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Improving LTE network performance after CDMA2000 to LTE migration

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ABSTRACT OF THE
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CDMA2000 technology has been widely used on 450 MHz band. Recently the equipment availability and improved performance offered by LTE has started driving the operators to migrate their networks from CDMA2000 to LTE. The migration may cause the network performance to be in suboptimal state.

This thesis presents four methods to positively influence LTE network performance after CDMA2000 to LTE migration, especially on 450 MHz band. Furthermore, three of the four presented methods are evaluated in a live network. The measured three methods were cyclic prefix length, handover parameter optimization and uplink coordinated multipoint (CoMP) transmission. The objective was to determine the effectiveness of each method. The research methods included field measurements and network KPI collection.

The results show that normal cyclic prefix length is enough for LTE450 although the cell radius may be up to 50km. Only special cases exist where cyclic prefix should be extended. Operators should consider solving such problems individually instead of widely implementing extended cyclic prefix.

Handover parameter optimization turned out to be an important point of attention after CDMA2000 to LTE migration. It was observed that if the handover parameters are not concerned, significant amount of unnecessary handovers may happen. It was evaluated that about 50% of the handovers in the network were unnecessary in the initial situation. By adjusting the handover parameter values 47,28% of the handovers per user were removed and no negative effects were detected.

Coordinated multipoint transmission has been widely discussed to be an effective way to improve LTE network performance, especially at the cell edges. Many challenges must be overcome before it can be applied to downlink. Also, implementing it to function between cells in different eNBs involve challenges. Thus, only intra-site uplink CoMP transmission was tested. The results show that the performance improvements were significant at the cell edges as theory predicted.

Keywords: LTE, Cyclic Prefix, CoMP, handover parameter optimization, KPI analysis, field measurement

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CDMA2000 teknologiaa on laajalti käytetty 450 MHz:n taajuusalueella. Viime aikoina LTE:n tarjoamat halvemmat laitteistot ja parempi suorituskyky ovat kannustaneet operaattoreita muuttamaan verkkoaan CDMA2000:sta LTE:hen. Kyseinen muutos saattaa johtaa epäoptimaaliseen tilaan verkon suorituskyvyn kannalta.

Tämä työ esittelee neljä menetelmää, joilla voidaan positiivisesti vaikuttaa LTE-verkon suorituskykyyn CDMA2000:ste LTE:hen tehdyn muutoksen jälkeen erityisesti 450 MHz:n taajuusalueella. Kolmea näistä menetelmistä arvioidaan tuotantoverkossa. Nämä kolme menetelmää ovat suojavälin pituus, solunvaihtoparametrien optimointi ja ylälinkin koordinoitu monipistetiedonsiirto. Tavoite oli määrittää kunkin menetelmän vaikutus. Tutkimusmenetelmiin kuului kenttämittaukset ja verkon suorituskykymittareiden analyysi.

Tutkimustulosten perusteella voidaan sanoa, että normaali suojaväli on riittävän pitkä LTE450:lle vaikka solujen säde on jopa 50km. Vain erikoistapauksissa tarvitaan pidennettyä suojaväliä. Operaattoreiden tulisi ratkaista tällaiset tapaukset yksilöllisesti sen sijaan, että koko verkossa käytettäisiin pidennettyä suojaväliä.

Solunvaihtoparametrien optimointi osoittautui tärkeäksi huomion aiheeksi CDMA2000:sta LTE:hen tehdyn muutoksen jälkeen. Turhia solunvaihtoja saattaa tapahtua merkittäviä määriä, mikäli parametreihin ei kiinnitetä huomiota. Lähtötilanteessa noin 50% testiverkon solunvaihdoista arvioitiin olevan turhia. Solunvaihtoparametreja muuttamalla 47,28% solunvaihdoista per käyttäjä saatiin poistettua ilman, että mitään haittavaikutuksia olisi huomattu.

Koordinoidun monipistetiedonsiirron on laajalti sanottu olevan tehokas tapa parantaa LTE-verkon suorituskykyä, etenkin solujen reunoilla. Monia haasteita pitää ratkaista, enne kuin sitä voidaan käyttää alalinkin tiedonsiirtoon. Lisäksi sen käyttöön eri tukiasemien solujen välillä liittyy haasteita. Tästä syystä monipistetiedonsiirtoa voitiin testata vain ylälinkin suuntaan ja vain yhden tukiaseman välisten solujen kesken. Tulokset osoittivat, että suorituskyky parani merkittävästi solun reunalla.

Avainsanat: LTE, suojaväli, CoMP, solunvaihtoparametrien optimointi, suorituskykymittareiden analyysi, kenttämittaus

Preface

This thesis was done for Ukkoverkot between April 2015 and January 2016. I would like to thank Jari Weckman and Kari Lehtinen for offering me the opportunity. I would also like to thank my advisor Kari Lehtinen for his guidance and support.

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Abbreviations

3GPP	Third Generation Partnership Project
ACK	Acknowledgement
ADSL	Asymmetric Digital Subscriber Line
AMC	Adaptive Modulation and Coding
AS	Access Stratum
BBU	Baseband Unit
BER	Bit Error Rate
BLER	Block Error Rate
BPSK	Binary Phase-Shift Keying
BTS	Base Station
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CoMP	Coordinated Multipoint
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CSIR	Channel State Information at the Receiver
DCI	Downlink Control Information
DFT	Discrete Fourier Transform
DL	Downlink
DMRS	Demodulation Reference Signal
eCP	Extended Cyclic Prefix
eNB	Evolved Node B
EPC	Evolved Packet Core
E-RAB	E-UTRAN Radio Access Bearer
E-UTRAN	Evolved UMTS Radio Access Network
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GPRS	General Packet Radio Service
GTP	GPRS Tunnel Protocol
HARQ	Hybrid Automatic Repeat Request
HO	Handover
HSS	Home Subscriber Server
ICIC	Inter-Cell Interference Coordination
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ISI	Inter Symbol Interference
KPI	Key Performance Indicator
LTE	Long Term Evolution
M2M	Machine to Machine
MCS	Modulation and Coding Scheme
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MME	Mobile Management Entity
NACK	Negative Acknowledgement
NAS	Non-Access Stratum

nCP	Normal Cyclic Prefix
OFDM	Orthogonal Frequency division multiplexing
OFDMA	Orthogonal Frequency division Multiple Access
PAPR	Peak-to-Average Power Ratio
PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PCI	Physical Cell Identifier
PCRF	Policy and Charging Rule Function
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PGW	Packet Data Network Gateway
PHICH	Physical HARQ Indicator Channel
PMCH	Physical Multicast Channel
PMI	Precoding Matrix Indicator
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PSCH	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RE	Resource Element
RI	Rank Indicator
RNP	Radio Network Planning
RRC	Radio Resource Control
RRM	Radio Resource Management
RRU	Remote Radio Unit
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSS	Received Signal Strength
SB	Scheduling Block
SC-FDMA	Single Carrier FDMA
SGSN	Serving GPRS Support Node
SGW	Serving Gateway
SIB	System Information Block
SIMO	Single Input Multiple Output
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SON	Self-Optimizing Network
SRB	Signaling Radio Bearer
SRS	Sounding Reference Signal
SSCH	Secondary Synchronization Signal
TDD	Time Division Duplex
TM	Transmission Mode
TPC	Transmit Power Control

TTT	Time to Trigger
UCI	Uplink Control Information
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
USIM	Universal Subscriber Identity Module

1 Introduction

The usage of mobile data has globally increased enormously during the past few years. To respond the growing demand, governments have allocated more spectrum for mobile data usage. That has enabled the operators to build new networks on new frequency bands. Many of the new networks utilize Long Term Evolution (LTE). By October 2015 3GPP had specified 45 LTE bands. [1]

This thesis is done for Ukkoverkot, who has recently set up the world's first commercial LTE network on band 31. Band 31 uses 450 MHz frequency, which is considerably lower than any previous commercial LTE network. Due to the low propagation loss provided by low frequency, very large cells can be used. This enables offering LTE service for rural areas with fairly low amount of base stations. Also, areas that do not have any land line network and no telecom towers can be reached from further away. Examples of such areas are coast areas and archipelagos. LTE on 450 MHz frequency can possibly offer internet connectivity up to 50 km away from the transmitter.

Band 31 is also very narrow as an LTE band. Most of the allocated frequency ranges for LTE vary from 10 to 50 MHz, while band 31 can offer maximum 5 MHz bandwidth. Thus it is important to plan the network in a way that no resources are wasted.

CDMA2000 technology is widely used on 450 MHz. These networks have proven to be suitable for especially M2M usage. Many of them are predicted to migrate to LTE in near future because of higher capacity, better flexibility and cheaper equipment. [2] Depending on the vendor the CDMA radio equipment and antennas may be suitable for LTE as well, making the migration cheap and fast. However, the technologies differ in many ways and the radio planning done for CDMA may not be optimal for LTE.

1.1 Objectives and research scope

This thesis focuses on studying ways to improve 450 MHz LTE network performance after CDMA2000 to LTE migration. All the tests are done in the LTE network of Ukkoverkot and thus particular focus is given to its performance. The network has been recently migrated from CDMA2000 network by simply changing cards in the baseband units (BBU) and changing the software in the existing Remote radio units (RRU). Thus, the radio network planning (RNP) has been done for CDMA and is suboptimal for LTE. This can be seen as decreased performance at cell edges and places where there is no clear dominant cell.

450 MHz antennas are relatively big so electrical antenna tilting is challenging and rarely used. Thus changing the antenna tilts as well as antenna heights or base station (BTS) locations require a lot of labor which is expensive. The purpose of this thesis is to evaluate few promising cost effective ways to improve the service level so that the need of physical changes would be minimized.

The practical performance of three functions is evaluated by running test in live network. These functions are cyclic prefix (CP) length, uplink (UL) coordinated multipoint (CoMP) transmission and handover parameter optimization. The evaluation is done from the perspective of both, operator and customer. Additionally, a fourth method (inter cell interference coordination) is discussed but it could not be tested in practice.

The reader should be familiar with the basic mobile communication principles and terms. The basics of LTE and network optimization are presented in this thesis as background information for the discussed functions.

1.2 Structure of the thesis

This thesis provides a literature review, which is divided into two parts, chapter 2 and 3. An overview of LTE is given in chapter 2. First the architecture and network elements are introduced. After that, the most important radio technologies related to LTE are presented in sections 2.1 – 2.5. The main principals of LTE physical layer structure is and LTE basic functionalities like scheduling and link adaptation are also covered in chapter 2.

The chapter 3 covers a brief overview LTE network optimization and introduces four promising methods to improve LTE network performance. Relevant references are considered to understand the principals of these methods and to evaluate the outcome.

The performance evaluations of three out of four methods introduced in chapter 3 are presented in chapter 4. The section 4.3 covers evaluation of cyclic prefix length, section 4.4 handover parameter optimization and section 4.5 evaluation of UL CoMP performance. The results and the reliability of the measurements are further discussed in section 4.6.

The thesis is concluded in chapter 5. Additionally, proposals for future study are suggested.

2 Long term evolution

LTE is fourth generation (4G) mobile network technology by 3GPP. The first LTE standard (release 8) was finalized 2008 and the first commercial LTE networks were launched during 2009. Since then it has been developed further to respond the growing demand of mobile data services. [3]

LTE networks can be divided into two parts, the radio access network (RAN) which is called evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and the evolved packet core (EPC). LTE architecture can be seen in figure 1. This thesis will focus on the radio interface but it is essential to understand the roles of EPC network entities, especially mobile management entity (MME).

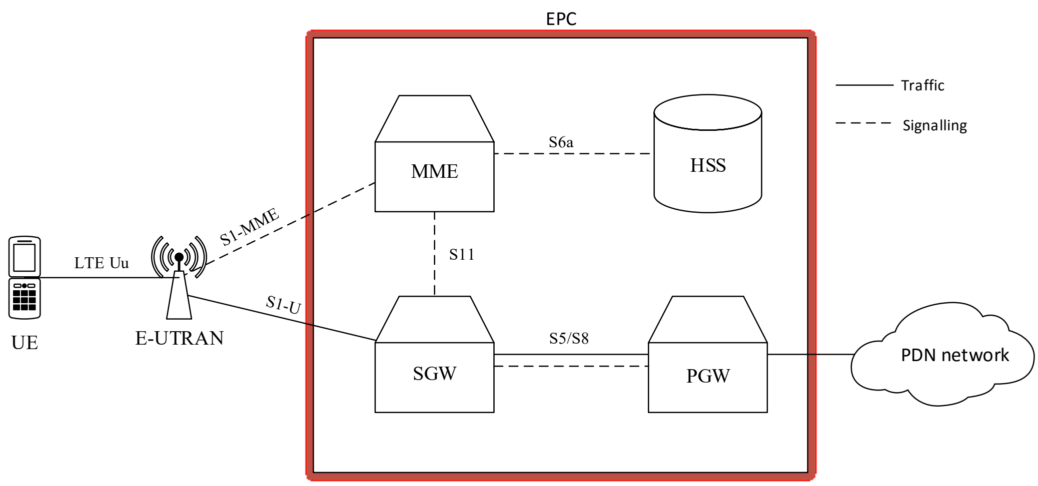

Figure 1: LTE architecture in its most simple form

The traffic in LTE network can be divided into signaling plane and user plane. Signaling plane is used for control signals and user plane for end user traffic. Signaling plane contains access stratum (AS) and non-access stratum (NAS). AS consists of radio interface related signaling between UE radio chipset and the eNBs. NAS is in turn covers all signaling between UEs and core network. [4]

Mobile management entity (MME)
MME is the most important control element in EPC. It takes part only on control plane traffic and has no role on the user plane. All NAS signaling is exchanged between MME and UEs and MME initiates further procedures accordingly if needed. MME is also responsible for authentication and security functions together with HSS. MME and HSS are connected with S6a interface. [5] It is also MME’s task to page subscribers that are in idle state. This is done according to tracking area list, which is a list that tells the area where each UE is located. UEs report their locations to MME periodically in idle state and immediately after tracking area change. The location information is transferred in tracking area update messages. As MME keeps track of every subscriber, it chooses the best fitting PGW and SGW for each one. [6] Another task of MME is handover management in cases of inter-RAT and inter-MME handovers or if X2 interfaces between eNBs are not configured.

Home subscriber server (HSS)
HSS is a central database of all permanent subscriber data and subscriber locations in MME level. Subscriber profiles including individual identifiers and possibly permissions to use certain services are stored on it. The encryption keys for each SIM-card are also stored in HSS. HSS is connected to every MME in the network.

Serving gateway (SGW)
SGW is the gateway for user-plane traffic between E-UTRAN and IP networks. It has only minor role on the control plane traffic. ENBs are directly connected to SGW for user plane traffic and it works as a packet router on IP transport layer. It is connected to PGW and MME which provide the control information about packet routing. SGW acts as a mobility anchor for UEs in case of inter-eNB handover. It remains the same while the path for user plane and signaling will be switched to another S1 interface. Mobility anchoring is defined also for inter-RAT handovers, where it works as the terminating point of S4 interface. When the UEs enter idle state, the data path through SGW will be terminated. If the UE is in idle state, SGW buffers the user plane packets and triggers paging of the UE. After receiving a successful paging response, new data path will be established and the packets will be sent to the UE. SGW monitors the user plane traffic in GTP-tunnels and the information may be used for accounting and charging. It is also used as a network element that provides connectivity and implementations for lawful interception.

Packet data network gateway (PGW)
PGW is the network element providing access from EPC to external packet data networks. The main task of PGW is to create, maintain and delete GTP-tunnels to SGW, or SGSN in case of inter-RAT scenario. It allocates dynamic IP addresses for users and routes the user plane traffic. It can also provide functions for lawful interception, charging and QoS/policy control. In case of policy control and charging, PGW can be connected to a Policy and Charging Rule Function (PCRF) that provides necessary information to treat the traffic in terms of throughput, priority or any other parameter defined in user's profile.

User Equipment (UE)
UE is a mobile device used by the end user. Typically LTE UEs are hand held devices such as mobile phones, tablets or USB-modems. However, 450 MHz band requires relatively big antennas and thus it is usually not supported by the typical LTE UEs. [7] Instead, a typical LTE UE supporting 450 MHz band is a mobile router designed for permanent or semi-permanent installations for vehicles, fixed wireless connections or M2M-solutions. UE contains the Universal Subscriber Identity Module (USIM), which is used to identify and authenticate the subscriber [7].

E-UTRAN
E-UTRAN is the radio access network used in LTE. It based on orthogonal frequency division multiple access (OFDMA) in downlink (DL) and single carrier frequency division multiple access (SC-FDMA) in uplink (UL). [7]

2.1 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA is a multiple access version of orthogonal frequency division multiplexing (OFDM) [8]. OFDM systems require a lot processing power and they have been rarely used because of the expensive design of such systems by using analog circuits. Nowadays the digital signal processing has become inexpensive which enables the use of OFDM systems in wide scale. In OFDM systems, data is modulated to small adjacent subcarriers within the available bandwidth using inverse Fast Fourier Transform (iFFT). These subcarriers are orthogonal to each other in order to prevent interference with each other. Because of the orthogonality the data is perfectly unmodulated and no guard band is required between the subcarriers. [6] However, a guard period in time domain between OFDM symbols is required in order to prevent inter symbol interference (ISI). This guard period is called cyclic prefix. Cyclic prefix is considered more closely in section 3.3.

Multiple access in OFDM is achieved by allocating time and frequency resources to multiple user signals. Figure 2 illustrates the resource allocation for three users in time and frequency domain. The user signal separation is done in time domain by OFDM symbols and in frequency domain by subcarriers. In LTE the allocation of frequency domain is not done at the level of subcarriers but at the level of physical resource block (PRB). One resource block consists of 12 subcarriers. The process of allocating resources to each user is done at eNBs and is called scheduling. Details of scheduling can be found at the section 2.9.

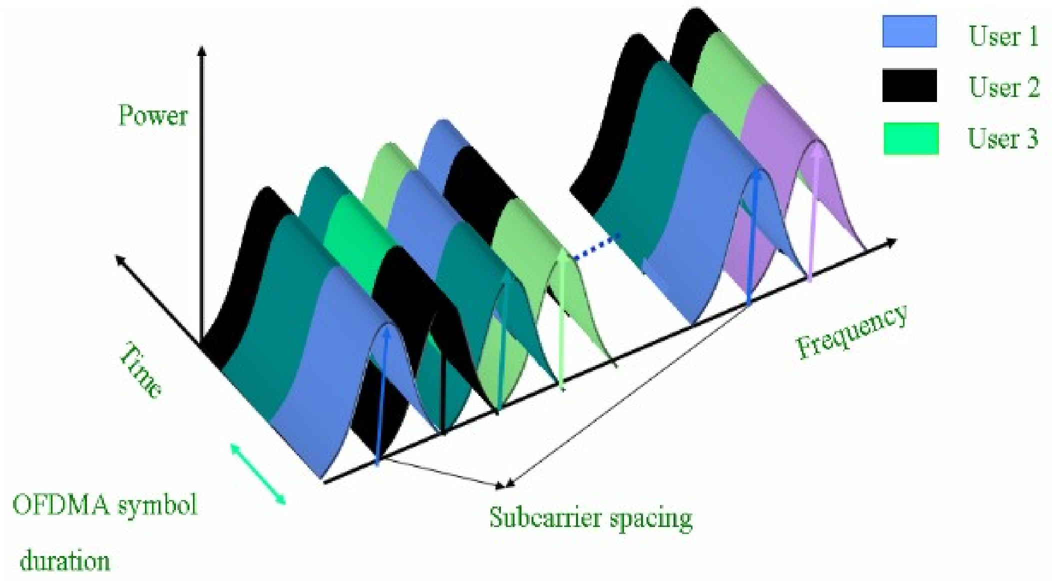

Figure 2: OFDMA signal [8]

Claimed advantages and recognized disadvantages of OFDMA over CDMA systems are considered in table 1.

Table 1: Advantages and disadvantages of OFDMA systems

OFDMA Advantages	**OFDMA Disadvantages**
It is robust against frequency selective fading because fading holes are bigger than subcarrier bandwidth which leads to flat fading of individual carriers	It is sensitive to phase noise and frequency offsets as they degrade the orthogonality between carriers
High spectral efficiency using MIMO and flexible usage of different bandwidths enable higher throughputs than CDMA systems	The robustness against frequency selective fading degrades if only few carriers are assigned to each user
Using the available bandwidth is more flexible than in CDMA	Co-channel interference from neighboring cells is more complicated to consider than in CDMA
OFDMA is easily scalable to different requirements	High PAPR
The receiver design is simple	

2.2 Single Carrier FDMA (SC-FDMA)

One drawback of OFDMA systems is high dynamic range after the frequency signal is transformed to time domain. This high peak-to-average power ratio (PAPR) leads to high power consumption of a transmitter and short battery life. It is not a problem for DL as eNBs have fixed power supply but especially disadvantageous for mobile devices running on battery. Thus LTE uses another transmission scheme for UL, SC-FDMA. Additionally, OFDMA amplifiers are not as cost-effective as SC-FDMA amplifiers. [6]

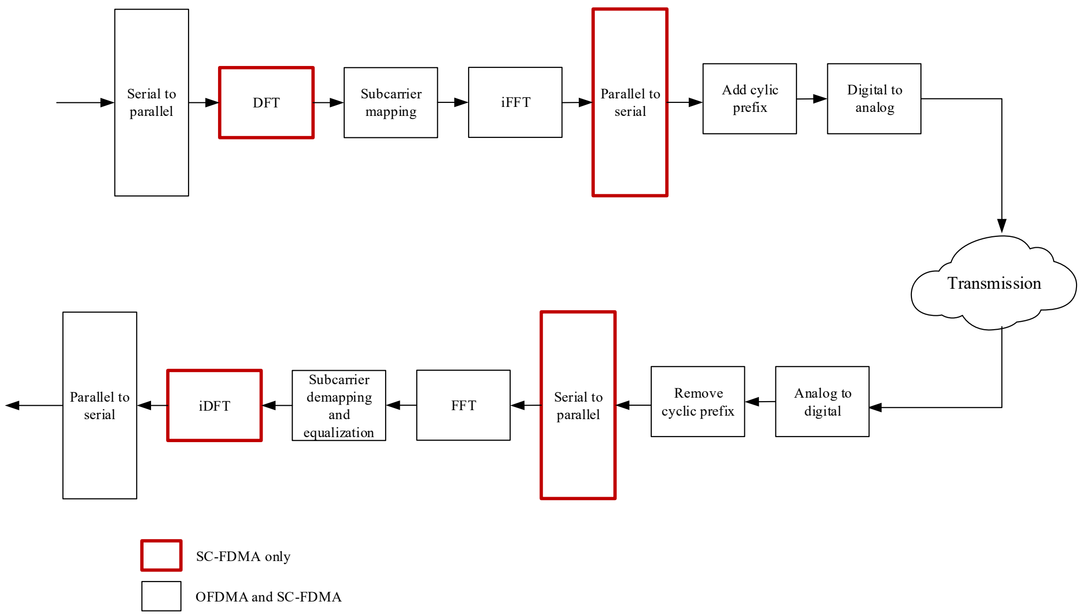

Figure 3: OFDMA and SC-FDMA receiver and transmitter difference

SC-FDMA is close to OFDMA but it can provide better PAPR. The main difference between OFDMA and SC-FDMA is DFT in the transmitter and iDFT in the receiver, as shown in the figure 3. Because of this difference, the data to be transmitted can be modulated to a time domain signal instead of modulating the subcarriers of a frequency domain signal. The output of DFT can be interpreted as the spectrum of the previously modulated symbols with the characteristics of consecutive modulated subcarriers. Thus it does not have dispersed spectral distribution. [6]

2.3 TDD and FDD

LTE systems are specified and used with two different duplex modes, time division duplex (TDD) and frequency division duplex (FDD). Currently most of the LTE licenses granted and networks made are based on FDD but TDD has become more popular lately [9]. The difference between these two is the way how downlink traffic is separated from uplink. FDD works in full duplex mode, the uplink and downlink have their own channels and there is a guard band in between. As the channels are not shared, uplink and downlink can happen in the same time. This is not possible in TDD systems. In TDD the same channel is shared with uplink and downlink traffic and thus it works in half duplex mode, meaning traffic can pass only one way at a time. TDD systems have many advantages like more efficient spectrum usage and ability to adjust the uplink-downlink traffic ratio. TDD is not considered more closely as the scope of this thesis only covers FDD systems. [10]

The LTE FDD band 31 is used to do all the tests in this thesis. The bandwidth of both, uplink and downlink channel, are nominally 5 MHz and there is a 10 MHz duplex gap in between. The uplink spectrum is 452,5 – 457,5 MHz and the downlink spectrum is 462,5 – 467,5 MHz. However, complete utilization of the band is currently not possible because the band is partly allocated for other uses in Finland [11].

2.4 MIMO transmission

Multiple input multiple output (MIMO) antenna setups are one of the key features in LTE to significantly increase the spectral efficiency and throughput accordingly. Instead of traditionally using transmit diversity, spatial multiplexing is used. Spatial multiplexing enables the utilization of multiple signal paths to carry additional traffic. LTE supports 2x2 and 4x4 MIMO for downlink since release 8, but uplink MIMO was not defined until release 10. [12] The use of MIMO, especially with complex antenna setups, requires good signal to noise and interference ratios (SINR). The parallel data streams are transmitted simultaneously and the transmission power is divided for each signal stream. Thus the received signal power is lower than with SIMO transmission. That, in addition to the fact that data streams are not doubled, makes the MIMO transmission error prone. The UEs report their signal qualities to eNBs that decide whether to use MIMO or SIMO transmission. Under the conditions where MIMO transmission is possible, the maximum throughput is nearly doubled in case of 2x2 MIMO and quadrupled in case of 4x4 MIMO compared to SIMO transmission. [13]

Due to the transmit and receive diversity 2x2 MIMO provides about additional 6-7 dB to the link budget compared to SISO. 3 dB from the doubled transmit power because of another amplifier is used, 3 dB from the two antenna reception and 0-1 dB from use of multiple signal paths. Thus, MIMO systems can provide significant improvements although spatial multiplexing was not used. [14]

2.5 Link adaptation in LTE

The link conditions in a radio network always greatly vary depending on the environment. Four methods are used in LTE to cope the varying conditions; adaptive modulation and coding (AMC), adaptive frequency selective scheduling, hybrid automatic repeat request (HARQ) and transmit power control (TPC). AMC controls the modulation scheme and forward error correction (FEC) coding rate according to block error rate (BLER). The modulation scheme can be QPSK, 16QAM or 64QAM. FEC is used to create redundancy to the data so that the message does not need to be retransmitted even though minor transmission error would occur. If the signal conditions are poor, more robust modulation scheme and coding rate must be used. Spectral efficiency greatly varies depending on these parameters.

Adaptive frequency selective scheduling is a way to handle frequency selective fading. UEs are sending SRS and DMRS to show possible frequency selective fading on the radio link. The scheduling is then done in a way that subcarriers not suffering from the fading are preferred. The third method to cope varying conditions is HARQ. It is responsible for transmission error detection, correction and retransmission. It uses FEC coding for possible error correction and if the data cannot be retrieved it requests for retransmission. The fourth method, TPC, is designed for assessing UE transmit power in order to address the near far effect. Near far effect means a situation where one UE is close to eNB and another one is further away. If they would transmit with the same power, the UE closer to the eNB would overwhelm the UE further away. TPC works in a way that UEs initially transmit with certain power level and the eNB tells them to either higher or lower their transmit power. The goal is to reach a situation where the signal power level at the receiver is same from every UE under that cell.

2.6 Mobility in LTE

Mobility is very important matter in mobile networks. Different technologies may use somewhat different techniques to achieve mobility but the basic idea is the same. End user should not be able to notice any difference in the service when moving from one base station to another. The big difference between CDMA and LTE is that LTE uses hard handover also known as break-before-connect and CDMA uses soft handover (connect-before-break).

Soft handover works in a way that the UE keeps always at least one radio link active. The serving cell will not be abandoned before a connection to the new cell is established. Thus it is possible for an UE to be connected to more than one cell simultaneously. Hard handovers work in the way that the serving cell is always abandoned before a connection to the new cell is established. Soft handover requires more complicated signaling and system architecture than hard handover. [15] On the other hand the soft handover benefits over hard handover are less delay, less overhead and elimination of ping pong effect. From network planning perspective, these two must be considered in a different way. As ping pong effect is eliminated in soft handovers, planning the network to avoid areas where it might happen is not as important as in case of hard handovers. [16]

2.6.1 Handovers in LTE

By the specifications, there are two types of handovers in LTE. They are called S1 and X2 handover procedures. X2-handover procedure is normally used for inter-eNB handovers. When there is no X2- interface available between two eNBs, an S1-handover is performed. S1-handovers are also used for communication to non-3GPP network technologies. Both handover procedures consist of three phase; preparation, execution and completion. On preparation phase UEs send periodical measurement reports about the RSRP and RSRQ levels of the serving cell and the neighboring cells to the serving eNBs and the eNBs decide whether the handover procedure should be started or not. Based on the reports, the eNB also decides the target cell. On the preparation phase, the target eNB prepares a buffer for the UE after receiving the control message requesting to prepare for handover. [15]

After the preparation has been completed, the source eNB sends a handover command to the UE. After receiving the command, UE disconnects from the source eNB and requests a new connection with the target eNB. During this procedure, the source eNB forwards all the packets of that specific UE to the target eNB and they are queued in the buffer prepared in the preparation phase. Once the UE has been connected to the target eNB, all the queued packets are transmitted to the UE. The execution phase ends after the UE informs the target eNB that the handover was completed by a handover complete message. The last phase is the completion phase. The purpose of it is to release all the resources used by the UE at source eNB. Also, the upper layer is informed to route all the packets to the target eNB. To make it happen, the target eNB tells the source eNB to release all the resources for the specific UE and MME to switch the UE path to the target eNB. [15]

3GPP defines an event called A3 as the triggering event when neighboring cell becomes stronger than the serving cell plus the serving cell offset. There are four parameters affecting the triggering of A3 event. First one is *A3offset*, which is a parameter used to make the serving cell better than it is compared to the other measured cells. The second one is *A3hysteresis*, whose purpose is to make the measured neighboring cell look worse than it actually is. The third parameter is *timetotriggerA3* (TTT). TTT is a time period used to prevent unwanted ping pong effect. The event A3 is triggered if the equation 1 is valid for *timetotriggera3*. *Cellindividualoffset* is an individually set value for each neighboring cell in order to make them more attractive. Optimization of these values is further discussed in section 3.4.

$$RSRP(target\ cell) > RSRP(Serving\ cell) + a3offset + a3hysteresis - individualoffset \quad (1)$$

2.7 LTE frame structure

In LTE downlink structure, a radio frame is the largest unit in time domain. Both TDD and FDD introduce frames that last 10 ms. However, the frame types are different for each duplex mode. Type 1 for FDD and type 2 for TDD. One frame can be divided into ten subframes, one millisecond each, and one subframe can be further divided into two slots. Hence one radio frame consists of 20 slots in total. This is illustrated in the figure 4.

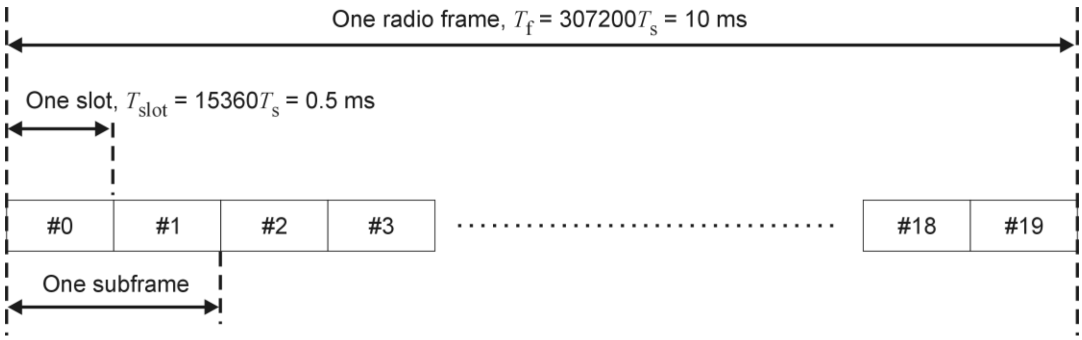

Figure 4: FDD radio frame [17]

Radio frame being the largest unit of in LTE structure in time domain, an OFDM symbol is the smallest. One subframe consists of 14 OFDM symbols when normal cyclic prefix is used and 12 when cyclic prefix is extended. The complete type 1 frame structure with normal cyclic prefix can be seen in figure 5. The first OFDM symbols are used for PDCCH. PDCCH area is used also for PCFICH and PHICH. PCFICH tells the number of OFDM symbols used for PDCCH in the current subframe. The amount can vary between 1 and 3 symbols depending on the amount of control information. This means that the size of PDSCH also varies between 11 and 13 symbols for normal CP and 9-11 symbols for ECP. In the middle of the sixth and the seventh OFDM symbols in the first and the eleventh subframe are six resource blocks wide synchronization signals, secondary synchronization signal in the 6th and primary synchronization signal in the 7th symbol. They are used for initial cell search and cell synchronization. [6] If 1,4 MHz bandwidth is used, only 6 resource blocks are available and the synchronization signals occupy the whole bandwidth.

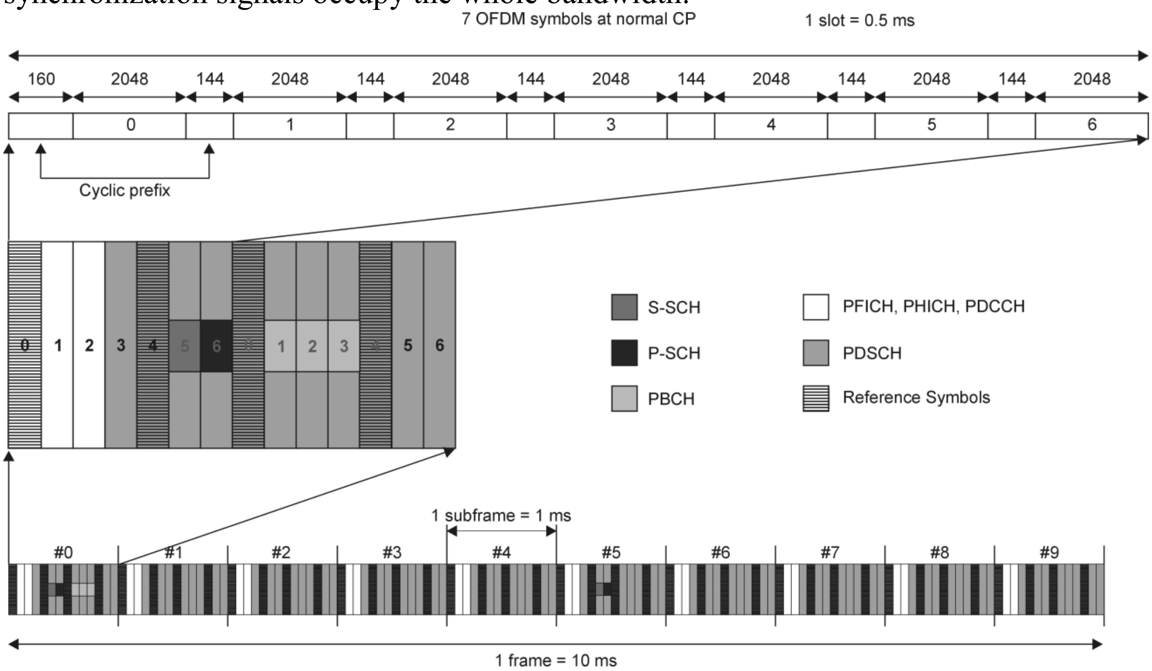

Figure 5: Type 1 LTE frame with normal cyclic prefix [6]

In section 2.1 resource blocks were introduced as a unit of resource allocation. One resource block consists of 12 consecutive subcarriers in frequency domain and one slot in time domain. This means a resource block is a size of 12*7=84 resource elements (RE) for normal cyclic prefix and 12*6=72 REs for extended cyclic prefix. This is illustrated in figure 6.

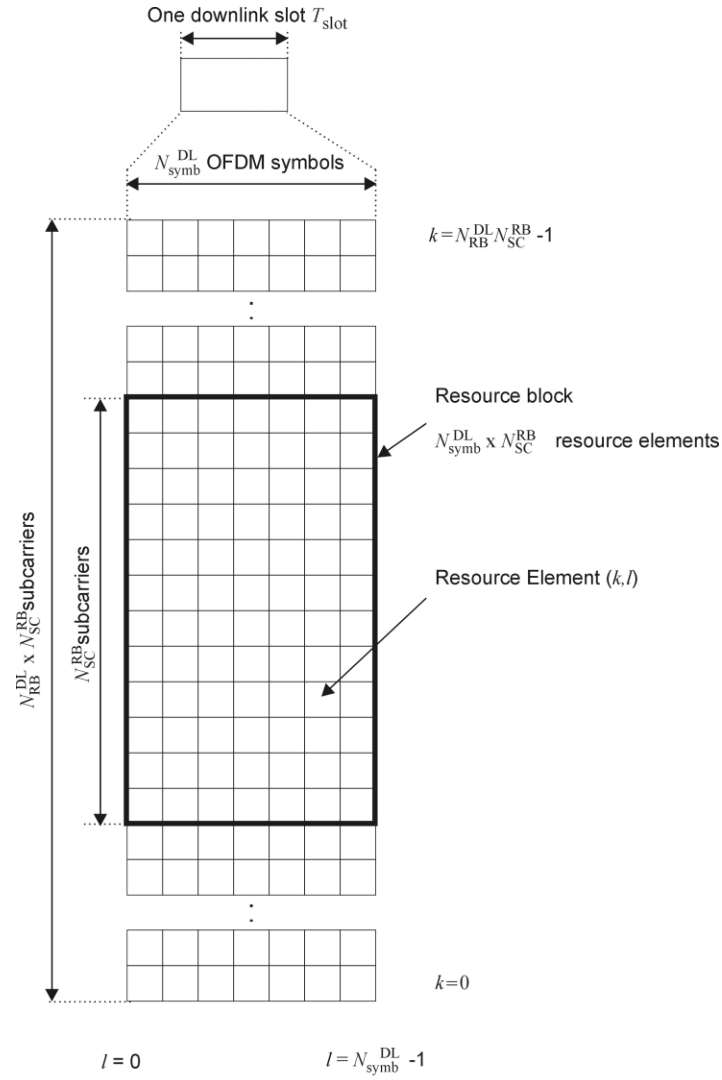

Figure 6: Resource blocks in 3 MHz channel [6]

LTE uplink frame structure is very similar to downlink frame. It lasts 10 ms and it is divided into ten subframes that are again divided into two slots. An uplink resource block consists of 12 subcarriers and 6 or 7 SC-FDMA symbols depending on the cyclic prefix format. The main difference is the way how resources are allocated between control channel and shared channel. Downlink frame has dedicated OFDM symbols for PDCCH and in uplink the PUCCH is carried at the lower and upper edges of the system bandwidth. An uplink frame does not have any synchronization signals as all UEs are time aligned at eNB. Uplink also has resources allocated for PRACH. PRACH is always six resource blocks wide in frequency domain and lasts for one subframe in time domain. The six resource blocks and the subframes carrying PRACH are variable and they are signaled in SIB2 messages.

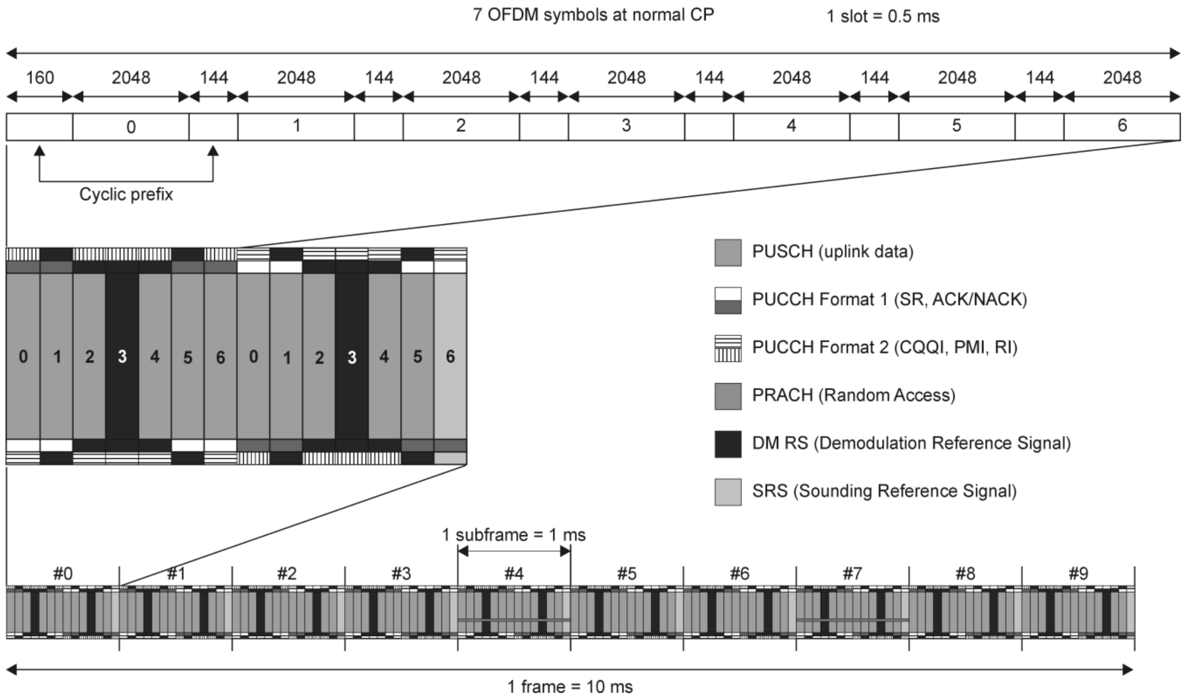

Figure 7: uplink frame structure [6]

2.8 Physical channels and signals

Physical channels carry data between eNBs and UEs. They are mapped on physical resources based on physical cell identifier (PCI) value, which means they are mapped differently in neighboring cells. [17] The channels used in LTE are listed below separately for uplink and downlink.

2.8.1 Downlink

Physical Downlink Shared Channel (PDSCH)
PDSCH is the channel to carry all the downlink user plane data from eNB to UE. It also carries in-band signaling. In-band signaling includes paging, system broadcast information messages in system information blocks (SIB) and UE-specific radio resource control (RRC) messages. Different transmission modes (TMs), such as MIMO apply on PDSCH only.

Physical Downlink Control Channel (PDCCH)
PDCCH is mapped to the first 1-3 OFDM symbols of every subframe. It is used to carry downlink control information (DCI) needed for scheduling and UL power control. There are ten DCI formats. More information about them can be found in 3GPP specification TS 36.211. [17]

Physical HARQ Indicator Channel (PHICH)
PHICH carries hybrid automatic repeat request (HARQ) feedback from eNB to UE. This means sending ACKs and NACKs related to the previous UL transmission. The feedback is only one bit, ACK or NACK, and it is repeated three times. Each triple is then orthogonally walsch spread to four symbols and robustly modulated with BPSK.

Physical Control Format Indicator Channel (PCFICH)
PCFICH is always carried in the first OFDM symbol in every subframe. Its only purpose is to determine how many OFDM symbols are used for PDCCH. The values can vary from 1 to 4 but with the current LTE releases maximum 3 OFDM symbols can be used for PDCCH. Value 4 is reserved for possible future use cases. PCFICH data is very well protected as it is essential for UE to receive this data in order to work.

Physical Broadcast Channel (PBCH)
PBCH is used to carry master information blocks (MIBs) logically every 40ms. MIBs are protected by derive four equal sized blocks that all carry all the MIB information. These blocks are transmitted in every radio frame meaning that MIBs are decodable every 10ms. PBCH is always located in the first subframe and is always 6 resource blocks wide in the middle of the bandwidth.

Physical Multicast Channel (PMCH)
PMCH is a not used in current LTE releases but must be already defined for backward-compatible physical layer.

Synchronization signals (PSCH and SSCH)
Primary synchronization signal (PSCH) is used for cell search and synchronization. PSCH signals are Zadoff-Chu sequences and there are three types PSCH signals. The signal type tells the physical layer identity. PSCH is located in the first 6^{th} OFDM symbol of the first and fifth subframe. This means UE can synchronize once every 5ms. Contrary to the primary, secondary synchronization signal (SSCH) already carries data with it. After receiving SSCH, UE will know the duplex mode, CP length and physical layer cell identity (PCI) group. From PCI group and physical layer identity, it can determine the cell it is interacting with. After the UE knows the PCI, it also knows the location of reference signals of the specific eNB. SSCH is located in the next subframe after PSCH.

Downlink reference signals
Unlike most of the mentioned channels, downlink reference signals exist only on physical layer. They are not mapped to any higher level logical channel and they do not carry any data. They are used only for estimating the downlink channel. When UE tries to find out the downlink power, it measures the reference signals. Downlink reference signals are carried in specific resource elements and their locations are determined by the antenna configuration. Figure 8 illustrates the mapping of downlink reference signals to specific resource elements in case of SIMO and 2x2 MIMO.

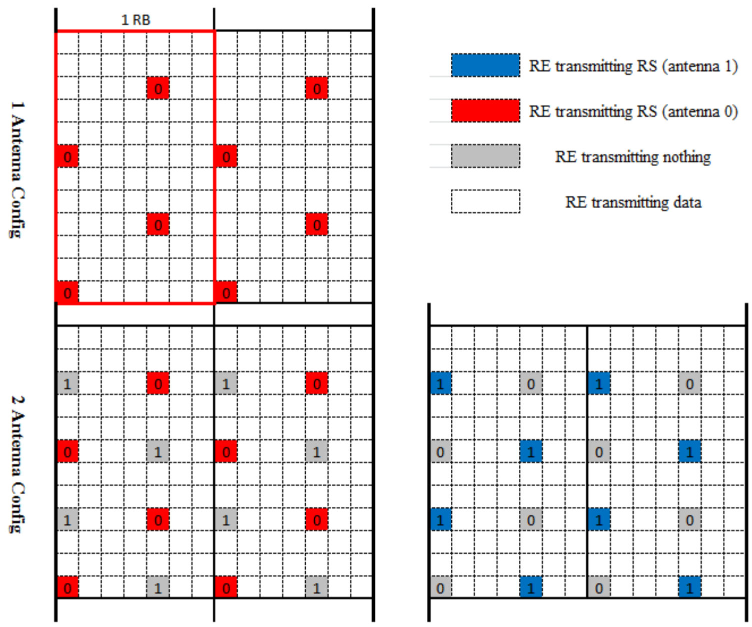

Figure 8: Reference signal mapping

2.8.2 Uplink

Physical Uplink Shared Channel (PUSCH)
PUSCH is the physical channel carrying all user plane data from UE to eNB. Physical layer control information and uplink higher layer control plane data, also called in-band signaling, are transmitted in PUSCH as well. The PUSCH resources are allocated to the UE by eNB in UL grants transmitted on PDCCH.

Physical Uplink Control Channel (PUCCH)
Uplink control information (UCI) is transmitted on PUCCH. To decrease interference and gain frequency diversity, PUCCH resources are allocated at the both edges of available bandwidth. UCI includes HARQ feedback, service request (SR), channel quality indicator (CQI), rank indicator (RI) and precoding matrix indicator (PMI).

Physical Random Access Channel (PRACH)
PRACH is the channel UE uses to inform eNB about its existence for the first time. The frequency and time location of PRACH resource blocks (RB) are signaled in SIB2 message. PRACH transmission is not synchronized as UL synchronization is not established yet.

Demodulation Reference Signal (DMRS)
DMRS is located in the middle of each slot and they do not carry any information. DMRS is used for channel estimation of PUSCH and PUCCH.

Sounding Reference Signal (SRS)
SRS is only transmitted after a request from eNB. It is used to estimate the channel quality for each UE. An eNB can request a UE to send SRS on the whole bandwidth or on some specific part of it.

2.9 Scheduling

Scheduler is the entity that decides how the radio resources will be allocated between UEs. Thus, the scheduling algorithms have great effect on network performance, especially from end user perspective. There are guidelines for different scheduling schemes, but the implementation is not specified. That opens up possibilities for vendors to differentiate. As the scheduler implementation is vendor specific and a way to gain competitive advantage, the detailed designs are often kept secret.

The scheduler decides the resource allocation based on the channel quality indicators (CQI) reported by UE, buffer status and UE quality of service (QoS) rules. Scheduling algorithms can be divided into categories depending which factor is pursued. Opportunistic algorithms like proportional fair and proportional fair exponential aim to maximize the overall system throughput. Fair algorithms aim for fairness and equity between users. Round Robin and Max-Min Fair are examples of fair algorithms. Throughput based algorithms try to maximize the data rate. Examples from this category are EXP Rule and Max-Weight algorithms. Other categories are QoS based, delay base and multiclass algorithms. The radio conditions and diversity of data flows affect the performance of the algorithms. Proportional fair algorithm or its variant is often used in mobile networks. [18]

The smallest schedulable unit in time dimension is one subframe, also called transmission time interval (TTI). As one resource block last 0,5 TTIs, two adjacent resource blocks, also called scheduling blocks (SB) are the smallest possible schedulable units. [18] Many studies and vendor specific features have tried to find out the most optimal ways to allocate scheduling blocks in multiuser scenarios. [19] [20]

3 LTE network optimization

Planning and optimizing a radio network is essential for its performance. This thesis only considers optimization methods post deployment where the base station locations and cell azimuths of current base stations are fixed. Also, network enhancements that only apply locally, like new base stations, modifications of antenna tilts or power levels are out of the scope of this thesis. Instead, ways that could improve the network performance in wider scale are the main focus. Such ways are feature configuration and network wide parameter adjustments. Particular attention is given to situation after CDMA2000 to LTE migration where the network planning is done for CDMA. As told in chapter 2.1, handling the interference from neighboring cells is harder in LTE than in CDMA. That in addition to use of hard handovers instead of soft handovers puts more weight on minimizing the co-channel interference from neighboring cells when planning an LTE network.

In this section, the basic guidelines for LTE planning are discussed and few methods to increase the performance are introduced. These methods are coordinated multipoint transmission (CoMP), inter cell interference coordination (ICIC), cyclic prefix length and adjusting handover parameters. These methods were chosen as they all potentially increase the performance under imperfect conditions.

When doing any kind of network optimization or any kind of optimization at all, deep knowledge about the current situation of the network is required. Thus drive testing and KPI metering is very important. Also, there must always be some kind of a goal what to pursue before taking any actions. All the actions should also be planned in a way that they can be measured and the result evaluated. [21]

Determining the user profiles

Most of the LTE network parameters and functions are always some kinds of tradeoffs. Whether it is between fairness and throughput or something else totally depends on the function. Thus knowing what is required by the end users is essential. Some solutions may require best possible coverage and very low capacity while others may require maximum throughput or maximal reliability in one place. If the user profiles are identified properly, the optimization process will most likely be more successful as it is known what to pursue and the results can be measured properly. [21]

Capacity/coverage limited cell

The performance of a network is always limited to a certain point. There are two main categories of the limitations. The first one is capacity, which means that there are not enough resources in a cell to serve all users on the required level. In other words the cell is overloaded and the network performance is limited. The second limitation is coverage, which means that there are enough resources to satisfy all users but the network performance is limited by cell coverage. Both cases require different approaches in order to get the best out of the situation. If the network performance is capacity limited, means to offload the most used cells should be pursued. It can be solved by building new eNBs but it is an expensive approach and not always even possible.

The coverage limitation can be further divided into two parts; interference limited or propagation limited. Practically almost all mobile networks are planned to be interference limited. Due to the fact that downlink signal can be almost always sent with much higher power than the uplink signal, uplink is usually limiting the cell coverage before downlink would. [22]

Interference
The high spectral efficiency requirements in today's mobile networks lead to more efficient reuse scenarios. Lower reuse factor always leads to higher levels of interference. Especially in LTE, which mostly uses reuse factor one, the interference scenarios may become very severe. [23] Interference is one of the main factors negatively affecting network quality in mobile networks. There are different types of interference in LTE coming from different sources. [24] Interference power can be divided into two parts; interference from own cell and interference from other cells. It can be also from an external source, but that is almost impossible to predict or affect. Even though LTE is often assumed orthogonal for simplicity, in reality the following non-idealities may cause own-signal interference [14]:

- Inter-symbol interference (ISI), which is caused by multipath propagation
- Inter-carrier interference caused by Doppler spread in high speeds
- Transmit signal waveform distortion caused by nonlinear transmitters

The eNB locations, antenna tilts and transmit powers should be planned in a way to prevent excessive interference. Both own cell and inter-cell interference can also be mitigated by optimizing network parameters such as cyclic prefix length or adding new features like ICIC and CoMP. These methods are further discussed in sections 3.2 and 3.1.

The effects of interference from end-user perspective are lower throughput and reduced coverage. Interference desensitizes the receiver and increases the noise floor, causing worse SINR and decreased receiver sensitivity. Worse SINR prevents from using higher modulation and coding schemes (MCS), which leads to lower transport block size and lower throughput. [25] Decreased receiver sensitivity diminishes the coverage area. Severe interference scenarios may also cause handover failures. [24]

Regulatory limitations
When an LTE network is planned and optimized, it is very important to take into account the limitations given by local regulator or site owner. The regulations have major difference depending on the country and location. For example signal power levels may be limited at specific areas as the spectrum may be in different use, the maximum transmit power may be given by the authority or the certain PCI codes must not be used in certain areas.

Border areas are particularly challenging as the same frequency band is most likely used on the other side of the border. This may cause severe interference scenarios without proper coordination and regulation between the stakeholders. The lower the frequency, the more extensive the propagation is, which means that guard zones at the borders reaches further away from the border.

Tilts, transmit powers and BTS locations
Changing the antenna tilts, antenna heights, transmit power or even base station locations are very efficient ways to adjust the network performance by influencing propagation scenarios. These kinds of changes are always local and the same changes cannot be applied on larger set of eNBs. Such changes also always need drive test data at the target area. [21] They also always require a lot of manual labor; especially on low

frequencies like 450 MHz because electrical tilting is rarely used due to large antenna sizes. Thus these kinds of network modifications are not considered in this thesis.

Fairness

In many cases changing a parameter value or a function is a tradeoff between cell throughput and fairness. This is a policy decision of the operator. Fairness means the variation of UE performance depending on the location in specific cell. Cell-edge users always have worse signal condition than users close to base stations and in the middle of the sector. Thus the UEs at cell edge always perform worse. The closer all users are to the average performance level, the fairer the network is considered. Increasing fairness means investing in improvements under the bad signal conditions, usually with the cost performance under good conditions. This often decreases the overall capacity of the system.

3.1 Coordinated multipoint (CoMP) transmission

Coordinated multipoint is one of the most promising concepts to improve cell edge user throughput [26]. This applies to the places where the cell performance is interference limited. The idea of coordinated multipoint (CoMP) is that one UE can simultaneously communicate with several cells. The cells then communicate with each other to dynamically coordinate their transmission and reception. This way the network can be utilized more optimal way, interference can be minimized and the reception quality can be increased to enhance the users' service level. There are different techniques of CoMP but the main goal is to reduce interference and possibly turn the interfering signal from neighbor cells into a useful signal. The more the neighboring cell coverage is overlapping the more benefit can be achieved by CoMP. There are still many implementation challenges related to CoMP, which slow down the deployment. Many studies have been made to overcome these challenges. If the challenges will be solved in an effective way, it might significantly change the way of radio network planning and optimization.

CoMP techniques can be divided into two major categories. One is joint processing, also called joint transmission, which means coordination of multiple cells that are all simultaneously transmitting or receiving to or from one UE. In all CoMP schemes, the control channels like PDCCH is sent from only eNB. If joint processing is used, the data on PDSCH is sent from multiple eNBs. Another category is coordinated scheduling. In coordinated scheduling, a UE is communicating with only one cell at a time, but the scheduling of neighboring cells are done in a way that no other transmission happens at the same time if possible. All CoMP techniques come with the cost of more demanding backhaul, increased synchronization requirements, more overhead and higher complexity [26]. Joint processing requires a lot higher capacity of the backhaul than coordinated scheduling as all the user data must be transferred to and from every eNB that is transmitting or receiving data to or from the UE. In coordinated scheduling, only the channel and scheduling information must be shared between the eNBs. If the coordination happens only between the cells of one eNB, it is called intra-site CoMP and specific X2 interface is not needed. The term inter-site CoMP is used if cells of multiple eNBs cooperate. Figure 9 illustrates inter- and intra-site CoMP in a simulation where each cell is presented as a hexagon.

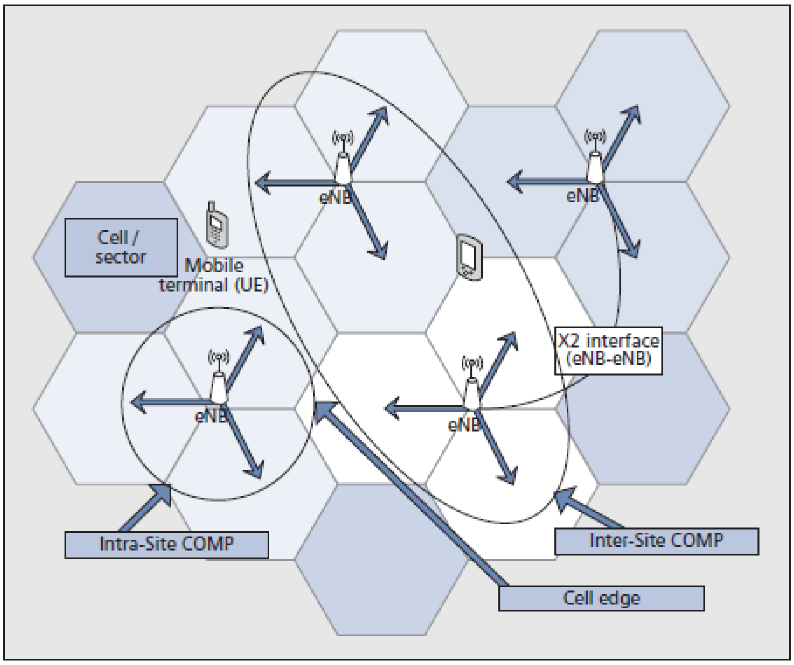

Figure 9: Inter-site and intra-site CoMP [26]

3.1.1 Uplink CoMP

Studies have shown that CoMP may significantly increase uplink throughput, especially at cell the edges [27]. It also increases the fairness of the network. A study by Marsch simulates real life aspects like imperfect channel knowledge and restricted backhaul network in order to achieve more realistic vision on the effects of CoMP. It suggests that intra-site cooperation alone can increase the throughput by 63% under imperfect channel state information at the receiver (CSIR). Also fairness is significantly increased which can be seen as the increase of 10^{th} percentile throughput by 72%. Using clustering and inter-site CoMP without proper backhaul gives only very marginal difference compared to intra-site CoMP. If required backhaul is built and inter-site cooperation is used with two site cooperation, additional 14% increase can be achieved under imperfect CSIR and additional 79% increase of the 10^{th} percentile throughput. The figure 28 shows the simulated uplink throughput gains of different CoMP implementation under perfect and imperfect CSIR. [28]

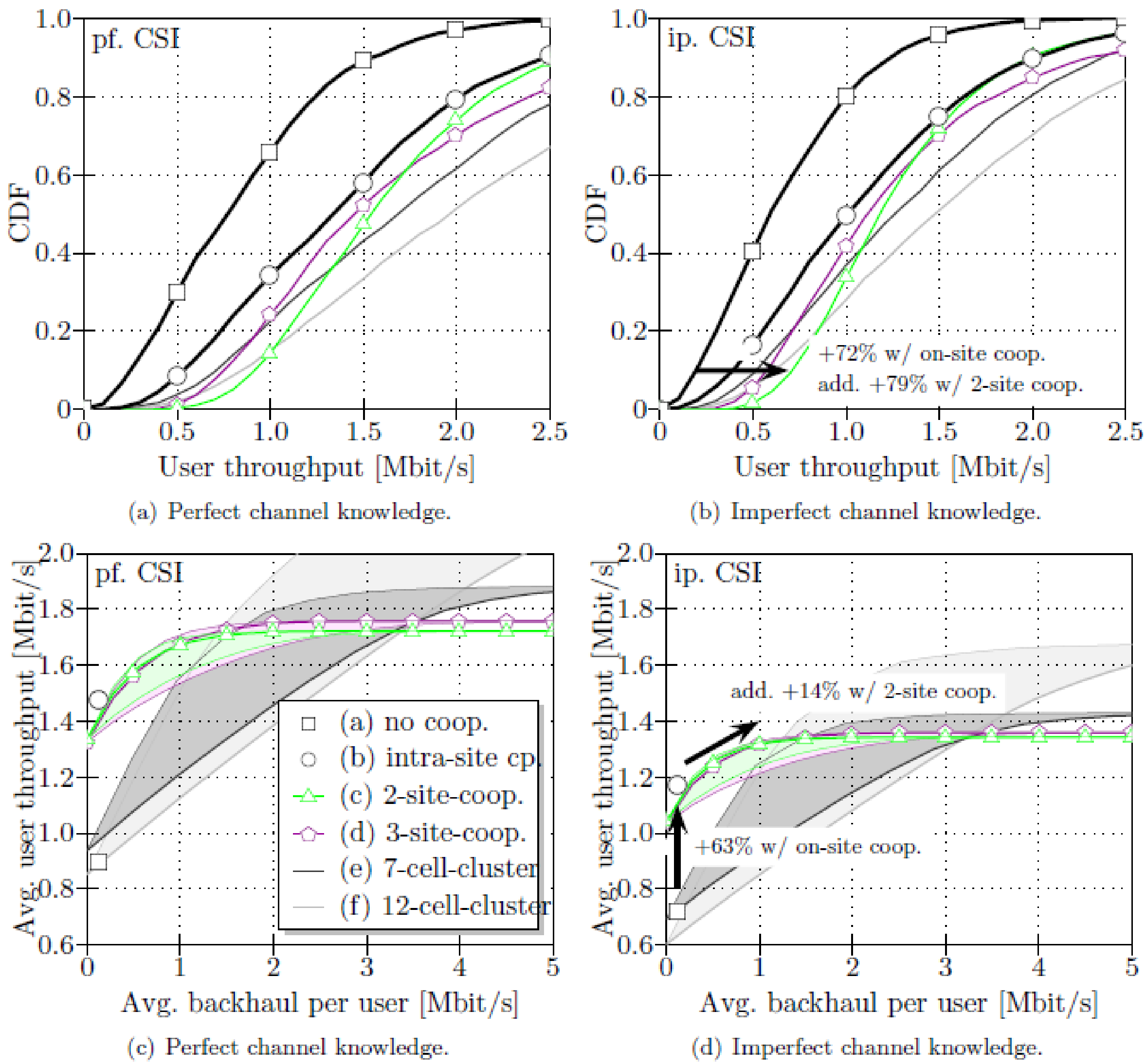

Figure 10: User throughput distribution and average user throughput under imperfect CSI [28]

The simulated network was 19 eNBs large and each eNB was 500m away from each other. The simulated frequency was 2,6 GHz and system bandwidth 5 MHz.

UL CoMP has also been studied in practice. EASY-C was a project by several operators, universities and standardization bodies to research future technologies for wireless access. Two testbeds with varying setups were built to research CoMP in practice. Two uplink coordination methods were tested, uplink interference prediction and uplink joint detection. Interference detection works roughly the same way as earlier mentioned coordinated scheduling. Scheduling and channel information is exchanged between eNBs to predict signal to noise and interference ratio (SINR). Link adaptation is performed according to the interference prediction. Using this method intra-site only showed little improvements in spectral efficiency and throughput. 25% gain in spectral efficiency and 29% gain in cell-edge throughput was achieved by inter-site interference prediction.

Joint detection provided better results. Intra-site joint detection resulted in 25% gain in spectral efficiency and 24% cell-edge throughput and inter-site joint detection as high as 35% and 52% respectively. As inter-site joint detection is very demanding for the backhaul, a combination intra-site joint detection and inter-site interference detection was also tested. It resulted in even better results than inter-site joint detection. All four test scenarios and the results are presented in figure 11. [26] It should be noted that in EASY-C field trials OFDMA was used in the uplink instead of SC-FDMA to reduce complexity. This cannot be done in production networks as all the existing UEs are using SC-FDMA. Using CoMP with SC-FDMA would make the equalization more complex [26].

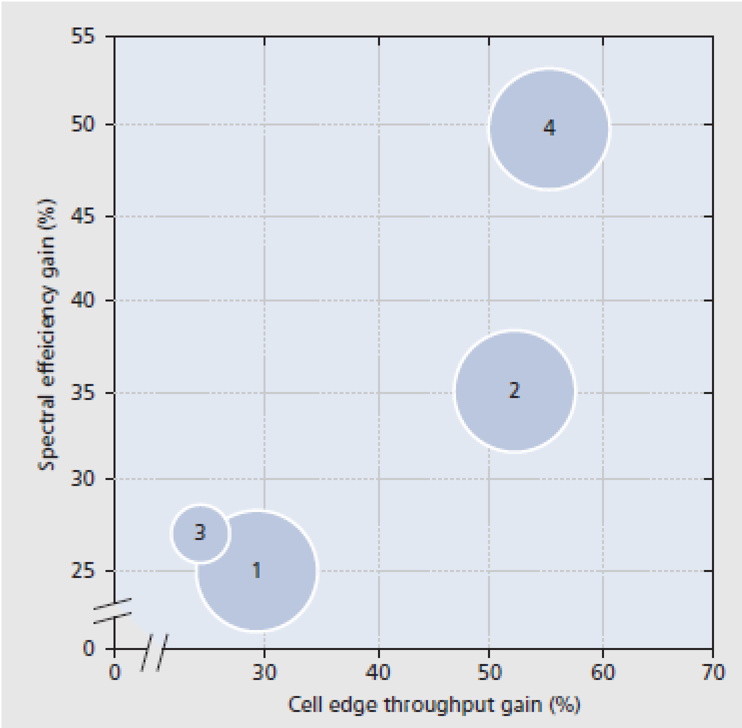

Figure 11: "*Performance of selected uplink COMP schemes: 1) inter-site interference prediction, 2) inter-site joint detection, 3) intra-site joint detection, 4) combining inter-site interference prediction with intra-site joint detection.*" [26]

A notable characteristic of intra-site UL CoMP is the ease of implementation, especially in an environment already in production. UL CoMP does not require support from UEs. They transmit their data the same way according to the uplink grant whether it is received by one eNB or several. Thus no software updates or new UEs are needed to be delivered in order to deploy UL CoMP.

3.1.2 Downlink CoMP

The simulations of Patrick Marsch show that the gain through CoMP in downlink is significantly smaller than in uplink, especially under imperfect CSI. This is mostly caused by more complex interference scenarios in downlink and the fact that contrary to uplink, a cell-edge user suffers only itself from bad interference conditions. In uplink a cell-edge user causes interference to multiple eNBs and thus deteriorates reception from multiple UEs. Coordination that reduces this interference affects positively to all of those UEs. Coordination in downlink only affects the users in bad interference conditions and may decrease the performance of UEs under better conditions. This leads to only 13% average throughput improvement while introducing intra-site CoMP and additional 7% from inter-site cooperation. However the increase at cell edge is huge if inter-site coordination is used. The throughput improvement of the 10th percentile may reach 137%. Intra-site cooperation increases the performance about the same percentage despite the starting performance. Thus the increase of the 10th percentile is only marginal. The throughput improvements are illustrated in figure 12. [28]

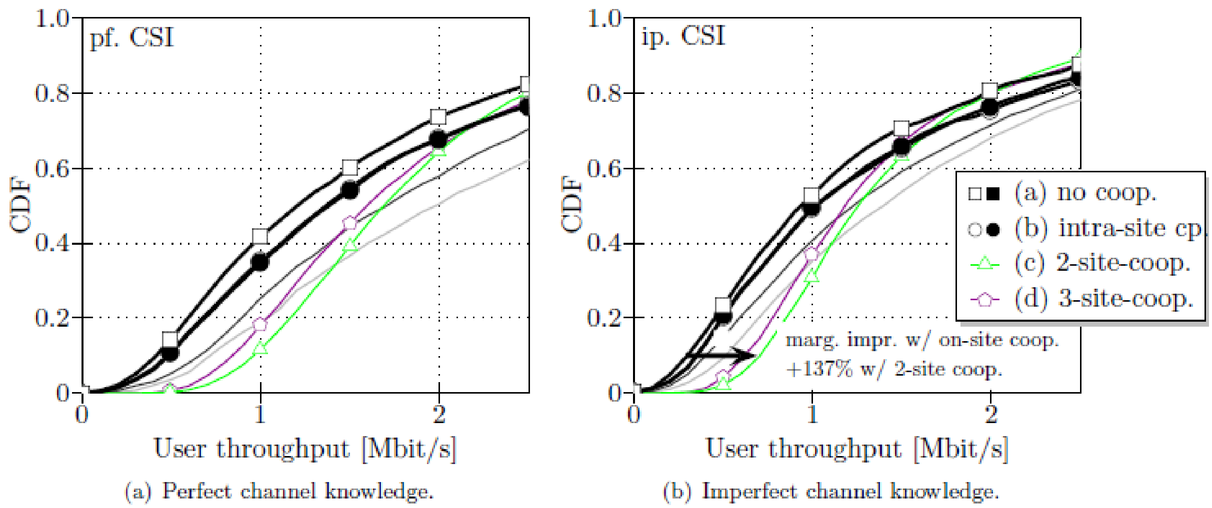

Figure 12: Downlink CoMP [28]

The field trials of EASY-C project in Dresden show great potential in downlink CoMP. According to the results, the more sectors are involved into a cluster the more benefit can be gained from CoMP. This however creates huge requirements for the backhaul between eNBs. The study also outlines many other implementation challenges for downlink CoMP that must be overcome before it can be cost efficiently deployed to live networks. [26] Besides the fact that implementing downlink CoMP is technically very demanding, it also requires hardware or software upgrades to the UEs. [29] It will be logistically very hard for an operator to get its customers to use devices with features required for CoMP.

Challenges

The studies and field trials about CoMP show that it can be managed in small real-world scenarios and significant benefits could be gained with it. However, all the studies outline the fact there are still many open issues that must be solved before the full potential of CoMP can be harnessed. Such remaining challenges are:

- Methods for finding suitable cooperation clusters. This is discussed more below
- eNBs must be synchronized in a way that inter-carrier interference or inter-symbol interference will not become a problem. This also sets a maximum distance between cooperative eNBs because of propagation delays
- Backhaul requirements for X2 interfaces are very strict. Building such backhaul is a challenge itself, not to talk about building it cost-efficiently
- Cost of eNB synchronization and low-phase-noise transmitters
- Efficient feedback compression and feedback delay
- Handling the interference coming outside of the cluster
- Efficient multi-user selection and scheduling

All of these challenges are related to downlink but only the first three concern uplink. Thus uplink CoMP is likely to appear in production networks before downlink CoMP. Especially intra-site uplink CoMP which is proven to have positive effect on performance and does not require the demanding backhaul. [26]

3.1.3 Clustering

As already mentioned, CoMP has very strict latency and throughput requirements for the X2 interface, the backhaul between eNBs. The throughput requirements and signaling overhead increase depending on the amount of cells that coordinate with each other. Thus the proper clustering of cells is essential. In practice small cooperation sizes must be used, mainly because five reasons. First, the time synchronization may become an issue because of signal propagation delays. Second, the resources used for orthogonal pilot sequences grow linearly with cluster size. Third, resources used for CSIR feedback grow at least linearly and may even grow quadratically in worst cases. Also the signaling overhead grows as more eNBs must agree on the scheduling decisions. [28] The last reason is requirements of X2 interface. A connection that can transport hundreds of Mbps or even several Gbps, and has latency less than one millisecond, practically requires straight fiber between the eNBs [26].

Knowing the fact that clusters must be small, the problem is how to determine which cells belong to the same cluster. Ideally UEs should be grouped so that their strongest interferers can be included into same cluster while interference outside the cluster is minimized and the limitations mentioned earlier are met. However, as interference is often asymmetric (A may interfere with B but not vice versa) this is not trivial. [28] The best solution for this would be adaptive cluster management depending on the RF channel measurements and UE positions. It would require eNBs to exchange information about their served UEs and agree how the resources are allocated. This kind of adaptive clustering algorithm should be planned in a way that it fits to existing LTE architecture. Self-optimizing networks (SONs) by the 3GPP already offer framework for such solutions. An adaptive mobilestation-aware clustering concept that is integrable with LTE after small standard changes were used in the EASY-C trials. [26]

Another way to do clustering is static. Fixed cooperation areas are defined and set up and those cells belonging to the same cluster always cooperate with each other. This is a more simple solution but presumably do not yield as good results as a functional adaptive clustering. [28] The practical solution would probably be something between these two as building the backhaul will be very limiting factor. Some cells that would benefit from cooperation may not be possible to be connected with required X2 interface.

3.1.4 Handover rates with CoMP

The handovers are initiated according to measurements by UEs. UEs measure reference signal received power (RSRP) and reference signal received quality (RSRQ). These two values provide cell-specific metric for signal strength which is used to determine the best serving cell. Handover is initiated in case RSRP and RSRQ values from a neighboring cell are better compared to the current serving cell. Handovers always happen at the areas where UE is under the coverage of the two cells. This means there is always interference from the other cell at the moment of handover, which may significantly affect the handover performance. Studies show that handover success rates can be improved by interference coordination.

A study by Aziz and Sigle proves that inter-cell interference coordination (ICIC) can improve handover performance in simulated environment. [30] CoMP differs from ICIC but the idea behind both of them is the same. Minimize the interference to improve the service. Thus it can be assumed that using CoMP would also improve handover performance. More information about interference cancellation effects on handover rates can be found on chapter 3.2.2.

3.2 Inter cell interference coordination (ICIC)

As already mentioned, inter-cell interference is a factor that limits the performance of LTE network significantly. The conditions are even worse in heterogeneous networks consisting of different types of cells (e.g. Macrocells, femtocells and picocells). Thus, methods for coping inter-cell interference are constantly investigated. Coordinated multipoint transmission, introduced in section 3.1, is one of the most promising methods. However, the requirements to properly implement it are very strict. Inter-cell interference coordination (ICIC) methods provide more feasible solution. [23]

ICIC is based on interference avoidance. It means the radio resource management (RRM) is done in a way that favorable channel conditions are improved for the users that are impacted by the inter-cell interference. This way higher spectral efficiency can be reached. The coordinated resource management can be achieved either fixed, adaptive or real-time coordination. Fixed coordination is planned and deployed as a part of the network planning. As it is fixed and does not adapt to any condition changes, it may waste lots of radio resources similarly to traditional reuse. Adaptive coordination is more complex but a lot more flexible solution. It can respond to changing conditions in cell-load and user-load in seconds. However, it cannot respond to varying channel conditions on radio frame level. That can only be achieved by real-time coordination. On the downside, real-time coordination significantly increases complexity and amount of signaling. And it also requires rapid backhaul for signaling, similarly to CoMP.

3.2.1 Selective interference avoidance

Traditional way to avoid inter-cell interference is to split the available bandwidth to parts and use the different frequencies in neighboring cells. This is called frequency reusing. LTE uses reuse factor one, which means the same spectrum is used in every cell**.** ICIC introduces selective interference avoidance to LTE. It means that resources in time, frequency or power domain can be partially reused. The most studied selective interference avoidance methods are selective frequency reuse and selective power reuse. These two methods are illustrated on figure 13. [23] Both techniques aim to minimize the inter-cell interference at cell edges by only using maximum output power for such frequencies that are not transmitted with maximum power output in the neighboring cells.

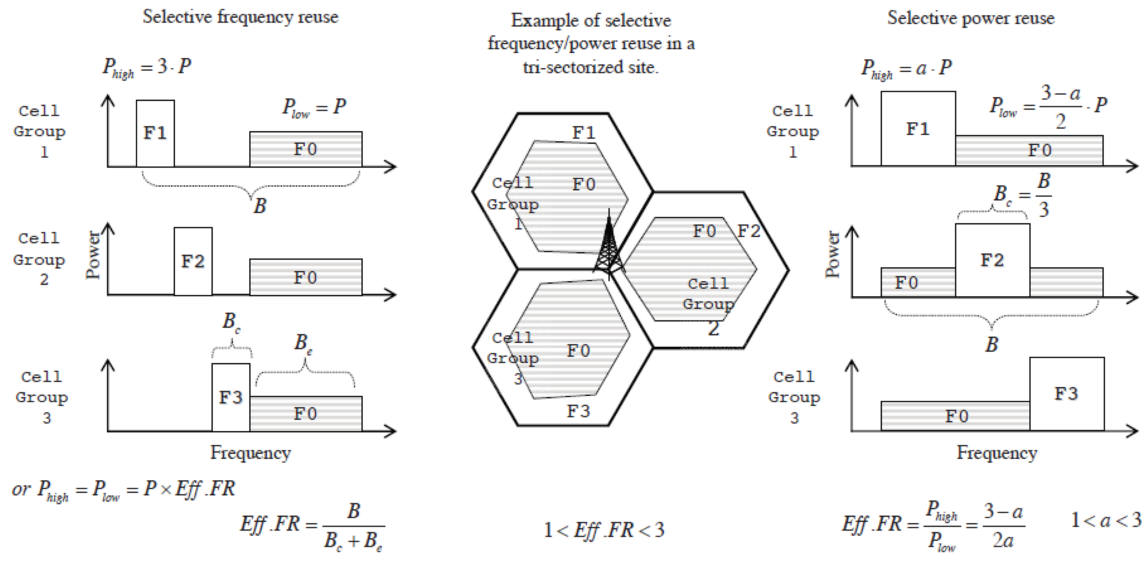

Figure 13: Selective frequency reusing and selective power reusing. [23]

When selective frequency reuse is used, part of the available bandwidth F0 is transmitted with reduced power P_{low} and cell specific small part of the bandwidth Fn where n varies depending on the cell is transmitted with higher power P_{high}. F0 frequency range is reserved for the users in middle of the cell and Fn for the cell edge users. The coverage areas of F0 do not overlap and neighboring cells use different Fn frequencies. Thus the neighboring cells do not interfere with each other as much as in normal reuse one scenario. Using selective frequency reuse may increase the capacity of OFDMA-based systems by 25% [31]. The major drawbacks are bandwidth loss and underutilization of resources at cell edges due to higher reuse factor, which may significantly decrease the cell capacity.

The idea of selective power reuse is the same as selective frequency reuse. Different frequency range and transmit power is used for users close to cell center and for the users at cell edges. However the frequencies used for the cell edge users in the one cell, can be used for the cell center users in another cell. Compared to selective frequency reuse, selective power reuse exhibits zero bandwidth loss and minimizes the resource utilization problem at cell edges. However, compared to normal reuse one scenario, significant capacity gain is not achieved as the interference avoidance is achieved at the cost of good channel conditions close to the cell center. Thus, selective power reuse is only a way to tune the performance between cell-edge and cell-center users.

According to Kosta et al, the main trends are to use selective power reuse when the cell-edge performance is to be slightly increased without deteriorating much of the throughput. Selective frequency reuse is in turn more optimal choice for higher cell-edge performance increases. Despite the technique, ICIC improves performance of the users under bad channel conditions, mainly at cell edges. On the other hand the users under perfect or very good channel conditions would suffer from implementation of ICIC. This means that the minimum throughput of a cell is increased and the maximum throughput decreased, which is the definition of network fairness. [23] In order to work dynamically (adaptive or real-time), ICIC requires support from scheduler. Thus, special scheduler design must be implemented as well.

3.2.2 Handover rates with ICIC

As told on chapter 3.1.4, a study by Aziz and Sigle shows that interference coordination may improve the handover performance in LTE systems. They ran simulation of an LTE system that used fractional frequency reuse based ICIC. Residual block error rate (BLER) was used as one metric for handover performance and the number of unnecessary handovers as another metric. The details about simulation setup can be found in [30]. The study shows that no matter how the handover parameters are set, high residual BLER appears in high loaded cells. High residual BLER leads to high probability of radio link failures. In these cases, using ICIC on top of parameter optimization can overcome the problem of radio link failures without affecting the handover rates. They also show that the benefits of ICIC do not depend on the HO parameter values. [30]

3.3 Cyclic prefix length

Cyclic prefix is a guard period in time domain between OFDM symbols to prevent inter-symbol interference (ISI). ISI may appear if the delay spread is large, meaning that the difference between propagation time via the shortest path from eNB to UE and via the longest path is large. If the difference exceeds the cyclic prefix duration the delayed OFDM symbol overlaps at the receiver with the next symbol. This is called inter-cell interference. It causes negative effect on the beginning of the OFDM symbols and distorts the data, making the transmission unreliable. As the delay spread stays within the cyclic prefix, OFDM symbols do not interfere with each other and they can be received more reliably. [32]

Two options for cyclic prefix (CP) has been standardized for LTE: normal CP and extended CP. The duration of normal CP is 4,7 μs and extended CP 16,7 μs. Converted to distance, this means the maximum difference between the shortest and longest path for normal CP is 1,5 km and 5 km for extended CP. [3] Extended CP is designed for environments where delay spread is larger than normal CP can handle. Such environments are for example large cells especially in hilly areas, archipelagos or dense cities. ISI caused by large delay spread in such areas may create “holes” to the network where service is poor or unusable. The use of extended CP in such areas can prevent those “holes”. [33]

As the duration of LTE subframe is fixed to one millisecond, increasing the cyclic prefix length between OFDM symbols causes the decrease in the amount symbols per subframe. If extended CP is used, one subframe consists of only 12 OFDM symbols instead of 14, which reduces the payload by 14,3%. In practice, because signaling amount is the same with both CP lengths, the difference is even more. The actual amount depends on the coding rate, MCS and channel bandwidth. Theoretically maximum downlink bit rates with normal and extended CP are illustrated on table 2. The values are calculated from the maximum possible amount of resource elements available for PDSCH. This means no retransmission, coding rate one, no paging, no signaling radio bearer (SRB), no SIB overhead nor protocol stack overhead. [33] According to the table 2, the average throughput increase from eCP to nCP for 3MHz channel is 22,13%.

Table 2: LTE bitrates [33]

		Channel bandwidth	1,4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Normal cylic prefix	1 PDCCH Sym.	QPSK Bit Rate (Mbps)	-	4,4	7,4	14,9	22,4	29,9
		16QAM Bit Rate (Mbps)	-	8,8	14,8	29,8	44,8	59,8
		64QAM Bit Rate (Mbps)	-	13,2	22,2	44,7	67,1	89,7
		2x2 MIMO 64QAM Bit Rate (Mbps)	-	25,3	42,5	85,8	129,0	172,2
		4x4 MIMO 64QAM Bit Rate (Mbps)	-	47,7	80,3	161,9	243,4	325,0
	2 PDCCH Sym.	QPSK Bit Rate (Mbps)	1,5	4,0	6,8	13,7	20,6	27,5
		16QAM Bit Rate (Mbps)	3,1	8,1	13,6	27,4	41,2	55,0
		64QAM Bit Rate (Mbps)	4,6	12,1	20,4	41,1	61,8	82,5
		2x2 MIMO 64QAM Bit Rate (Mbps)	8,8	23,1	39,0	78,5	118,1	157,7
		4x4 MIMO 64QAM Bit Rate (Mbps)	17,2	44,8	75,5	152,4	229,2	306,0
	3 PDCCH Sym.	QPSK Bit Rate (Mbps)	1,4	3,7	6,2	12,5	18,8	25,1
		16QAM Bit Rate (Mbps)	2,8	7,3	12,4	25,0	37,6	50,2
		64QAM Bit Rate (Mbps)	4,2	11,0	18,6	37,4	56,4	75,3
		2x2 MIMO 64QAM Bit Rate (Mbps)	8,0	20,9	35,3	71,4	107,4	143,3
		4x4 MIMO 64QAM Bit Rate (Mbps)	15,4	40,5	68,3	137,9	207,4	277,0
	4 PDCCH Sym.	QPSK Bit Rate (Mbps)	1,3	-	-	-	-	-
		16QAM Bit Rate (Mbps)	2,5	-	-	-	-	-
		64QAM Bit Rate (Mbps)	3,8	-	-	-	-	-
		2x2 MIMO 64QAM Bit Rate (Mbps)	7,1	-	-	-	-	-
		4x4 MIMO 64QAM Bit Rate (Mbps)	13,7	-	-	-	-	-
Extended cylic prefix	1 PDCCH Sym.	QPSK Bit Rate (Mbps)	-	3,7	6,2	12,5	18,8	25,1
		16QAM Bit Rate (Mbps)	-	7,3	12,4	25,0	37,6	50,2
		64QAM Bit Rate (Mbps)	-	11,0	18,6	37,5	56,4	75,3
		2x2 MIMO 64QAM Bit Rate (Mbps)	-	21,0	35,4	71,4	107,3	143,4
		4x4 MIMO 64QAM Bit Rate (Mbps)	-	39,1	66,0	133,2	200,4	267,5
	2 PDCCH Sym.	QPSK Bit Rate (Mbps)	1,3	3,3	5,6	11,3	17,0	22,7
		16QAM Bit Rate (Mbps)	2,5	6,6	11,2	22,6	34,0	45,4
		64QAM Bit Rate (Mbps)	3,8	9,9	16,8	33,9	51,0	68,1
		2x2 MIMO 64QAM Bit Rate (Mbps)	7,1	18,8	31,8	64,2	96,6	128,9
		4x4 MIMO 64QAM Bit Rate (Mbps)	13,8	36,2	61,2	123,6	186,1	248,5
	3 PDCCH Sym.	QPSK Bit Rate (Mbps)	1,1	3,0	5,0	10,1	15,2	20,3
		16QAM Bit Rate (Mbps)	2,2	5,9	10,0	20,2	30,4	40,6
		64QAM Bit Rate (Mbps)	3,3	8,9	15,0	30,3	45,6	60,9
		2x2 MIMO 64QAM Bit Rate (Mbps)	6,3	16,6	28,2	56,9	85,8	114,6
		4x4 MIMO 64QAM Bit Rate (Mbps)	12,0	31,9	54,0	109,2	164,3	219,5
	4 PDCCH Sym.	QPSK Bit Rate (Mbps)	1,3	-	-	-	-	-
		16QAM Bit Rate (Mbps)	2,5	-	-	-	-	-
		64QAM Bit Rate (Mbps)	3,8	-	-	-	-	-
		2x2 MIMO 64QAM Bit Rate (Mbps)	7,1	-	-	-	-	-
		4x4 MIMO 64QAM Bit Rate (Mbps)	13,7	-	-	-	-	-

Choosing the CP length is a tradeoff between coverage and capacity where extended CP is needed. You will nearly always get higher average throughput if normal CP is used but with the cost of possible blind spots. In most places the additional gives more than what is lost due to the Bit Error Rate (BER) caused by ISI. It is a decision of the operator to choose from. However, implementing extended CP where normal CP would be enough to cope the delay spread is huge waste of resources. [34] The challenge is that it is very hard to estimate the delay spread. Besides sophisticated simulation tools, an accurate topography including all the buildings and even knowledge about the vegetation would be needed for proper simulations. Even onsite, measuring the delay spread requires specific tools.

3.4 Handover parameter optimization

As told in chapter 2.6, LTE systems use hard handovers. This means that the connection to current serving cell is dropped before a connection to another cell is established. Handovers are based on UE measurements of RSRP and RSRQ sent after event A3 has been triggered. When the RSRP from any neighboring cell is higher than the RSRP from current cell + handover hysteresis margin+ handover offset, time to trigger (TTT) period is started. If the conditions for event A3 is valid for the whole duration of TTT period, the handover procedure is started. If the UE does not receive the handover command from eNB after the TTT period is over, it will send a new measurement report and start a timer called *reportingintervala3*. When this timer expires, the UE sends a new measurement report unless it received the handover command from eNB or A3 conditions are not valid anymore. This is repeated as many times as defined in parameter called *reportingamount*. This procedure is illustrated in figure 14. [35]

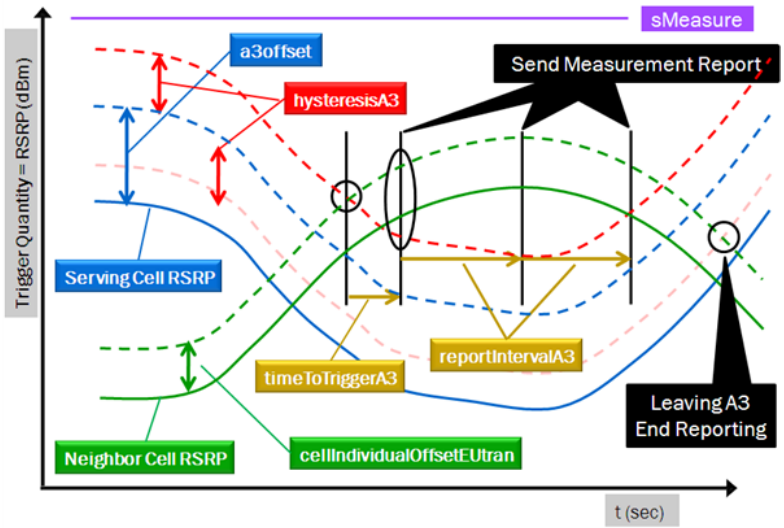

Figure 14: Hard handover procedure [35]

The hard handover process is designed to be totally seamless and no data should be lost. However, if the handover fails for some reason, it appears as a short disconnection period for end users, which should be avoided. Another unwanted handover scenario is ping ponging between two cells at the cell edges where signals from both cells are almost equal. Ping pong effect is often caused at places where there is not a clear dominant cell. The unnecessary HOs caused by ping pong lead to excessive resource usage for signaling and higher probability of handover failures. [36] Excessive signaling is a problem especially with narrow bandwidths.

To avoid the unwanted scenarios mentioned above, the handover parameter values must be optimized. Increasing the TTT period, hysteresis or offset significantly prevents the ping pong effect but also slow down the handover procedure, which may increase the amount of link failures. Thus, adjusting these parameters is always a tradeoff between BLER and handover rates. [30]

There are few guidelines for planning the handover parameters. The offset should always be higher than the hysteresis if the target cell RSRP is required to be at least on the same level as the serving cell RSRP. Setting offset higher than hysteresis prevents the ping pong effect. The lower the *offset+hysteresis* is the faster UEs are released to the neighboring cells and vice versa. Small *offset+hysteresis* value is optimal for very dense network where there are a lot of cells within a given geographical area. Larger *offset+hysteresis* value is on the contrary very useful at areas where there are holes in coverage. The TTT value should also depend on the offset and hysteresis values. If *offset+hysteresis* is relatively small, time to trigger period should be long. On the other hand, if the *offset+hysteresis* is large, time to trigger period does not need to be that long as the neighboring cell is already clearly stronger when A3 conditions are met. [35]

The studies show that increasing the handover margin (*offset+hysteresis*) from 0 to 2 dB significantly decreases the amount of handovers for moving users while not affecting the uplink SINR almost at all. Increasing the HO margin from 2 dB to 4 dB results in similar results, the amount of HOs is significantly decreased but the SINR decreases only slightly. From 4 dB to 8 dB both SINR and amount of HOs are reduced. Increasing the HO margin from 8 dB to 10 dB or higher decreases the amount of handover only little but the SINR is decreased considerably. [37]

4 Performance evaluation

This section presents the results bout testing the methods to improve network performance in live network. The methods are introduced in chapter 3. Due to a limitation from the network equipment vendor, ICIC could not be tested. It can be argued that ICIC would not be a good choice for such narrow bandwidth as 3 MHz. Consequently this section covers measurements about cyclic prefix length, handover parameter changes and UL CoMP performance. They are further discussed in sections 4.3, 4.4 and 4.5, respectively. All these methods are in a one way or other related to mitigating the effects of some kind of interference. Thus they are assumed to be effective for 450MHz band, especially after CDMA2000 to LTE migration.

The measurements were done at the time when the network was already in production and there were active users in it. However, the user count and density was fairly low and there were completely empty cells in the network. This had to be considered when the test setups were planned and results analyzed. The network used for the measurements contains cells with 3 MHz and 1,4 MHz bandwidths. The 1,4 MHz cells are used at the border areas and only 5,9% of all cells are using 1,4 MHz bandwidth. Thus, the tests are done only in the cells which use 3 MHz bandwidth.

The results and their reliability are further discussed in section 4.6. Also the effect of each method is evaluated from the perspective of the typical customer categories.

4.1 Testing in operational live network

Many features cannot be properly tested in laboratory environment and building such environments in laboratory may be expensive and slow. Thus some test can only be tested in operational networks. Testing in live networks has to be carefully considered as the environment is constantly changing. The user behavior may change significantly either randomly or by following some kind of a pattern. An example of a pattern could be dependence on the day of the week or time of the day. When measurements are performed in a live network, additional data about the environment should be collected to make sure the conditions have not changed and there are not external sources biasing the data.

All tests in this thesis are done in Ukkoverkot live network. The network was still in a pilot phase during the measurements were performed but there already were active customers that could possible affect the results. This has been considered by collecting and analyzing additional data about the environment.

4.2 Customer profiles

Globally, 450 MHz band is typically used for M2M-connections. CDMA2000 technology is the most common radio access technology used on the band. [2] LTE offers higher capacity and thus enables 450 MHz band to be used for wider set of use cases. Based on the existing customer base of Ukkoverkot, few typical categories of use cases are presented below.

Vehicle installations
Thanks to the extensive propagation on 450 MHz, relatively little amount of effort is required to build a network with great coverage. Internet connectivity via such a network is very suitable for widely moving vehicles requiring internet connectivity. Such solutions are trains or busses for example. Service level requirements of such

solutions are often best effort. The coverage is the key factor, but most of the time they use all the capacity they can get. Thus, increasing the user throughput, especially at the cell edges, would significantly improve the service for customers in this category.

Fixed wireless installations
In many countries, including Finland, mobile broadband, ADSL or fiber connection cannot reach every citizen, household or summer place. LTE on band 31 can be a solution for such places. The requirements are similar to the previous category. From the end user's perspective, mobile networks are often evaluated based on the throughput. Thus system capacity and maximum throughput are the most important factors. As the installations are permanent, mobility plays little to no role. These users should not create any handovers, and if they do, the network is not properly parametrized.

Reliable solutions
The most important factor for the users in this category is high availability, meaning they should have the connection available always when they need it. Examples of such solutions are online credit card payment systems and authoritative systems like police or border control. The amounts of transferred data may not be much but it is essential that it can be transferred reliably. 450 MHz band is suitable for this kind of usage because the coverage area is wide and because the most handsets do not support LTE band 31, it does not get congested during mass events. Considering these users in network planning, fairness and coverage would be important factors to pursue.

M2M-connections
450 MHz band has been globally used for M2M solutions. The narrow bandwidth is enough for the amount of data even though there would be lots of devices in the same cell and the band is not congested by the most used handset as introduced above. One requirement for M2M-systems is the possibility to support hundreds or even thousands of devices in the same cell [38]. From network planning and optimization perspective this means minimizing the overhead per UE. Considering the methods studied in this thesis, it is very important to prevent unnecessary handovers.

4.3 Cyclic prefix length

In this section the difference between extended and normal cyclic prefix is examined in a commercial network. The functions of cyclic prefix are introduced in chapter 3.3. It is suggested that the benefits of eCP would overcome the disadvantages only in special cases and it would be mainly meant for broadcast networks. The motivation of these measurements is to find out whether eCP would be required in 450 MHz LTE network that contains very large cells.

Prior to the CDMA2000 to LTE migration, the hypothesis was that such big cell sizes that Ukkoverkot have, require extended cyclic prefix to be used. This hypothesis was used when the migration was done and extended cyclic prefix was set as the default value network wide. As the effects of changing it to normal length are almost impossible to simulate, it must be tested in the operational network. Theoretically the change would increase the cell capacity by at least 16,7% at cells where the normal cyclic prefix length is enough. The cost of this increase is possible holes in the network coverage.

The tests were performed in two parts. First the change from extended CP to normal CP was done in a test cluster to avoid affecting all customers in case of very bad results. And after analyzing the results, the same was done in the whole network.

The plan was that if the results of the test cluster would be positive, the normal CP area would be expanded. There were two possibilities for this step. Either to expand the normal cyclic prefix area cluster by cluster and measure the results in each cluster or change the whole network at once. As there would also be a lot of non-performance-related benefits for using normal cyclic prefix network wide, the choice to expand it to the whole network at once was made. The most significant benefit is wider variety of end devices as all UEs do not support extended cyclic prefix. Thus using a mixture of extended and normal cyclic prefix is not desirable either. It could create a scenario where all customers would not be able to use their devices everywhere in the network. Also the handover performance between eCP and nCP cells was a concern as no field trials about it were found. It should be tested separately.

4.3.1 Measurements of test cluster

Measurement setup

First a cluster of cells that probably would not need extended CP was determined. This cluster had to also cover enough users already in the pilot stage of the network so that the measurement results would be statistically meaningful. The only cluster meeting the criteria was capital area. Totally 13 eNBs from Helsinki, Espoo, Vantaa, Sipoo and Tuusula were chosen for this measurement. All these eNBs were using 3 MHz bandwidth and SIMO transmission. The radius of the largest cell in the test cluster was approximately 13 km and the average cell radius about 3 km.

All the measuring was passive, meaning that no actions were made to either generate traffic or drive around the area. All the results were evaluated based on certain network KPIs before and after the change. The KPIs used were average user throughput (both uplink and downlink) and total traffic volume (UL and DL). Negative customer feedback was also considered and investigated.

The selected KPIs were measured for one week before the change and one week after the change. The measurement period was kept fairly short to avoid the increasing number of subscriptions biasing the results. The change was made at 00:00 between Sunday and Monday. Each KPI sample represents a value over the latest 15 minutes from one cell. 15 minute resolution was the smallest possibility provided by the KPI monitoring equipment. This was considered reasonable as that would create 52416 samples for each KPI during the two-week-long measurement period. One measurement sample for user throughput represents the average data throughput of every user in one cell during the latest 15 minutes. The average user throughput values are calculated by dividing the transmitted data with the transmission time. Thus the value is counted only from the UEs that are actually transferring data and idling users do not affect the statistics. The traffic volume values are amounts of data transferred through once cell during the latest 15 minutes. All KPI values were collected from the eNBs by a network monitoring server. The network monitoring server was used for fetching and preprocessing the data. Further analysis and the figures were produced with Microsoft Excel.

Results

The change from eCP to nCP was beneficial in terms of all four KPIs. The KPI values are represented in table 3. Also the total traffic volume as gigabits through all 39 cells during each week has been presented in the tables.

Table 3: Cyclic prefix measurement results in test cluster

Extended CP							
	UL User throughput (kbps)	DL User throughput (kbps)	DL traffic volume (Mbit/15min)	UL traffic volume (Mbit/15min)		Total traffic DL (Gbit)	Total traffic UL (Gbit)
Average	705,3	1931,6	152.99	26,1		2546	30,8
median	639,2	1480,0	21.143	2,8			

Normal CP							
	UL User throughput (kbps)	DL User throughput (kbps)	DL traffic volume (Mbit/15min)	UL traffic volume (Mbit/15min)		Total traffic DL (Gbit)	Total traffic UL (Gbit)
Average	870,7	2239,9	181.4	32,3		3102	36,9
Median	797,3	1822,4	26,7	4,2			

The average downlink user throughput was increased by 15,96%, which follows closely the theoretical 16,7% increase from additional OFDM symbol. However, the median value is increased by 23,14% which means that the users with worse throughput benefitted more. This can be explained by higher MCS. The users with highest bitrates already had such high MCS that it could not be improved the same way as for users with more robust MCS. The downlink user throughput distribution is presented on the figure 15. It can be seen that the worst 5% remained the same.

The increase in uplink was more even, excluding the bottom 5% that again did not improve at all. Average user throughput was increased by 23,45% and median 24,73%. This can be explained with the fact that an UE has very much lower transmit power than an eNB. The area where the signal conditions are good enough for the best modulation and coding schemes to be used is smaller for uplink than what it is for downlink. The uplink user throughput is illustrated on figure 16.

The total traffic volume was also increased on both, uplink and downlink. The increase on downlink was 21,85% and 19,76% on uplink. This however is not unambiguous because the user behavior was slightly different.

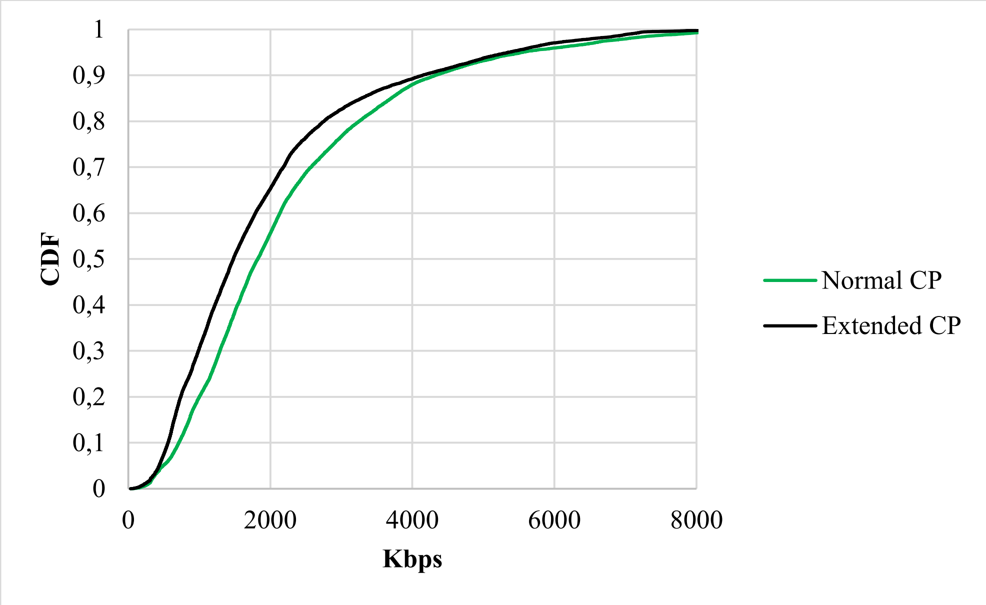

Figure 15: Distribution of average downlink user throughput

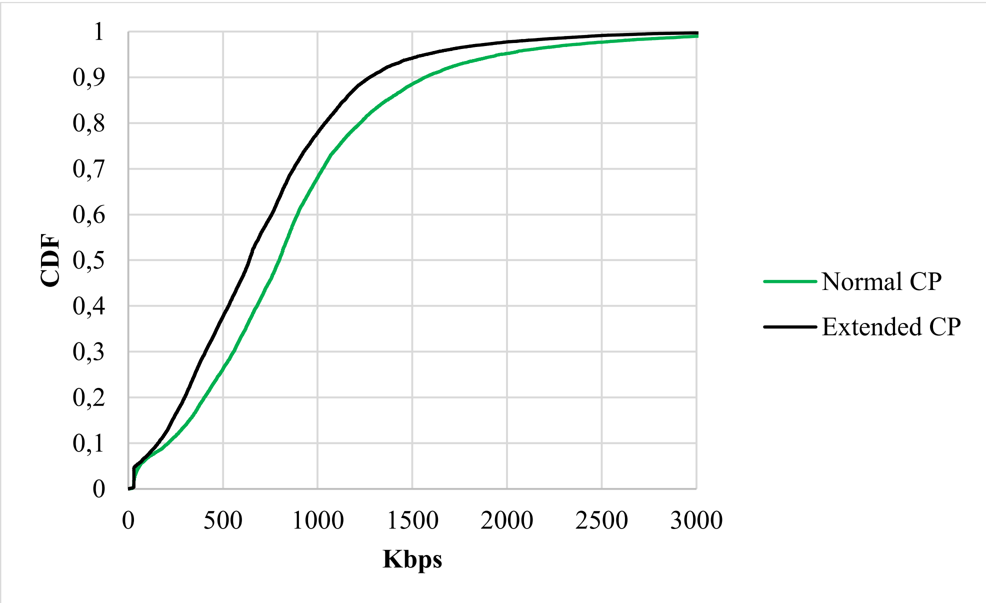

Figure 16: Distribution of average uplink user throughput

The traffic pattern was fairly similar in downlink during the whole test period and very similar in uplink. The total traffic distribution during the week can be seen on figures 17 and 18. The change in the downlink traffic pattern (more data transferred during the nights) increased the total traffic volume roughly by 189 gigabits, which is 34 percent of the increase in total traffic volume. It could have also slightly impacted the average throughput. Discarding all the measurement samples at the time when there were additional "peaks" during the night in the traffic volume show that the average downlink throughput was not affected by those peaks.

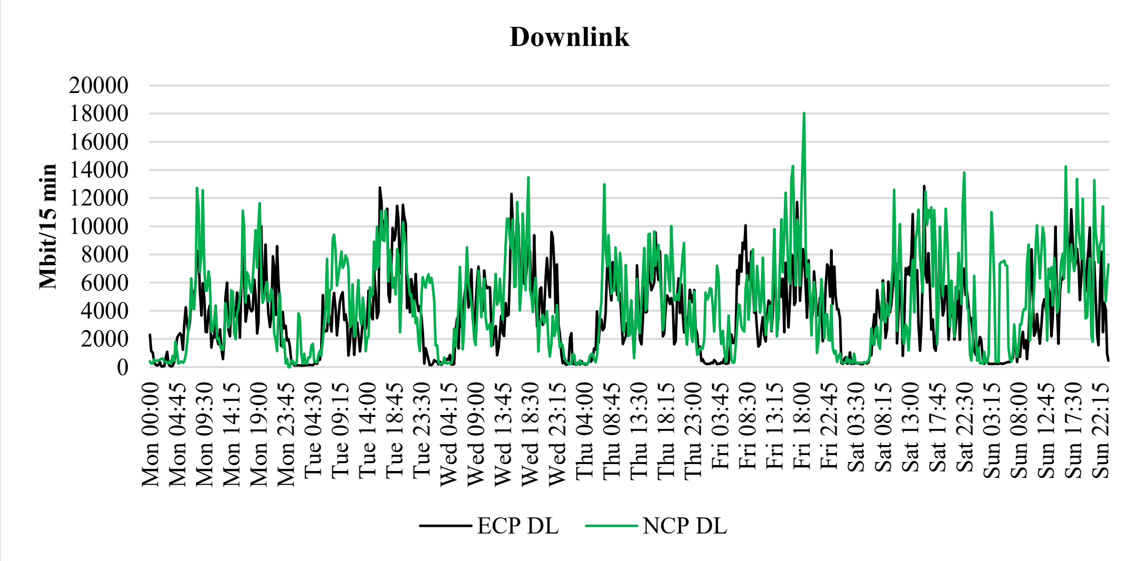

Figure 17: Downlink traffic volume

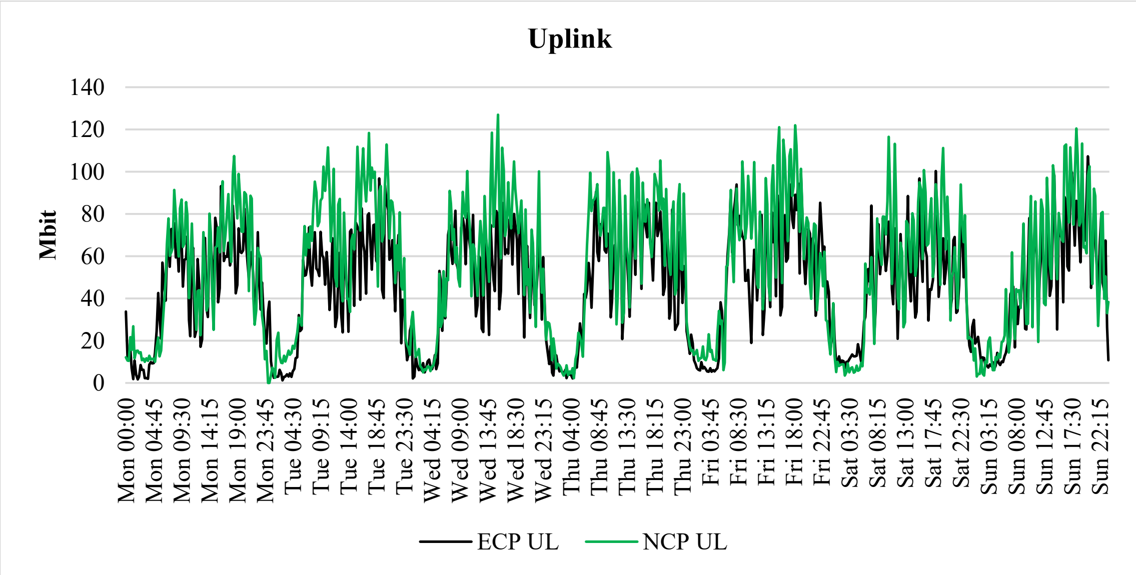

Figure 18: Uplink traffic volume

Besides the positive change in numbers, no negative customer feedback could be connected to the eCP to nCP change. These results were enough to justify the test in whole network. An area containing all test cluster eNBs was also drive tested for Ukkoverkot internal purpose two months after the change and no “holes” in the network were reported, which verified the success of the change.

4.3.2 Measurements of the Whole network

As the results from the test cluster were very positive, it was decided that normal CP would be tested network wide. As it was more likely that problems caused by inter-cell interference (ISI) would have occurred in the larger cells, deeper knowledge of the effects were needed. Thus, additional KPIs were monitored besides the traffic volume and user throughput. The new KPIs were call drop rate, 4G establishment success rate, handover success rate, number of RRC setup failures and time between E-RAB abnormal releases. Also, the negative customer feedback was evaluated more carefully.

Test setup

The measurements were done in the same way as for the test cluster except more KPIs were monitored. The measurement period was prolonged from one week to ten days pre and after the cyclic prefix change to get more reliable results. Longer measurement period could not be used in order to avoid the increasing number of subscriptions biasing the results. As there are about 20 times more cells in the whole network as in the test cluster the sample duration was increased from 15 minutes to one hour. Totally 342168 samples were recorded for each KPI. All zero values caused by a cell being totally unused during the sampling period were removed from the dataset.

Main KPI for the performance measurement was the average user throughput. Other KPIs were mainly used for identifying possible negative effects and evaluating the reliability of the measurements. Areas where extended cyclic prefix are needed but normal cyclic prefix is used would most likely suffer from call drops, handover fails and poor throughput.

It was a lot more likely that the change on whole network would show signs of impaired service than it was on the test cluster. The maximum cell sizes are bigger, the biggest cell radius being over 50km. Also, different kinds of terrain are covered, including archipelago, Finnish lake district, hilly areas in northern Finland, etc. Because the measurement period took place at the time right after the commercial launch of the network, the user density was very sparse. Thus, all problematic places would not be identified during the test period. After the measurement period, negative customer feedback was tracked and analyzed.

Results

Similarly to the test cluster measurements, the results were very positive. The measured KPI values are presented in the tables 4 and 5. 10% of the cells contain over 63% of all users in the network. Because the subscriber population is very unequally distributed, the KPI values from the cells are considered without giving more weight to the cells that contain more users. Also, all the most used cells are at an area where the cell density is high. Thus all these users are under good or moderate radio conditions. If all the KPIs would be considered by giving weight to the amount of users in a cell, the effects in the rural areas would be overwhelmed by the dense areas. The average throughput in a cell was increased by 21,64% for UL and 28,51% for DL users. If considering the amounts of users in each cell as a weight for the average, the throughput was increased by 22,89% for UL and 29,97% for DL. The difference means the throughputs were increased slightly more in the areas where user density was higher. Both, uplink and downlink throughput, were increased a lot more than the 16,7% gained from the additional OFDM symbol. This means that the gain for the link budget plays a huge role. On average a jump to one higher MCS increases the throughput by 12,97% for 3 MHz bandwidth assuming all 15 PRBs are fully utilized. This means that on average 97,5% of users were able to use one higher MCS on downlink and 92,3% on uplink.

The downlink traffic volume were increased by 12,82% but the uplink traffic volume were not increased at all. This means that higher throughput does not always mean more traffic. One could have certain data to be transferred and it does not change whether it happens in a minute or in an hour. On the other hand, using for example a video service, higher throughput enables higher video quality that increases the volume.

Thus, the total traffic volume is not a good KPI of performance in such low populated network as Ukkoverkot had during these tests. It is more useful for determining user profiles

Table 4: Cyclic prefix measurement results in whole network

Extended CP							
	UL User thrput (kbps)	DL User thrput (kbps)	Call drop rate (%)	Handover success rate (%)	Minutes between abnormal releases	Number of users per cell	RRC Setup Success Rate (%)
Average	661,6	1991,7	1,61	99,933	147,1	0,211	98,81
Median	509,2	1803,1	1,68	99,934	138,1	0,0016	98,74
Normal CP							
	UL User throughput (kbps)	DL User throughput (kbps)	Call drop rate (%)	Handover success rate (%)	Minutes between abnormal releases	Number of users per cell	RRC Setup Success Rate (%)
Average	804,8	2559,6	1,48	99,927	149,6	0,216	99,1
Median	622,8	2295,1	1,41	99,939	149,8	0,0018	99,09
Difference in percent							
	UL User throughput (kbps)	DL User throughput (kbps)	Call drop rate (%)	Handover success rate (%)	Minutes between abnormal releases	Number of users per cell	RRC Setup Success Rate (%)
Average	21,64 %	28,51 %	-8,07 %	-0,01 %	1,70 %	2,37 %	0,29 %
Median	22,31 %	27,29 %	-16,07 %	0,01 %	8,47 %	12,50 %	0,35 %

Table 5: Traffic volumes during the cyclic prefix measurements

	Downlink traffic volume	Uplink traffic volume
Extended cyclic prefic	30422	6266
Normal cyclic prefix	34323	6259
Difference	12,83%	-0,10%

The median values and the average values were increased almost equally which means that the performance increase was distributed throughout the population as it was in the test cluster. However, the CDFs on figures 19 and 20 show that that the top and bottom parts of the population do not benefit as much and the average benefit is. The benefit in uplink for the worst 20% was little to none. In downlink, the worst 10% did not benefit nearly at all. These values are higher than in the test cluster (5%) due to the fact that the network was denser in the test cluster than the average in whole network.

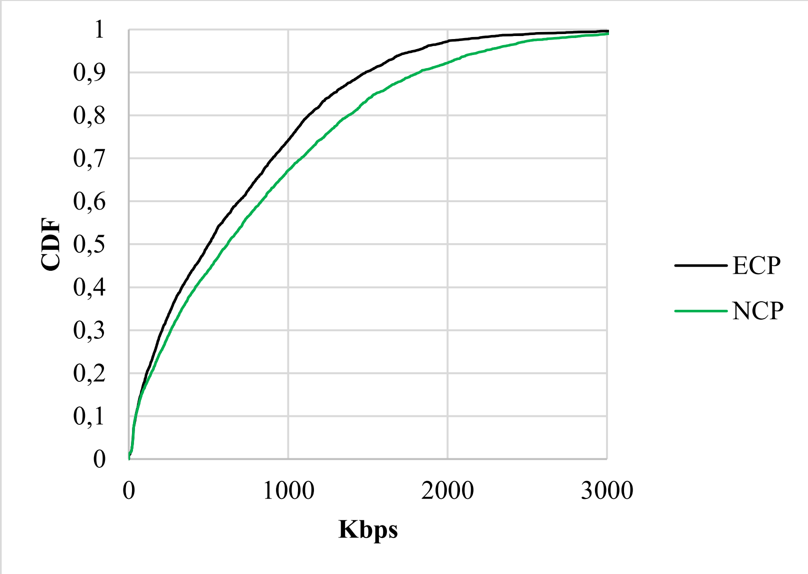

Figure 19: Average uplink user throughput

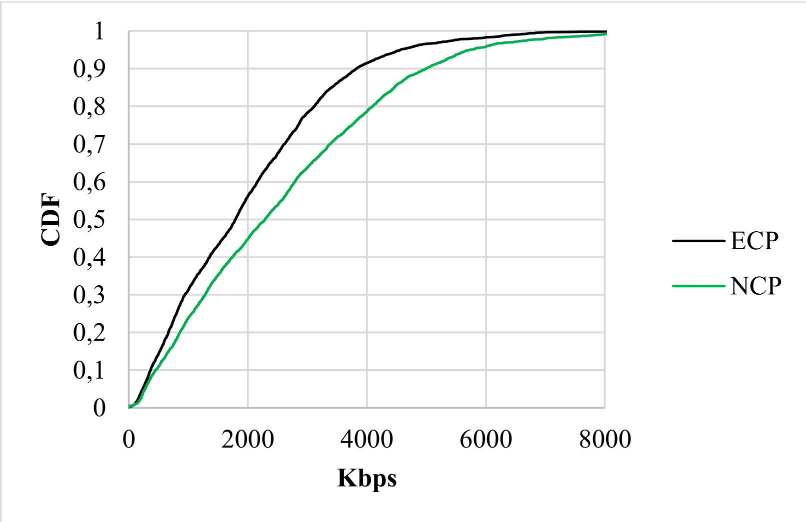

Figure 20: Average downlink user throughput

Call drop rate, handover success rate, time between abnormal releases and RRC setup success rate were followed mainly in order to identify possible negative effects. According to these KPIs, no negative effects were found. The average value of all these KPIs was about the same or slightly better. The small variation can be explained by a small change in user behavior. As the user density is very low, some problematic areas most likely remained unrevealed. For this purpose, negative customer feedback was tracked. During a 3 month period after the change, only two places had been identified to possibly suffer from the too large delay spread for NCP to handle. Both of these can be handled by adjusting eNB locations, antenna tilts and transmission powers or additionally building a new eNB.

All the measurements related to cyclic prefix are directional. The measurements were done in a dynamic environment where user behavior was not constant and it could have affected the results. However, the user amount per cell was very low as can be seen on the figure 21 and thus lack of cell capacity was not a factor that should have been seriously considered. The amount of active users were increased by 2,37% during the measurement period but as the users are distributed the same way, it is assumed to have minimal to no effects on the average user throughput.

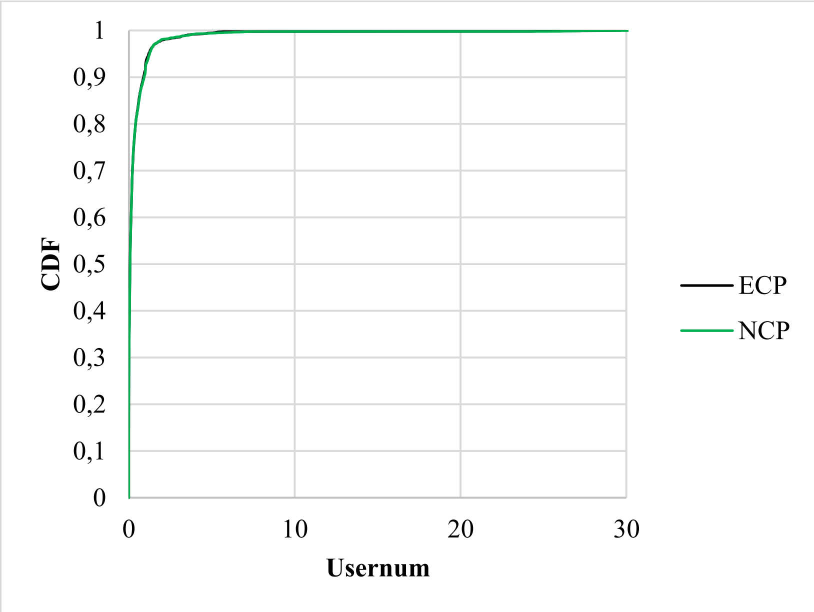

Figure 21: Distribution of average amount of user per cell

4.3.3 Summary

The cyclic prefix measurements included KPI based analysis of cyclic prefix length. The measurements were performed in two parts, first on a test cluster and then on whole network. The main purpose of these measurements was to find out whether normal cyclic prefix length would be enough for LTE on 450MHz frequency and what is the difference in performance between extended and normal cyclic prefix.

The cyclic prefix measurements showed that extended cyclic prefix is not beneficial even in LTE networks where maximum cell size reaches 50 km. Network wide the average user throughputs were increased 21,64% for uplink and 28,51% for downlink when transferring from extended to normal cyclic prefix. Negative effects could not be found by monitoring network KPIs (Call drop rate, Handover success rate, RRC setup success rate and time between E-RAB abnormal releases). However, it must be considered that the user density in these measurements was very low and parts of the network were totally unused. Also, the network coverage is so wide that it cannot be drive tested in feasible amount of time. Thus the effect of cyclic prefix length should be investigated in case of further negative end user feedback. During a 3 month period, two places were identified that may have suffered from the use of normal cyclic prefix. In case the negative effects emerge this infrequently, it is much easier and favorable for an operator to handle these cases individually by local network optimization.

4.4 Handover parameter optimization

This section is about optimizing the handover parameters in terms of absolute amount of handovers and handover success rate. First the initial situation is evaluated. Then few of problematic sites are selected and parameter changes are tested on these sites. The effects of the parameters are measured and optimal values are estimated. Based on the estimation, changes are made to the test sites and afterwards to the whole network.

4.4.1 Initial situation

After a CDMA2000 to LTE migration, it can be assumed that there are many places where handover performance is not optimal because ping pong effect is not as severe with soft handovers as it is with hard handovers. Also, new plans about the handover parameters were not made when LTE was taken into use and thus the vendor's default values were used. That strengthened the hypothesis that the handover performance was suboptimal.

Despite the fact that only part of the customer profiles was mobile, network wide there had been 250-500 handovers per user every day during a 30 day period. Also in over 2% of the cells there had been over 300 handovers per user in a day. It was very unlikely that users would have moved back and forth under those sites so many times. Roughly half of the users were highly mobile and they should do 100-400 handovers per day. The rest of the users were either stationary or only slightly mobile. They should do 0-50 handovers per day. Thus, the average amount of handovers per users should have been 100-150. This means that there were users causing huge amounts of handovers due to unwanted ping pong effect. Even though there were too many handovers, they succeeded on a very high rate. The handover success rate was 99,9% and only 0,2% of the cells had handover success rate less than 95%.

As the bandwidth on band 31 is so narrow, the additional overhead caused by ping pong can have a major impact on service. It should also be noted that even at high speeds, the handovers do not need to very rapid because of the large cell sizes. The cell edge area is wide and a user practically cannot move through it in few seconds. Also, as the cell radius may be up to 50 km, the handovers do not happen very often. Thus the handovers should be planned to prevent unnecessary ping pong instead of rapid execution.

Considering the initial handover success rate and the facts stated above, the handovers did not need to be as robust and rapid as on high frequency bands. It was assumed that in an optimal situation either the time to trigger interval should be higher, the conditions for event A3 should be stricter or both. Based on the calculation above, over 50% reduction to the amount of handovers was considered possible.

The handover performance between 1,4 MHz cells and 3 MHz cells is assumed to poor because the center frequencies of these cells are different due to spectrum coordination at border areas. They are different but so close to each other that the payload of neighboring cell overlaps with the center frequency of the other. This might cause severe interference to the synchronization and reference signals. However, there were so few users around those areas at the time when this thesis was done that no statistically meaningful data could have been gained.

4.4.2 Test setup

The handover parameter effect evaluation was initially done by changing each of the three parameters introduced in section 3.4 (*Handover offset, Handover hysteresis and time to trigger*) individually and monitoring specific KPIs. The main KPIs to follow were amount of handovers and handover success rate. To recognize possible negative effects on service, number of E-RAB abnormal releases, average user throughput and data volume was monitored as well. Each parameter setup was monitored for at least five days. The KPI values were collected by a network monitoring server. The measurement sample length was 60 minutes and each sample represented a value from one cell.

As the changes could have had severe effects to the service, only four eNBs were chosen for this test. ENBs that had particularly many handovers under them were chosen. Two of the eNBs were such that many of the moving users pass the eNB coverage every hour and two covered only stationary users and randomly few moving customers. This way it would be possible to see the effects on two main cases. First, an eNB that has a lot of handovers to and from it and at least most of them are appropriate. As these handovers should happen in order to the network to operate correctly, they should not be affected much. The second case is an eNB under which there are a lot of handovers that happen because of ping pong effect. The optimal parameter values should be such that the handovers in the second case are minimized but the performance in the first case is not affected.

The default values for the parameters were 1 dB for both offset and hysteresis and 320 ms for TTT. In the initial test setup, each parameter was first increased by 100%, measured for at least five days, decreased to 50% of the original value, again measured for five days and returned to the original value. This was then repeated for another parameter. Totally the measurement period was 68 days. This test did not take into account the basic guidelines introduced in section 3.4 for parameter relations. The test did not give reliable data as the variation between measurement samples was very high, leading to inconsistent results. Consequently the correlation between each parameter and the handover KPIs could not be reliably identified.

Instead, more radical changes were made to offset and hysteresis, while keeping TTT untouched. That resulted in more desired outcome. The procedure was iterated few times in order to estimate a function between *offset+hysteresis* and handover KPIs. Each iteration considered the guideline to keep hysteresis value smaller than offset.

4.4.3 Results

Doing the test on only four eNBs (12 Cells) did not provide results reliable enough to calculate the correlation between a single parameter and amount of handovers. A test set of 12 cells was not enough to flatten the possible handover peaks caused by randomly moving customers around a problematic area. One customer could generate even half of all the handovers if he stayed at a problematic area, but if the user stayed offline during testing another parameter, the results seemed totally different even though the situation might not have changed much at all. The figure 22 illustrates the situation. The amount of handovers is shown on a time line and the vertical lines show the moments when parameter changes were made. When changing a parameter value, the previously made changes were returned to default values.

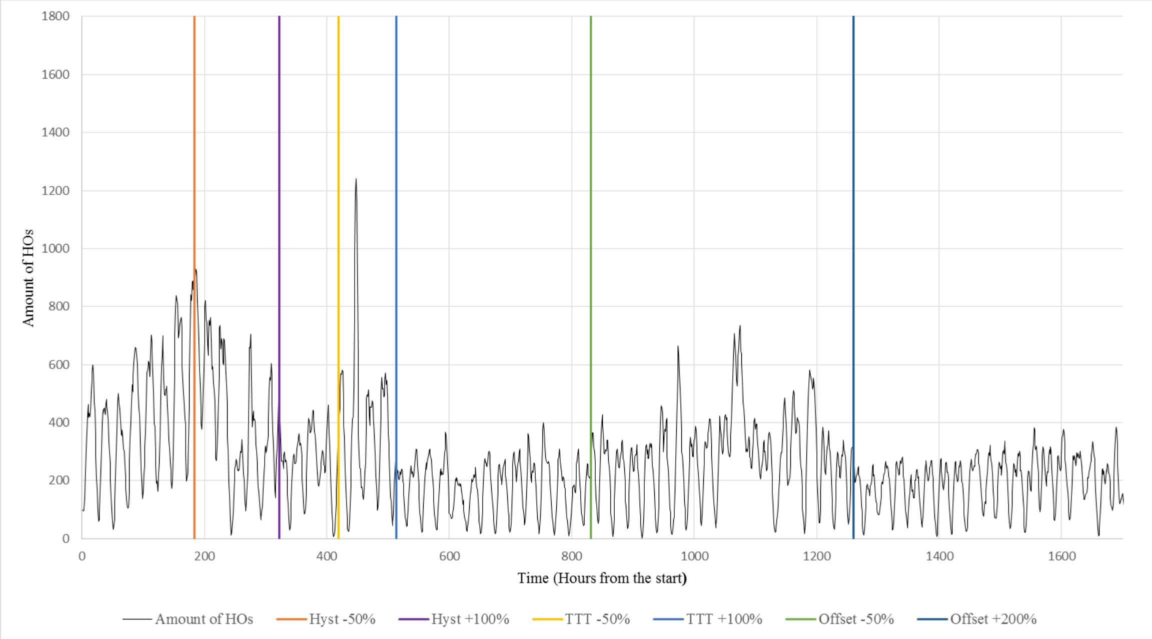

Figure 22: Amount of handovers per hour during the first test period

Even the parameter changes that should have significantly increased the amount of handovers according to the theory, like halving the offset or TTT, did not increase the amount. However, increasing the offset and increasing the TTT reduced the amount of handovers. The average values of each KPI during each parameter setup are presented in table 6. Each value represents average over the 12 cells. The values that are better than the values during the initial situation are marked as green and the values that are worse are marked as red.

Table 6: KPI values for initial test

	Amount of HOs	DL User Throughput(kbit/s)	E-RAB abnormal releases	UL User Throughput(kbit/s)	Amount of users	Call Drop Rate (%)	Handover Success Rate (%)
Default values (O: 1dB, H: 1dB, TTT: 320ms)	34,40	2369,47	0,14	986,38	0,44	0,99	99,92
Hysteresis -50% (0,5 dB)	34,69	2493,58	0,15	942,49	0,40	1,23	99,98
Hysteresis +100% (2 dB)	21,26	2513,22	0,08	956,37	0,45	1,13	99,89
TTT - 50% (160 ms)	30,81	2631,60	0,35	1071,61	0,39	0,52	99,98
TTT + 100% (640 ms)	14,71	2456,72	0,08	1012,36	0,32	1,69	99,97
Offset -50% (0,5 dB)	23,15	2490,65	0,13	1023,87	0,36	0,71	99,99
Offset +100% (2 dB)	15,99	2358,14	0,12	946,65	0,38	0,93	99,95

To reach better results, more radical changes were made to the hysteresis and offset values. This was done by following the guidelines presented in section 3.4 to minimize the possible negative effects to the service. TTT was also kept untouched. The importance of TTT value decreases as the offset and hysteresis values increase.

The measurement process was iterative. The offset and hysteresis values were changed, the results were analyzed and further changes were made based on the results from previous measurements. First the offset value of 6 dB and hysteresis value of 4 dB were set, meaning the offset was increased by 500% and hysteresis by 300%. In this setup, the signal from neighboring cell must be over 10 dBs more powerful than the serving cell before handover is made. This was done for all 4 eNBs. The four eNBs were further divided into two categories for the measurement analysis; two eNBs that covered mostly mobile users and the other two that mostly covered stationary users.

The amount of handovers dropped to practically 0 in the cells covering stationary users. Under those sites, the number of EUTRAN radio access bearer (E-RAB) abnormal releases was also decreased to almost zero. The number of abnormal releases was very little in the first place so even though the change was large if measured in percentage, the absolute decrease was very little. On the negative side, the average downlink user throughput was decreased by 10%. As the change in uplink user throughput was reciprocal (increased by 20%), it could have been caused by variation in the user behavior under the sites. As there were almost no handovers at all and the few that occurred were successful. The success rate was 100.

Under the eNBs that covered mostly mobile users, the number of handovers was decreased by 52%, while the success rate remained very high. The call drop rate and number of E-RAB abnormal releases were slightly decreased. However, both UL and DL throughput values were also decreased by 24%.

After analyzing the results of 10 dB *offset+hysteresis* setup, another change was made. As the handover amount in cells covering stationary users were already decreased to almost 0, it would have been unnecessary to test higher values. Thus the two eNBs with stationary users were set to use offset value of 4 dB and hysteresis value of 2 dB. For the eNBs covering mobile users, the values were increased further to 9 dB offset and 6 dB hysteresis.

Under the cells containing mobile users the amount of handovers was decreased another 48%, the uplink throughput decreased 3,4% and downlink throughput increased 2,4%. Other values remained relatively same. In the cells covering stationary users the average amount of handovers was increased from 0,2 to 4,9 per hour, which is 14,4% of the initial amount. Other values did not differ significantly from the ones during 6dB+4dB setup.

By using these two measurements, the initial 1dB+1dB setup and two test setups from the first measurements, vague functions between the KPI values and the offset + hysteresis combination were illustrated. They can be seen in figure 23. The two test setups used from the first measurements were the only ones meeting the guidelines introduced in section 3.4: 1 dB offset + 0,5 dB hysteresis and 2 dB offset + 1 dB hysteresis. As the measurement setups and the results of the two scenarios were very different, they were plotted on different graphs.

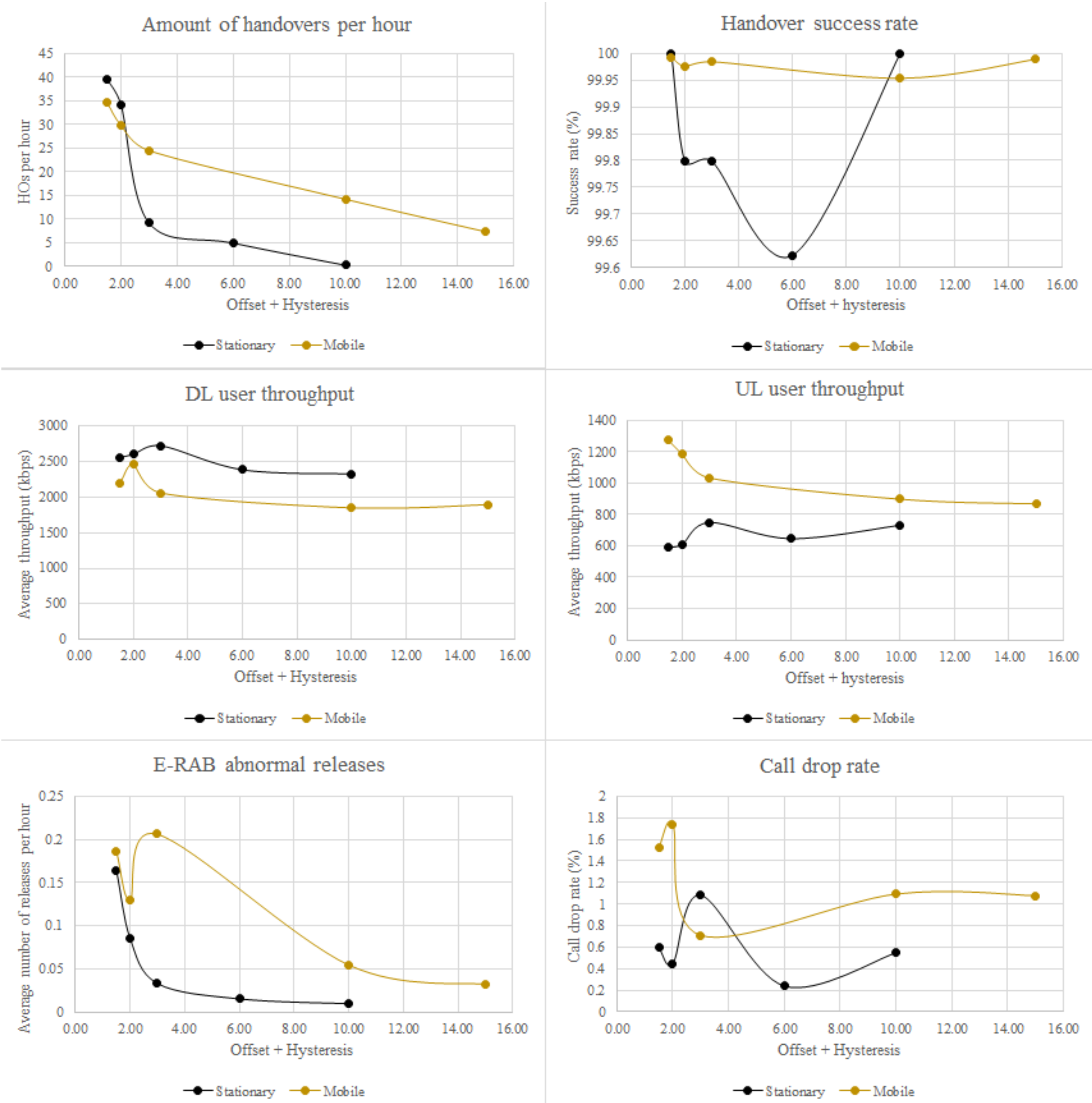

Figure 23: The functions between handover *Offset+Hysteresis* and handover KPIs

It can be seen that the amount of handovers decrease quite linearly under the sites covering mobile users if the offset and hysteresis values are increased. With the higher offset and hysteresis values, an UE does not do handovers to eNBs whose signal is only little stronger. An example of such scenario would be a user moving straight from one eNB to another. At the cell edge area where neither of the eNBs can provide a strong signal, a signal from third eNB may be the strongest. If the *offset+hysteresis* is high, the UE does not hand over to the third eNB but instead it waits until it is under good coverage of the new cell before abandoning the first serving cell. If the offset + hysteresis values would be further increased, at some point the connection to the serving cell would drop before the neighboring cell is strong enough to meet the A3 event conditions. This would cause more E-RAB abnormal releases, higher call drop rate and lower HO success rate. Under the test eNBs 15 dB was not enough to reach this point, as it can be seen from the figures. On the contrary, the call drop rate and E-RAB abnormal releases were reduced when *offset+hysteresis* was increased. The only negative effect can be seen as user throughput, both UL and DL, was slightly decreased with higher *offset+hysteresis* values. However, as seen in the first test period, four eNBs are not enough to provide reliable results in a time frame of 5-20 days.

The figures of eNBs covering stationary users were more interesting than the ones covering mobile users. It was shown that nearly all handovers could be prevented with higher *offset+hysteresis* value and the amount of handovers decrease logarithmically. This clearly reveals that most of the handovers under those eNBs were caused by ping pong effect. When the *offset+hysteresis* values were increased over a certain point, almost no handovers happened at all. Also, the number of E-RAB abnormal releases and call drop rate closely followed the amount of handovers. Other values can be said to be close to equal, only random variation to one or other direction occured.

Even though these estimations were not completely reliable due to the small set of eNBs and only few measurement points, a rough trend between the amount of handovers and *offset+hysteresis* values could be made for both mobile and stationary scenarios. It was enough to justify changes to the whole network. The offset value was increased to 3 dB while keeping the original hysteresis value of 1 dB. That was considered to be enough to prevent most of the handovers caused by ping pong effect. A higher value would have done it more certainly, but the mobile curve showed possible slight decrease in throughput values which was undesirable.

The setup was measured for 7 days and the KPI values were compared to the values 7 days prior the modification. The data from all eNBs that went through any other changes during the 14-day measurement period was removed. The total number of measurement samples was 117418 for each KPI both prior and after the modification. The sample length was 60 minutes and they were collected from each cell individually. The average, median and maximum values are presented in tables 7 and 8. The samples with zero values from cells which did not cover any active users during the 60-minute sample duration were excluded from the statistic.

Table 7: Average and median values in whole network

Average values per cell							
	Amount of Hos	DL user throughput (kbps)	E-RAB abnormal releases	UL user throughput (kbps)	Amount of users	Call drop rate (%)	HO success rate (%)
Initially configuration	11,35	2425,24	0,084	795,19	0,70	3,01	99,89
Offset increased to 3 dB	6,21	2472,20	0,078	832,25	0,73	2,88	99,91
Difference	-45,29%	1,94%	-6,80%	4,66%	3,78%	-4,31%	0,03%

Median values per cell							
	Amount of Hos	DL user throughput (kbps)	E-RAB abnormal releases	UL user throughput (kbps)	Amount of users	Call drop rate (%)	HO success rate (%)
Initially configuration	4,00	1521,29	0,00	602,94	0,27	0,00	100,00
Offset increased to 3 dB	2,00	1537,41	0,00	661,85	0,29	0,00	100,00
Difference	-50,00%	1,06%	0,00%	9,77%	7,75%	0,00%	0,00%

Table 8: Maximum values in whole network

Maximum values per cell					
	Amount of Hos	DL user throughput (kbps)	E-RAB abnormal releases	UL user throughput (kbps)	Amount of users
Initially configuration	740,00	15177,63	17,00	5722,77	42,70
Offset increased to 3 dB	172,00	15664,67	15,00	5492,98	39,21
Difference	-76,76%	3,21%	-11,76%	-4,02%	-8,18%

The average amount of handovers was decreased by 45,29% and the median value dropped to half of the initial, although the amount of active users was slightly increased. Considering the slight increase in the amount of active users, the amount of handovers per user was decreased by 47,28%, which is close to the estimation of 50% reduction given in section 4.4.1. The difference was the largest in problematic cells constantly causing large numbers of handovers. This can be seen from the 76,76% decrease in the maximum amount of handovers per hour in one cell. The distribution of handovers per cell prior and after the modification can be seen in figure 24. To increase the readability of the figure, the distribution only covers the samples that did not have zero handovers.

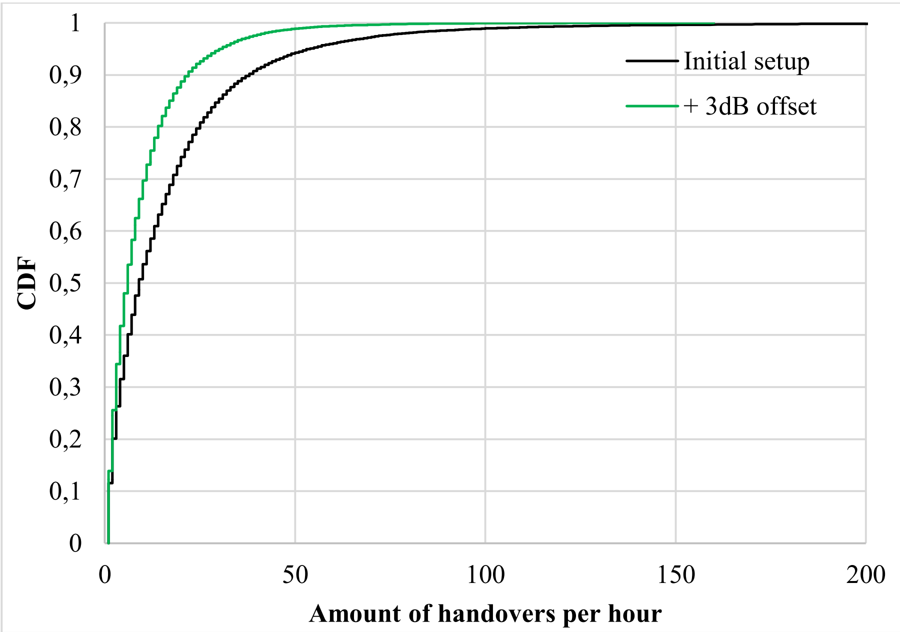

Figure 24: Distribution of handover amount per cell

Besides the huge decrease in amount of handovers, all other KPIs showed positive results as well. Both UL and DL user throughput was increased, the amount of E-RAB abnormal releases was decreased, call drop rate was decreased and handover success rate remained equal. The differences were only minor and may have been caused by the randomness of customer behavior. However, it is safe to say that no negative effects were caused. If the amount of users were higher, the additional overhead caused by the unnecessary handovers would have probably affected the service more. That could have been seen as a larger difference in the other KPIs but amount of handovers.

Even though the impact was positive, the situation could be further optimized. After the modifications, few eNBs were still identified to perform more handovers than they should in an optimal situation. However, fine tuning the values further to more optimal ones would require much longer measurement periods and excessive drive testing. This was not feasible in the time frame of this thesis.

4.4.4 Summary

The objective of the measurements related to the handover parameters was to remove unnecessary handovers by finding optimal values for A3offset, A3hysteresis and timetotriggerA3. The tests were first run on four eNBs (12 cells). It was found out that 12 cells were not enough to provide reliable results because of the fact that radically changing behavior of one or few users under those eNBs could bias the results. However, with larger modifications of the parameters, vague trends how offset + hysteresis affect the chosen KPIs were identified. This was done for two different scenarios; eNBs that covers mostly mobile users and eNBs that cover mostly stationary users. The results are presented in figure 23.

Based on these estimations, new values for the handover parameters were set to every eNB in the network. The offset value was increased 200%, from 1 dB to 3 dB. TTT value was kept the same at 320 ms and hysteresis also remained the same 1dB. This provided results close to the estimation done in section 4.4.1. On average the amount of handovers were decreased 45,29% per cell and 47,28% per user. Additionally, both UL and DL user throughput were slightly increased, amount E-RAB abnormal releases were decreased and call drop rate were decreased as well. The success rate of handovers remained equal as it already was very high.

4.5 Uplink coordinated multipoint transmission

UL CoMP is theoretically a very promising way to enhance the network performance in terms of user throughput and total capacity as presented in section 3.1. In this section the effects of uplink CoMP are tested in a live LTE network and the results are analyzed. The measurements are divided into two parts. First part covers mobile drive test measurements around one eNB, which are analyzed in section 4.5.1. The second part (4.5.2) is a KPI based analysis in a larger set of eNBs. The performance is mainly considered in terms of application layer and PUSCH throughputs. The used uplink coordination method was joint reception.

4.5.1 Mobile measurements

The studies show that the benefit of UL CoMP highly depends on radio conditions [26] [28]. The objective of the mobile measurements was to evaluate the average benefit of UL CoMP under the area of its effect. An assumption of average throughput increase and total capacity gain network wide is made, which is further tested in section 4.5.2. Also, the effects of UL CoMP to the correlation between radio conditions and UL throughput is analyzed.

Test setup

The mobile measurements were performed under one eNB using Nemo Outdoor software. The criteria to choose the eNB was very low utilization and possibility to drive around it. For each measurement, the same route under two cells of the eNB was driven on a car. The route is shown in figure 25. It was chosen so that the radio conditions would change from good to bad during the route and both of the cells would cover the whole route. Perfect radio conditions were unwanted because CoMP would not be able to improve the situation as the used MCS would already be very high [39]. Very poor radio conditions were also avoided as in normally the UE would most likely hand over to another eNB if the radio conditions were very poor.

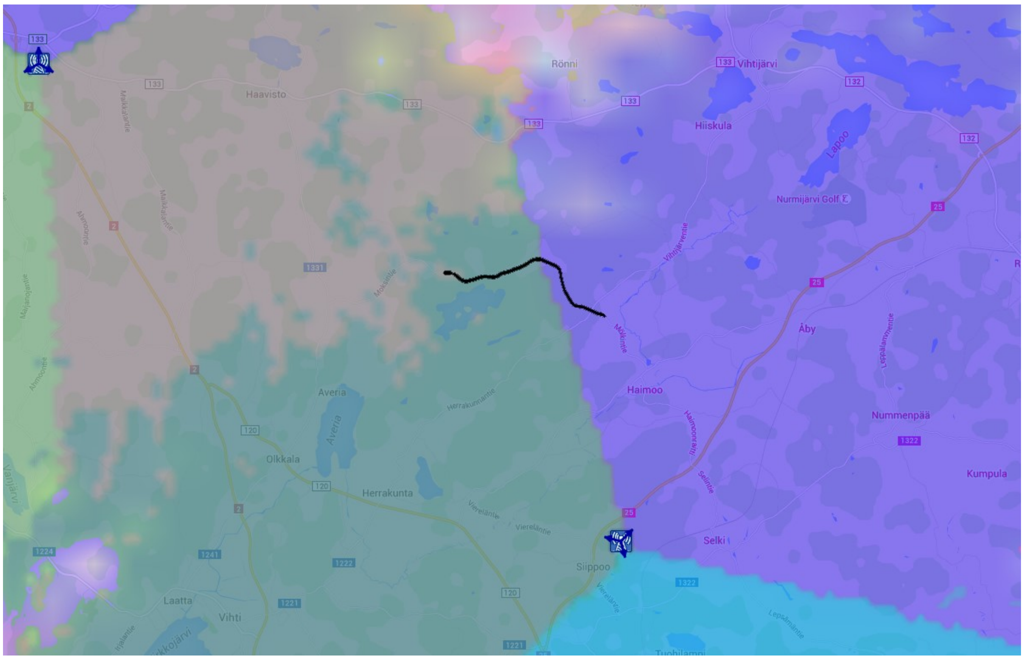

Figure 25: The UL CoMP mobile measurement route

The route was driven 29 times in total, each one lasting approximately 5 minutes. Three runs had to be discarded due to insufficient data caused by external distraction such as other active users in the cell. See section 4.1 for measuring in live network. From the 26 successful measurements 13 times the eNB did not have UL CoMP activated and 13 times it did. The measurements were done during the same day and the radio conditions remained equal.

All LTE network neighbor relations were removed from the chosen eNB to prevent handovers to other eNBs. This way it was made sure that either one of the two cells would remain as the serving cell during the measurements. The scheduling algorithm was not reconfigured for the test and thus one UE could only utilize 70% of the total resource blocks. For 3 MHz bandwidth 70% means constantly allocating 10,5 PRBs. As the minimum schedulable unit (one SB) equals two adjacent resource blocks [18], the amount of allocated resource blocks varied between 8 and 12 so that the average would remain at 70%.

The throughput was measured by running an ftp-transfer to a server connected to Gi interface in EPC. This way it was made sure that the only restricting network entity would be the radio interface. All other links had much higher capacity and low latency. Both application layer throughput and the PUSCH throughput were monitored and are presented in the results.

Results

All results were analyzed with Nemo Analyze software. [40] The data consisted of 5498 measurement samples with CoMP configuration and 5336 samples with default configuration. Default configuration means the situation prior implementing coordinated multipoint functionalities. All other configuration was identical on both cases. All measurement samples at the time when resource block utilization was less than 65% were discarded to avoid the resource block utilization to affect the results. The resource block utilization values were the average values over the sample period. The average sample length was 515 ms. The filtered and unfiltered resource block utilizations are presented in figure 26. About 20% of all measurement samples were dropped resulting the average resource block utilization to differ between CoMP and non-CoMP measurements by only 0,18%. The difference was so small that PRB utilization did not need to be considered while analyzing the results.

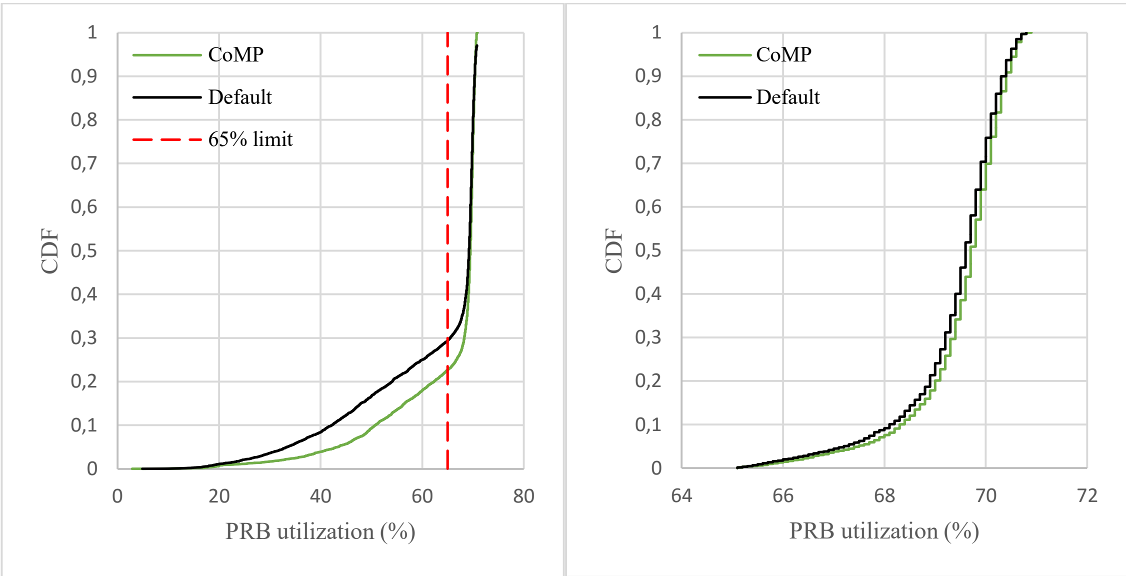

Figure 26: Resource block utilization

On the route, the serving cell RSRP varied between -81,5 dBm and -118,3 dBm during CoMP measurements and between -79,4 dBm and -118,6 dBm during non-CoMP measurements. Average RSRP was -101,4 dBm and -101,7 dBm respectively. The RSRP distributions can be seen in figure 27. As well as the resource block utilization, the average RSRP difference was so small that it did not affect the results. The average RSRP of the neighboring cell was -107,27 dBm during non-CoMP measurements and -107,22 during the CoMP measurements. The difference was only 0,05%, which can be said to be equal.

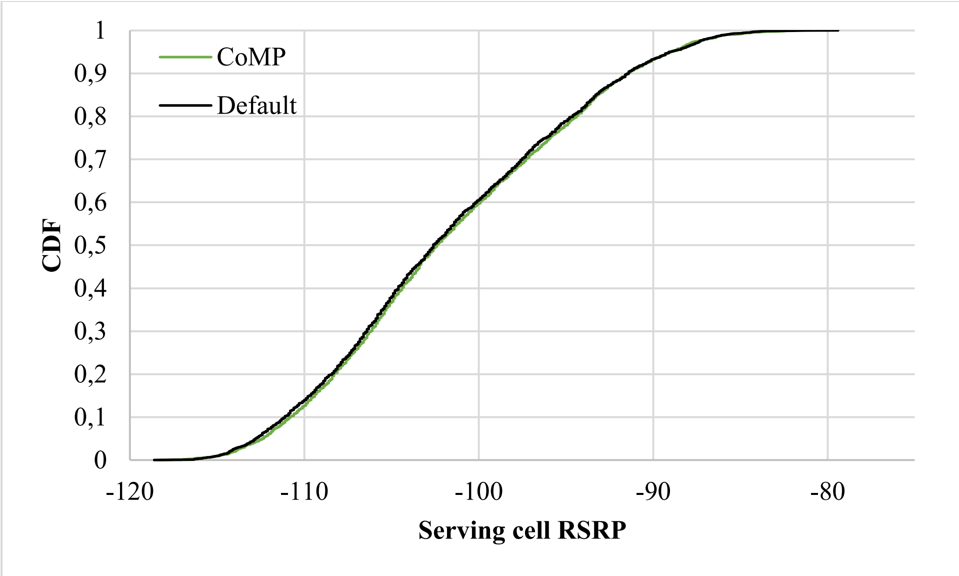

Figure 27: Distribution of serving cell RSRP

As the radio conditions were the same and the resource block usage was filtered to the same level, the measurement sets can be quite reliably compared in terms of throughput. The average and median values for serving cell RSRPs, PRB utilization, application layer throughput and PUSCH bitrate are presented in table 9. Also the difference between default and CoMP measurements is presented.

Table 9: CoMP mobile measurement results

Default				
	RSRP (dBm)	PRB utilization (%)	Application throughput (Kbps)	PUSCH throughput (Kbps)
Average	-101.73	69.39	2391.6	3021.3
Median	-102.6	69.6	1914.2	2474.5

CoMP				
	RSRP (dBm)	PRB utilization (%)	Application throughput (Kbps)	PUSCH throughput (Kbps)
Average	-101.44	69.51	2649	3242.8
Median	-102.4	69.7	2176	2848.7

Change in percent				
	RSRP (dBm)	PRB utilization (%)	Application throughput (Kbps)	PUSCH throughput (Kbps)
Average	-0.29%	0.18%	10.76%	7.33%
Median	-0.19%	0.14%	13.67%	15.12%

The average increase on the test route was 10,76% for the application throughput and 7,33% for the PUSCH bitrate. The median value was increased more than the average value, meaning that the increase was bigger under bad radio conditions as the theory predicted [26]. Besides increased average service level, this also means increased fairness in the network. The throughput distribution has been illustrated on figure 28. The average amount of increase in the worst 25% was 16,35% for the PUSCH throughput and 22,49% for the application layer throughput. The median amounts of increase were respectively 14,40% and 19,48%. The improvement at cell edges is remarkable but did not quite reach the suggested cell edge user improvement by Irmer et al [26].

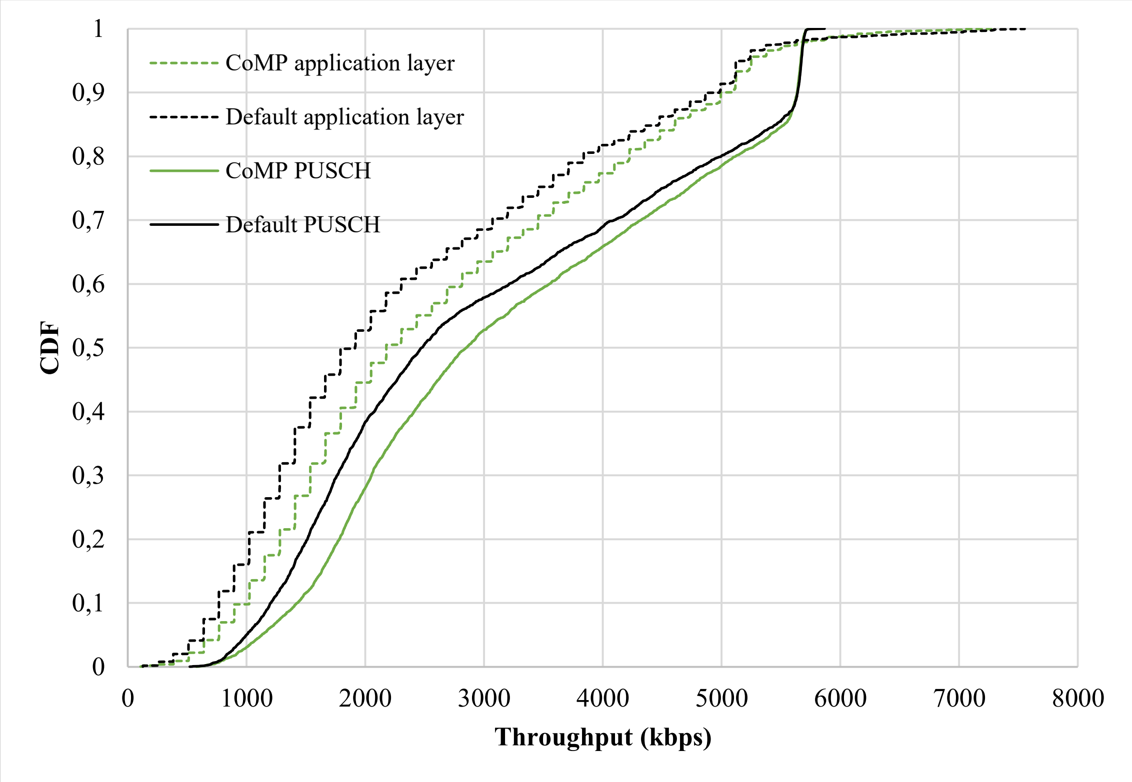

Figure 28: Throughput distribution in CoMP mobile measurements

It can be seen that most of the benefit is gained in the worse half of the distribution. The higher the throughput originally was, the less benefit is gained through CoMP transmission. It should also be noted that no benefit is gained under very good conditions because the best possible MCS is already in use. Most of the throughput gain comes from the possibility to use higher MCS due to higher signal to noise ratio (SNR) when using CoMP. The SNR levels are presented in figure 29. It can be observed that activating CoMP had a positive effect on signal to noise ratio, especially at lower SNR levels. The correlation between increase in SNR and increase on application throughput was 0,719 and 0,689 between SNR and PUSCH bitrate. The strong correlation between increase in SNR and increase in throughput shows that UL CoMP advantages are mainly achieved by increased SNR levels.

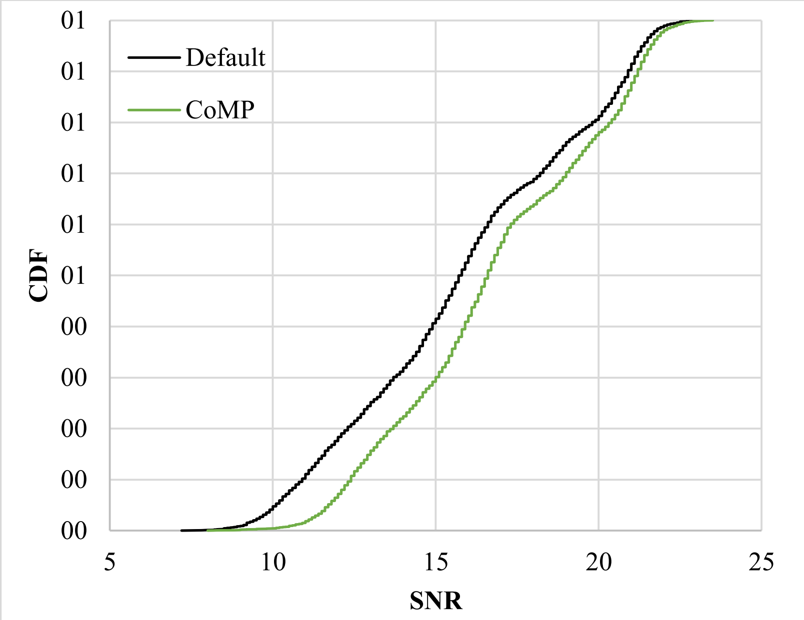

Figure 29: SNR distribution during CoMP mobile measurements

On figure 30 the correlation between serving cell RSRP and PUSCH throughput is presented. The linear lines present the trends with CoMP and without it. It can be seen that with worse serving cell RSRP levels, CoMP can be used to achieve higher throughput values. The benefit of CoMP decreases as RSRP increases. The RSRP levels required to achieve the maximum throughput is the same with or without CoMP.

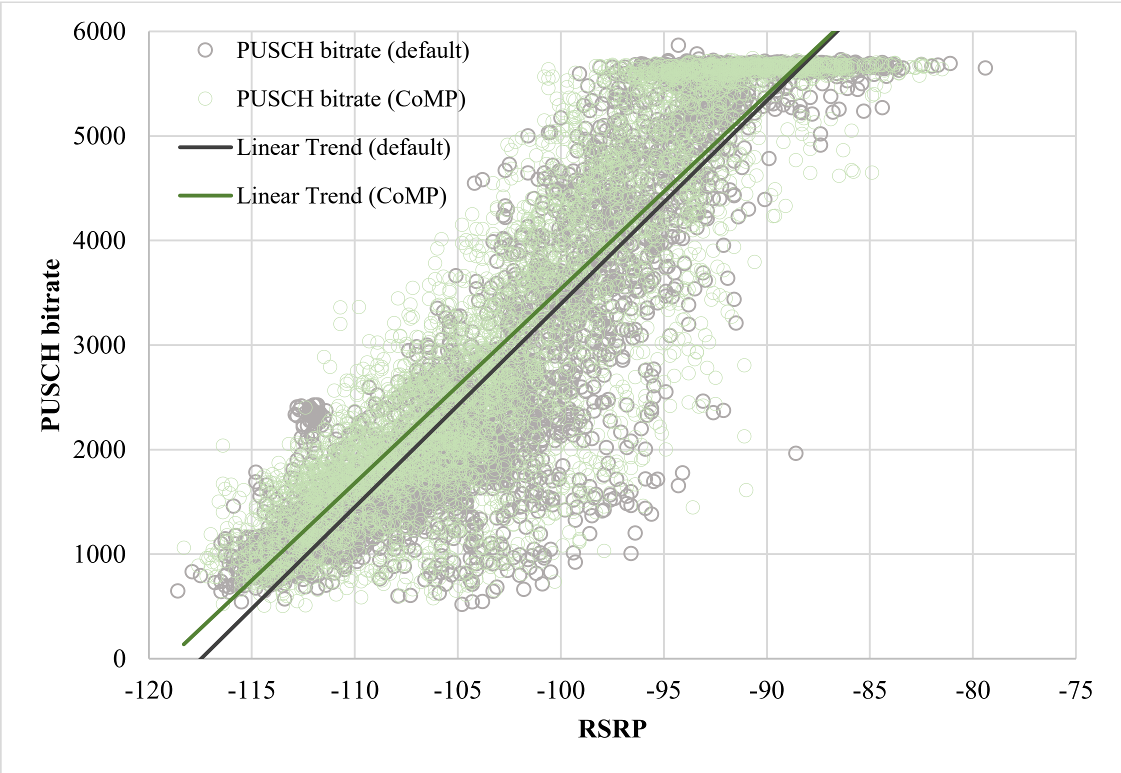

Figure 30: Correlation between RSRP and PUSCH bitrate and linear trendlines

Assuming that the test site represents an average site in the network, the total benefit of CoMP can be estimated from the coverage simulations. Based on the CDMA2000 network simulations provided by a third party network planning company and the test drive around the site, the cells overlap on approximately 25-30% of the total eNB coverage area. The average increase in the test area was 10,76% which means that the average throughput in the eNB coverage would be increased by approximately 3%. The average throughput in the whole network would be increased by the same 3% if it would be implemented to the whole network. This assumption is very directional as every eNB is different in the means of environment. It does not take into account restriction caused by lack of capacity either. However, the effect can be said to be clearly positive and it should be pursued.

4.5.2 KPI analysis

Based on the results in mobile measurements, UL CoMP was tested in 10 eNBs all over the network to see the actual effect in areas containing more users. The eNBs were chosen to represent the whole network and thus had to be chosen all over Finland. Few minimum criteria were set. The sites needed to have at least one cell whose utilization would be in top 30% of the network in terms of traffic volume and resource block utilization. However, none of the eNBs could contain two or more cells that would have been very highly utilized. This way it was made sure that empty eNBs were not chosen and the lack of capacity would not affect the results. Also, only sites that used 3 MHz bandwidth in every cell were chosen.

The implementation method of CoMP depends on the vendor and the performance may change between vendors. Also, CoMP operation under eNBs whose all cells are highly utilized may change between the vendors. Investigating CoMP performance under highly utilized eNBs is out of this study as the test network does not currently offer proper environment for it. It is assumed that CoMP benefits would suffer under such eNBs as all resource blocks in the neighboring cells are already allocated to other users and cannot be used for CoMP.

In the EASY-C project field trial OFDMA was used also for uplink because CoMP on SC-FDMA channel would cause a lot more complex equalization [26]. Thus, it was expected that using CoMP on SC-FDMA channel might cause some negative effects like higher CPU utilization of the eNBs. If the CPU load of the eNBs were high, it would increase the power consumption and might also affect the service in negative manner as well. Thus, several KPIs were chosen to track whether any negative effects are caused by UL CoMP.

Test setup

The KPI setup was similar to the cyclic prefix tests. KPI Data from chosen eNBs was collected by a network monitoring server. The measurement period was one week prior and one week after the activation of UL CoMP function. The measurement sample duration was 60 minutes and each sample value represented the average rate or cumulative amount over the 60 minute period, depending on the KPI. Totally 5040 measurement samples of each KPI were collected for both default and UL CoMP configuration. Monitored KPIs were UL user throughput, UL traffic volume, UL PRB utilization, PRBs allocated for UL CoMP use, amount of active users, eNB CPU load, eNB power consumption, amount of E-RAB abnormal releases, handover success rate and RRC setup success rate. The main KPI for performance improvements was the average UL user throughput.

Results

On average 31,07% of all active users under the eNBs were using UL CoMP transmission, which is close to the estimation of the effective CoMP area in section 4.5.1. Nine out of the ten test eNBs contained at least some users which were under conditions where they could use UL CoMP feature during the measurement period. It means that one site was unaffected by the changes made for this test and thus the data from it is not considered for the throughput and capacity analysis. The amount of active users in the nine other eNBs decreased 2,93% which can be considered to be close enough for the results to be meaningful. However, the data usage profile changed significantly as can be seen on figure 31. Hence, the results cannot be acknowledged to be accurate.

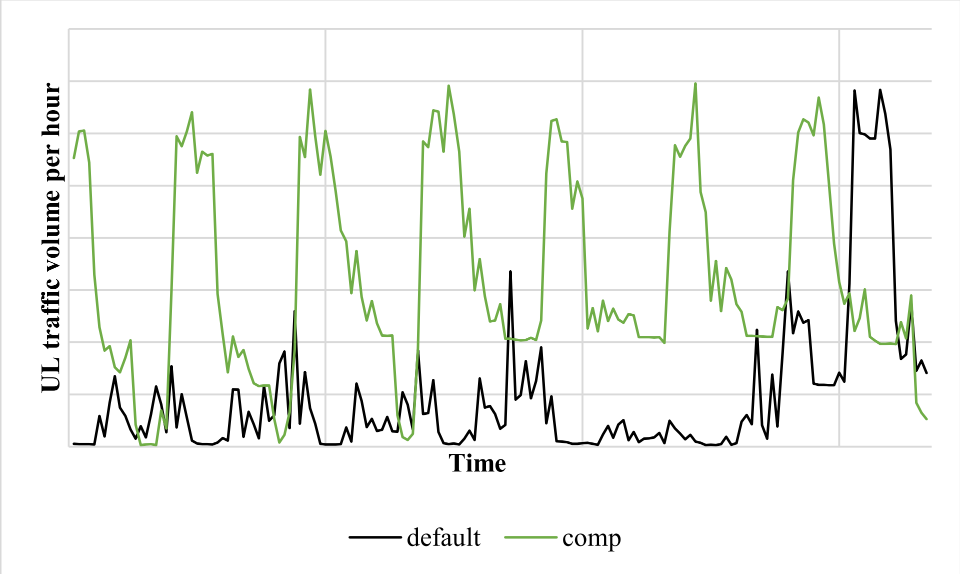

Figure 31: Traffic profile during the CoMP measurement on test sites

Under four out of the nine eNBs, the uplink user traffic increased 30-250 %, under three sites the traffic decreased 10-50% and under two sites it remained close to equal. However, the average user throughput increased under all of the eNBs despite the changes in traffic volume. The amount of increase varied a lot between the sites, from 3% to 40%. The average increase in the all nine eNBs was 22,04 % and average increase in the sites where the traffic volume was close to equal was 9,20%. The traffic volume was considered to be close to equal if it had changed less than 15%. Four eNBs passed the criteria. The average values of uplink traffic volume per hour, uplink user throughput, uplink resource block utilization, amount of active users and amount of active users using UL CoMP from the nine sites can be seen on table 10.

Table 10: Average and median KPI values of CoMP test sites

		UL traffic volume per hour (Mbits)	Throughput (kbps)	Active Users	CoMP Users	PRB utilization (%)
Average values	Default	122,9	829,2	2,82	0	25,44 %
	CoMP	359,5	987,1	2,73	0,85	26,27 %
	Difference	192,60 %	19,05 %	-2,93 %		3,29 %
Median values	Default	5,95	634,7	2,04	0	25,33 %
	CoMP	6,1	704,7	1,68	0,3	25,33 %
	Difference	3,11 %	11,03 %	-17,25 %		0,00 %

The uplink traffic volume median value was much lower than the average value because part of the cells was almost unused, especially during the night time. According to the median values the effect of activating UL CoMP was positive in the terms of average user throughput, which were the main KPI.

Activating the UL CoMP feature did not reveal any negative effects in this test setup. All the KPIs used for measuring the possible negative effects remained equal during the whole measurement period. Even CPU utilization and power consumption of the eNBs, which were expected to possibly rise, remained equal.

4.5.3 Summary

The UL CoMP measurements showed that intra-site uplink coordinated multipoint transmission significantly increases the uplink performance for the cell edge users when SC-FDMA is used. The users under bad radio conditions could gain application layer uplink throughput improvements up to 22%. That is close to the study by Irmer et al which suggested that intra-site joint detection could increase the cell edge throughput by 24% when OFDMA transmission is used [26].

The measurements were performed in two parts; first mobile measurements by driving under one eNB and after that KPI analysis about the UL CoMP effects on 10 eNBs. The average increase in application layer uplink throughput according to the drive test results was 10,76% and the median value was 13,67%. The results are presented in table 8. The increase in throughput was mainly gained by higher MCS enabled by better SNR.

The KPI analysis did not produce reliable results about the throughput increase due to the challenges of measuring in live network. However, it showed that on average 31,07% of the users were able to use CoMP transmission. The KPI analysis also showed that activating UL CoMP feature did not increase the CPU load or power consumption of the eNBs even if SC-FDMA is used. No other negative effects were found either.

The measurements did not include testing in congested environment and it is assumed that CoMP would not offer as good performance in such scenarios. Uplink CoMP does not affect the downlink transmission and thus other methods must be used to enhance downlink transmission.

4.6 Discussion

In this section the reliability of the measurements is further discussed and the results are evaluated from the perspective of typical customer profiles. The customer profiles are presented in section 4.2. Few proposals for future research are also mentioned.

Two measurement methods were used for the tests in this thesis, active field testing and passive KPI analysis. Field testing was only used for UL CoMP performance measurements as both handover parameter measurements and cyclic prefix length measurements required data from very wide area and from multiple sources. Such an excessive field testing was not feasible within the time frame of this thesis.

The number of samples provided for each measurement was from 5000 to 340000. All the results were tested with T-test in order to ensure the statistical significance of the measurement data. The null hypothesis of equal data sets was rejected in every test performed. In that sense, all the measurements provided enough measurement samples for reliable comparison. However the changing conditions, caused by the difference in customer behavior, significantly decreased the reliability of the results. This applies only to the KPI measurements as the drive test results were mostly unaffected by other users.

The field test measurements were performed with a commercial LTE UE that supports LTE band 31. The software used for the testing was Nemo Outdoor, which is highly appreciated in the industry [41]. They were also performed under conditions where the influence of other users was minimized. An eNB that served no users most of the time was chosen and all measurement samples that had been biased by another user under the same cell were deleted. It was also made sure that the conditions remained equal throughout the measurements. Thus, the field trial results can be kept fairly reliable.

The conclusions based on the KPI analyses, should be only kept directional. They show the magnitude of the impacts but due to the constantly varying end user behavior, the numbers should not be considered exact. The amount of active users and the way they use the service vary. The more eNBs and consequently more users are considered in a measurement, the more reliable it is. Thus, the cyclic prefix length measurements and the handover parameter measurements performed for the whole network can be said to be fairly reliable. It must still be remembered that the network was on a pilot phase during the measurement periods. The results may have been different if the network was utilized on higher level.

The conditions for every measurement were such that the network was not congested. It would have been interesting to see how UL CoMP affects the performance under a congested eNB and how the users under neighboring cells are affected. The reduction of ping pong effect could have also affected the other KPIs more under heavily utilized network. That could be studied in a future research. However, building such a laboratory environment is challenging and doing any experiments that might deteriorate the service is risky in heavily utilized commercial network.

Each of the three methods evaluated in this thesis was measured individually. The combined effect of them was out of the scope of this thesis, and should be tested in future. It can be assumed that if the offset + hysteresis values are set high, the benefit of UL CoMP transmission is increased, which can be explained by the higher average RSRP of the neighboring cell. That is caused by the UEs remaining connected to the current cell more tightly after the neighboring cells become stronger.

The network topology was such that UL CoMP could only be tested intra-site. Another interesting issue and topic for future research would be inter-site CoMP operation. It can be argued to be unnecessary for 450 MHz band because the base stations are located so far from each other and inter-site CoMP sets very strict requirements for the X2 interfaces between them.

The use of normal cyclic prefix length instead of extended mostly benefits the vehicle installations and fixed wireless customer categories. Over 20% increase in capacity and maximum throughput highly increases the service level for such customers. Capacity is not an important factor for M2M customers and reliable solution customers. They would either remain unaffected or maybe even suffer from the modification due to possible holes in the coverage. However, extended cyclic prefix must be supported by the UE, which significantly reduces the range of applicable end devices. Thus, extended cyclic prefix should only be used in special cases.

Implementing UL CoMP transmission significantly increases the capacity at cell edges and slightly the capacity of whole network, meaning that fairness in the network is increased. That is beneficial especially for the highly mobile customers using high amounts of data, in this case the vehicle installation customers. The fixed wireless customers located at cell edges also benefit significantly.

M2M customers usually do not require high capacity but they exist in large quantities creating a lot of overhead. The additional capacity gained from UL CoMP or normal cyclic prefix is mainly irrelevant for M2M customers. Instead, minimizing the unnecessary handovers is essential for the network performance. Thus close attention should be given to the handover parameters in case operator's customer base consists of massive amounts of M2M customers.

Many previous studies have considered these topics in theory and provided calculations and simulations about the outcome. However, performance evaluations in commercial networks are rare. Furthermore, research on low frequency and narrow LTE band such as band 31 has not been previously published. This thesis provided one of the first published measurements related to UL CoMP, cyclic prefix length and handover parameter optimization in commercial network. Generally the results follow to the expectations provided by previous studies and simulations.

5 Conclusions

Band 31, that uses 450 MHz frequency, has so far been unusual for LTE network. Instead, it is widely used for CDMA2000 networks. Due to the better performance of LTE, there is interest to migrate these networks from CDMA2000 to LTE. In some cases, this can be done very easily by upgrading only the software and parts of the hardware. This might cause the network performance to be suboptimal.

This thesis presented a study on methods to improve LTE network performance after CDMA2000 to LTE migration. The literature review gave an overview on principles of Long Term Evolution and LTE network optimization. Also, four promising methods to improve network performance were introduced. Three out of the four were tested in commercial LTE network. The tested methods were cyclic prefix length, uplink coordinated multipoint (CoMP) transmission and handover parameter optimization. The results about performance evaluation of these methods are presented in this thesis.

The methods have been studied before but most studies have used a lot higher frequency and wider bandwidth. Also, studies in commercial networks have not been published before.

5.1 Objectives and Results

The main objective of this thesis was to study the ways to cost effectively improve the performance of 450 MHz LTE network after CDMA to LTE migration. All the measurements were performed in a commercial LTE network. The main measurement method was to analyze network KPI values in order to see the effects in large scale. To achieve more reliable data, some field measurements were performed. As the network was still in a pilot phase during the measurements, the amount of users was relatively low in many parts of the network.

The KPI analysis method, especially when only few eNBs were considered, was found unreliable due to varying user behavior. Consequently the results of KPI analyses should be considered directional and the magnitude of the improvements should be emphasized.

Extended cyclic prefix (CP) is specified by 3GPP to be used in scenarios where multipath propagation causes delay spread to be larger than normal cyclic prefix length. As no scientific material about using it in LTE 450 MHz networks was found at the time when Ukkoverkot CDMA2000 network was migrated to LTE, a hypothesis was made that the large cells of 450 MHz LTE network require extended cyclic prefix to be used. This hypothesis was proven wrong in this thesis. After changing to normal cyclic prefix, only two geographical locations were identified to have probably suffered from the modification. If less than 1% of the cells are negatively affected, it is better to handle each of those cases with physical modification and keep the cyclic prefix length normal. Normal cyclic prefix provided 21,64% increase for average uplink user throughput and 28,51% for downlink compared to extended CP. Additionally, normal CP enables wider selection of end devices.

LTE band 31 has been widely proposed as an M2M traffic band in the future. Due to the huge amount of devices in such networks, minimizing the amount of overhead is essential. Optimizing the handover parameters is one way to greatly influence the amount of signaling overhead, especially in suboptimal situation after CDMA2000 to LTE migration. It was shown, that changing the parameter values hugely affects the amount of handovers. Relatively light test setup was enough to decrease the average amount of handovers 45,29% per cell and 47,28% per user. The parameter values were set to 3 dB offset, 1 dB hysteresis and 320 ms TTT, instead of the original 1 dB offset, 1dB hysteresis and 320 ms TTT. By making the conditions of A3 event stricter, not only the amount of handovers was decreased, but the average DL and UL throughput was also slightly increased. With a longer measurement period and supporting field testing, more optimal parameter values may have been found. Such excessive field testing was not feasible in the time frame of this research.

Coordinated multipoint (CoMP) transmission has recently been studied a lot. Many calculations and simulations show that it can increase the spectral efficiency and capacity significantly, especially at the cell edges. As the requirements for inter-site CoMP are very strict and downlink CoMP requires support from the UE, only intra-site UL CoMP could be tested. It can be concluded that UL CoMP increased the cell edge throughput as expected, but it did not quite reach the numbers presented in simulation studies done on higher frequency and wider bandwidth. Depending on the conditions, UL throughput was increased up to 22% and the average increase was 10,76% under the area where UL CoMP could be used. It was also shown that on average 31,07% of users were in an area where they could benefit of intra-site UL CoMP. As normally in LTE, SC-FDMA was used for uplink transmission.

All of the three tests were done individually but it is assumed that UL CoMP would enhance the performance more if implemented together with stricter handover parameters.

5.2 Future work

At the time the measurements were done, nearly all of the eNBs in the network used old CDMA2000 radios and thus SIMO transmission. One of the key features in LTE is MIMO transmission. Performing similar test, especially UL CoMP performance evaluation, in network using only MIMO transmission should be considered.

The CoMP measurements were also performed with only one UE and in non-congested environment, as it was not possible to artificially create the environment for such tests. Studying CoMP transmission in such environment would be a clear continuum for the study presented in this thesis.

Band 31 is 5 MHz wide. That provides the possibility to use either 1,4 MHz, 3 MHz or 5 MHz bandwidth. Mainly cells with 3 MHz bandwidth were studied in this thesis. Only the tests done in the whole network also covered few cells with 1,4 MHz bandwidth. Local spectrum limitations, co-existence of CDMA2000 and LTE or frequency reuse could be reasons to use different center frequencies and bandwidths in the different cells. The co-existence of such eNBs might cause anomalies at the areas where such cells overlap. The handover success rate or amount E-RAB abnormal releases might become worse because the reference and synchronization signals from the other cell are getting overwhelmed by the payload from the other. Investigating such problems and trying to improve service around those areas would be an interesting topic for future research.

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