 2.10: Interruption time in the Handover Process [Stefania Sesia and Baker, 2011]

If there are multiple frequency layers, the network may request the UE to perform measurements on only one of the frequency layers. For the other layer the UE may perform "blind" handovers, meaning that it has to detect a cell before accessing it. This results in a higher interruption time [Stefania Sesia and Baker, 2011].

The RACH procedure is also found in case there are any failures of the radio link, during the handover or the reconfiguration procedure. In the case of failure, the UE starts the *RRCConnectionReestablishment* procedure. For the re-establishment, the timer $T311$ is started and the UE performs cell selection. When it finds a suitable cell on an LTE frequency, the timer is stopped and the UE initiates a contention based RACH procedure, by starting another timer, $T301$. The RACH procedure enables the *RRCConnectionReestablishmentRequest* message, which contains information about the cell identity in which the failure occured, a message authentication and the cause of the failure [Stefania Sesia and Baker, 2011].

This section explained how the random access procedure works when the UE first initiates a connection, how it is used during a handover or in case there is a failure in the system. For detailed information about the message exchange between the UE and the eNodeB, check Section A (p. 77).

2.2.6 Mobility Failures

There are several problems that can occur in the system when trying to trigger the handover. These will be briefly presented in this subsection, along with the causes that produce them.

The types of failures that can occur in an LTE system are as follows:

- **ping-pong**: back and forth handover between cells when the time the UE stays connected to the target cell is less than a minimum amount of time (ping-pong timer, usually equal to 1 second [TR36.839, 2012]).

- **radio link failure (RLF)**: detected based on the radio link quality of the serving cell when the UE is in RRC connected mode. The UE can be in-sync or out-of-sync with the serving cell. The RLF is defined by a set of parameters, which can be found in Table 2.2 [Stefania Sesia and Baker, 2011].

- **handover failure**: it can occur in the following cases:
  - a RLF occurs during the handover preparation or execution steps;
  - no capacity is left in the neighbouring cells;
  - handover is performed too early/late.

For tracking a *radio link failure*, the UE uses two channel quality indicators, Q_{in} and Q_{out}. A UE is considered out of synchronisation RLF is declared if the signal-to-interference-plus-noise (SINR) ratio is below -8 dB (Q_{out}) and stays below -6 dB (Q_{in}) for the duration of the timer T310. The timer is stopped once the SINR value is larger than -6 dB. A *handover failure* is declared if the timer T310 is still running when the handover command is sent or if the SINR is still lower than Q_{out} after the handover complete message. The process of failure detection can be depicted in Figure 2.11.

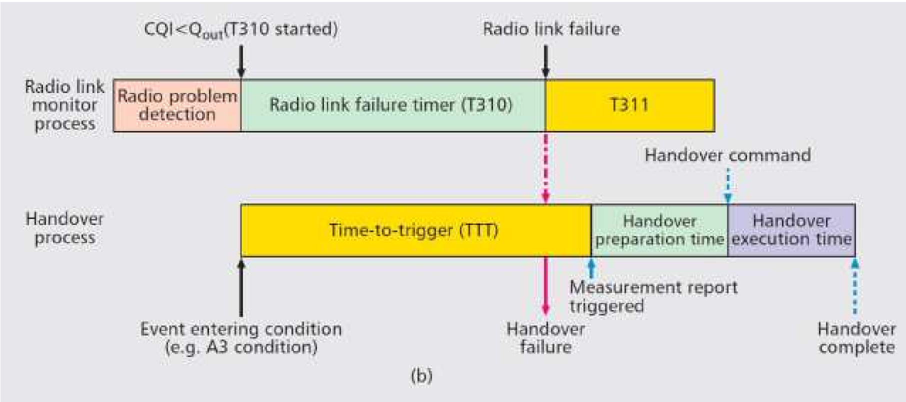

Figure 2.11: Timers in Handover Process and RLF Detection [Lopez-Perez et al., 2012]

It may happen that before the handover command the $SINR > -6$ dB while the time T_{310} has not expired, then the system can recover from the RLF. The recovery is made through the RRCConnectionReestablishment command, which has been described in Section 2.2.5 (p. 15).

Q_{in} and Q_{out} are simulation modelling parameters, while the parameters presented in Table 2.2 are real configuration parameters. The parameters are set according to the simulation setup described in the 3GPP specifications [TR36.839, 2012].

Parameters	Description
T_{310}	RLF timer has expired
N_{310}	RLF timer stops after 1 out-of-sync indication
N_{311}	RLF timer stops after 1 in-sync indication

Table 2.2: Description of Parameters for RLF Occurrences [Stefania Sesia and Baker, 2011]

2.3 Carrier Aggregation

This section will introduce the basic concept and the motivation for using carrier aggregation. The purpose of this section is to create a background for the techniques that will be further used for this project. The focus of the description will be on the mobility procedures with carrier aggregation, the performance of the system and in which networks carrier aggregation can be utilized (heterogeneous networks).

The concept of carrier aggregation is the first step of LTE-Advanced used to optimize the network efficiency, as the demand for spectrum is constantly increasing. Meeting the 150 Mbps downlink target for LTE-Advanced requires at least 20 MHz of bandwidth. This problem is addressed by carrier aggregation by combining multiple carriers together. The benefit from this is that the available capacity can be used more efficiently, more users can be served and the delay of services can be reduced.

According to Release 10 LTE specifications, carrier aggregation can be utilized for both downlink and uplink UE transmissions. LTE-Advanced allows the aggregation of up to 5 carrier components, each one having up to 20 MHz bandwidth. Therefore, a total of 100 MHz transmitter bandwidth can be obtained by allocating the carriers in three different modes, depending on the spectrum allocation: contiguous intra-band, non-contiguous intra-band and inter-band carrier aggregation. These three modes can be depicted in Figure 2.12 [Holma and Toskala, 2012].

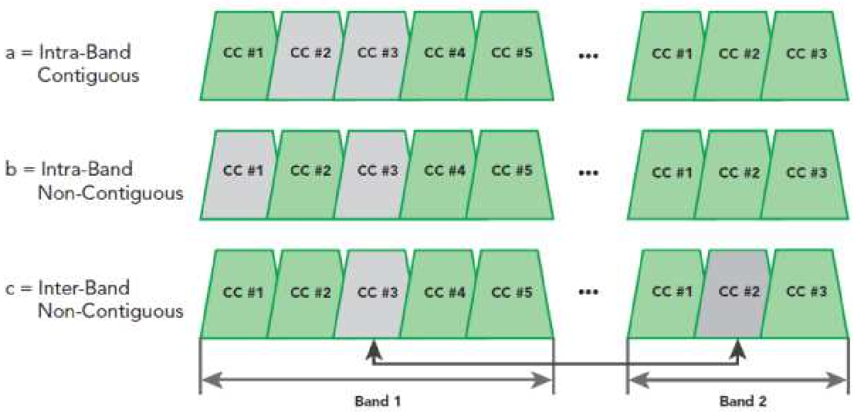

Figure 2.12: Types of carrier aggregation allocation in LTE-Advanced [Anritsu, URL]

The principle for the contiguous case is transmitting in two or more adjacent carriers, so the aggregated channel can be seen as a single enlarged channel at the receiver end. This is possible for unpaired spectrum allocation. The non-contiguous aggregation refers to transmitting non-adjacent carriers, but belonging to the same frequency band. The inter-band carrier aggregation mode is used for transmitting two or more carriers with each of the carriers on a different frequency band [Holma and Toskala, 2012].

Carrier aggregation can be used for both downlink and for uplink. In the case of downlink, multiple carriers of 20MHz can be aggregated to send information to the same UE. These carriers are received by the UE on multiple frequency bands at the same time. This is also known as fragmentation of the spectrum. Although the principle for this design would allow using 5 carrier components for downlink communication, the RF performance limits the number of carriers to 2. The possible scenarios for using carrier aggregation with 2 components is illustrated in Figure 2.13.

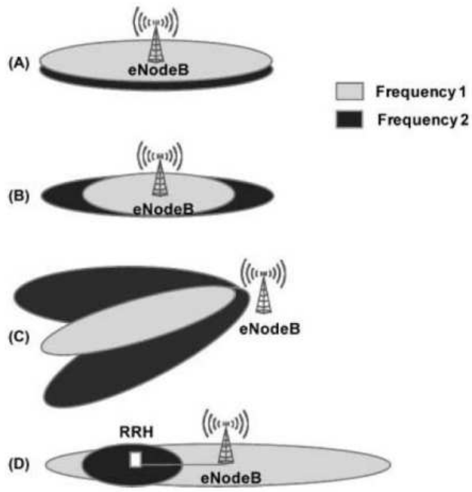

Figure 2.13: Downlink carrier aggregation deployment scenarios [Holma and Toskala, 2012]

The different deployments in Figure 2.13 can be using the same coverage (A), different coverage for the two carriers (B), different latter induced by antennas and antenna tilts (C). The advantage of carrier aggregation in this case is directing the second carrier to an area which is less or not covered by the other carrier frequency, as it is presented in case C of Figure 2.13. This will enhance the performance for the UEs at the cell edge, which are not covered by high frequencies. Therefore, using carrier aggregation between a high and a low frequency band will improve the performance of these users located at a cell edge, by reserving them more of the low frequency band.

A new aspect of the eNodeB introduced by Release 10 is the concept of Primary Cell (PCell) and Secondary Cell (SCell). The PCell is the only one to which the UE exchanges RRC signalling and and it is changed or removed during handover. One PCell is active at a time, while more than one additional SCells can be active at the same time. PCells and SCells are both serving cells, but the measurements and mobility procedures are based on the PCell. The activation/deactivation of the SCells is done at the MAC layer. Thus, the scheduling of the carrier components is done at the MAC layer. The mobility with carrier aggregation is not changed: the mobility measurements are done on the PCell, also known as the Primary Carrier Component (PCC). The SCells are added, reconfigured or removed by the eNodeB through RRC Connection Reconfiguration procedure section A (p. 77). The measurement events with carrier aggregation are events A1, A2, A3 and A5 as they are presented in 2.1. For carrier aggregation, a new event is introduced: A6. This informs if the neighbouring cell becomes better with an offset related to the current SCell. The A6 event is useful for SCell intra-frequency measurements, when its strength is very different from the strength of the PCell [Holma and Toskala, 2012].

In uplink, carrier aggregation enables the UE to transmit data on multiple carriers at the same time. Same as in downlink, the number of carriers to be aggregated is limited to 2 (Figure 2.14).

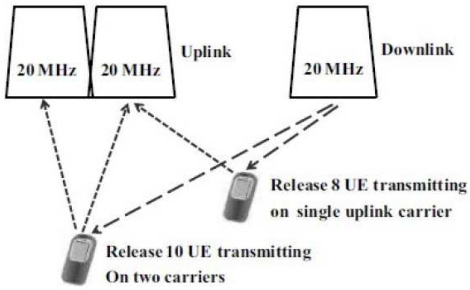

Figure 2.14: Uplink carrier aggregation deployment [Holma and Toskala, 2012, p. 51]

The scheduler at the MAC layer in uplink carrier aggregation decides whether the UE has enough transmit power to handle transmissions on two carriers simultaneously of it should just transmit on one carrier. Uplink carrier aggregation is also visible to the UE through the mobility procedure and the SCells operations are also done through RRC Connection Reconfiguration.

The performance of a system with carrier aggregation in uplink differs from the downlink with respect to the transmission power. Since the UE transmits data with less amount of power than the eNodeB, the users at the cell edge do not gain from using carrier aggregation, since they don't have enough power to access the extended bandwidth. The most typical carrier aggregation mode is C, as they are presented in Figure 2.12 (p. 19), based on the 3GPP band combinations. The aggregated carriers can be transmitted in parallel from the same UE, thus an increase in throughput will be obtained [Holma and Toskala, 2012]. A concrete example of a system using carrier aggregation will be presented in section 5.3 (p. 54).

Conclusion This chapter gave an overview on the handover process in LTE, the message exchange between architectural entities when performing the handover, the challenges and failures that may occur in the system and how the system can recover from these failures. Further on, the following chapters will be based on this information for analysing real measurements performance.

Chapter 3

LTE Performance at Low Speed

This chapter describes the performance of the operational LTE system by means of filed measurements in Aalborg city center at low speed. The analysis investigates the performance in terms of RSRP, downlink throughput and mobility performance (RLF and ping-pong effect). Furthermore, the real scenario is reproduced by means of simulation and then compared with the test. The comparison with the simulation is done in order to validate the model used to generate the results.

3.1 Measurement analysis Aalborg city center

In order to analyse the performance of the LTE system measurements are performed in the city center of Aalborg. The chosen path is shown in Figure 3.1, which was already taken into account in [Chavarría et al., 2014] for a 3G study. The tests are performed using the Telenor 4G network. The network consists of macro cells and it is characterized by two carrier frequencies: 1.8 GHz and 2.6 GHz with 20 MHz of bandwidth each.

The 1.8 GHz network has 34 sites deployed throughout the city center. The average height of the antenna sites is 30 metres. In general, most of the sites have three sectors while some have two or one sector. The average antenna down tilt is 3.7 degrees. The 2.6 GHz network has less number of sites compared to the 1.8 GHz: only five. For the 2.6 GHz network the average height is 30 metres and the downtilt average is 6.8 degrees.

Figure 3.1: Path for the measurements

3.2 Measurements campaign

For this study it is chosen to analyse separately the two frequencies, thus a total of four tests are conducted: two for 1.8 GHz and two for 2.6 GHz. The measurements are performed during 10:00 AM and 13:000 PM by bike at an average speed of 15 km/h.

The phone used for the tests is a Samsung Galaxy III that supports the LTE tecnology at 1.8 GHz and 2.6 GHz. The UE category is 3 which supports a maximum data rate of 100 Mbps on downlink and 50 Mbps on uplink assuming 2 x 2 MIMO system. The UE is programmed to download 100 MB from a FTP server regularly and it waits two seconds before re-starting the download. Furthermore, the position of the UE is recorded by using the Global Position System (GPS). This is necessary in order to evaluate where the handovers occur. The UE is forced to stay in one frequency at the time. This means that there are no inter-frequency measurements. A software installed on the phone makes it possible to extract the RRC messages that the UE exchanges with the serving eNode.

In the following sections the results for both frequencies regarding the signal level, throughput and mobility are shown.

3.2.1 Performance at 1.8 GHz carrier frequency

This section highlights the measurements at 1.8 GHz carrier frequency for two tests along the chosen path. In Table 3.4 are shown the minimum and maximum values for the RSRP, RSRQ and RSSI from the serving cells found in the two tests. The table shows that the RSRP values from the two tests are quite close as well as the RSRQ. The RSSI of the second test is only 2 dB off compared with test one.

Test	RSRP (dBm)	Value	RSRQ (dB)	Value	RSSI (dB)	Value
1	RSRP Min.	-120.1	RSRQ Min.	-26.6	RSSI Min.	-82.7
	RSRP Max	-68.8	RSRQ Max	-6.5	RSSI Max	-35.9
2	RSRP Min.	-120	RSRQ Min.	-29.3	RSRQ Min.	-80.7
	RSRP Max	-66.9	RSRQ Max	-6.9	RSRQ Max	-37.2

Table 3.1: Minimum and maximum values of RSRP, RSRQ and RSSI at 1.8 GHz

Since the values from the the two measurements are close on average, it is chosen to show the RSRP value along the path only for the test one. In Figure 3.2 (p. 25), the RSRP values are shown, together with the corresponding network layout and the antenna height. In the figure the antenna site is depicted by a blue point from which three lines are traced. These lines represent the orientation of each antenna. The red line is used to indicate that during the measurements the UE is connected to the latter.

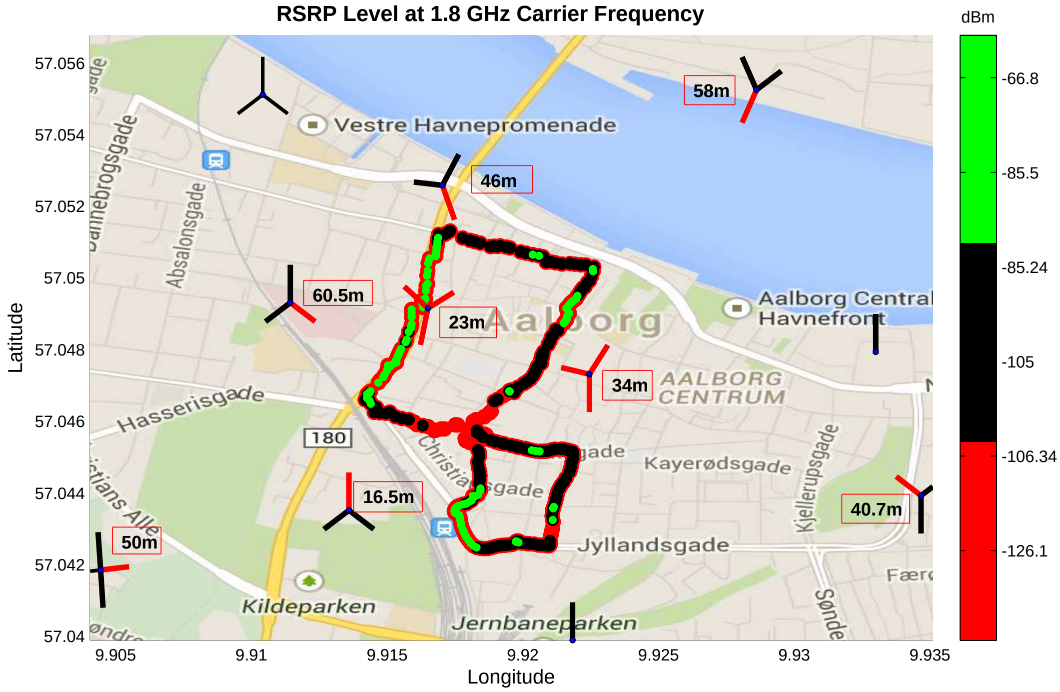

Figure 3.2: RSRP Level at 1.8 GHz Carrier Frequency

The minimum and the maximum values can be depicted in the color bar on the right of the picture. The minimum and maximum values of the color bar are the minimum and the maximum RSRP values extracted from the measurements at 1.8 and 2.6 GHz carrier frequency (Table 3.4). The three ranges of values are defined in red, black and green, from bad signal strength (minimum) to very good signal strength (maximum).

From the figure it is possible to see that the RSRP reaches high levels (green zone) in several areas mostly where the UE is closer to the BS. The lowest values of RSRP are found in the intersection of the streets. This indicates a poor coverage in that area.

From Figure 3.2 it can be concluded that in general the signal strength that the UE receives is good, but this is not enough to evaluate the performance of the system. Another important aspect to take into account is the data-rate that the UE experiences as well as the mobility performance. In the following sections these aspects are investigated.

Throughput

In Figure 3.3 (p. 26) the CDF of the throughput is shown relative to the test in Figure 3.2. The peak data-rate value is reached at 26.3 Mbps, while the 80 % of the time is below 10 Mbps.

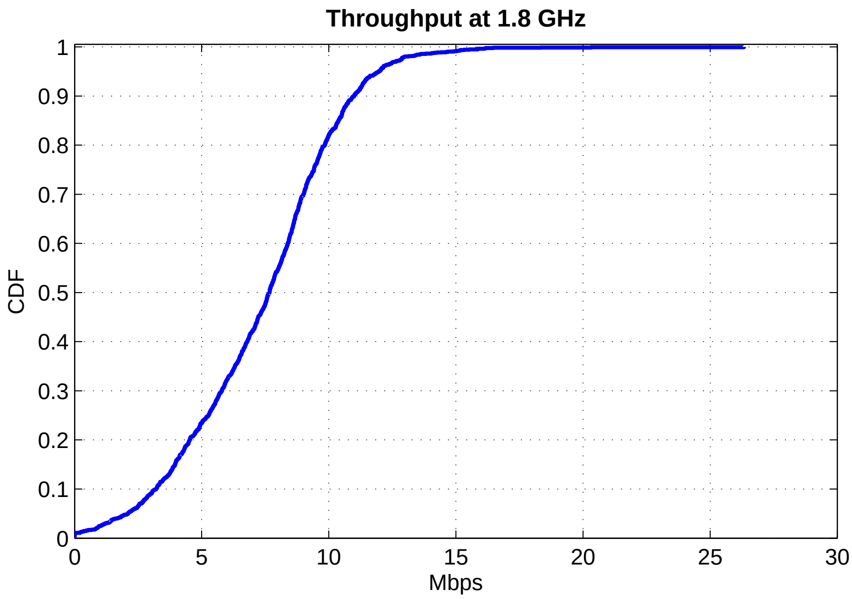

Figure 3.3: CDF Throughput at 1.8 GHz

By comparing the maximum throughput that the phone can support (100 Mbps) and the average throughput from the measurements (8 Mbps) it can be noticed that the performance in real life is far away from the theoretical assumption. The UE could get only the 20% of the theoretical throughput (100 Mbps).

Mobility

For this measurements the mobility aspect is also investigated: the handover performance in the system is related to the radio link failures and the ping-pong effect. In order to understand how the mobility works and which event triggers the handover, the message exchange between the UE and the eNodeB is analysed (see Appendix A). The information extracted from the messages highlights that the event that triggers the handover is the A3 event. For this event two different set of parameter values are found. This means that the handover is triggered with two different configurations of A3. The set of values used for triggering the handover are shown in Table 3.2. Most of the cells where the phone is connected to during the measurements use

A3 Configuration 1	Value	A3 Configuration 2	Value
TTT	1024 ms	TTT	1280 ms
Offset	2 dB	Offset	2 dB
Hysteresis	2 dB	Hysteresis	2 dB

Table 3.2: Different A3 event configuration

Configuration 1. Configuration 2, the one with a larger TTT, is used by the cell beyond the fiord (see Figure 3.2 (p. 25)). The reason for this choice might be related to the position and the antenna height of this specific cell. Even though the antenna is placed far away from the city the UE receives signal from it. The large TTT value ensures that the signal strength of the target cell remains better than the signal strength of the serving cell for a bigger amount of time. This would prevent an early handover.

Under these circumstances, the number of handovers performed by the UE for Test 1 are 1.58 per minute. No RLFs are detected during the measurements. The reason for this is related to the value of the timer T_{310}. This timer is used to allow the UE to get back in synchronization with the BS. If this timer expires and the phone is still out of synchronization, the RLF is declared. By analysing the Layer 3 messages the value of T_{310} is found to be 2 seconds. With this large value, the UE has enough time to go back in synchronization with the BS.

To calculate the ping-pong effect (PP), the 3GPP recommends the ping-pong timer to be 1 second [TR36.839, 2012]. In this case, the latter timer value can not be applied to this measurement. This is because the TTT (Time To Trigger) value for the A3 event is more than 1 second. This means that the UE has to be connected to the cells at least the TTT timer. Due to this, the ping-pong timer has been chosen to be 1.5 seconds. In this study, according to this value no ping-pongs are detected on the simulations as well as radio link failures.

Test	**HOs/min**
Test 1 (∼15 km/h)	1.58
Test 2 (∼15 km/h)	1.75

Table 3.3: Number of HO, RLF and PP per minute at 1.8 GHz

Table 3.3 summarizes the number of handovers per minute occurred in the all tests. The two measurements show on average 1.66 handovers per minute.

3.2.2 Performance at 2.6 GHz carrier frequency

The same measurements are done for 2.6 GHz. In this scenario the number of antennas is less compared to the 1.8 GHz network. As in the case of 1.8 GHz the signal level, throughput and mobility performance are presented.

In Table 3.4 the minimum and maximum values of RSRP, RSRQ and RSSI obtained from the two measurements are shown.

Test	**RSRP (dBm)**	**Value**	**RSRQ (dB)**	**Value**	**RSSI (dB)**	**Value**
1	RSRP Min.	-125.7	RSRQ Min.	-19.1	RSSI Min.	-92.3
	RSRP Max	-68.20	RSRQ Max	-5.9	RSSI Max	-37.9
2	RSRP Min.	-126.1	RSRQ Min.	-20.1	RSRQ Min.	-92.6
	RSRP Max	-67.5	RSRQ Max	-6.2	RSRQ Max	-39.4

Table 3.4: Minimum and maximum values of RSRP, RSRQ and RSSI at 2.6 GHz

By comparing these values with those obtained in 1.8 GHz (see Table 3.4) it can be noticed that in general the signal in 2.6 GHz scenario is 5 dB weaker. Figure 3.4 shows the RSRP level for the Test 1, since there is not much difference between the two tests. On top it is also plotted the network layout, where the BS which the UE is connected to are marked with a red line. As in the case of 1.8 GHz, the lowest signal is found in the junction. This is due to lack of coverage in that area. In general the signal strength level (RSRP) is quite satisfying, as well as the RSRQ and RSSI values.

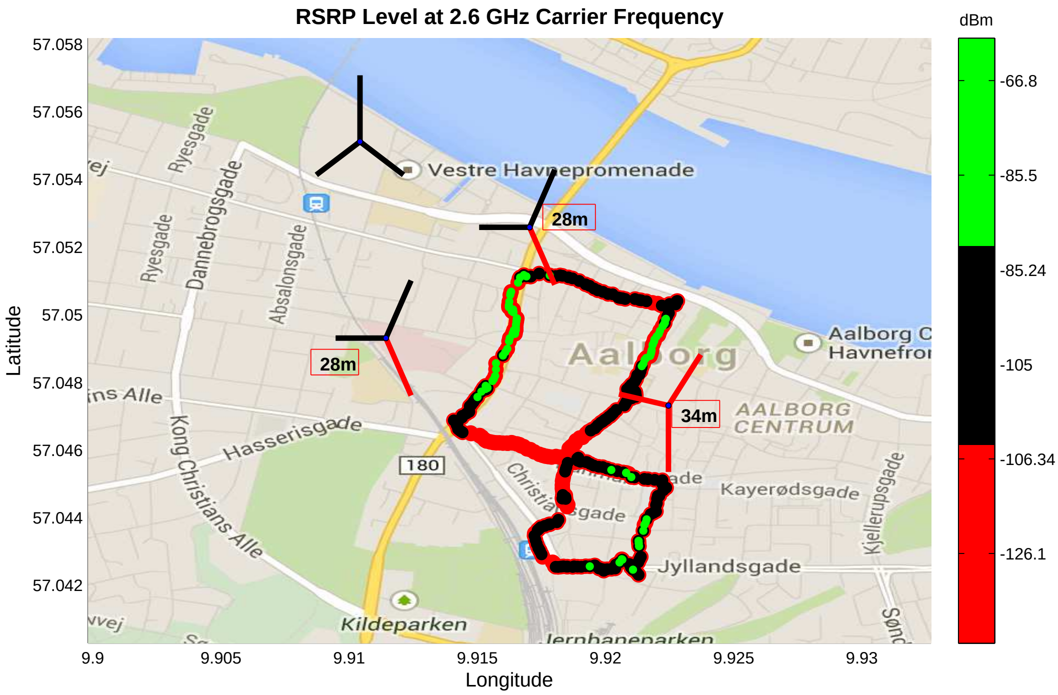

Figure 3.4: RSRP Level at 2.6 GHz carrier frequency

Throughput

Figure 3.5 (p. 29) shows the CDF of the throughput at 2.6 GHz relative to the measurement in Figure 3.4. The peak is reached at 16 Mpbs while on average the UE experiences 7.5 Mbps. The throughput peak value for this measurement is lower that the peak obtained for 1.8 GHz. The reason for this can be related to the unoptimized coverage, since the number of sites deployed in the 2.6 GHz network is limited.

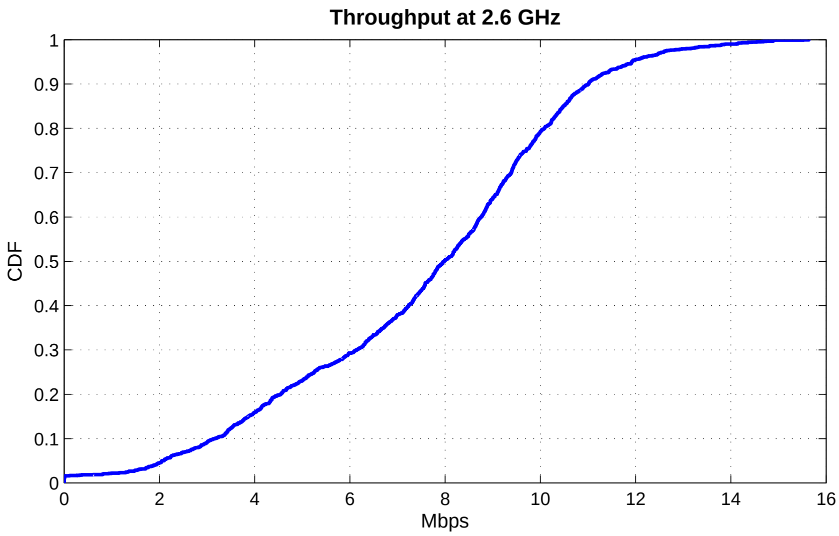

Figure 3.5: Throughput CDF at 2.6 GHz

Mobility

Also in this case, by analysing the Layer 3 messages, it is found that the event that triggers the handover is event A3. For this event two different configuration are also found, as the Table 3.5 shows. The choice of having different configurations might be for avoiding too early/late handovers.

A3 Configuration 1	**Value**	**A3 Configuration 2**	**Value**
TTT	1024 ms	TTT	320 ms
Offset	2 dB	Offset	3 dB
Hysteresis	2 dB	Hysteresis	3 dB

Table 3.5: Different A3 event configuration

The number of handovers per minute during this measurement campaign is 0.91. Similarly to the case of 1.8 GHz no RLF are detected as well as ping-pongs. The reason for this is already explained in Section 3.2.1. Table 3.3 (p. 27) summarizes the handovers, RLF and ping-pong per minute occurred in all the performed measurements.

3.3 Simulation versus real measurements

In the telecommunication field simulations play an important role, since the introduction of new features in the system needs to be tested before the commercialization. For this reason the comparison between the performance obtained in the real measurements and the simulation is presented in order to verify the reliability of the model used to represent the reality. In the following it is also described how the simulation methodology is working as well as the utilized model.

3.3.1 Simulation methodology and model environment

A MATLAB based dynamic system level simulator is used to simulate a cellular network characterized by multiple cells and multiple users. The users are placed in the network and they are moving at constant speed.

In order to replicate the scenario, a 3D map of the city center of Aalborg is used. The map contains 3D data for streets and buildings, as well as open area and the fiord. The path loss map of the area is computed by using ray-tracing techniques based on the Dominant Path Model. The path loss map also takes into account the shadowing computation. The propagation is assumed to be constant within a $25m^2$ metres (5m x 5m).

The antenna sites in the network are placed according to the data provided by the operator, as well as the height and the antenna tilt. In the simulation the users are following the same path as in reality and they are moving with a constant speed of 15 km/h. In addition, the users are uniformly distributed along the path. The used traffic model is full buffer where the UEs are transmitting all the time. This choice replicates the reality of the measurements, where the phone was downloading a file all the time from a FTP server.

In Table 3.6 (p. 31) are shown the parameters used for the simulation at 1.8 GHz and for 2.6 GHz. The values of the A3 event (TTT, Offset and Hysteresis) are taken from the values found in the messages for each frequency as explained in Section 3.2.1 (p. 24) and Section 3.2.2 (p. 27). The Q_{out} and Q_{in} are the SINR values for the entering condition and leaving condition of the radio link failure. Meaning that, when the SINR is below -8 dB the timer T310 starts. If after this time the SINR is below -6 dB a RLF is declared. The T310 value is set according to the value found in the Layer 3 messages. All these parameters together with the created propagation maps are loaded in the simulator.

Parameters	1.8 GHz Settings	2.6 GHz Settings
Scenario Setup:		
- Carrier Frequency	1.8 GHz	2.6 GHz
- Bandwidth	20 MHz	20 MHz
- PRB Number	100	100
- DL Transmit Power	46 dBm	46 dBm
- Propagation Model	Ray tracing DPM	Ray tracing DPM
- Antenna Height	According to the reality	According to the reality
- Traffic Model	Full buffer	Full buffer
Handover Parameters:		
- HO Trigger Event	A3 Event	A3 Event
- TTT	1024 ms or 1280 ms	1024 ms or 320 ms
- Hysteresis	2 dB	3 dB
- Offset	2 dB	3 dB
Failure Detection Parameters:		
- RLF Qout	-8 dB	-8 dB
- RLF Qin	-6 dB	-6 dB
- T310	2 sec	2 sec
User setting:		
- Num. of users in the street	300	300
- Distribution of the users	Uniform	Uniform
- User speed	15 km/h	15 km/h
- Background users	None	None

Table 3.6: Simulation Parameters at 1.8 GHz and 2.6 GHz

3.3.2 Simulation at 1.8 GHz

By using the parameters in Table 3.6, this section will be shown the outcome from the simulation at 1.8 GHz carrier frequency and compare it with the real test. In Figure 3.6 (p. 32) it is shown the handover position from the measurements at 1.8 GHz carrier frequency. The area where the handover occurs is marked with a black ellipse. In order to see if the the outcome from the simulation reflects the reality, in Figure 3.7 (p. 32) the position of the handovers is shown.

Figure 3.6: Handover position 1.8 GHz from the measurement

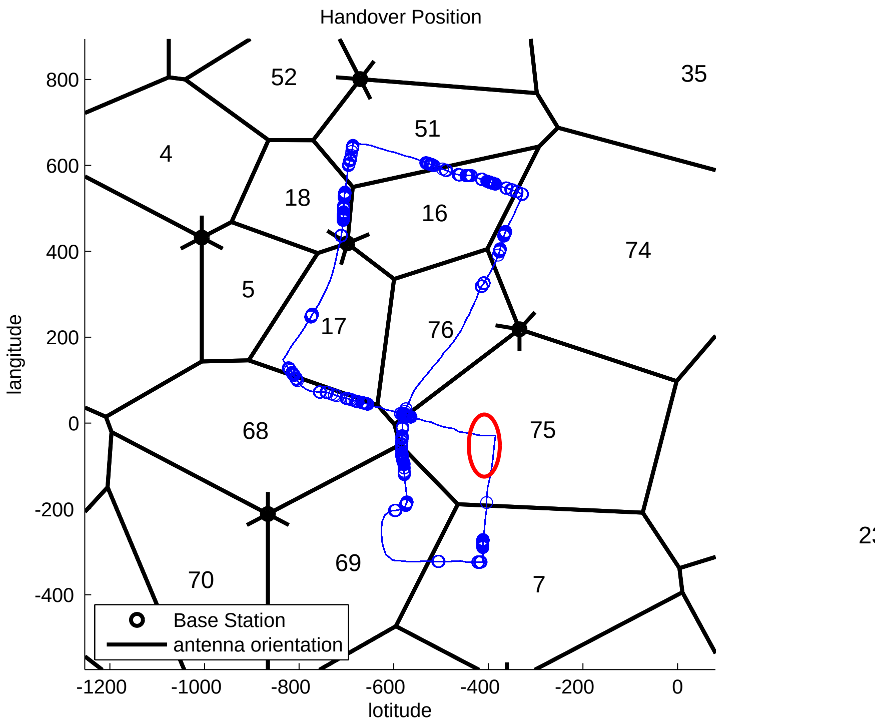

Figure 3.7: Handover position 1.8 GHz from the simulation

In Figure 3.7 the blue dots represent the position where the handovers occur in the simulation. By comparing the two figures is possible to see that the simulation matched quite well with the measurements. Only one discrepancy with the reality is found. This is marked by an red ellipse in Figure 3.7. The reason for this is related to the resolution of the propagation map, where within $25m^2$ the signal is constant. In fact, due to the resolution, some street pass close to buildings. Also the signal strength is lower due to the penetration loss close to buildings. In addition, the calculation of the signal in a certain point is made by taking the interpolation of the values of the surrounding point. Thus, if the distance between the street and the building is low in that point the signal strength will be low too. So it might not be possible to replicate the same conditions as in the reality. From the point of view of the RLF the result from the simulations matched with the reality. The number of handovers per minute is 3.1 which results to be the double compared with the value obtain from the reality (1.58 on average).

3.3.3 Simulation at 2.6 GHz

In this section the results from the simulation at 2.6 GHz are shown by taking into account the parameters in Table 3.6. In Figure 3.8 it is shown the handover position obtained from the measurement marked with a black ellipse and in Figure 3.9 (p. 34) it can be seen the handover position that the users experience from the simulation, which is represented by blue dots.

By comparing the two figures, it can be noticed that in the simulation there is an area where the handover does not occur in the reality. This area is marked with a red ellipse in Figure 3.9 (p. 34). This is due the presence of a "coverage island" from another cell. The number of handovers per

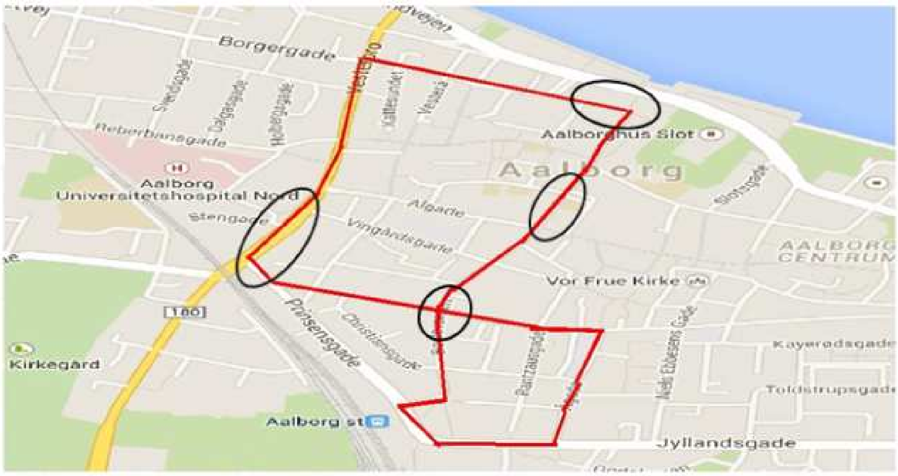

Figure 3.8: Handover position from the measurement at 2.6 GHz

minute that occur in the simulation is 1.96. This value results to be higher compared to the one obtained from the reality (0.91 on average).

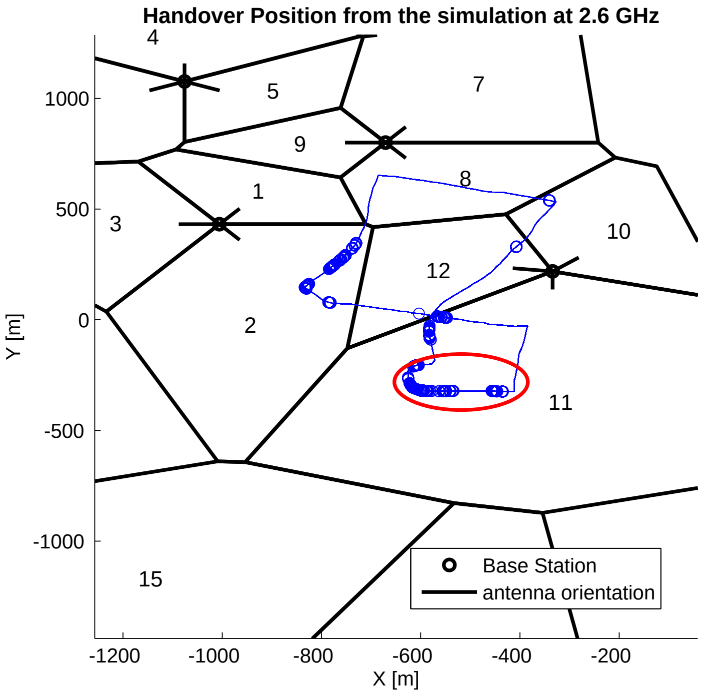

Figure 3.9: Handover position from the simulation at 2.6 GHz

3.4 Discussion

For this particular scenario no RLFs are found. Different result are found in [Chavarría et al., 2014] for 3G system, where RLFs are detected. The absence of RLF is justified by the use of a large TTT (more than one second) and a larger timer T_{310} (2 seconds) which in charge of declaring a RLF when it expires.

From the point of view of the throughput, in average the throughput for the both frequency is found to be (8 Mbps) instead the peak was higher for the 1.8 GHz (26 Mbps) than the 2.6 GHz case (16 Mbps). The difference in the peak values is due to the coverage, since for the 1.8 GHz case the deployed network was dense compare with the 2.6 GHz case. Another reason might be related to higher interference.

By analysing the simulation and making a comparison with the reality, it is possible to say that the simulation matched quite well the result from the test. In fact, the area where the handover occurred in the reality it could be replicated in the simulation, even though some problems relate to the resolution of the used propagation map are detected. Also, the number of handovers in the simulation for 1.8 GHz case is larger than the one for the 2.6 GHz reflected the reality.

Chapter 4

On the way towards 5G

This chapter highlights the mobility performance of the LTE system in a high speed scenario. The focus is on evaluating the mobility failures and the throughput received by the UE. Simulations are performed in order to recreate the scenario from the measurements. It is wanted to prove that in this scenario the current LTE system cannot satisfy the increased request for data (10000 times more traffic) [Nokia, 2015a], therefore the simulations are used as a baseline for implementing other technologies. For the purpose of this thesis the assumption for the 5G are taken into account. In fact the 5G will need the use dense network, high frequency and dual connectivity with small cells and macro cells.

The first section of the chapter describes the measurements performed on the highway in Aalborg. The next sections will give an insight of the heterogeneous networks concept, which will be the baseline for creating a new scenario that will be introduced later in the following chapter. The last section in this chapter gives an overview of the targets for the 5G technology and some study proposals will be taken as an example for an insight of what this technology is expected to offer.

4.1 Measurement analysis Aalborg highway

After having analysed the data from the measurements in the city center of Aalborg at a relative low speed and verified that at that specific speed the LTE system is quiet reliable in terms of mobility performance, it is essential to see if increasing the speed of the UE the system is still stable. In this section, the outcome from the measurements on the highway in Aalborg are presented. The measurements were performed using the same setup as in the previous measurements in the city center (Chapter 3). Due to the GPS it is possible to record the position of the UE and evaluate where its connectivity in certain positions. The same parameters as in the previous measurements are evaluated: RSRP, downlink throughput, mobility performance and system failures. Afterwards, the scenario will be reproduced with simulations and their outcome will be analysed. As Figure 4.1 (p. 36) shows the measurements are taken from exit 26 to exit 39 in the highway E-45.

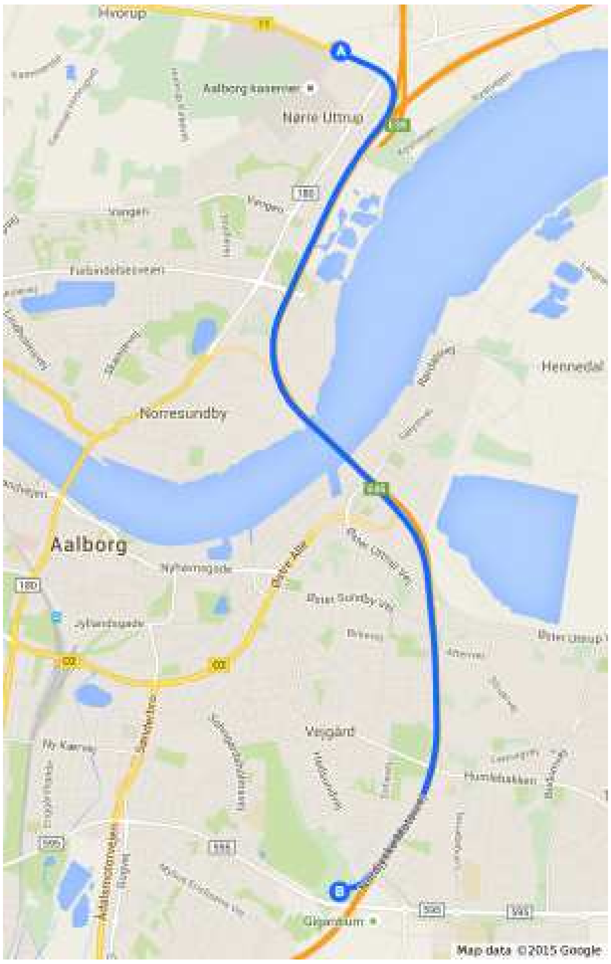

Figure 4.1: Path for the measurements

The chosen route has been travelled at two different speeds: 80 km/h and 100 km/h. In total 8 measurements have been taken: 2 from point A to point B (Figure 4.1) and 2 vice versa from B to A, all four of them at 80 km/h; the same has been done for 100 km/h.

The measurements will be analysed only for the 1.8 GHz carrier frequency, since it is the only frequency provided by the network in this specific area. Therefore the phone is forced to stay in 1.8 GHz carrier frequency during the drive tests (intra-frequency measurements).

- **Measurements at 80 km/h**
  First, the measurements at 80 km/h will be analysed. The minimum and maximum values of the RSRP, RSRQ and RSSI from the tests are shown in Table 4.1 (p. 37). To show how the system performs at high speed, Test 1 has been chosen to represent the path A-B and Test 2 for the path B-A.

Drive Test	RSRP (dBm)	Value	RSRQ (dB)	Value	RSSI (dB)	Value
1 A-B	RSRP Min.	-126.3	RSRQ Min.	-24.8	RSSI Min.	-87.1
	RSRP Max	-68.7	RSRQ Max	-6.3	RSSI Max	-40
2 B-A	RSRP Min.	-122.6	RSRQ Min.	-20.7	RSRQ Min.	-83.1
	RSRP Max	-74.6	RSRQ Max	-6.3	RSRQ Max	-47.1
3 A-B	RSRP Min.	-125.5	RSRQ Min.	-24.9	RSRQ Min.	-85.4
	RSRP Max	-69.3	RSRQ Max	-5.6	RSRQ Max	-37.6
4 B-A	RSRP Min.	-132.1	RSRQ Min.	-26.8	RSRQ Min.	-85.4
	RSRP Max	-72.5	RSRQ Max	-5.5	RSRQ Max	-45.4

Table 4.1: Minimum and maximum values of RSRP, RSRQ and RSSI obtained for 80 km/h

Figures 4.2 and 4.3 show the RSRP values for the route A-B and for B-A, respectively. As in the previous measurement campaign, the minimum and maximum values of the RSRP can be depicted in the color bar, from bad to very good signal strength. Once again, the three ranges of colors have been chosen to represent the signal: red, black and green, as shown on the bar. In order to evaluate the signal changes along the path and be able to compare the two routes, the same ranges for the three colors have been chosen. These can be observed on the color bar.

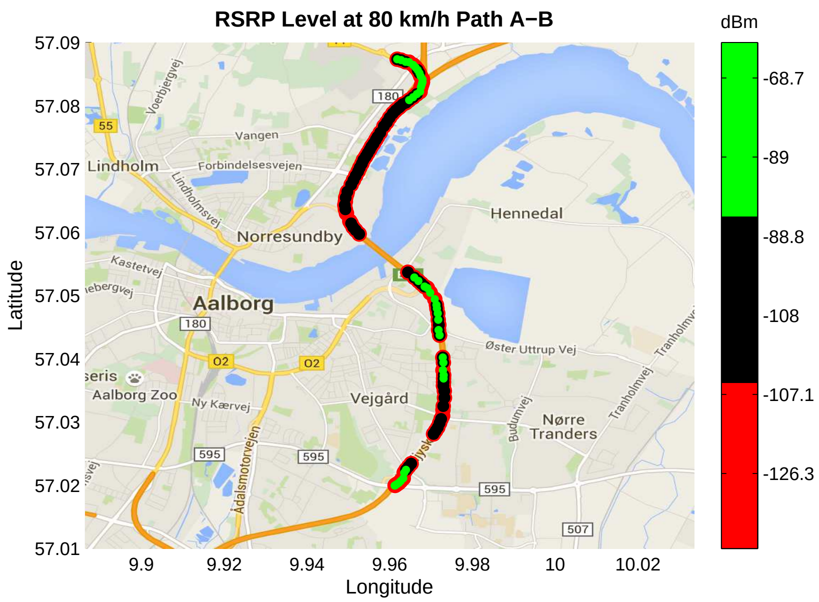

Figure 4.2: RSRP Level at 80 km/h for Path A-B

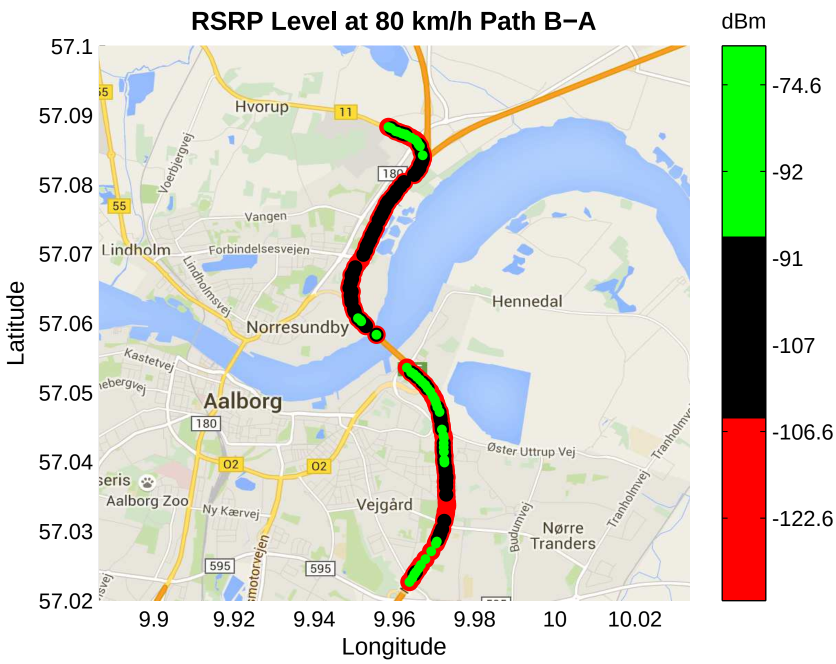

Figure 4.3: RSRP Level at 80 km/h for Path B-A

As it can be noticed, the RSRP for the two paths is quite similar, apart from some small differences. Most of the values are above -106 dBm, marked in black, indicating a good signal strength. Some areas, like the beginning and the end of the route have very good signal strength (indicated with green) and the areas with poor signal strength (red) are very few.

Throughput The throughput for the two routes is shown in Figure 4.4 (p. 39). For both paths, almost 65 % of the time the throughput is below 10 Mbps and the peak data rate is around 19 Mbps.

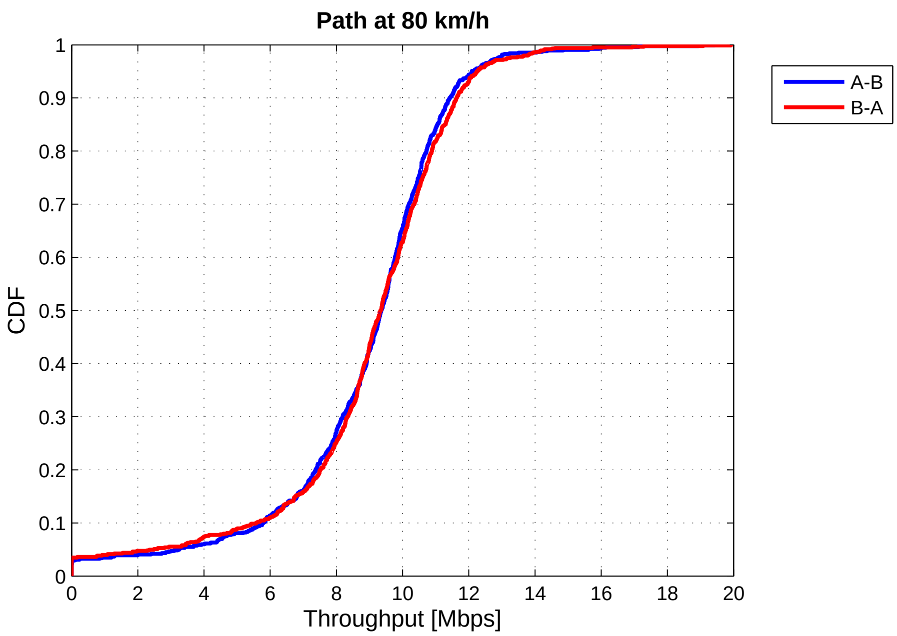

Figure 4.4: CDF Throughput at 80 km/h for both paths

The average throughput found in the measurements is 9 Mbps for the two routes. As in the previous drive tests at low speed, this result is far away from the maximum throughput of 100 Mbps that the phone can support.

- **Measurements at 100 km/h**
  The second set of tests has been conducted at 100 km/h, following the same paths as before in order to see how increasing the speed would affect or not the performance of the LTE system. The RSRP, RSRQ and RSSI values have been collected from these tests and they are shown in Table 4.2.

Drive Test	RSRP (dBm)	Value	RSRQ (dB)	Value	RSSI (dB)	Value
5 A-B	RSRP Min.	-122.7	RSRQ Min.	-23.2	RSSI Min.	-81.6
	RSRP Max	-69.5	RSRQ Max	-6.1	RSSI Max	-40.6
6 B-A	RSRP Min.	-115.9	RSRQ Min.	-29	RSRQ Min.	-76.2
	RSRP Max	-61.3	RSRQ Max	-5.9	RSRQ Max	-34.8
7 A-B	RSRP Min.	-118.1	RSRQ Min.	-23	RSRQ Min.	-80.3
	RSRP Max	-63.6	RSRQ Max	-6.1	RSRQ Max	-35.9
8 B-A	RSRP Min.	-114.6	RSRQ Min.	-25.7	RSRQ Min.	-77.1
	RSRP Max	-68.8	RSRQ Max	-6.1	RSRQ Max	-38.7

Table 4.2: Minimum and maximum values of RSRP, RSRQ and RSSI obtained for 100 km/h

Once again, one test representing each path was chosen for the system evaluation. The values of the RSRP along the two paths are presented in Figure 4.5 and Figure 4.6.

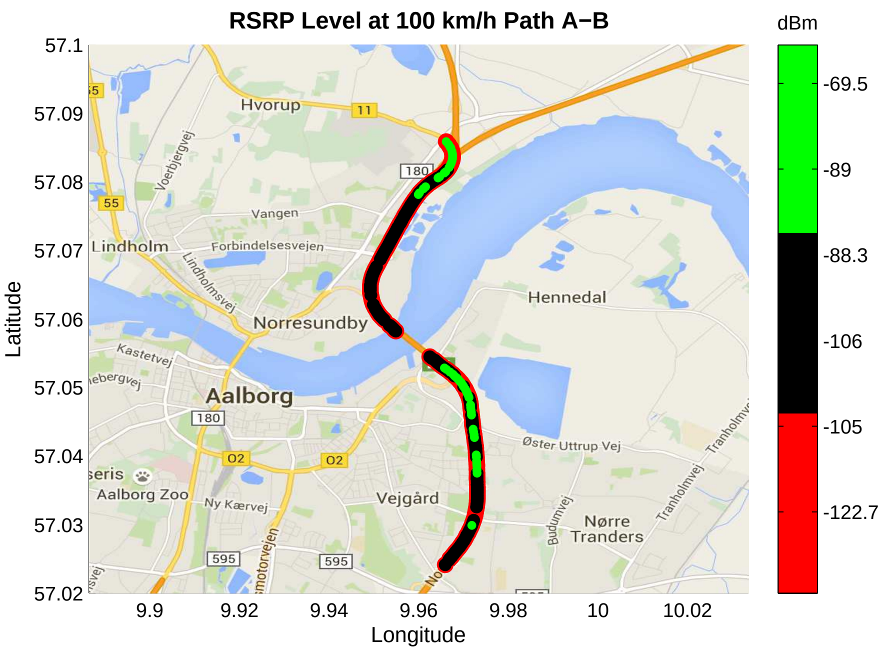

Figure 4.5: RSRP Level at 100 km/h for Path A-B

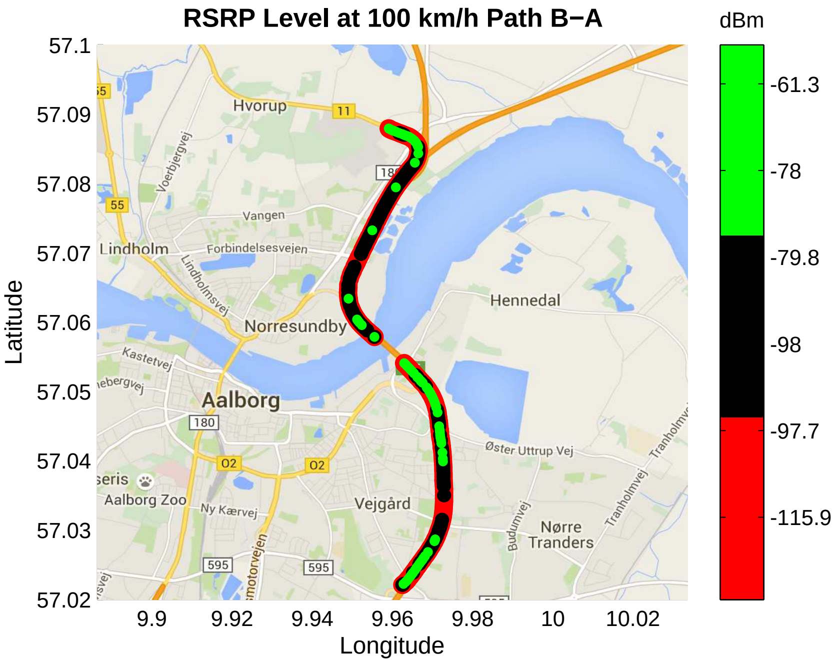

Figure 4.6: RSRP Level at 100 km/h for Path B-A

The figures show that compared to the tests at 80 km/h, the values are slightly greater at 100 km/h, as it can be noted on the color bar to the right side of the figure. Most of the values along the path are above the average, since they are represented in black and green, meaning that the overall signal strength is good. Next, it is wanted to check if high speed would affect the system in terms of received throughput and mobility performance.

Throughput Figure 4.7 shows the cumulative distribution function of the throughput extracted from the two measured paths. The peak data rate obtained is 20 and 23 Mbps. The average throughput is also analysed and it is again found to be 9 Mbps, as in the measurements of 80 km/h, still very different from the theoretical assumptions.

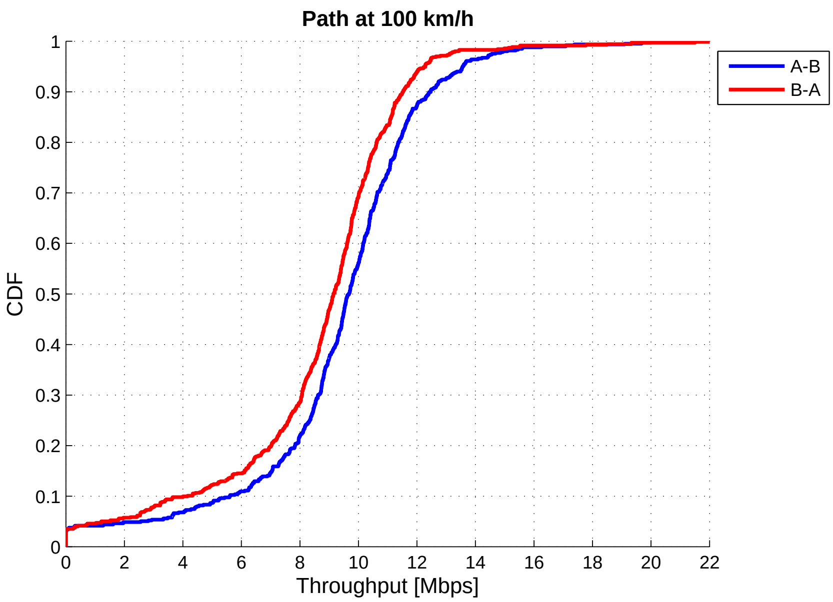

Figure 4.7: CDF Throughput at 100 km/h for both paths

4.1.1 High Speed Mobility

Failures in the system are an important aspect in the mobility procedure, as it has been previously discussed in Section 2.2.6 (p. 17). Therefore, radio link failures, handovers and ping-pong effect will be further analysed for both speeds used for the drive tests.

For this chosen path on the highway, different configurations have been assigned to the cells regarding the TTT, offset and hysteresis values. As in the measurements analysis from the city center, it has been found that the handover is triggered by the A3 event and the cells that the UE connected during measurements are configured with different values of the event. These are shown in Table 4.3. Most of the cells have Configuration 1, while only two others are configured differently. As for most of the cells the TTT value is more than 1 second, it can be stated again that the ping-pong timer should be set to 1.5 seconds in order to be able to analyse the

A3 Configuration 1	Value	A3 Configuration 2	Value
TTT	1024 ms	TTT	320 ms
Offset	2 dB	Offset	2 dB
Hysteresis	2 dB	Hysteresis	2 dB

Table 4.3: Cells configured with different A3 event parameters

ping-pong effect. Using this value of 1.5 seconds, no ping-pong effect has been noticed.

Even though the speed of the UE was higher during these sets of measurements compared to those made in the city center, only one RLF has been detected by analysing the Layer 3 messages. This failure is irrelevant given the number of measurements. This is a really good result since there is also a tunnel that goes under the fiord (600 metres long): while the UE is passing through the tunnel the connection never dropped, only paging messages are recorded.

Simulations are made to model the scenario from the measurements. The simulations are based on the highway scenario, where the real network from the measurement is taken into account, meaning that the position of the antennas is based on the data provided by the operator, as well as the highway position and shape.

4.1.2 Simulation for High Speed Mobility

The simulation methodology used to perform simulation of the scenario for high speed mobility is different to the one described in Section 3.3.1 (p. 30). In fact, in this case, the 3D map used to generate the path loss model for the simulation in Aalborg city center is not available. This is because the position of the highway result to be outside the borders of the map. For this reason, is necessary to use another propagation model.

For this simulation, most of the parameters for the 1.8 GHz carrier frequency are the same as in Table 3.6, except for the propagation model and the TTT values of the cells, which can be found in Table 4.3 (p. 41). One drive test (measurement) described previously has shown the movement of the UE from point A to point B and another test was taken from B to A and so on. The simulations for this scenario are performed a bit differently, since the movement of the users in not made separately from A to B and from B to A as in the drive tests. But instead, the movement is simulated an entire circular path, where the user departs from point A and finishes its route in the same point, so the whole path is covered in one simulation. The layout of the streets and network used for the simulation is shown Figure 4.8 (p. 43).

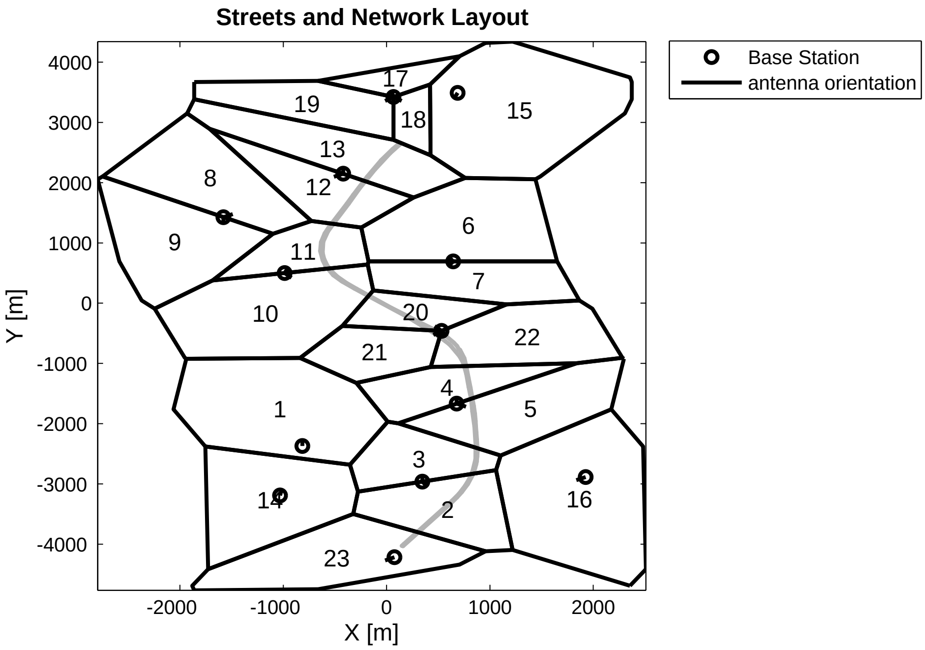

Figure 4.8: Macro Network at 1.8 GHz and Streets Layout in Simulations for 100km/h

Path loss model The network for simulation of high speed mobility is made of 23 macro cells, with their coordinates taken from the real measurements. Also the street model has been created using the real geographical coordinates with two lanes on each side. The *propagation model* used for this simulation is expressed in equation 4.2 according to the 3GPP standard ([TR25.942,]):

$$PL = 40 \cdot (1 - 4 \cdot 10^{-3} Dhb) log_{10}(R) - 18 log_{10}(Dhb) + 21 log_{10}\left(\frac{f_c}{MHz}\right) + 80 \qquad [\text{dB}] \quad (4.1)$$

Where:

- R is the distance between the BS and the UE
- Dhb is the antenna hight in metres from the average rooftop
- f_c is the carrier frequency

Since in the reality the antennas have different heights, while the model above takes as an input only one value for the *antenna height*, it is important to check if the model fits with the scenario. In order to do that, the average antenna height from the reality has been found: 30 metres. The path loss model considers the antenna height from the rooftop so it is needed to scale the real antenna height according to that. It is assumed that the buildings are 3 storeys high with 3 meters per floor. Thus, each building is approximated 10 meters high. This leads to having an antenna height from the rooftop equal to 20 meters. Thus, using 20 meters antenna height and 1.8 GHz as carrier frequency (according to the measurement), the equation 4.2 becomes:

$$PL = 124.94 + 36.8 \cdot log_{10}(R) \qquad [\text{dB}] \quad (4.2)$$

The *antenna gain* value is found in the data sheet relative to the model antenna used ([Kathrein, 2009]), the frequency and bandwidth used are taken from the measurements as well as the values of event A3 (TTT, Offset and Hysteresis). A full buffer traffic model is also considered, meaning that the users always have unlimited amount of data to transmit. The transmission of their data never ends and therefore this model allows a simplified analysis of the simulation. An overview of the parameters used in the simulation is shown in Table 4.4.

Parameters	**Setting**
Scenario Setup:	
- Carrier Frequency	1.8 GHz
- Bandwidth	20 MHz
- PRB Number	100
- DL Transmit Power	46 dBm
- Macro Path Loss Model	$124.94 + 36.8 \cdot log_{10}(R)$
- Antenna Height	20 meters from the rooftop
- Antenna Gain	17.5 dBi
- Number of sites	23
- Network Type	4G Macro
- Traffic Model	Full buffer
Handover Parameters:	
- HO Trigger Event	A3 Event
- Time To Trigger (TTT)	1024/0.320 ms
- Hysteresis	2 dB
- Offset	2 dB
Failure Detection Parameters:	
- RLF Qout	-8 dB
- RLF Qin	-6 dB
- T310	2 sec
- Time PP Detection	1.5 sec
User Setting	
- Num. of user in the street	200
- Distribution of user	Randomly placed along the street
- User Speed	80/100 km/h
- Background users	None
- Speed of background users	None

Table 4.4: Parameters used for the high speed mobility simulation

Further on, the simulated LTE system is pushed to have minimum data-rate of 10 Mbps and then it is verified how many users in the system are getting the minimum required.

Simulation Outcome The outcome from the simulation is related to the handovers, failures in the system and achieved data rate. Table 4.5 shows the number of handovers per minute both in real measurements and in simulations.

Speed (km/h)	HOs/min Real Measurements	HOs/min Simulations
80	9.3	1.86
100	7	2.31

Table 4.5: Number of handovers per minute in drive tests and simulations

There is a big discrepancy between the results found in simulations and the real drive tests. The reasoning for this can be that in the drive tests, due to the variations in the radio propagation of the signal (surrounding cars, trucks movement), additional handovers take place. These are not reproduced in the simulator. Furthermore, in the Table 4.5 the numbers of the handovers from the measurements are the sum of the handovers obtained from the point A to B and vice versa. In the simulation the entire path is covered will all the users. So, it is more correct compare the number of the handovers for each path (from A to B or B to A) instead that with both. In fact, if the number of handover per minute for the measurements in Table 4.5 is divided by two it get closer to the handovers per minute in the simulation.

The presence of the tunnel in the real measurements is another aspect which is not considered in the simulations. Therefore, the simulations for this scenario do not match the measurements because there are handovers in the area where the tunnel exists in reality.

However, no radio link failures or ping-pongs have been found in the simulations. From this point of view, the simulations match the reality.

After having proved that the simulation outcomes do not alter the reality, a step forward is needed. Figure 4.9 (p. 46) shows the throughput obtained from the simulation. The figure shows that 30 % of the time the UEs are experiencing 1 Mbps but most of them are not achieving the minimum required (10 Mbps) for this project.

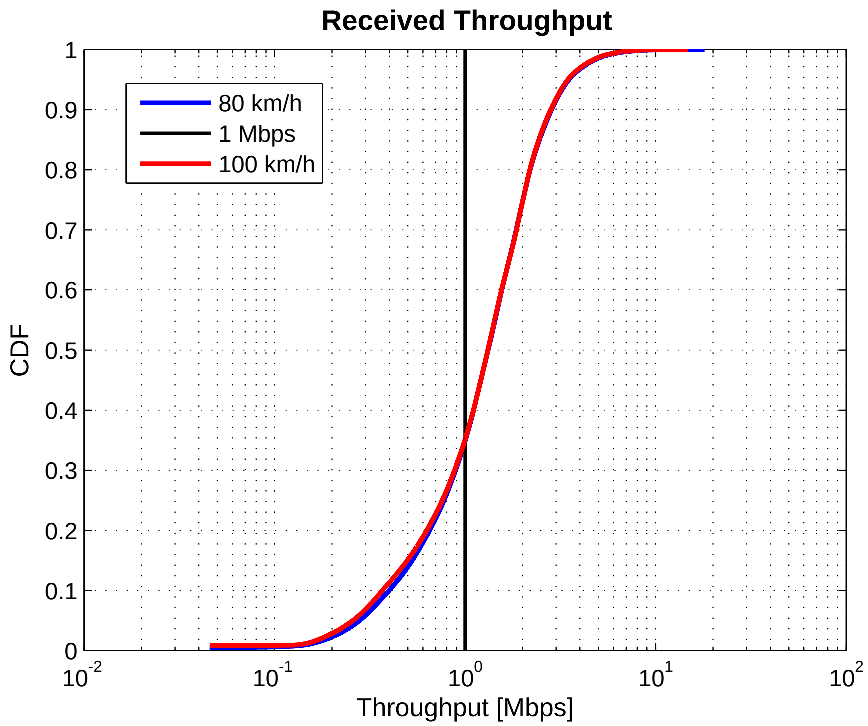

Figure 4.9

Therefore, it is wanted to find a way of improving this result, which means implementing a different kind of scenario. This will be discussed in Chapter 5.

Conclusion By analysing the outcome of the measurements on the highway it can be concluded that LTE is stable and reliable for this particular scenario. It is resilient to radio link failures and ping-pong effect even at high speed. But LTE can not guarantee to support the requested volume of data to come in the next few years. Therefore, new technologies and new methods have to be investigated to have more capacity available. For this reason, the next section will introduce the approach for heterogeneous networks and how it can provide the increasing number of users with their requested data volume.

4.2 Heterogeneous Networks approach

The rapidly growth of users using mobile broadband has lead the researchers to find new solutions to support the demand of high data rates and system capacity. For this reason the LTE system is constantly evolving. The fist release of LTE specifications, Release 8, was completed in 2008, which provides downlink peak data rate of 100 Mbps within a 20 MHz downlink spectrum allocation [TR25.913, 2008]. The Release 9 introduces the concept of heterogeneous networks (HetNet), which means the introduction of small cells on top of the macro layer. The Release 10, known as LTE-Advanced, proposes a method to increase the capacity of the system using spectrum flexibility (carrier aggregation) that allows to reach a peak data rate of 1 Gbps for downlink.

The HetNet configuration plays an important role for the future technology because increasing the number of small cells will result in an increase of capacity per area. This new network topology will bring challenges from the mobility point of view since the UE may trigger several handovers when passing through the small cells. Under these circumstances, the UE speed has a crucial role in the mobility performance. In a HetNet scenario, using the same TTT value for all the cells (macro and small) may deteriorate the mobility performance. For this reason is needed to specify different values of TTT according to the events specific for each layer (macro and pico) [Lopez-Perez et al., 2012].Since the next-generation will need to coexist with the actual deployment the HetNet configuration is chosen in order to be closer to the reality. As mentioned above, carrier aggregation is one of the new features of LTE-Advanced. With its introduction it is possible to increase the data rate enormously. For example, drive test have been performed by Nokia Networks. In this test 10 + 10 MHz aggregation is used. Using only 10 MHz the data rate is around 30 Mbps, but it doubles if the carrier aggregation is used: 60 Mbps. The more bandwidth is allocated the more throughput the UE will get [Nokia, 2015b].

Due to the benefit of carrier aggregation together with the HetNet configuration the combination of the two is used in this thesis, by focusing on the mobility design. For the macro layer the real highway network is considered with the information provided by the operator and measurements (Section 4.1 (p. 35)) and for the small cells it is applied the concept of 5G. An overview of what 5G will be is described in the next Section 4.3.

4.3 5G overview

As it has been proved in the previous chapter, it is not possible to achieve the minimum of 10 Mbps per UE in a high-speed environment with LTE. For the goal of this thesis, it is essential to look for a new technology. Lately the interest of many engineers and researchers goes towards 5G. So far there is no clear explanation of what exactly the 5G is, but it is possible to identify the challenges that would lead to its development.

The aim of 5G is to support the growth of the data volume, the increasing number of devices and the request of high-speed data rate. In order to achieve this it is the bandwidth should increase and the network type will gravitate towards an ultra dense network (UDN). The main changes will be further discussed and they are based on [Jeffrey G. Andrews et al., 2014]:

- **High Data Rate**: the aim of 5G is to support the great request of data. It is expected that the total amount of data rate would increase 1000 times from the current 4G technology, with the implementation of UDN, increasing the bandwidth and advancing in MIMO techniques.
- **Bandwidth**: in order to increase the bandwidth it is necessary to increase the carrier frequency. This is because the spectrum from hundreds of MHz up to few GHz is already occupied by different technologies. Until now is not clear what it will be the specific range

of frequencies, but for example METIS (*Mobile and wireless communications Enablers for the Twenty-twenty Information Society* - European project that lay the foundation for the 5G) is actually investigating up to 90 GHz.

- **Ultra Dense Network**: having an UDN is also one of the important features. This is due to the usage of high frequencies. An important benefit is that using small cells will allow to reuse the spectrum more often, there would be less users per cell, each base station being able to serve less users and therefore the traffic will be more bursty.
- **Multi-RAT**: the concept of heterogeneous networks will become more frequent on the way towards 5G, since their benefit is to reduce coverage holes, minimize the distance between the transmitter and receiver, especially for very populated areas. Multiple RATs will be combined in order to support 5G technology together with 3G or LTE. For this type of implementation, there are challenges regarding the load for each base station, users being able to switch base stations according to the gains to those specific base stations and the load.

This project will focus mainly on achieving high data rate. For this study concepts like UDN, increased bandwidth will be implemented, which have been briefly introduced. Other topics like millimeter waves and massive MIMO are presented in [Jeffrey G. Andrews et al., 2014]. The main idea of the millimeter waves is utilizing the idle spectrum where wavelengths are about 1-10 mm, requiring many antennas to steer the beam. Concerning the technique of massive MIMO, it refers to equipping the base stations with a very large number of antennas, which would help focusing signals on very small regions of space. These two concepts will not be further analysed, since they do not make the subject for the study.

As the studies for a new technology are progressing, each concept comes with its own implementation challenges. Mobility in a very dense heterogeneous network is difficult to model and analyse as additional layers at different frequencies are being introduced. For this reason, multiple studies have been conducted in order to find methods for improving the mobility performance in such a system.

For example, one of the studies presented in [Ishii et al., 2012], proposes a method of splitting the control plane (C-plane) and the user plane (U-plane) of the radio link in a HetNet scenario consisting both of macro and small cells. The C-plane is defined at the macro layer, which operates at a small frequency because of the need for reliable coverage (improved mobility), while the U-plane is set for the high frequency small cells layer, resulting in improved data rate. Another concept presented in the study is the *Phantom cell*. This is the name given for the small cells, since they are only used for carrying user traffic and are not configured with cell specific parameters. The basic mobility performance is obtained as the macro cell manages the RRC signaling between the UE and the phantom cell. As a conclusion, improvements in capacity and cell edge users data rates will be obtained.

Another study conducted by [Song et al., 2014] introduces the signal-to-interference ratio as the handover trigger quantity. This study is made for high speed scenarios and handover occurrences are predicted by taking into account the N+1 samples of the measured quantity. This type of prediction is called *Grey system*. The predicted values are used for triggering the handover, resulting in improved handover success probability.

This project also approaches mobility studies in a high speed HetNet scenario, as some of the 5G elements discussed in this chapter are introduced in the scenario. The detailed implementation and the utilized parameters will be further presented in Chapter 5, along with the results that will be obtained.

Chapter 5

5G Implementation

As it has been stated in the previous chapters the need for satisfying the growing number of subscribers and the increase in mobile data traffic adds a great complexity to the wireless networks. The challenge is to optimize the network efficiency given that there are many different technologies to manage (LTE on top of GSM and HSPA, for example), thus there is a trade off between quality and cost effectiveness. The purpose of this chapter is to present the implementation of a new scenario whose target is to manage mobility through two different network technologies in order to satisfy the minimum required data rate of 10 Mbps per UE.

In the first section the network deployment will be shown, which is a HetNet consisting of macro cells and small cells that operate in frequencies belonging to two different radio access technologies. The emphasis will be on the small cell deployment according to the 5G target.

The next sections of the chapter will describe the prameters chosen for this scenario, such as path loss, antenna gain and height or number of PRBs. The focus of the scenario is to investigate the mobility using carrier aggregation implementation. This is an important part of the simulation, given that the carrier aggregation technique will allow connections during mobility with the small cells operating at high frequency. This will impact the achieved data rate and the throughput for each user.

The outcome of the simulations will be evaluated in terms of achieved data rate, throughput, handovers and other key performance indicators (radio link failures, handover failures), as it has been done for the previous measurements for the LTE system in low and high speed (Section 3.2 and Section 4.1). Given the outcome of the simulations performed, the influence of the chosen frequency, base station power and trigger events parameters will be analysed. It is wanted to find the optimum values and a good trade off between these latter parameters, so that the minimum data rate of 10 Mbps is achieved with a small outage value.

5.1 Network Presentation

The implementation of the scenario departs from the initial measurements performed on the highway in Aalborg which are described in Section 4.1 (p. 35). The network deployment consists of the LTE macro cells to which the UE has been found to connect during the measurement and an additional layer of small cells, set to fulfil the requirements of a 5G network. Therefore, a HetNet is simulated, where the carrier frequency for the macro cells remains the same as in the previous measurements, 1.8 GHz, and for the small cells it is set to 10 GHz (according to simulations performed by Nokia employees). The chosen path for the simulation remains the same as the one from the measurements and the small cells have been manually deployed along this path, in order to bring the network closer to the UE and thus to provide a good coverage during the simulations. The geographical distance between every two consecutive small cells is set to approximately 100 meters, thus 108 small cells have been deployed in order to cover the path. The small cells are not deployed along the tunnel, which is 600 meters long. A general overview of the deployed scenario is shown in Figure 5.1.

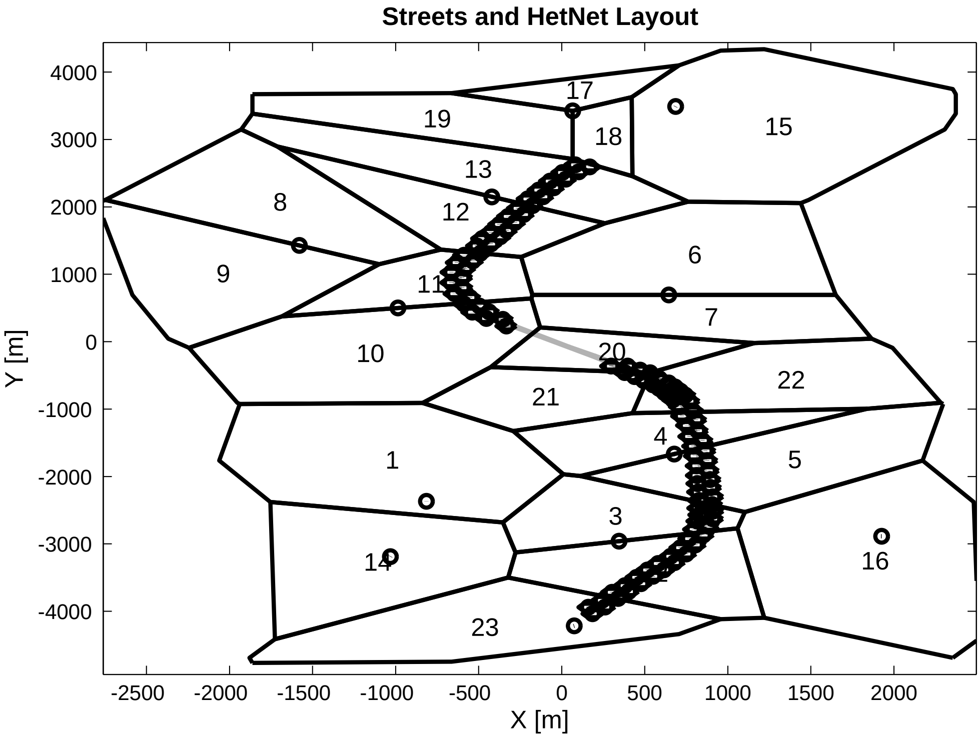

Figure 5.1: HetNet Scenario with LTE and 5G

5.2 Path loss models

This subject of this section is the path loss models used in the simulation of the HetNet presented in the introduction of this chapter. For the macro layer the 3GPP path loss model has been chosen (utilized in Section 4.1.2 (p. 42)) and for the small layer the model is the one tested in METIS.

Assumptions have been made for choosing the antenna heights for the two models. As it has been previously described in Section 4.1 (p. 35), the model uses the antenna height over the rooftop. For the macro cells the base stations have uniform height of 20 meters and the path loss is calculated according to [TR25.942,], which was shown in Section 4.1 (p. 35). According to the specifications, this model is used for test scenarios in suburban areas, which is why it is chosen for the purpose of the simulations on the highway.

The antennas for the small cells are assumed to be omnidirectional and the height for the corresponding base stations is chosen in accordance with the METIS model, so it is set to 10 meters from the ground level. The small cells are assumed to have an hexagonal layout and the path loss model according to the assumption for the layout and the height of the antennas is calculated using equation 5.1 [TR36.814,]. This model takes into account both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions, needed for the propagation in the small cells along the highway.

$$\begin{aligned} L =& 20 \cdot log_{10}(\frac{f}{MHz}) + 28 + 22 \cdot log_{10}(R) + \\ & 26 \cdot log_{10}(\frac{f}{MHz}) + 22.7 + 36.7 \cdot log_{10}(R) \end{aligned} \tag{5.1}$$

Where

- f is carrier frequency (10 GHz)
- R is the separation between the UE and the base station

The first line of the equation is for the LOS condition and the second line is for the NLOS condition. The values found for computing the path loss are used in [METIS et al., 2015, p. 15] for testing an urban micro path loss model for a frequency range between 0.8 and 60 GHz. The results found in [METIS et al., 2015] state that the tested path loss model fits the LOS measurements for frequencies higher than 6 GHz. However, for the NLOS case, the tested model seems to differ a lot from the measurements. By assuming that along the highway a UE is in LOS due to the suburban type of scenario (less reflections), the LOS map has been created for the small layer and it can be depicted in Figure 5.2 (p. 53).

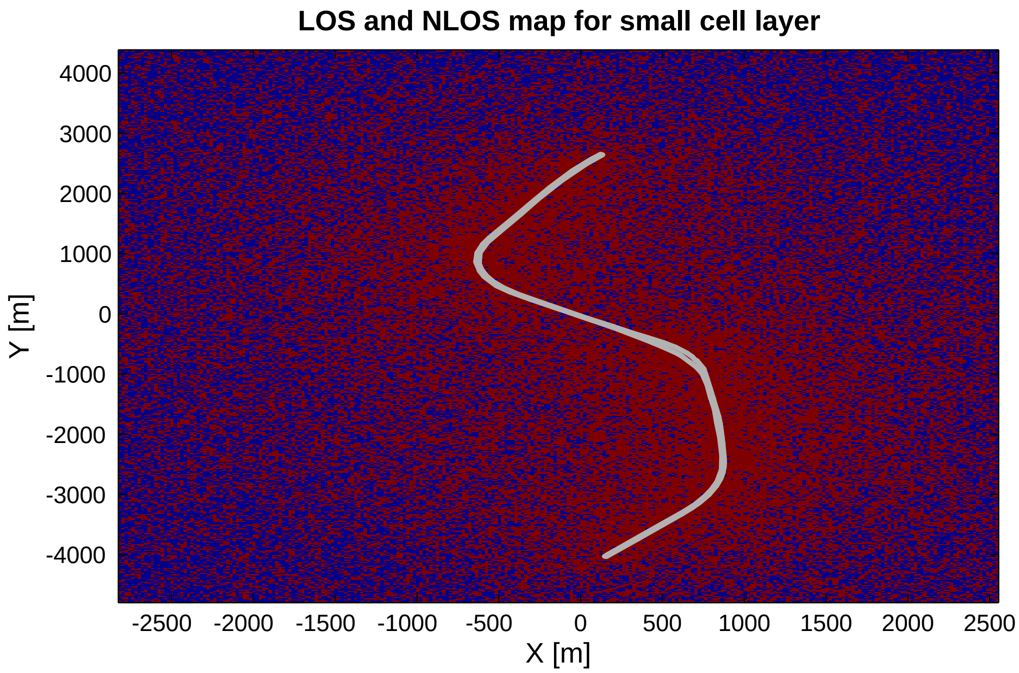

Figure 5.2: Line of Sight map for small layer

The red points represent the LOS conditions and the NLOS is represented in blue. The LOS seems to fit with the network, since the line-of-sight conditions follow the deployment of the small cells along the highway (represented in white).

In the standard [TR36.814,] it is also specified the shadow fading standard deviation for the urban micro scenario is LOS ($\sigma = 3$) and NLOS ($\sigma = 4$), which are utilized in the simulation.

Another parameter given by the specifications [TR36.814,] is the antenna gain for HetNet scenarios, which for the small cells is 5 dBi. The antenna gain for the macro cells is as defined in Section 4.1 (p. 35).

The simulation is done per physical resource block (PRB), notion which is described in Appendix B. Therefore the number of PRB is set to 100 for the macro cells, as it has been found in the measurements campaign. For the 5G context, high carrier frequency is assumed (10 GHz), with overall bandwidth of 100 MHz. At very high carrier frequency, the coherent bandwidth is wider. Consequently, it is assumed that the bandwidth can be partitioned over 10 MHz. Thus, there is a total of 10 PRBs each with 10 MHz bandwidth.

An overview of the general simulation parameters is summarized in Table 5.1, taking as a reference the paper [Barbera et al., 2012]. The tables includes the scenario setup and the user settings.

Parameter	**Macro Cells**	**Small Cells**
Scenario setup:		
Network Type	4G	5G
Carrier Frequency	1.8 MHz	10 GHz
Bandwidth	20 MHz	100 MHz
PRB Number	100	10
Base station Transmit Power	46 dBm	30 dBm
Path-Loss	$124.94 + 36.8log_{10}(R)$	$108 + 22log_{10}(R)$ for LOS $126.7 + 36.7log_{10}(R)$ for NLOS
Shadowing Standard Deviation	8 dB	10 dB
Shadowing Correlation Distance	50 m	13 m
Antenna Height	20 m (from rooftop)	10 m (from ground)
Number of Cells	23	108
Traffic Model	Fixed Buffer	Fixed Buffer
User Settings:		
Street users Number	200	200
Users Speed	120 km/h	120 km/h
Users Distribution	Random	Random
Background Users	None	None
Speed of Background Users	None	None
Simulation Time	400 sec	400 sec

Table 5.1: Parameters used for the mobility simulation of the HetNet with LTE and 5G

5.3 Mobility with Carrier Aggregation

Since the network is a HetNet with two layers operating at different carrier frequencies, downlink carrier aggregation is utilized in order to simulate this kind of scenario. The basic concepts for carrier aggregation have been introduced in Section 2.3 (p. 19). The implementation of the mobility procedures will be presented in this section. A UE entering a cell is configured by a measurement setup with specific TTT values to this cell. The TTT is specified for each type of cell (macro or small cells). Intra-frequency handovers between two macro cells or between two small cells are based on the measured RSRP values. For handovers between a macro and a small cell and vice versa, the trigger value is the RSRQ [Barbera et al., 2012]. It is wanted to analyse the mobility in such a HetNet scenario and the impact of the offset, time-to-trigger (TTT) and hysteresis values on the mobility. The failures in the system will be further investigated and how can they be minimized by adjusting the values of the parameters.

The use of inter-band carrier aggregation can be observed in a heterogeneous network which can be depicted in Figure 5.3 (p. 55).

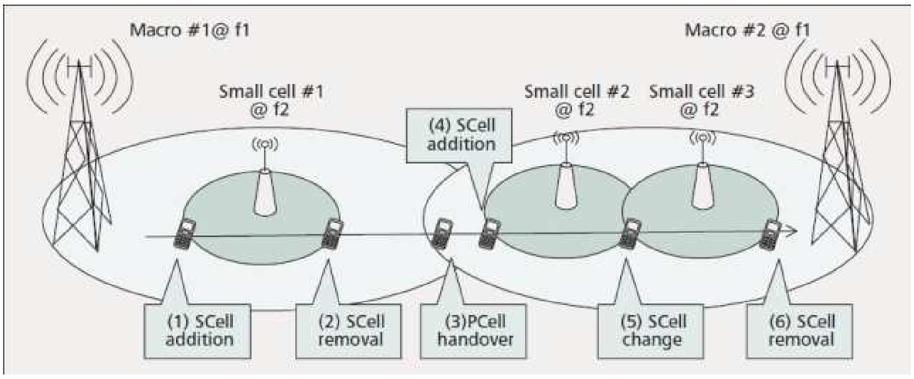

Figure 5.3: Mobility with carrier aggregation in a HetNet scenario [Pedersen et al., 2013]

The base stations have different transmit power levels. Macros and small cells are assumed to be interconnected, for example through X2 interface. Figure 5.3 shows the mobility in such a HetNet scenario. The main handover events at the SCell layer are based on adding, changing/re-configuring or removing an SCell.

While the UE moves under the coverage of the same macro cell (PCell), it has a constant stable connection. The **addition** of an SCell is based on event A4 (neighbour cell becomes better than threshold). For this event, the threshold is -12 dB and the TTT value is 160 ms [Pedersen et al., 2013].

The A6 event defined in section 2.3 (p. 19) is the event that triggers the handover between two small cells and it is configured by the network. This is equivalent with **changing** the current serving SCell with another target SCell. The TTT value for the A6 event is currently set to 160 ms.

When the UE leaves the coverage of a small cell, this event is called SCell **removal**. In this scenario, a new event is introduced for the removal of an SCell, which is the event A7, not defined in the 3GPP standard. This event is triggered when the neighbour SCell becomes worse than threshold, similar to the event A2 defined in table 2.1, from Section 2.2 (p. 8). The threshold value for SCell removal is -17 dB and the TTT is as for the other events, 160 ms.

An overview of the parameters used to simulate the mobility with carrier aggregation is presented in Table 5.2.

Parameter	**Macro Cells**	**Small Cells**
Handover Parameters:		
Trigger Event	A3	-
A3 TTT	1.024/0.320 sec	-
A3 Offset	2 dB	-
A3 Hysteresis	2 dB	-
Carrier Aggregation setup:		
SCell Addition		
Add Trigger Event	-	A4
Add TTT	-	160 ms
Add Threshold	-	-12 dB
SCell Change		
Change Trigger Event	-	A6
Change TTT	-	160 ms
Change Offset	-	1 dB
SCell Remove		
Remove Trigger Event	-	A7
Remove TTT	-	160 ms
Remove Threshold	-	-17 dB

Table 5.2: Parameters for mobility with carrier aggregation

After having explained how mobility works with carrier aggregation, the message exchange in the scenario will be discussed in the next chapter.

The outcome of the simulations using the values presented in the two tables will be further evaluated. Since the purpose of the scenario is obtaining the minimum data rate of 10 Mbps, the throughput and data rate will be investigated, as well as how the presence of the small cells affect it. The mobility failures and the handovers are also analysed.

5.3.1 Simulation Outcome

The scenario is created such as the UE has always a connection to a macro cell, while adding, changing or removing the small cells as it moves in high speed. Therefore, one UE is connected to the PCells 100 % of the time, but it is connected to the SCells only 33 % of the time, meaning when adding or changing an SCell. These statistics are depicted in Figure 5.4 (p. 57) which shows how much of the simulation time one user is connected to a SCell.

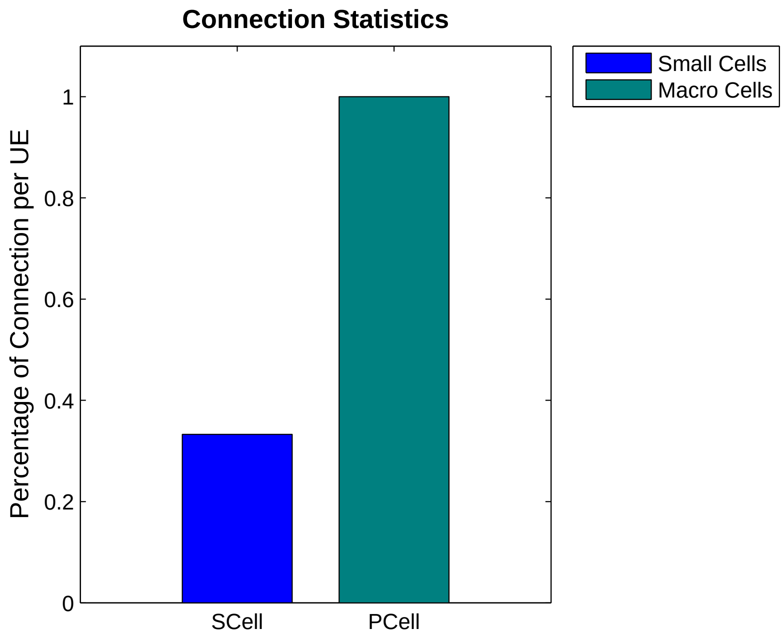

Figure 5.4: Percentage of one UE connection to the cells

From the figure it can be noticed that many of the SCells which take part in the mobility are removed or there is no SCell addition at all. The lack of SCell deployment in the tunnel area has its contribution to this fact. Another reasoning for the little connection to the SCells is the high speed of the UE, which doesn't allow frequent SCell connections because their coverage is very small compared to the one of the PCells.

In order to explain the little connection time to the SCell it is investigated which one of the events at the 5G layer is more frequent. This is shown by the plot in Figure 5.5 (p. 58).

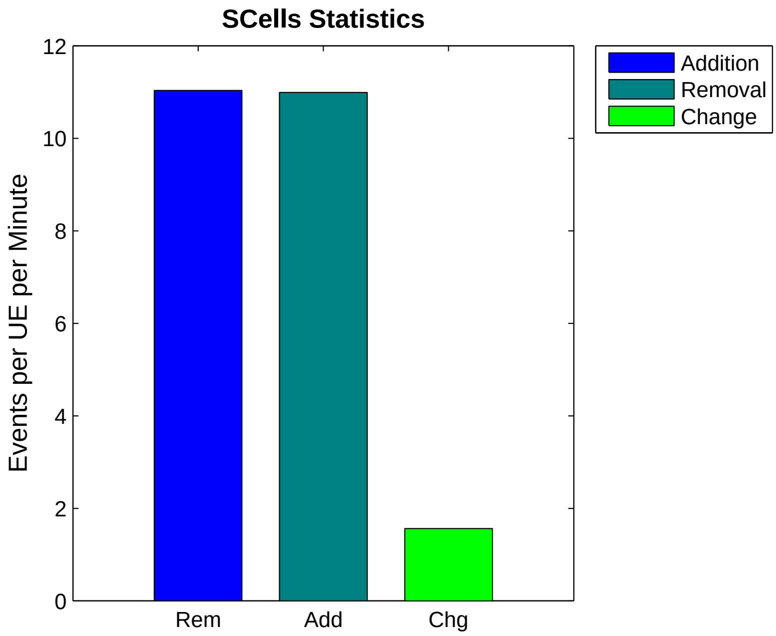

Figure 5.5: Percentage of one UE connection to the cells

It can be noticed that compared to the addition and removal events, the UE SCell change rate is way smaller. There are 1.56 cell changes per UE per minute compared to 11 additions and removals per UE per minute. This means that instead of having a constant connection to the small cells during mobility, these are added and removed frequently. The reasons for these are the low values of the RSRP, which is the triggering quantity for the SCell change.

Throughput

The throughput that the UE experiences along the whole path is shown in Figure 5.6 (p. 59), as it can be seen 80% of the time the throughput is below 10 Mbps. One of the reason is because the UE does not experience a continuous connection to the small cells. One other factor that can affect the throughput is the absence of small cell along the tunnel where the UE is only connected to the macro cells.

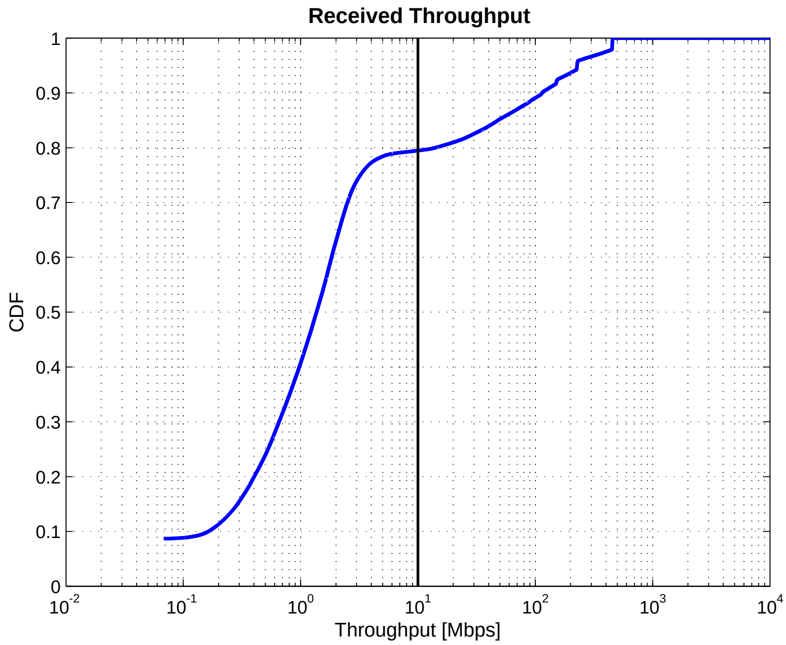

Figure 5.6: Throughput outage value for the entire simulation

Mobility Failures for the Implemented Scenario

Another outcome of the simulation scenario is related the radio link failures and handover events. The handover and failure events are only related to the PCell, while the events at the SCell layer are only the addition, change and removal. From the simulation, it is found that there are 5.25 handovers per UE per minute and 0.56 radio link failures per UE per minute. There are three types of RLF that can be extracted from the measurements: pure RLF (given by low SINR values), RLF during handover preparation and RLF during handover execution (handover failures).

Figure 5.7 (p. 60) shows the number of RLF per UE per minute for all the users during the simulation time, which is 6.83 minutes. The number of pure RLF per UE per minute obtained from low SINR values is approximately 0.5 and 0.05 during handover execution. No RLF have been found during handover preparation.

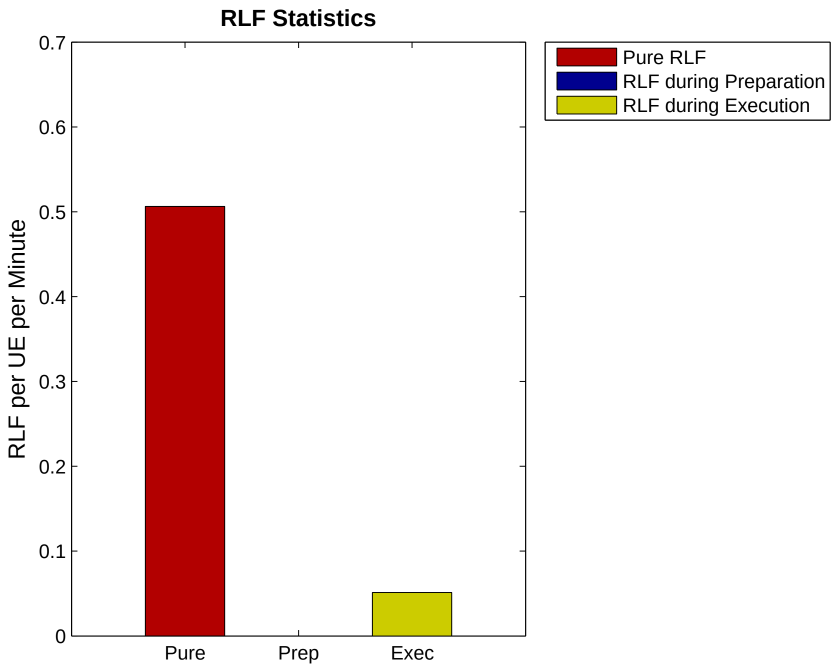

Figure 5.7: Number of RLF per Minute obtained from the Simulation

The TTT parameter has an impact on the overall handover time. Thus, it is wanted to find a new configuration of the TTT value that will result in less failures. This will be the subject for the next chapter, where the results from changing some of the system parameters will be shown.

Conclusion: The presented scenario which uses as a macro layer the real highway scenario and small cells along the highway is not be able to reach the minimum desired data rate. The reason for this is related to a non-continuous connection to the small cells. This means that the parameters set in Table 5.2 (p. 56) and Table 5.1 (p. 54) need to be reexamined.

Chapter 6

Optimizing the scenario

This chapter presents the results obtained from changing some of the parameters from the simulation scenario described in Chapter 5. The aim for changing the parameters is to minimize the radio link failures at the PCell layer (macro cells) and to obtain a better connection with the small cells at the SCell layer. The latter change is done in order to improve the received throughput at the UE end.

The findings in Chapter 5 have shown frequent addition and removing of SCells. A reasoning for this might be that the high frequency of 10 GHz that is utilized in the scenario will give a "spotty" coverage in terms of small cell connections. In order to fix this issue, two approaches can be followed: either lowering the frequency or densifying the SCell network. Lowering the frequency will result in a better coverage from the SCells and therefore the removals will not be so frequent any more. Another approach is to keep the carrier frequency of the small cells to 10 GHz and add more small cells in the network. For the purpose of this project it is chosen to lower the carrier frequency to the minimum required for this model, meaning 6 GHz [METIS et al., 2015].

6.1 Radio Link Failure evaluation

In this section, the RLF in the system are investigated by changing the time-to-trigger value to shorter values than in the initial scenario. The TTT values for the A3 event are set to 480, 256 and 128 ms and the number of radio link failures is analysed for each of the values. The reason for choosing shorter TTT is that for fast moving users the users will be experiencing many handovers, which would lead to too early, too late or even unnecessary handovers. It is desired to minimize the radio link failures and handover failures . In Figure 6.1 (p. 62) is shown the impact of the TTT values on the number of RLF per UE per minute during the whole simulation time (6.83 minutes).

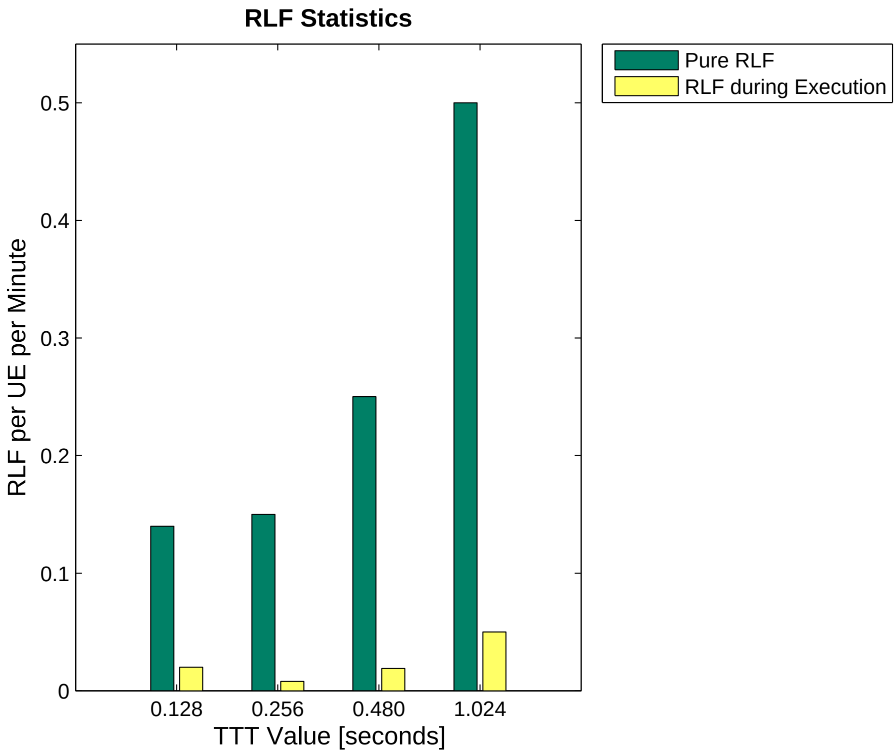

Figure 6.1: Handovers and RLF per UE per minute with different TTT values

As it can be noticed from the figure, the high values of TTT will result in an increased number of radio link failures. The reasoning for these findings is that since the users move in high speed, there is no need for high values of TTT, because the timer will not expire early enough for the UE to trigger the handover even though a neighbouring cell might meet the triggering condition.

Given the findings from the statistics presented in Figure 6.1, it is chosen to set the TTT timer to 256 ms, since this it seems to be the optimum value for having less RLF. Then, with this setting it will be investigated how to prolong the connection to the SCells by having more changing of small cells than addition and removal. In order to do this, some parameters for the SCell layer actions will be changed in terms of thresholds and TTT values.

6.2 Frequency evaluation

The purpose of this section is to show the effects of different frequencies on the scenario. For this reason simulations are run for a frequency range between 6 GHz and 20 GHz. Figure 6.2 shows the trend of the outage probability to have 10 Mbps and the percentage of the connection to the small cells for each frequency.

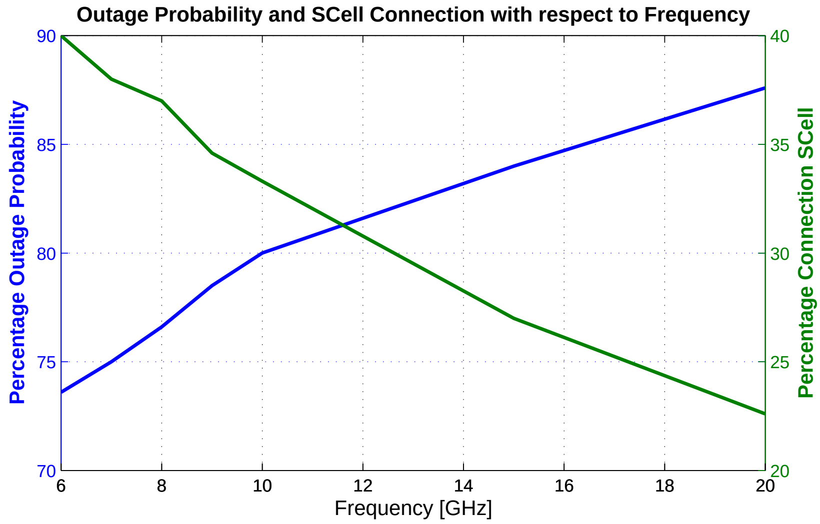

Figure 6.2: outage probability and SCells connection respect to frequency

The figure shows that as the frequency increases, the outage value increases as well. This means that the probability of having the satisfaction of 10 Mbps for the UEs decreases. The reason for this is that increasing the frequency will result in the shrinking of the propagation area in the small cells. This can be seen in the trend represented in green in Figure 6.2, which shows that the percentage of connection to the small cells decreases with the increase in frequency. After the point where the two curves intersect, close to 12 GHz, it can be concluded that there is no point in keeping to increase the frequency for this particular scenario, since the connection to the small cells keeps dropping and as a result, the outage probability increases.

Therefore, for this specific scenario it is most convenient to choose a carrier frequency of 6 GHz, where the outage value is minimum and the connection to the small cells in maximum.

6.3 Small cell events optimization

As it has been concluded in the previous section, the more convenient frequency for this particular scenario is 6 GHz. In this section methods to improve the scenario are investigated. So far, from the analysis of the scenario it is clear that the the high outage probability is due in general to a little connection to the small cells as well as a discontinuous connection to the small cells. For these reasons, is wanted to investigate a method that can allow a continuous connection and therefore an increase in the throughput. This leads to evaluating the parameters that trigger the adding, removal and changing of the small cells.

The values of the parameters for adding, removing and changing a small cells used for the simulations so far are shown in Table 5.2(p. 56). The main idea is to decrease the value of the threshold that adds the small cell and at the same time lower the relative TTT value in order to trigger more frequent addition. Also the TTT and offset of the changing event are modified. In this case the TTT value is also wanted to be smaller so that more continuous connection to the small cells is obtained. It is wanted to make the removal difficult so that the connection to the small cells is more constant and more changing is made possible. This is done by increasing the TTT value as well as the threshold. In Table 6.1 the two chosen configurations are shown for the small cell events according to the previous proposal.

Parameter	**SCell Conf. 1**	**SCell Conf. 2**
Carrier Aggregation setup:		
SCell Addition		
Add Trigger Event	A4	A4
Add TTT	120 ms	80 ms
Add Threshold	-14 dB	-16 dB
SCell Change		
Change Trigger Event	A6	A6
Change TTT	80 ms	40 ms
Change Offset	1 dB	1 dB
SCell Remove		
Remove Trigger Event	A7	A7
Remove TTT	250 ms	480 ms
Remove Threshold	-19 dB	-19 dB

Table 6.1: Different configurations for the small cell events

The threshold for removing the small cell, which is based on RSRQ measurements, is set to be very close to the acceptable limit (-19.5 dB [Salo, 2013]).

The impact of the two configurations on the throughput with 6 GHz is shown in Figure 6.3 (p. 65). The red and blue curve represent the throughput at 6 GHz using the event Configuration 1 and 2 respectively. The green curve instead is the throughput of the original configuration (Table 5.2 (p. 56)).

The figure shows that lowering the frequency brings benefits with respect to throughput, as well as designing a better configuration for the events at the small cells. In fact, with this combination of parameters it is possible to gain around 30-40% in throughput outage compared to the original configuration (green curve).

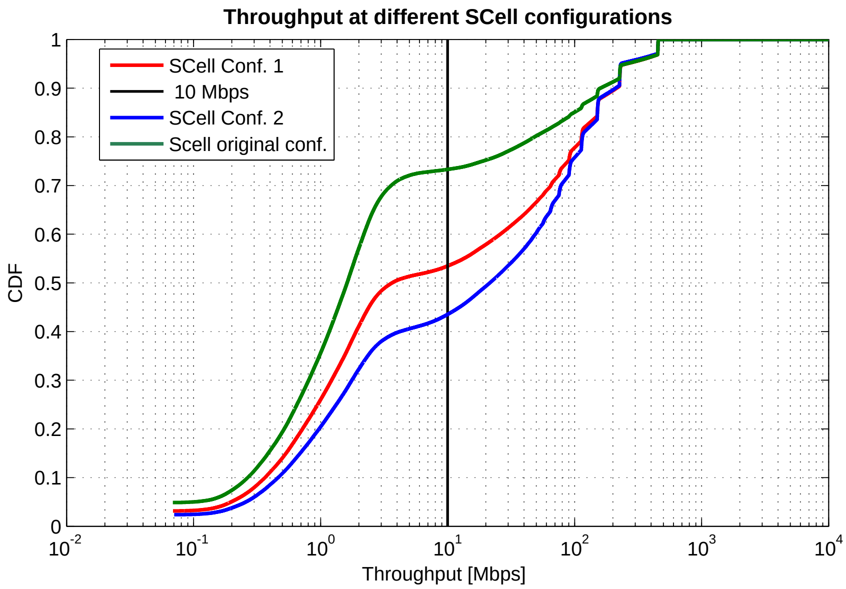

Figure 6.3: Throughput according to the two chosen configurations

The reason for this is related to a better coverage due to the low frequency (6 GHz) together with an optimization for continuous connection between the small cells. Figure 6.4 shows the SCell events per UE per minute according to different configurations. Where "Initial" represents the original SCell values (Table 5.2 (p. 56)). "Conf. 1" and "Conf. 2" are the configurations shown in Table 6.1(p. 64).

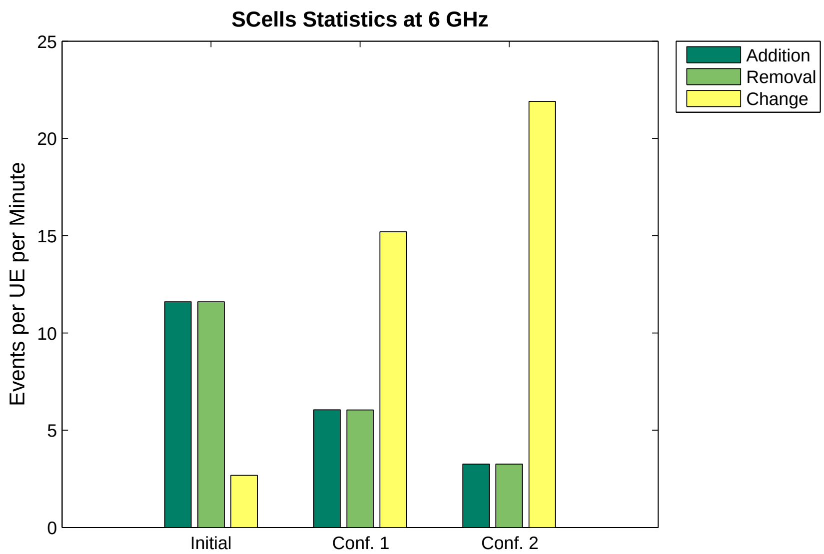

Figure 6.4: Statistic at 6 GHz with different configurations

The figure shows that Configuration 2 has the best result. This means that having a really low TTT value for adding a cell in the system is crucial, so the UE can connect to a small cell faster. Also having a longer TTT for the removal event has a great impact. In fact, a longer TTTs allow longer connection to the small cells and at the same time the probability that the RSRP of the neighbour small cell is stronger increase. This leads to having more changing between the cells and less removal and addition events.

It can be also proved that with the changing of configuration more percentage of connection to the small cells is achieved. This is shown in Figure 6.5.

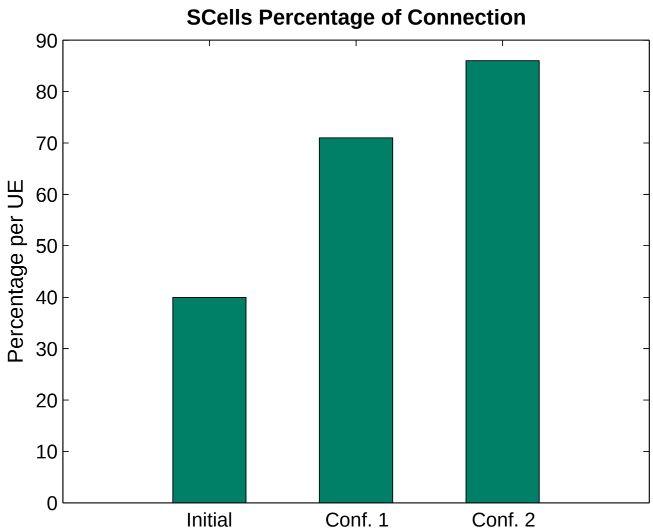

Figure 6.5: Statistic for SCell connections at 6 GHz with different configurations

It can be seen in the figure that using Configuration 2, the percentage of connection to the small cells is double compared to the initial configuration.

In order to understand how the absence of these cells along the tunnel effects the performance of the throughput Figure 6.6 (p. 67) shows the CDF of the throughput when the UE is connected all the time both to the SCells and to the PCells. Meaning that the samples where the UE is connected only to the macro cells are cut away.

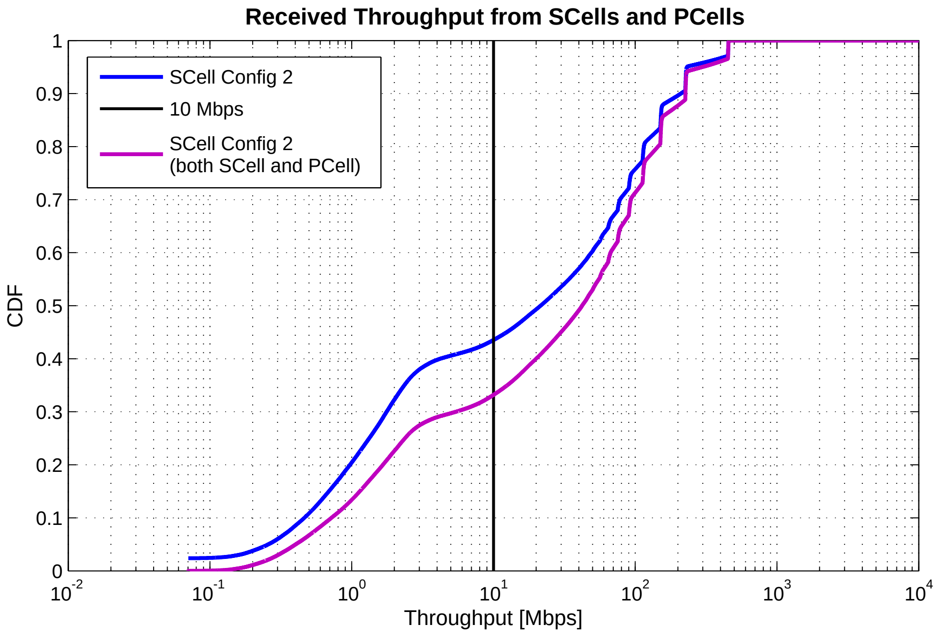

Figure 6.6: Throughput when the UE is connected to PCells and SCells all the time

From this CDF plot, it can be seen that continuous connection to the SCells improves significantly the received throughput. Therefore, it is wanted to make this connection constant, by having more SCell changing than removing and adding. This would help decrease the outage probability with 10 % for more users to get minimum 10 Mbps.

Conclusion: This section has shown that the deployed scenario in Chapter 5 can be optimized at both network layers. The macro cell layer performance can be improved in terms of minimizing radio link failures and handover failures. This can be achieved by lowering the TTT value. Using this improvement, the next step is optimizing the connectivity to the small cell layer. It has been shown that it is possible to adjust the parameters of the events at the small cell layer so that the changing event of the cells is predominant compared to the addition and removal of cells. Therefore, having more connection to the high frequency operating cells (SCells) will result in higher user throughput. The minimum target of 10 Mbps is achieved for 60 % of the users.

Chapter 7

Conclusion and Future Work

The focus of this project was to investigate the real performance of LTE in a high speed scenario and compare real measurements with simulations in order to validate the used models. Also it is wanted to verify if the actual system is be able to support the increase of the data demand, that is expected to increase by 1000 until 2020. Furthermore it is investigated a new technology that is able to support 10 Mbps at the user end while high speed is involved and also the mobility performance.

From the study of the LTE system performance at low and high speed, it is possible to conclude that LTE is resilient to radio link failures and ping-pong effect compared to the previous technology (3G). Therefore, the mobility performance of LTE is good. From the throughput point of view, the difference between the performance at low and high speed is not so large. In fact, on average the throughput obtained from both scenarios is around 8 Mbps. Instead the peak value reached in low speed is on average 5 Mbps higher that the high speed.

The outcome from the simulations that reproduced the two scenario shows positive results in terms of used models. The number of handovers in the real measurements is found to be slightly different from the number of handovers obtained from the simulation. This is because in the simulation the local variations of the propagated signal are not taken into account. In general it is possible to state that the simulations have a good match with the measurements and that the models used in this project do not alter the reality.

Another important finding is that LTE is not able to support an increase in data request in high speed scenarios. In fact, the results from simulations show that the UE can achieve 1 Mbps 65% of the time but only the 7% of the time it can reach 10 Mbps. In order to guarantee minimum 10 Mbps data rate at the user end, 5G assumptions are implemented. This implies the use of dense cells, high frequency and dual connectivity between different radio access technologies. The macro layer (LTE) is also present in order to support the small cells (5G).

The implemented scenario uses a 4G macro layer with carrier frequency of 1.8 GHz and the 5G small cell layer at 10 GHz. The results from simulations show that with 10 GHz and inter site distance (ISD) of 100 metres it is not possible to reach the minimum required. In fact, only the 20 % of the users are satisfied. Another factor that influences the performance of the system is the mobility. It is found that the UE does not have a continuous connection to the small cells and this causes the decrease in throughput. Thus, it is necessary to have less ISD distance or to lower the frequency. Another goal was to improve the mobility performance.

By lowering the frequency at 6 GHz, the outage probability of 10 Mbps decreases and at the same time the connection to the small cells becomes better. Without making any changes in the mobility parameters the outage probability is still high (around 70%) due to a discontinuous connection to the small cells. Thus, the mobility parameters are manipulated by lowering the TTT value that allows (*changing event*) of the small cells, as well as making it difficult to leave the cells (*removal event*). Also adding a cell (*adding event*) is configured in order to add the cells easier. So, the combination of lower frequency together with the optimization of the mobility performance allows to have an outage probability of 40%.

As a general conclusion it is needed to densify the network compared to the deployment presented in this project and design it such that the changing event is predominant to the removal and adding.

From the results obtained in this work some research starting points can be developed. Fist of all, building a new network where the inter site distance between the cells is smaller (25 - 50 metres) and evaluate the performance of this network by changing the carrier frequency. Meaning that it is wanted to find a relationship between frequency and ISD. Furthermore a definition of the KPI specifications for the small cells should be investigated in terms of radio link failures, handover failures, handovers etc. Furthermore, it would be interesting to analyse the message exchange between the UE and the eNodeBs of the macro and small cells.

Chapter 8

List of references

Figures and tables are produced by the project group unless otherwise specified.

List of Figures

List of Tables

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Chapter 9

Annex Index

The annex is to be found on the attached CD. This includes the articles and material used in the project.

ALL ANNEXES ARE ON THE ACCOMPANYING CD

A list of folders and their contents are listed below:

List of articles and notes

- 3rd Generation Partnership Project; Technical Specification Group (TSG) RAN WG4; RF System Scenarios
- 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9)
- 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Mobility enhancements in heterogeneous networks (Release 11)
- LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version 10.0.0 Release 10)
- LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements (3GPP TS 36.214 version 10.1.0 Release 10)
- 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (Release 9)
- A Novel Architecture for LTE-B. C-plane/U-plane Split and Phantom Cell Concept - Hiroyuki Ishii
- Handover Scheme for 5G C/U Plane Split. Heterogeneous Network in High-Speed Railway - Hao Song, Xuming Fang and Li Yan
- Improved Mobility Performance in LTE Co-Channel HetNets Through Speed Differentiated Enhancements - Simone Barbera, Per Henrik Michaelsen, Mikko Säily*, Klaus Pedersen
- LTE-Advanced Carrier Aggregation Optimization - Nokia Networks
- METIS Channel Models - Deliverable D1.4
- Mobility Enhancements for LTE-Advanced Multilayer Networks with Inter-Site Carrier Aggregation - Klaus I. Pedersen, Per Henrik Michaelsen, and Claudio Rosa, Nokia Siemens

Networks Simone Barbera

- Mobility Management Challenges in 3GPP Heterogeneous Networks - David López-Pérez,Ismail Güvenc, Xiaoli Chu
- Mobility Parameter Planning for 3GPP LTE: Basic Concepts and Intra-Layer Mobility - Jari Salo
- Universal Mobile Telecommunications System (UMTS); LTE; Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN) (3GPP TR 25.913 version 8.0.0 Release 8)
- Understanding LTE-Advanced Carrier Aggregation - Anritsu
- Validation of Mobility Simulations via Measurement Drive Tests in an Operational Network - Gimenez, Lucas Chavarria; Barbera, Simone; Polignano, Michele; Pedersen, Klaus I.; Elling, Jan; Sørensen, Mads
- What Will 5G Be? - Jeffrey G. Andrews

List of other material

- Project Proposal - Design of optimized mobility capabilities in future 5G systems

Appendix A

Phone messages

In this part of the report is explained the message exchange between the UE and the eNodeB which are involved in the handover procedure. This helps to find the values of the events A2, A3 and A5. First of all, it will be explained how the UE reports the measurements. Then, based on this, the messages the contain the handover command will be presented.

A.1 Measurement report

In this section is presented how the phone (UE) reports the measurements to the eNodeB. In general, the UE performs different types of measurements[TR36.331, 2012, p. 73]:

- Intra-frequency measurements
- Inter-frequency measurements
- Inter-RAT measurements

For the measurements described in Section 4.1 (p. 35) and Chapter 3, the type measurements that is taken in account is *intra-frequency*. This is because the phone is forced to work in only one frequency during the measurements. By analysing the messages got from the measurements taken in Aalborg, it is found that the measurement report can be: periodic or event triggered, for example when the event A3 occurs (see the definition in the Table 2.1). In order to recognize the related messages to the type of measurement, the UE uses different measurement ID.

Figure A.1 is utilized to map the measurement ID to the type of measurement performed by the UE.

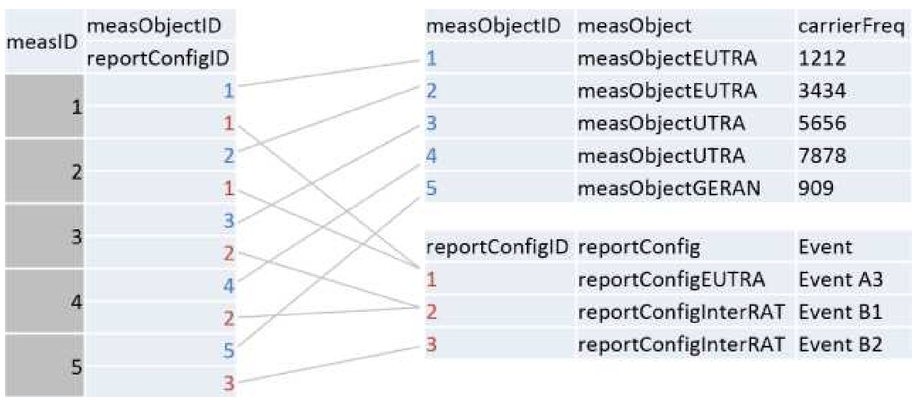

Figure A.1: Measurement ID [TechBarnWireless, URL]

As figure A.1 shows, the measID is the combination of two elements:

- measuObjectID: identifies which carrier frequency is measured and therefore the network

- reportConfigID: this identifies the cause of the measurements (e.g events, periodical measurement)

For example, the $measID = 1$ refers to a measurement in a LTE network with a code carrier frequency equal to 1212 due to the A3 event. The $measID = 3$ refers to measurements in a 3G network with a code carrier frequency equal to 5656 due to the event B1 (inter RAT neighbour becomes better than a threshold).

So, taking as a reference the table in Figure A.1 (p. 77), it is possible to extract the information stored in the measurement used for this project. This information has been found in the *RRCConnectionReconfiguration* messages.

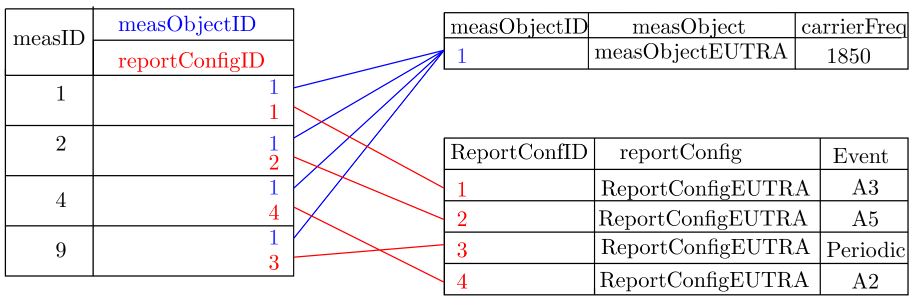

Figure A.2: Measurement ID

From Figure A.2, it can be noticed that the measObjectID is always equal to 1. This is because the measurements related to this thesis are taken only for LTE network and only for one frequency (2.6 GHz or 1.8 GHz). On the other hand, the ReportConfigID has four values:

- $ReportConfigID = 1$: refers to the A3 event
- $ReportConfigID = 2$: refers to the A5 event
- $ReportConfigID = 3$: refers to the a periodical measurement
- $ReportConfigID = 4$: refers to the A2 event

So it is possible to summarize the measurement report ID as follows:

- $measID = 1$: refers to a LTE measurement caused by the A3 event
- $measID = 2$: refers to a LTE measurement caused by the A5 event
- $measID = 4$: refers to a LTE nett due to periodical measurement
- $measID = 9$: refers to a LTE measurement caused by the A2 event

As a confirmation of the discussion above, in Figure A.3 (p. 79) is depicted an RRC message that contains the information about mapping the ID measurement.
In the measurements that have been performed for this project two measurement reports were found: triggered by the A3 event and periodic. In the figures below these two cases are shown, where the respective measurement ID is highlighted.

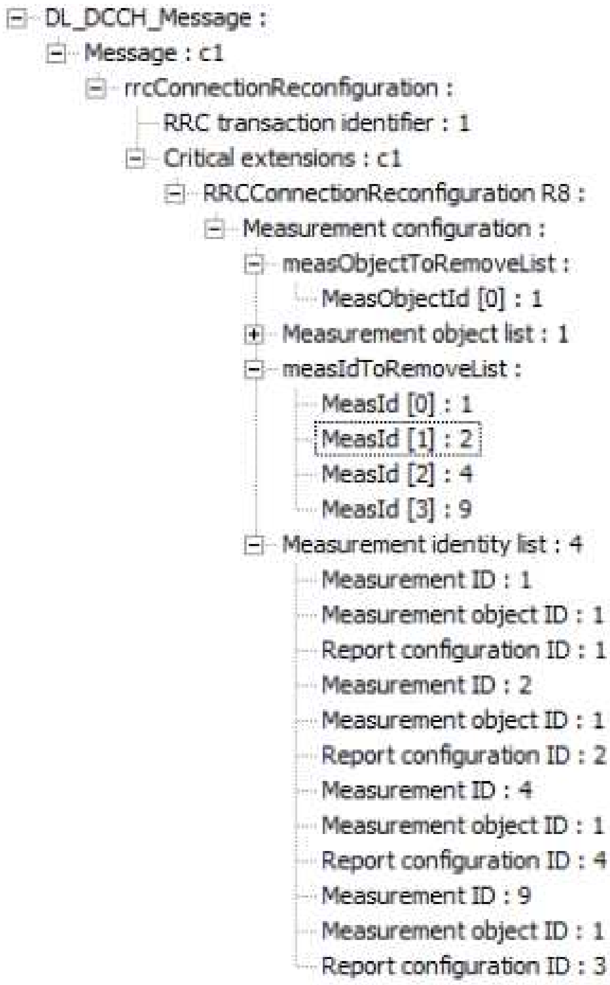

Figure A.3: RRC message containing the information about the measurement ID

Each time that the phone changes cell it receives from the base station an RRC connection reconfiguration message. This contains all the information about the connection, including the measurement configuration. The next section will expand this discussion.

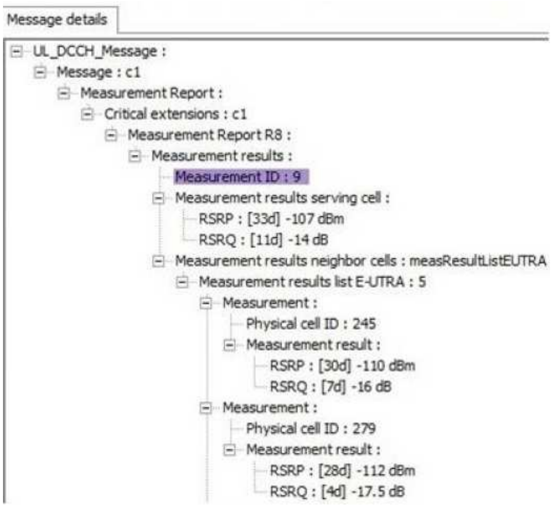

Figure A.4: Message Report due to A3 event

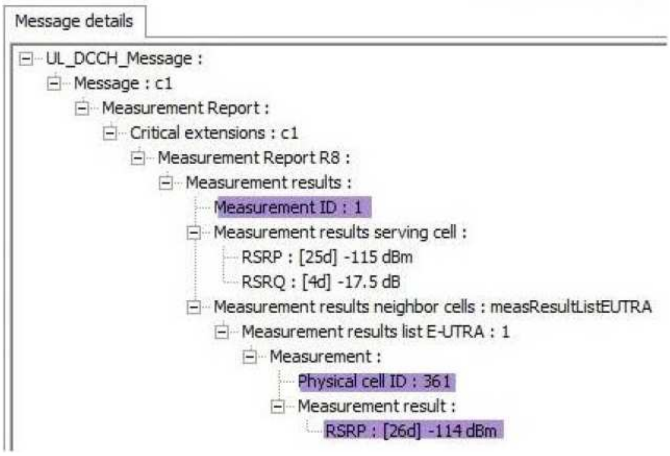

Figure A.5: Message Report due to a periodic message

A.2 RRC Connection Reconfiguration

According to the standard [TR36.331, 2012, p.], *RRC CONNECTION RECONFIGURATION* is the command that modifies RRC connection. The purpose of *RRC CONNECTION RECONFIGURATION* is to perform handover, to setup/modify/release measurement, dedicate NAS information and to establish/modify/release Radio resource configuration.

In the RRC Connection reconfiguration message the measurement configuration parameter is used to configure the measurements for the UE and the measurement report is used for reporting. The reporting configuration contains the reporting criteria and configuration for a UE to trigger a measurement report. The measurement report can be triggered by and event or it can be a periodic measurement [Holma and Toskala, 2009]. These concepts have been presented in Appendix A.1.

Based on the measurement result received from the UE, the eNodeB triggers the handover. For the measurements described in Section 4.1 (p. 35) and Chapter 3 where intra-LTE handovers are performed, the RRC connection reconfiguration message is used as a handover command.

Appendix B

Overview of OFDMA and SC-FDMA

The following section covers the LTE multi carrier technology that are used in LTE. In downlink the multi access is based on *Orthogonal Frequency Division Multiple Access* (OFDMA), in uplink the multi access is based on *Single Carrier Frequency Division Multi Access* (SC-FDMA).

B.1 OFDMA

Orthogonal Frequency Division Multiple Access (OFDMA) is a special case of multicarrier system.

In general multicarrier divides the channels in a certain number of sub-channel separated by guard-band in order to avoid the selectivity in frequency. The advantage of OFDMA is that the carrier frequencies are orthogonal among each other and this allows to save bandwidth and therefore makes OFDMA highly spectral efficient [Stefania Sesia and Baker, 2011, p. 123]. The different can be seen in figure B.1.

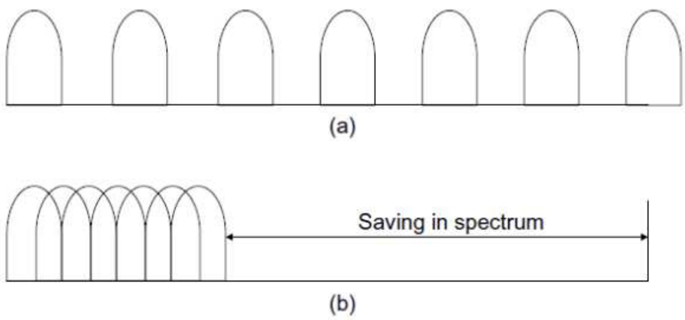

Figure B.1: (a) classical multicarrier system spectrum; (b) OFDMA system spectrum [Stefania Sesia and Baker, 2011, p. 124]

The reasons why the OFDMA is used in LTE are mentioned below:

- good performance in frequency selective fading channels;
- link adaptation and frequency domain scheduling;
- good spectral properties
- increased user data rates

As mentioned above, the carrier frequencies in OFDMA are orthogonal, a more exact representation can be seen in figure B.2 (p. 82), where the center frequencies of the each sub-carrier is chosen in order that the neighboring sub-carriers have zero value at the sampling instant of the desired sub-carriers. In LTE, the distance in frequency among each sub-carrier is 15kHZ [Holma and Toskala, 2009, p. 69].

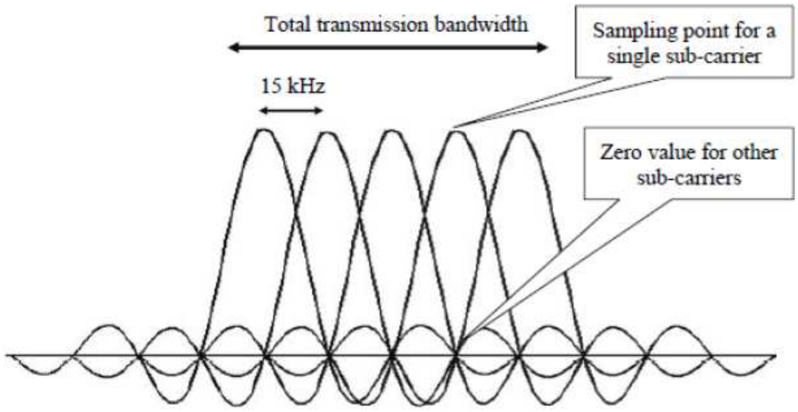

Figure B.2: Sub-carriers orthogonality [Holma and Toskala, 2009, p. 69]

In order to understand how the OFDMA works is essential to analyze how the signal is transmitted. The OFDMA signal is based on the usage of FFT (Fast Fourier Transform) and IFFT (Inverse Fast Fourier Transform). A schematic representation is given in figure B.3, where the data symbols is first serial-to-parallel converted and further are send in the IFFT block. To each

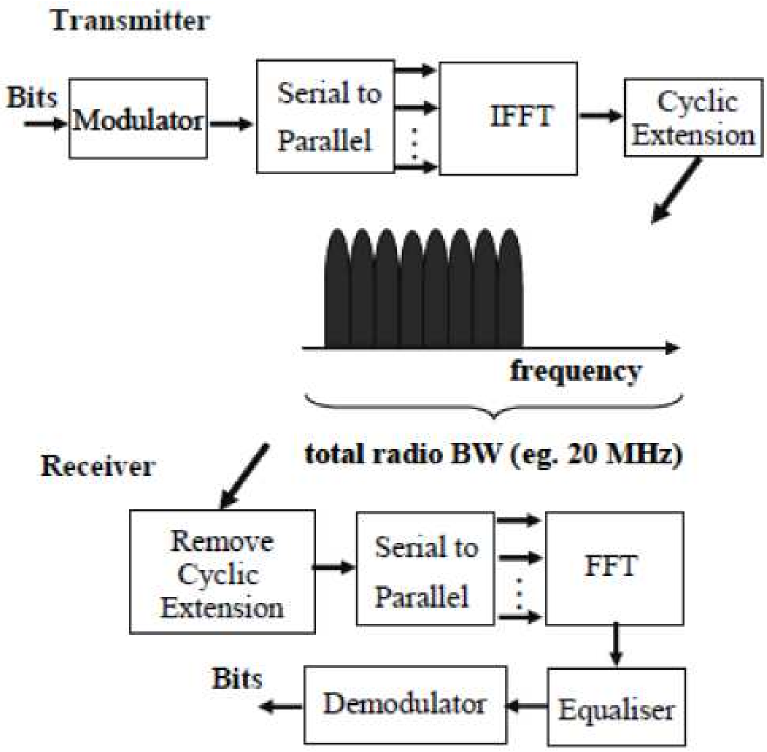

Figure B.3: OFDMA Transmitter and Receiver Scheme [Holma and Toskala, 2009, p. 71]

input of the IFFT will be assign a particular sub-carrier. After the IFFT block a cyclic prefix is added, in order to avoid inter-symbol interference (ISI) caused by multipath propagation. The cyclic prefix is a copy of the last part of the symbol which it is added at the beginning of the symbol.

Thus, based on what it has been explain before, the transmitted signal in time domain (due to the IFFT) is the sum of all these subcarriers, and the amplitude of this signal can be very high if they are summing up on phase.

At the receiver the reverse operations are executed to demodulate the OFDM signal. The cyclic prefix is removed from the signal and after the serial to parallel conversion, the FFT is applied in order to recreate the original signal.

Another important aspect for the OFDMA system to take into account is how the transmission resource are allocated to the users. This will be clarify in the next paragraph.

Resource Structure

In downlink, the LTE standard defines a resource allocation structure in time and frequency domains thanks to the usage of OFDMA. This paragraph will show how the symbols are transmitted in LTE.

In the time domain the LTE transmissions are organized into frames of 10 ms length, where each frame is catheterized of 10 subframes with a duration of 1 ms. These subframes are made of two slots of 0.5 ms each. Each slot is composed of seven or six OFDM symbols depending upon whether a short or long cyclic prefix is used.

In the frequency domain, 12 sub-carriers are grouped together (which occupy a bandwidth of 180kHz since the 12 sub-carriers are spaced at 15kHz) over a time slot of 0.5 ms. This resource representation is called Resource Block (RB). It is possible also identify the smallest unit of resource with the name of Resource Element (RE), which consists of one subcarrier for a duration of one OFDM symbol.

So, one RB consist of 84 RE when a normal cyclic prefix length is used (7 symbols $\cdot$ 12 subcarriers), otherwise is 72 RE for the extended cyclic prefix.

Figure B.4 (p. 84) shows the resource structure.

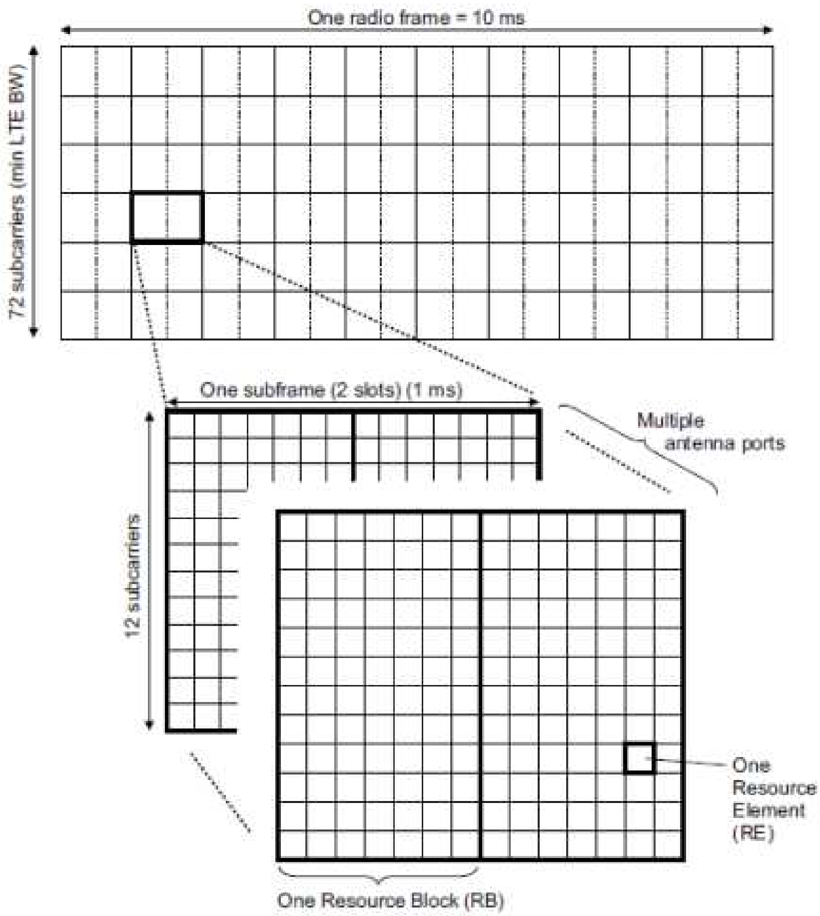

Figure B.4: Resource structure of LTE [Stefania Sesia and Baker, 2011, p. 146]

In summary, the minimum resource that an user can get is one RB: one single user can get minimum 0.5 ms in time domain and 180 kHz in frequency domain.

B.2 SC-FDMA

SC-FDMA is the access used for the uplink which uses some principles of OFDMA in order to achieve a good spectral efficiency. As it has describe for the OFDMA, in this subsection it will be explain the principles of SC-FDMA. In the figure B.5 (p. 85) it is depicted the transmitter and receiver schema for SC-FDMA system.

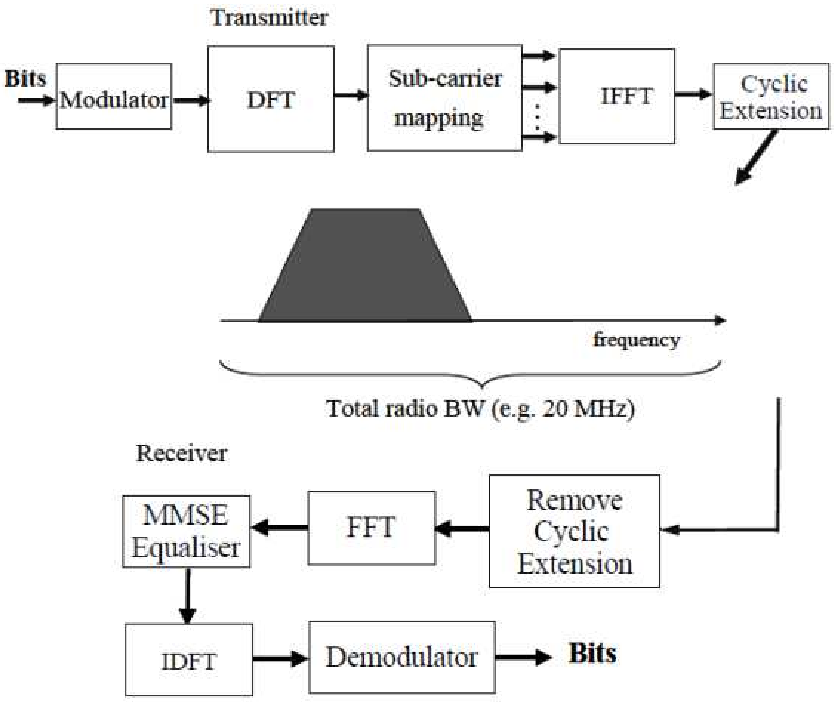

Figure B.5: SC-FDMA transmitter and receiver [Holma and Toskala, 2009, p. 146]

The fist step is to perform a DFT operation of the data symbols in order to produce a frequency domain representation. After that, it maps each of the DFT output in the N orthogonal subcarriers. As in OFDMA, an inverse Fourier Transform (IFFT) convert the subcarriers amplitude in to time domain signal. The last step for the transmission is insert a CP in order to avoid ISI. therefore, each symbol is sent one at a time in the air.

The inverse operation is required at the receiver to demodulate the SC-OFDMA signal.

Resource Structure

The resource block in uplink is similar to the downlink. The frame consist in 20 slot each of them of 0.5 ms and one subframe is formed by 2 slot. The sub-carriers are grouped into sets of 12 sub-carriers, spaced of 15 kHz among each other, corresponding to the uplink resource blocks. The 12 sub-carriers in one slot correspond to one uplink resource block, as the same in the downlink part.

Appendix C

Statistics of the configured events for Aalbog city center scenario

In this part of the report some statistic from the measurement done in Aalborg city center are presented. The absence of link failures in the system during measurements needs to be justified. For this reason, the subject of this section is the analysis of the time-to-trigger, hysteresis and offset parameters used in the mobility procedure. This is done statistically, meaning that it is investigated how the values of the parameters change from cell to cell. Each cell to which the UE connects is configured with different parameters.

After analysing the messages, it has been noted that at the beginning of the measurements the UE receives an RRC Connection Reconfiguration message that includes all the values of the configured events. Three events are found to be configured during the measurements: A2, A3 and A5. Each cell has a different configuration for these events depending on the carrier frequency in which the cell operates (either 1.8 or 2.6 GHz).

Each time the UE makes a handover from a serving to a target cell, it will receive an RRC Connection reconfiguration message with the configuration of the target. From the message analysis it is found that all cells operating in both 1.8 and 2.6 carrier frequencies are configured with the same values of the parameters for the A5 event. The values for A5 are as follows:

- TTT = 640 ms
- Hysteresis =2 dB
- RSRP Threshold 1 = -106dBm
- RSRP Threshold 2 =-105dBm

As for the A2 and A3 events, their parameters have different values depending on the cell configuration. Therefore, the subject for this appendix is to investigate the different configurations of the cells extracted from the measurements. The focus is on the values of the TTT, since this parameter has an impact in the handover event and it can be used to explain the absence of radio link failures.

C.1 Statistic for Cells Operating in 1.8 Ghz

- **Event A2**

  At 1.8 GHz carrier frequency, there are two possible configurations for the parameters of the event A2. The two configurations of A2 are shown in Figure C.1 (p. 87), along with the respective values for each configuration. The figure also shows how many cells are using each of the A2 configurations.

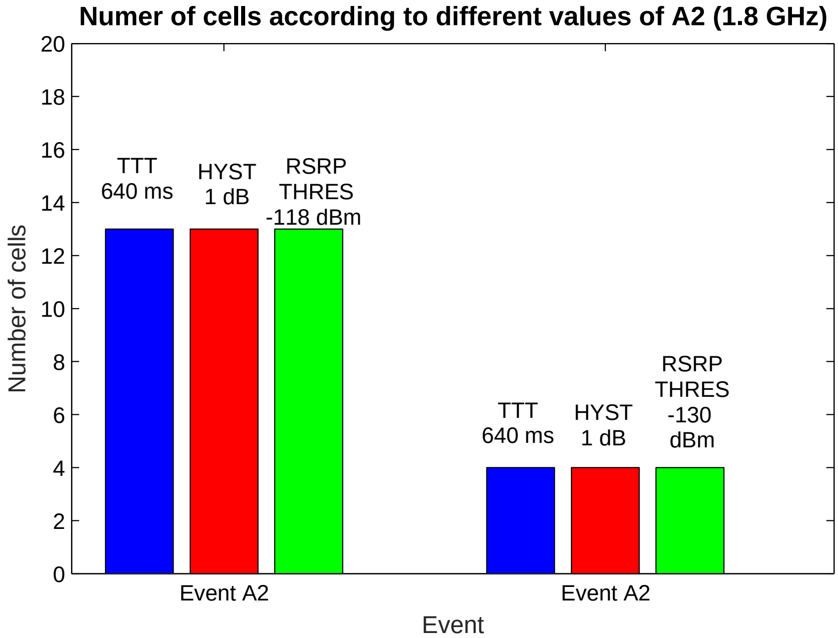

Figure C.1: Number of cells configured with two different values of A2 parameters at 1.8 GHz

It can be noted that for the 17 cells operating in 1.8GHz, the TTT (640 ms) and hysteresis (1 dB) values remain the same for all cells. The RSRP threshold is the only one that changes: -118/-130 dBm. In order to visualize how each cell is configured, the plot in Figure C.2 (p. 88) is used. The information about the cells to which the UE connected during the measurements has been collected and they are represented with different colors (green and brown), according to the different A2 configurations. The rest of the LTE 1.8 GHz cells are represented in white.

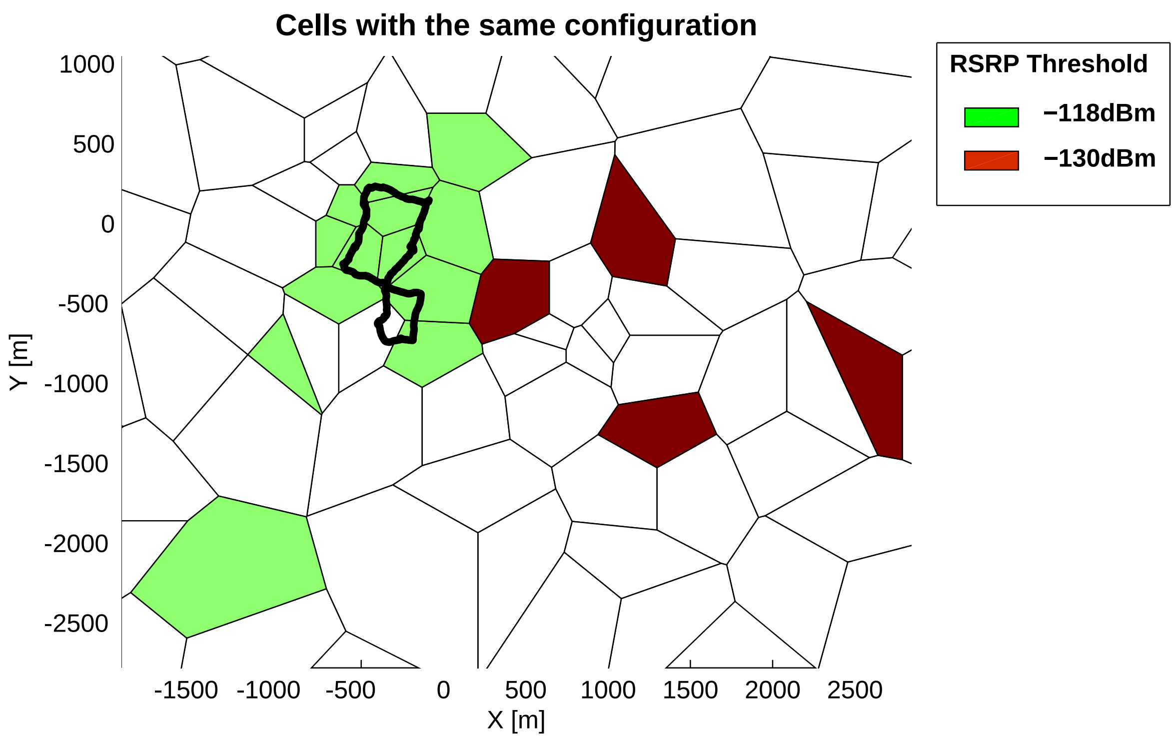

Figure C.2: Location of the cells configured with different A2 parameters at 1.8 GHz

The cells represented with green are the cells for which the RSRP threshold is -118 dBm and the cells represented with brown have the RSRP threshold equal to -130 dBm. The chosen path is also included and it is shown with the black line.

- **Event A3**
  For the event A3 at 1.8 GHz the configuration of the parameters is shown in Figure C.3 (p. 89). There are also two possible configurations for this event, given by the change in the TTT values.

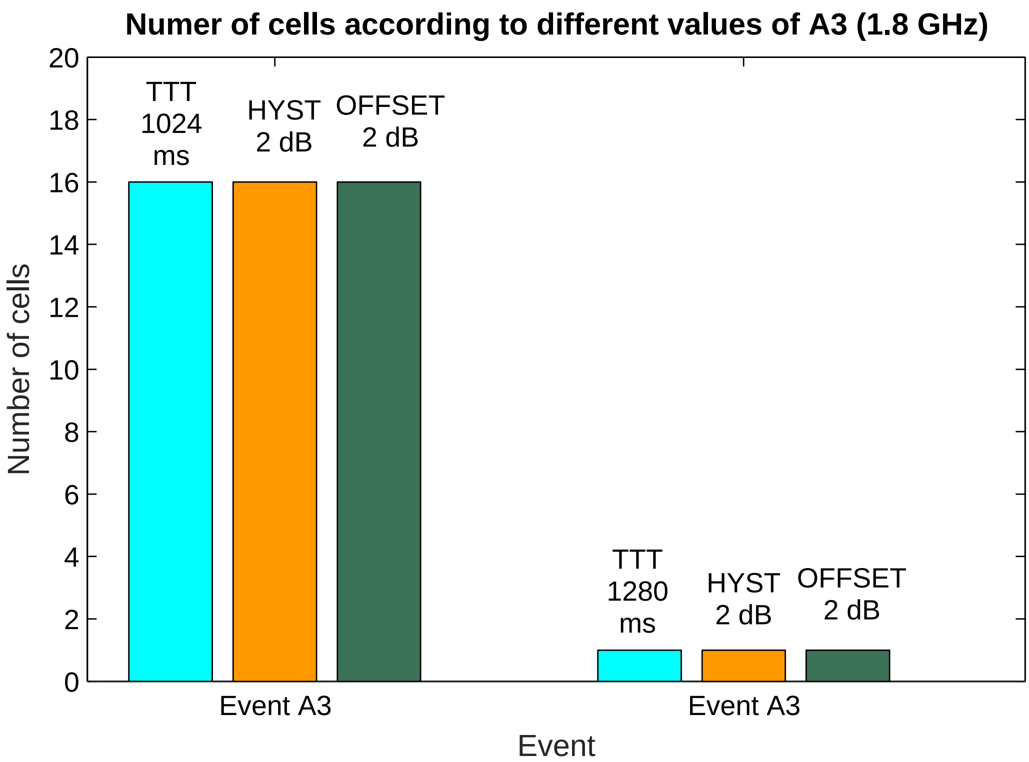

Figure C.3: Number of cells configured with two different values of A3 parameters at 1.8 GHz

For the 17 cells the hysteresis and offset values are the same: 2 dB. The value of the TTT is changing for one cell (1280ms) and remains the same for the others (1024ms). The map of all the 4G cells in 1.8 GHz is used to localize the different cell configurations for the event A3 and it can be depicted in Figure C.4, together with the path chosen for the measurements.

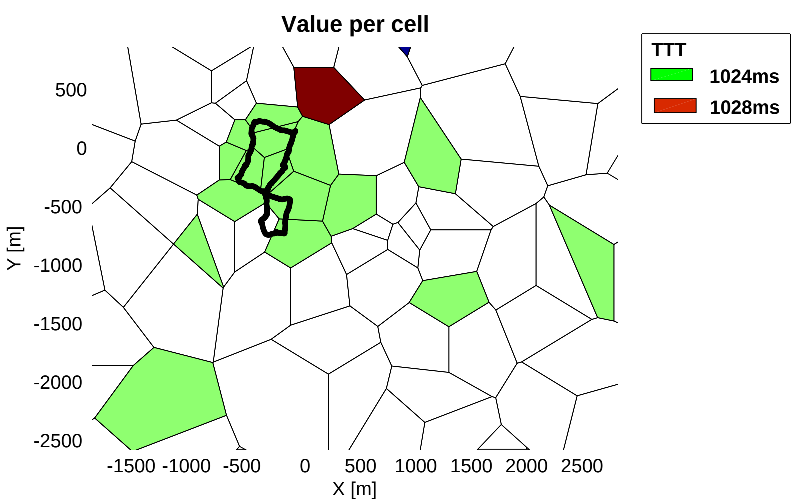

Figure C.4: Location of the cells configured with different A3 parameters at 1.8GHz

In this figure, the cells represented with green are the ones with the TTT value of 1024 ms and the brown cell has the TTT equal to 1028 ms. The one cell with different configuration is localized beyond the fiord.

After having performed the statistic for the configurations of the cells and knowing that the handover is being triggered by the A3 event (Section A (p. 77)), it can be concluded that the lack of radio link failures in the measurements is due to the high values of the TTT (more than 1 second). This allows more time for the handover to be triggered. Having a larger TTT also ensures that the level of the RSRP of the neighbour cell is strong enough to avoid a handover failure. Further on, the same procedure is used to explain the lack of failures at 2.6 GHz carrier frequency.

C.2 Statistic for Cells Operating in 2.6 Ghz

- **Event A2**
  During the measurements, five cells to which the UE connects have been found while setting the carrier frequency at 2.6 GHz. All the cells have the same configuration for the event A2:
  - TTT = 640ms
  - Hysteresis = 1dB
  - RSRP Threshold = -118dBm
- **Event A3**
  In the case of the event A3, two different configurations have been reported at 2.6 GHz. They can be depicted in figure C.5.

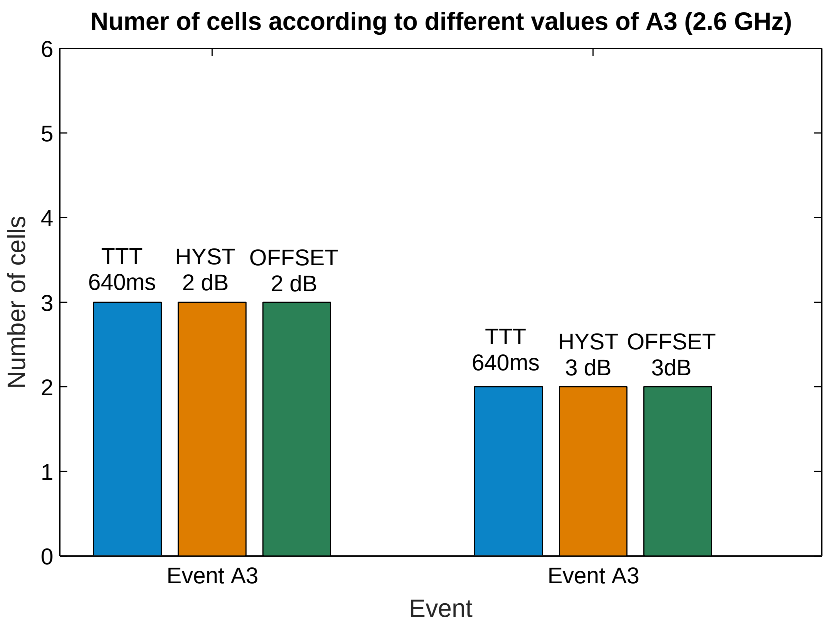

Figure C.5: Number of cells configured with two different values of A3 parameters at 2.6 GHz

The first configuration can be found in three of the cells and has the TTT value equal to 1024 ms and the hysteresis and offset 2 dB. The other two cells have another configuration, with 320 ms TTT value and hysteresis and offset of 3 dB. They can also be localized on the 4G map containing the cells which operate at 2.6 GHz, in figure C.6.

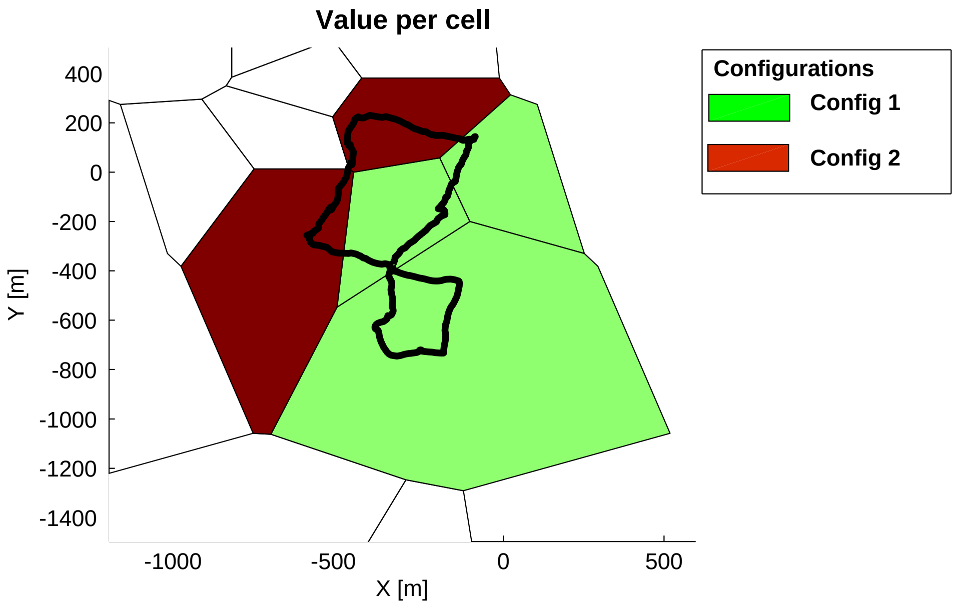

Figure C.6: Location of the cells configured with different A3 parameters at 2.6GHz

It can be noted from the figure that a big part of the path used for measurements is covered by the cells with the high value of TTT(1024ms), represented in green. For this reason it can be explained the absence of radio link failures also when operating at 2.6 GHz carrier frequency.