Evaluating the effectiveness of Cooperative/Coordinated Multipoint (CoMP) LTE feature in Uplink and Downlink Transmissions

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This minor dissertation is submitted in partial fulfilment of the academic requirements
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As the candidate's supervisor, I have approved this minor dissertation for submission.

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Date: 2017-10-28

Declaration

I declare that this dissertation is my own work. Where collaboration with other people has taken place, or material generated by other researchers is included, the parties and/or materials are indicated in the acknowledgements or are explicitly stated with references as appropriate.

This work is being submitted for the Master of Science in Electrical Engineering at the University of Cape Town. It has not been submitted to any other university for any other degree or examination.

Mark Charangwa Signed 29 March 2017

Name Date

Dedication

I dedicate this work to everyone who provided technical, moral and financial support.

Abstract

Shannon demonstrated that the channel capacity depends of the ratio of the received signal power to interference plus noise power (SINR). Inter-cell interference caused by neighbouring base stations (BSs) has been identified as one of the most severe problem towards the deployment of LTE technology as it can significantly deteriorate the performance of cell-side User Equipment (UE).

However, because of regulatory and radiation restrictions as well as operational costs, signal power may only be increased only up to a certain limit to reduce the interference. The other common radio propagation impairment is multipath. Multipath refers to a scenario where multiple copies of a signal propagate to a receiver using different paths. The paths can be created due to signal reflection, scattering and diffraction. As will be discussed later the effects of multipath contribute little to intercell interference because multipath characteristics such as delay spread are compensated for using cyclic prefixes.

In this work, we will limit our scope to interference as it has been identified as the main cause of performance degradation for cell edge users due to the full frequency reuse technique used in LTE. To mitigate interference 3GPP devised options of increasing the capacity in LTE-Advanced Release 12 which include the use of spectral aggregation, employing Multiple Input and Multiple Output (MIMO) Antenna techniques, deploying more base stations and micro and femto cells, increasing the degree of sectorisation and Coordinated Multipoint (CoMP). We are primarily interested in evaluating performance improvements introduced when uplink (UL) and downlink (DL) coordinated/cooperative multipoint (CoMP) is enabled in LTE Advanced Release 12 as a way of reducing interference among sites. The CoMP option of reducing interference does not require deployment of new equipment compared to the other options mentioned above hence network deployment costs are minimal. CoMP in theory is known to reduce interference especially for cell edge users and therefore improves network fairness. With CoMP, multiple points coordinate with each other such that transmission of signals to and from other points do not incur serious interference or the interference can even be exploited as a meaningful signal.

In September 2011 work on specifications for CoMP support was started in 3GPP LTE-Advanced as one of the core features in LTE-Advanced Release 11 to improve cell edge user throughput as well as the average network throughput.

We set to do field measurements in the evaluation of the effectiveness of CoMP in LTE. 3GPP LTE Release 12 was used and cell edge users' performance was the focus. The network operates in 2330 – 2350 MHz band (Channel 40). From the field measurements, it was demonstrated that the CoMP (Scenario 2) feature indeed effective in improving service quality/user experience/fairness for cell edge users. CoMP inherently improves network capacity. A seven (7) percent throughput was noticed.

Acknowledgements

I would like to sincerely thank my family, Professor M. E. Dlodlo, Syed Baarrij for their patience, insight and invaluable contribution into my work.

My family had to put up with the time that I invested into this work as well as providing moral support.

Professor M. E. Dlodlo, my supervisor, scrutinised my work and provided technical guidance in addition to moral support and encouragement.

Syed Baarrij is the Project Manager for Liquid Telecom Group and the overseer in the deployment of LTE in Zambia. He provided technical direction and allowed me to use the network for my research

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Chapter 1
1 Introduction

1.1 Background

As more and more applications that try to make our day to day life convenient and improve business processes are being developed and churned out, so have the requirements for high data rates (throughput) also increased. Up until 3G and 4G technologies cellular networks employed the concept of network planning with frequency reuse patterns leading to inefficient scarce resource utilisation. LTE-Advanced uses the concept of full frequency reuse to address the inefficiencies associated with network planning [1] leading yet to another problem of intra-cell and inter-cell interference. However, theoretically CoMP has been shown to be able to reduce interference and therefore address interference caused by full frequency reuse.

To understand the CoMP scheme there is need to fully appreciate the technologies used in LTE and the LTE architecture itself. Therefore, in this document we are going to review the theory of technologies that form the foundation of the LTE technology and these include Information Theory, Orthogonal Frequency Division Multiplexing, Multiple Antenna Techniques, LTE air interface as applicable to LTE and finally, our focus, Cooperative MultiPoint (CoMP). Are the review we will then conduct measurements in a real and live commercial network to ascertain practically the interference reduction and therefore performance improvements brought by CoMP

1.2 Objectives and Goals

The objective of the dissertation is to practically and quantitatively evaluate the benefits derived from using or activating the CoMP feature in an LTE network.

The project uses Intra-freq HO out Success Rate (%), DL Throughput /DL User Edge Throughput (Kbps), Call drop Rate (%) and RRC/S1 Signalling/ E-RAB Success Rate (%) Key Performance Indicators (KPIs) in quantifying performance improvements brought about by using CoMP.

1.3 Scope and limitations

The project scope is limited to using CoMP as a technological feature to reduce interference as it has been identified as the main cause of performance degradation for cell edge users caused by full frequency reuse technique used in LTE.

From Equation 1 below we can clearly see that the major limiting factor for a radio system with frequency reuse is interference (I) since there is not much we can do about the noise (N) hence motivating the basis for this work.

To mitigate interference 3GPP devised options of increasing the capacity in LTE-Advanced Release 12 which include the use of spectral aggregation, employing Multiple Input and Multiple Output (MIMO) Antenna techniques, deploying more base stations and micro and femto cells, increasing the degree of sectorisation and Coordinated Multipoint (CoMP).

Also, from a practical point of view since this is a live commercial network we had to be cautious in terms disrupting customers' services, that is, not to cause significant downtime. We therefore could not manage all CoMP parameters as to evaluate the maximum performance improvement we can achieve with this feature.

$$SINR = \frac{s}{N + I} \tag{1}$$

Where: S = the signal strength,

I = interference from other base stations, and,

N = thermal noise

1.4 Strategy

The LTE network is benchmarked six days before enabling the CoMP features and measurements (KPIs) will be collected for another six days after CoMP is enabled.

These KPIs are collected before and after enabling the CoMP feature using a commercial Operations Support Systems (OSS) and well as conducting drive tests to generate traffic.

The KPIs are chosen for reasons below and the detailed explanation of the KPIs is in chapter 4;

Intra-freq HO out Success Rate (%) – for a handover to be successful the radio channel must be reliable. Therefore, we can safely infer that a high HO success rate indicated that good channel. Conversely, a low HO success rate infers that the radio channel between a UE and a eNodeB is not good. This is especially true in the network being used because fibre backhaul is used and the MME is lightly loaded since the network is still new.

DL Throughput /DL User Edge Throughput (Kbps) - this KPI provided an indication of the overall user experience.

Call drop Rate (%) - this retainability KPI occurs when a radio access bearer (E-RAB) is abnormally released. Again, this points to the channel state between the UE and eNodeB

RRC/S1 Signalling/ E-RAB Success Rate (%) - according to [2] the KPI's measurement scope is in a cell or radio network. A high E-RAB success rate directly relates to QoS Class Identifiers (QCI).

1.5 Summary

In this introductory chapter, the objectives and goals of this investigation were outlined. The scope, strategy and limitations are also defined.

Since the project is based on measurements it was necessary for Key Performance Indicated (KPIs) that are relevant in evaluating the effectiveness of enabling the CoMP feature to be stated.

We looked at some of the motives for the need of more bandwidth. In Chapter 2 we review the Information theory, Orthogonal Frequency Division Multiplexing, LTE as a technology employing (Information Theory and OFDM) and the CoMP feature.

1.6 Project Outline

This introductory Chapter gave an outline of the Objectives, Goals, Scope and the limitations encountered in the field experiments carried out. The Chapter also explained the strategy used in evaluating the LTE improvements brought about by using CoMP, that is, benchmarking and relevant KPIs measured.

Chapter 2 provides literature review of the theories, building blocks and core technologies used in LTE.

Chapter 3 explains the field measurement setup used in our experiment.

Chapter 4 presents the research output as well as explanations of the relevant KPIs used in evaluating the effectiveness of the CoMP feature.

Finally, conclusions and recommendations with respect to the field measurements and output, and recommendations for further work to be carried out in LTE are made in Chapter 5. I am of the strong opinion that as LTE matures “best practices” documents which can be used as references by Network Operators should also be produced so that maximum performance is realised in LTE deployments.

Chapter 2

2 Literature Review

2.1 Information Theory

In [3], Shannon provided the basic theoretical tools necessary in determining the maximum rate, also known as the channel capacity, by which information can be transferred over a given communication channel reliably or in other words error free. For practical purposes, the tools are relatively complicated in the general case. However, for the special case of communication link impaired only by additive white Gaussian noise, for instance a radio link, the channel capacity C is given by the simple expression (2)[3]

$$C = BW \cdot \log_2\left(1 + \frac{S}{N}\right) \tag{2}$$

From (2) we can clearly observe that there are two main parameters that can be varied to achieve a certain capacity – the signal to noise ratio (S/N) and bandwidth (BW) (Hz). Due to the shortage or finiteness or scarcity of radio spectrum one can increase the bandwidth only to a certain extent. Also, the equipment which operate with high bandwidth are also relatively expensive because the filter design is generally complicated. As indicated above, techniques such as Multiple Input and Multiple Output (MIMO) Antenna techniques, deploying more base stations and micro and femto cells, increasing the degree of sectorisation and Coordinated Multipoint (CoMP). CoMP features are proposed and are continuously being researched on and implemented to improve the SINR.

2.1.1 Channel Coding in LTE

With reference to LTE Channel coding consists mainly of the Cyclic Redundancy Check and Turbo Coding schemes. Below we will take a review of both schemes.

2.1.1.1 Cyclic Redundancy Check

In digital communication systems and storage devices the error-detection code/scheme predominantly employed is the cyclic redundancy check (CRC) to detect data errors due to a number of phenomenon. Blocks of data entering these systems have a short value calculated and attached. The calculation is based on the remainder of a polynomial division of the block of data contents. Upon retrieval of the data the exact same calculation is repeated and the newly calculated value is matched to the one calculated when the blocks of data entered the system. An error would have occurred when these CRC values do not match warranting an error correction action can be taken on the corrupted data.

gCRC24A and gCRC24B schemes are two cyclic redundancy check schemes used for a Physical Downlink Shared Channel (PDSCH) used in LTE. These schemes use a 24 parity bits length though they use different cyclic generator polynomials. The ‘gCRC24A’ focuses on a transport block, while the ‘gCRC24B’ focuses on the code block, which is the segmentation of a transport block when the size of a transport block is larger than the upper limit (6144 bits). See figure 1.

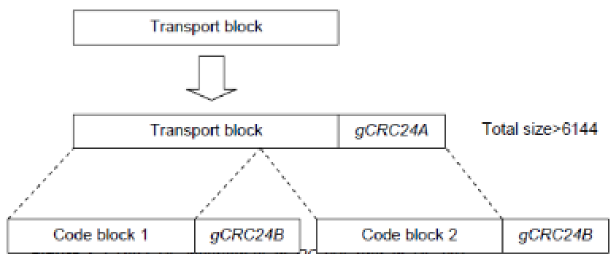


Figure 1

2.1.1.2 Turbo Coding

Physical Downlink Shared Channel (PDSCH) channel coding scheme uses Turbo Coding. Turbo coding is considered a robust channel coding. Scheme because when using an AWGN channel, the performance of Turbo codes can approach to the theoretical Shannon capacity limits. An example of a typical error performance of an un-coded versus a turbo coded forward error correction coded system is shown in figure 2.

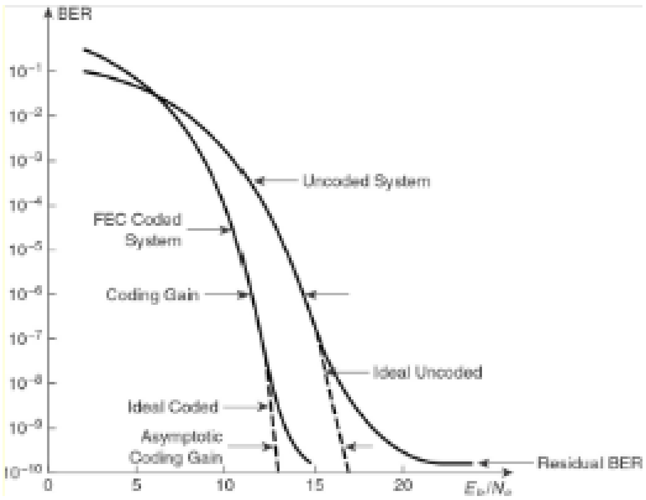


Figure 2

The scheme of the Turbo encoder for LTE is a Parallel Concatenated Convolutional Code (PCCC) with two 8-state constituent encoders and one Turbo code internal interleaver. The theoretical structure of a Turbo encoder is depicted in figure 3.

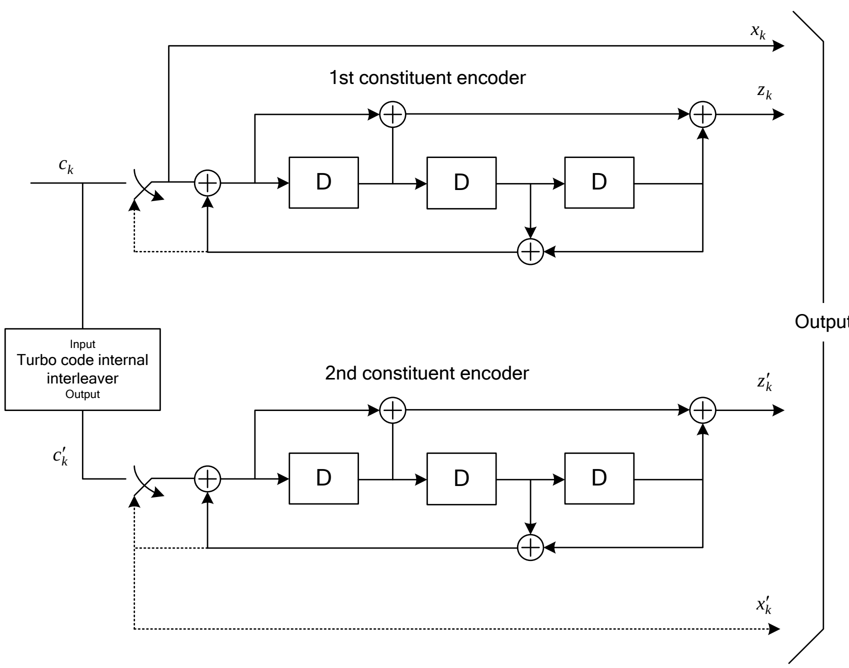


Figure 3 [4]

The tail bits are independently appended at the end of each information bit stream to clean up the memory of all registers, for example, by terminating the encoder trellis to a zero state. Generally, the length of the tail bits is equal to the number of registers in one constituent encoder (3 registers are used in one constituent encoder in LTE). The sequence of tail bits is rearranged and 4 tail bits are attached after each information bit stream. Hence, the length of each bit stream becomes 4+K.

With the three information bit streams, the original Turbo coding rate is 1/3. However, after padding tail bits, the coding rate will decrease a bit. Furthermore, by puncturing or repeating the output of Turbo coding, it can accomplish an alterable channel coding rate under different scenarios, according to the channel conditions. Such process is implemented by the circular buffer at the rate-matching block.

2.2 Orthogonal Frequency Division Multiplexing Overview

Wireless channels have memory, due to the multipath phenomenon, making them dispersive which in turn causes inter-symbol interference (ISI). Typical outdoor environments like GSM experience maximum delay spreads in the order of 15microseconds [3]. The Inter-symbol interference is more pronounced when the transmitted symbol duration is short compared to the delay spread. In other words, transmission error statistics can be made negligible if the transmitted symbol duration is made significantly longer relative to the delay spread. One method of combating the inter-symbol interference is to employ equalisation in receivers. An alternative solution is the use of OFDM. The use of orthogonal subcarriers allows more subcarriers per bandwidth resulting in an increase in spectral efficiency.

OFDM employs multiple overlapping carriers in the frequency domain. OFDM is different from a pure multicarrier system in that OFDM uses many narrowband subcarriers whereas a multicarrier system consists of a smaller number of subcarriers with wide bandwidth compared to OFDM. Rather than transmit a high-rate stream of data with a single subcarrier, OFDM makes use of many closely spaced orthogonal subcarriers that are transmitted in parallel. Orthogonal Frequency-Division Multiplex was named accordingly because two modulated OFDM subcarriers x and y are mutually orthogonal over the time interval $mT_u =< t < (m+1)\,T_u$, that is:

$$\int_{mT_u}^{(m+1)T_u} x_{k_1}(t)x^*_{k_2}(t)\,dt = \int_{mT_u}^{(m+1)T_u} a_{k_1}a^*_{k_2}e^{j2\pi k_1\Delta ft}e^{-j2\pi k_2\Delta ft}\,dt = 0 \quad \text{for } k_1 \neq k_2$$

[3]

Where T_u is the symbol duration

A basic OFDM signal in complex baseband notation for a per subcarrier modulation symbol time is represented as;

$$x(t) = \sum_{k=0}^{N_c-1} x_k(t) = \sum_{k=0}^{N_c-1} a_k^{(m)} e^{j2\pi k\Delta ft}$$

[3]

The number of OFDM subcarriers can range from less than one hundred to several thousand, with the subcarrier spacing ranging from several hundred kHz down to a few kHz. The size of subcarrier spacing to use depends on the environment the network is to operate in. The environment can be described by such aspects as the maximum expected radio-channel frequency selectivity (maximum expected time dispersion) and the maximum expected rate of channel variations (maximum expected Doppler spread).

2.2.1 OFDM Implementation using IFFT/FFT Processing

Digital signal processing transforms like the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) are very crucial from an orthogonal frequency division multiplexing point of view because they can be perceived as mapping digitally modulated input data (data symbols) onto the orthogonal subcarriers. When an orthogonal frequency division system is implemented digitally input data bits are grouped and mapped to source data symbols that are a complex number representing the modulation constellation point, for example the binary phase shift keying or quadrature amplitude modulation symbols that would be present in a single subcarrier system.

The transmitter treats the complex source symbols as being in the frequency-domain and these symbols in turn form the inputs to an IFFT block to transform the data into the time-domain. N source symbols are taken by the IFFT at a time with each of these N input symbols having a symbol period of T seconds. Here N is the number of subcarriers in the system. The output of the IFFT is N orthogonal sinusoids and these orthogonal sinusoids each have a different frequency and the lowest frequency being a DC.

As stated above the input symbols are complex values representing the mapped constellation point and therefore specify the phase and amplitude for that subcarrier sinusoid. The output of the IFFT process is a summation of all N sinusoids. Therefore, the IFFT block is a simple method of modulating data onto the N orthogonal subcarriers. Thus, a single OFDM symbol is made up of a block of N output samples from the IFFT.

After some additional processing, the time-domain signal that results from the IFFT is transmitted across the radio channel. At the receiver, an FFT block is used to process the received signal and bring it into the frequency domain which is used to recover the original data bits.

2.2.2 Channel Coding with OFDM

Every wireless channel is subject to frequency selectivity meaning that the channel quality varies in the frequency domain. WCDMA uses a single wideband channel, hence the modulated symbol is transmitted over the entire signal bandwidth. For these wideband technologies or implementations with a highly frequency selective channel, the symbol is transmitted in both good and bad frequency bands as depicted in figure 4 (a) below.

However, since OFDM uses narrow subcarriers meaning that the OFDM modulation symbol is transmitted over a relatively narrow bandwidth. Therefore, in a frequency selective channel an entire modulation symbol can be confined to a frequency band with poor quality. It is against this that the basic error-rate performance of OFDM transmission over a frequency selective channel is relatively poor and especially much worse than the basic error rate in the case of a single wideband carrier. See figure 4 (b).

The poor error rate performance of OFDM warranted the need to implement a form of channel coding. Channel coding means that the bit of information to be transmitted is spread over several code bits.

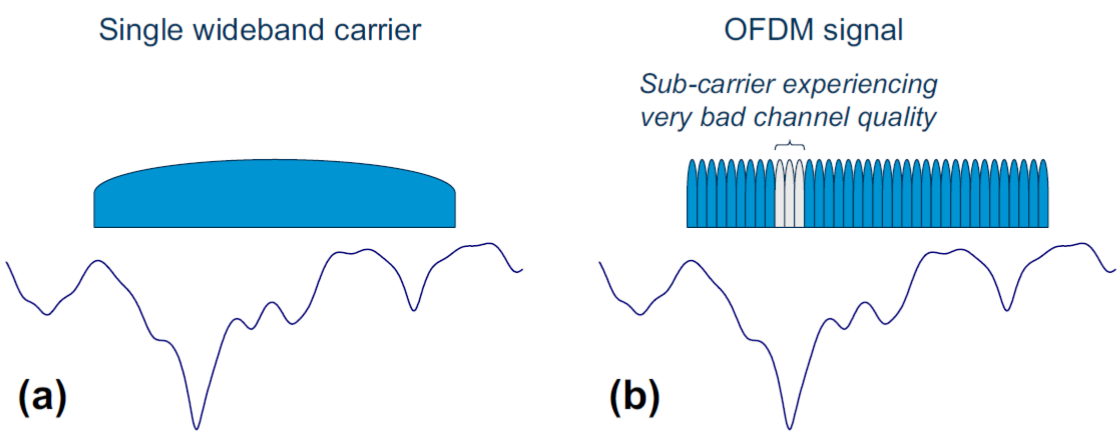


Figure 4 [5]

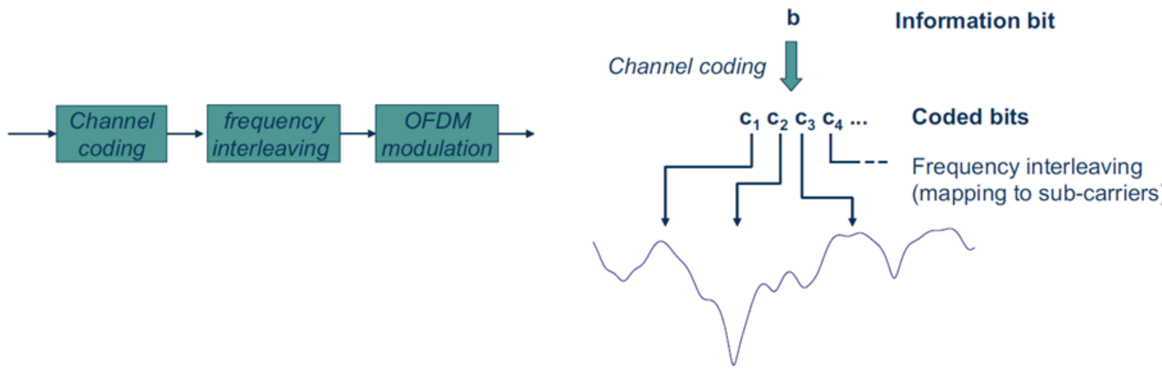


Figure 5 [5]

Frequency interleaving on the other hand means that the code bits are distributed bits in the frequency domain. As illustrated in figure 5 above the code bits will experience diversity when transmitted over frequency selective channel. It is quite evident that channel coding in combination with frequency interleaving is an indispensable tool for OFDM transmission to be able to improve performance in a frequency-selective channel at the same time benefiting from the frequency diversity [14].

2.2.3 OFDM Parameters

For OFDM to be used in mobile networks the below parameters need to be decided upon for good performance achievement.

- The subcarrier spacing, $\triangle f$.

- The number of subcarriers Nc, which, together with the subcarrier spacing, determines the overall transmission bandwidth of the OFDM signal.

- The cyclic-prefix length T_{CP}. Together with the subcarrier spacing $\triangle f \doteq 1/T_u$ the cyclic-prefix length determines the overall OFDM symbol time $T = T_{CP} + T_u$ or, equivalently, the OFDM symbol rate [14].

2.2.4 Summary

This section explored the benefits and implementation strategies for Orthogonal Frequency Division Multiplexing. The section also expanded on the concept of coding as introduced in section 2.1, in particular, and as it is used in LTE. It also introduced some of the parameters to be decided upon to achieve high performance. Section 2.3 is used to introduce the Long-Term Evolution (LTE) technology, its goals, design and architecture.

2.3 LTE Design Targets, Basics and Building Blocks

3GPP started working on LTE in 2004 by defining its performance and capability targets [1]. The objective was to design a new radio protocol suited for packet switched data only. Among the targets included peak data rates, spectral efficiency, control and data plane latency as well as user/system throughput. Release 8 was the first LTE specifications and completed in 2008. Release 12 which forms the basis for this document was largely completed in March 2015.

Design targets for LTE Release 12 are documented in 3GPP TR 25.913. The target capability when operating in a 20 MHz spectrum allocation is a peak data rate of 100 Mbit/s in the downlink and 50 Mbit/s in the uplink.

With LTE release 10 3GPP did not specify exact targets for peak data rates. However, peak spectral efficiency targets of like 6.75 bit/s/MHz and for uplink 15 bit/s/Hz for downlink were specified relative to the channel. The above peak spectral efficiency targets assumed 20MHz channel bandwidth, 4x4 MIMO in the uplink and 8x8 MIMO in the downlink.

2.3.1 LTE Basics

In UMTS the base station is named NodeB and in LTE it is renamed an Evolved Node B. The renaming emphasises the added functionalities of these base stations. For instance, the eNodeBs carry the handover functionality of the radio connection to a neighbouring base station which was carried out by the RNC in UMTS [6].

For the purposes of this work we will mainly look at the radio aspect of LTE. LTE uses OFDM as the downlink transmission scheme and SC-OFDM in the uplink to combat peak average power radio (PAPR) effects inherent with OFDM which affect the design and cost of power amplifiers in the base station receive path (uplink). The OFDMA symbol is a combination of symbols from other subcarriers hence in-phase subcarrier voltages can add within the symbol resulting in high instantaneous power that is much higher than the average power. The transmitter power amplifier efficiency is reduced due to this dramatic power variation. For this reason, SC-FDMA is used in the uplink to save on terminal battery. Another characteristic of LTE is its spectrum flexibility in that

LTE transmission scheme employs the use of shared-channel transmission with users dynamically sharing the overall time–frequency resource dynamically. The shared channel transmission scheme is very appropriate since LTE uses packet data communication. The task of sharing the time-frequency resources is done what is called, and appropriately named, a scheduler. Since the scheduler varies resource assignment based on data rate requirements by users. This makes the scheduler as another dimension in the determination of the overall system capacity. Put differently the scheduler is seen to perform the rate adaption function. The scheduler also considers the channel conditions in its scheduling of resources and this is known as channel dependant scheduling. Channel-dependent scheduling relies on channel-quality variations between users to obtain a gain in system capacity.

In LTE, scheduling decisions can be taken as often as once every 1 ms and with a granularity of 180Hz in the frequency domain.

The RAN is responsible for all radio-related functionality of the overall network including, for example, scheduling, radio-resource handling, retransmission protocols, coding and various multi-antenna schemes.

The LTE radio-access network uses a flat architecture with a single type of node called the eNodeB. The eNodeB is a logical node responsible for all radio-related functions in one or several cells. One common implementation of an eNodeB is a three-sector site, where a base station is handling transmissions in three cells. The X2 interface that connects the eNodeBs is used for supporting active mobility and multi-cell radio resource management (RRM) functions e.g. ICIC and CoMP.

2.3.2 Radio Protocol Structure

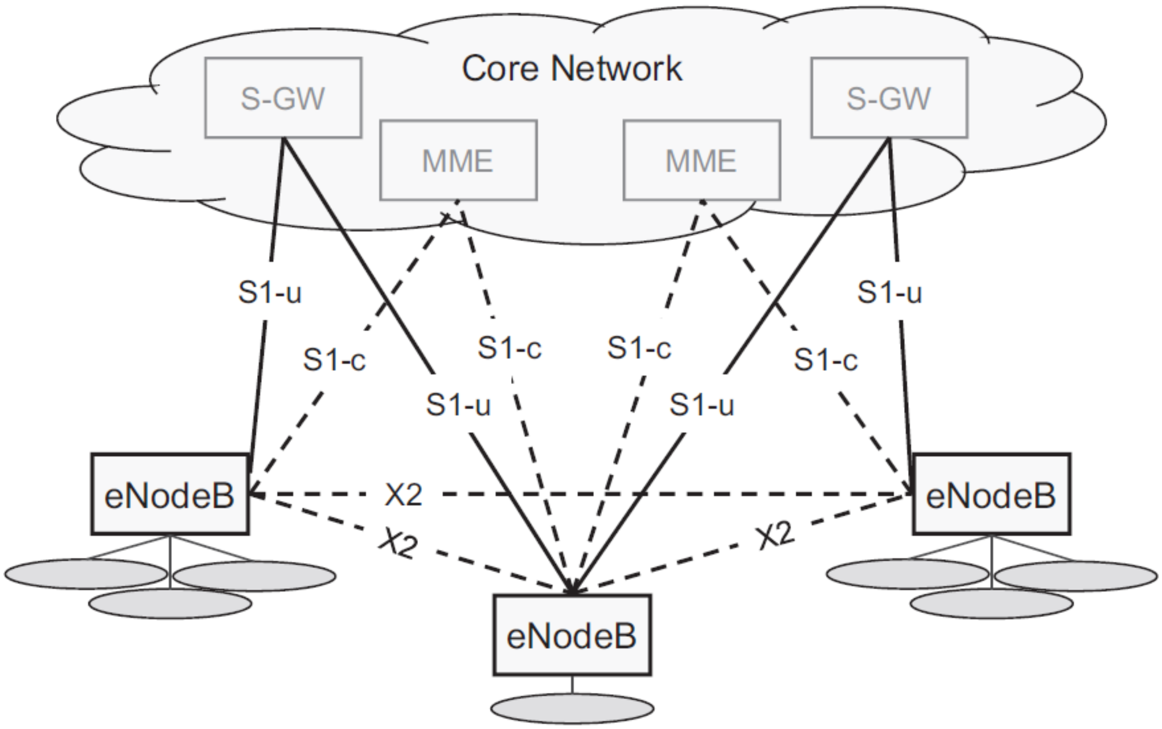


Figure 6 [7]

Figure 7 below shows the layered structure of LTE radio protocol architecture. The radio protocol layers include the Packet data convergence protocol (PDCP), radio link control (RLC), media access control (MAC) and the physical (PHY) layers. Header compression and ciphering at the transmitter and header decompression and deciphering at the receiver functions are carried out by the PDCP.

Radio-Link Control (RLC) takes care of the segmentation & concatenation, retransmissions, detection of duplications and naturally the in-sequence delivery to higher layers. As can be seen in figure 7, the radio link control renders services to the PDCP. Multiplexing of the logical channels is the responsibility of the medium-access control (MAC) as well as hybrid-ARQ retransmissions, and uplink and downlink scheduling. The scheduling functionality is in the eNodeB for both uplink and downlink.

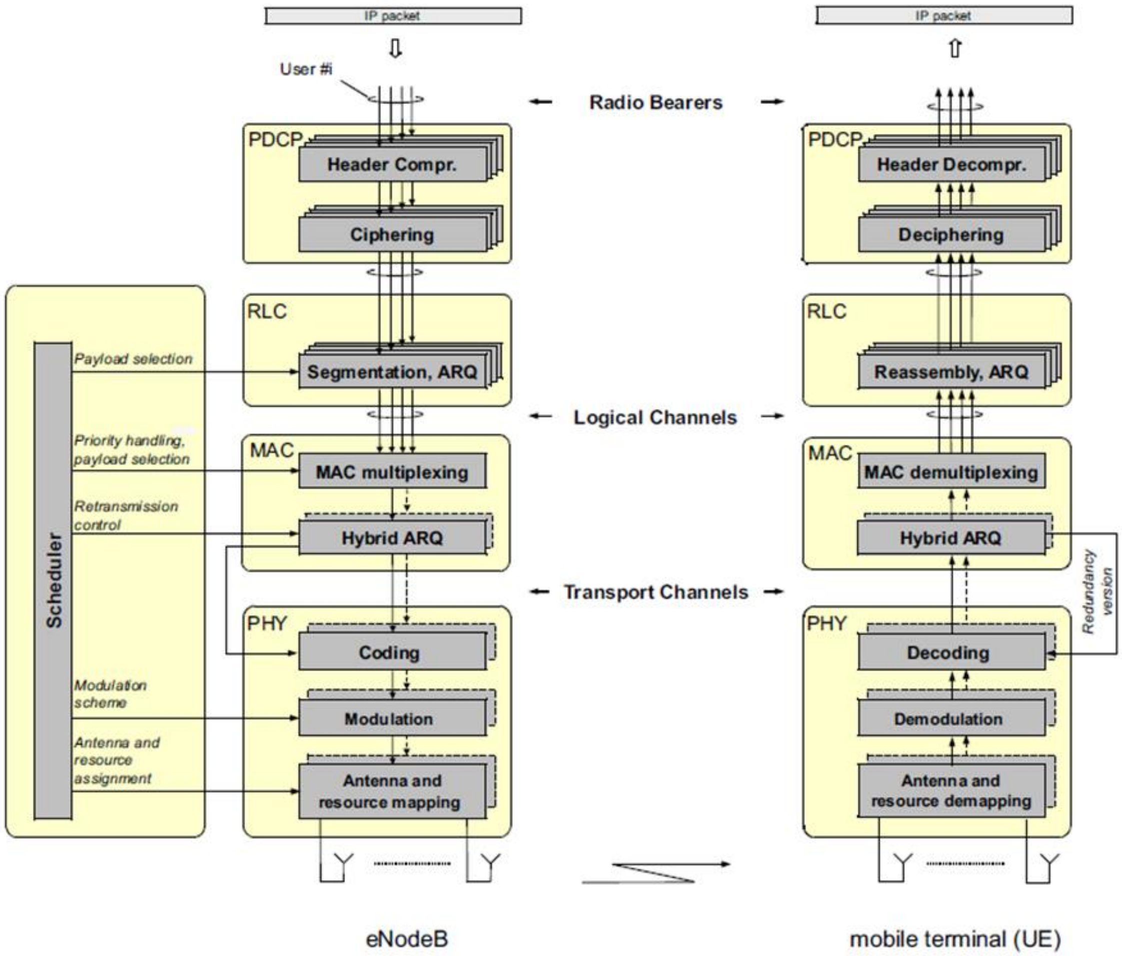


Figure 7 [7]

Coding or decoding, modulation or demodulation, multi-antenna mapping together with other physical layer functions are handled by the Physical Layer (PHY). The physical layer offers services to the MAC layer in the form of transport channels. Depending on how and the characteristics of the information to be transmitted on the radio interface define a transport channel.

Data on a transport channel is organized into transport blocks and at one transport block is transmitted in what is termed a Transmission Time Interval (TTI). The transport block transmitted on the radio interface is of dynamic size. One transport block is transmitted over the radio interface to and from a terminal when spatial multiplexing is not used. Were spatial multiplexing (MIMO) is used, a maximum of two transport blocks can be transmitted per TTI. Associated with each transport block is a Transport Format (TF), specifying how the transport block is to be transmitted over the radio interface. The transport format includes information about the transport-block size, the modulation-and-coding scheme, and the antenna mapping. By varying the transport format, the MAC layer can thus realize different data rates. Rate control is also known as transport-format selection.

2.3.3 Scheduler

With LTE data uses what is called a shared channel transmission, basically meaning that the time-frequency resources are dynamically allocated to users. This function of dynamically allocating resources is carried out by the scheduler which resides in the MAC layer. The scheduler has the autonomy to control assignment of uplink and downlink resources in terms of resource-block pairs. A resource block pair is defined as corresponding to a time-frequency unit of 1ms and 180 kHz.

For downlink transmissions, the eNodeB had to naturally perform or coordinate the TF selection. As alluded to above this is the selection of transport block size, modulation scheme, and antenna mapping. Downlink channel dependent scheduling is performed in conjunction with the channel state information as reported by user equipment.

In the uplink channel static information necessary for channel dependant scheduling can be based on the sounding reference signal transmitted from the UE the eNodeB requires to estimate the channel state.

Hybrid ARQ, HARQ in short, provides a mechanism of robustness against transmission errors in LTE. This is accomplished by having a receiver send an acknowledgement bit indicating success or fail in decoding a received. In the case of a decoding failure the transport block is retransmitted. HARQ is supported for Downlink Shared Channel (DLSCH) and the Uplink Shared Channel (ULSCH) traffic. Broadcast traffic types do not have the HARQ functionality since the traffic is intended multiple terminals.

2.3.4 Control Plane Protocols

Control messages can originate from the MME or RRC in the eNodeB and these messages are connection setup, mobility and security. The RRC controls the radio access network related procedures which include;

- Measurement configuration and reporting.
- Determination of user equipment capabilities
- Management of connections and this includes setting up bearers and mobility
- Broadcast of system information necessary for terminals to be able to communicate with cell.

RRC messages are transmitted to terminals using Signalling Radio Bearers (SRB) which are in turn mapped to the Common Control Channel (CCCH) during connection setup and to the Dedicated Control Channel (DCCH) thereafter.

A Bearer can be visualised as a pipe that connects two or more points in a communication system, through which the data flows.

More technically a bearer is a channel that carries user data, that is, a logical connection between different nodes that guarantees the quality of service attributes for packets flowing on the bearer. For quality of service guarantees it therefore implies that each bearer channel must be associated with QoS parameters. Examples of such parameters include delay, jitter and packet loss.

2.3.5 Physical Transmission Resources

In LTE both downlink and uplink transmissions use radio frames that are 10ms in duration. Two types of frames are defined or supported in the Evolved UTRAN. Type 1 is defined for Frequency Division duplexing and Type 2 for time division duplexing. A system frame number (SFN), which is a group of 10 bits, is used to number the frames. From the 10 bits, the integer values range from 0 to 1023.

Due to wireless characteristics like multipath which result in the wireless channel being dispersive two cyclic prefixes have been defined in LTE. The normal (short) cyclic prefixes are defines more for urban environments where there is a dense deployment of small cells. On the other hand, extended (long) cyclic prefixes is meant for environments with large cell deployments, like rural areas, were the delay spreads are long. Also, the extended CP is suitable for transmissions like in MBSFN were many cells are involved in the transmission of a signal to terminals. In the case the extended CP mitigates against timing differences between cell transmissions.

The figure 8 and figure 9 below shows the structure of the both frame type 1 and type 2.

2.3.5.1 Frame Type 1

Type 1 frame structure is used for both full-duplex frequency division duplexing as well as hall duplex frequency division duplexing schemes. In frame structure type 1, as illustrated in Figure 8, 10 equally subframes make one 10ms radio frame. Further each subframe is composed two consecutive and equally sized, a slot being 0.5ms in duration. It is in these 0.5ms slots that the OFDM symbols are contained. The number of OFDM symbols contained in each slot can be either be seven or six depending on whether the normal cyclic prefix or the extended cyclic prefix is used. As figure 8 below depicts, the useful symbol time is Tu 52048Ts 566:7 μs. For a normal cyclic prefix, the first symbol has a cyclic prefix lengths of TCP 5160Ts 55:2 μs [8].

The remaining six OFDM symbols have a cyclic prefix of length TCP 5144Ts 54:7 μs so that the different cyclic prefix lengths of the first symbol are to make the overall slot length in terms of time units divisible by 15,360. For the extended mode, the cyclic prefix is TCP 5512Ts 516:67 μs. The cyclic prefix duration is designed to be longer compared to the delay spread of a few microseconds normally experienced in real world environments. Urban environments usually have small cell sizes, for capacity reasons, and therefore the normal cyclic prefix is utilised for such environments. On the other hand, in very large cells the extended cyclic prefix is used.

A 1ms transmission time interval (TTI) is used for both E-UTRA downlink and uplink. The TTI is defined as the duration of the transmission of the physical layer encoded packets over the radio air-interface [8].

The number of sub-carriers used in the frequency domain varies from 128 to 2048, depending on the channel bandwidth. For instance, 512 and 1024 are used for 5 and 10 MHz bandwidths respectively. As discussed in section 3.7 a sub-carrier spacing of 15 kHz is used in LTE. [8].

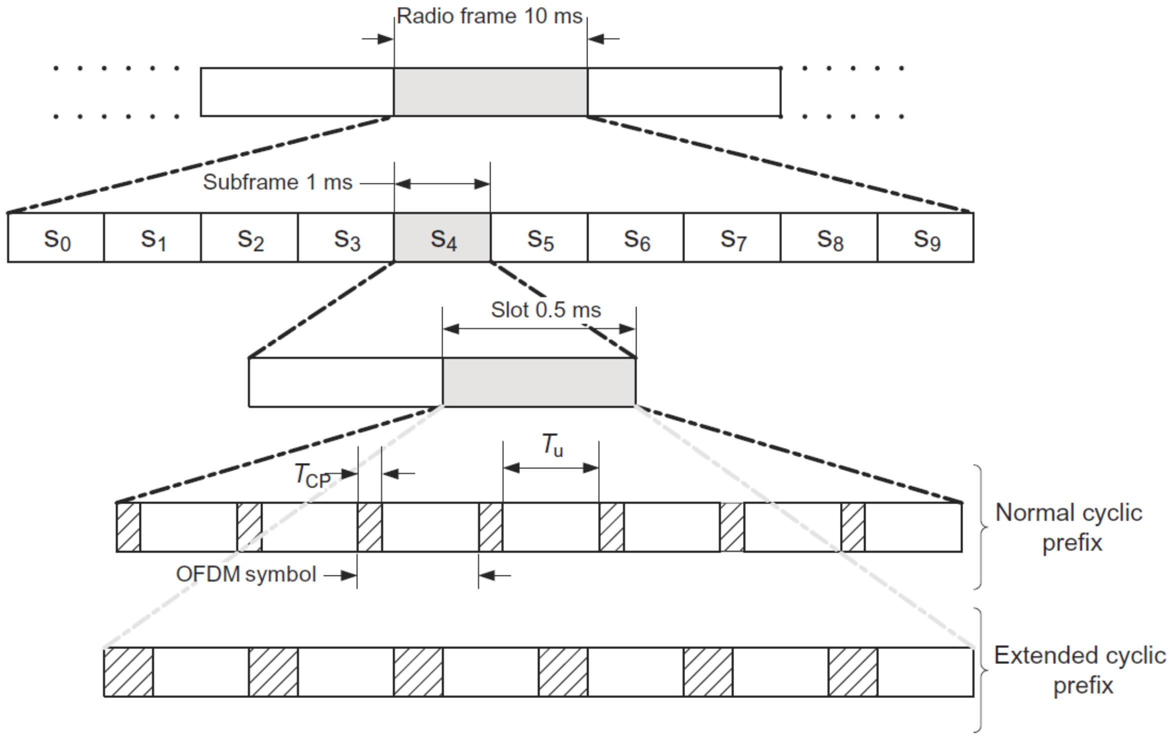


Figure 8 [4]

2.3.5.2 Frame Type 2

Frame structure type 2 are utilised in a time division duplexing duplex scheme in which the downlink and uplink transmissions are time-multiplexed over the extent of a radio frame, see Figure 9. Like Type 1 the radio frame is 10ms in length and is composed of two half-frames, with each half-frame consisting of five subframes of length 1 ms.

Table 1 below shows the 3GPP defined downlink/uplink ratios, that is, the ratio of downlink and uplink subframes in a frame and shown in Figure 9. In each radio subframe, DL represents the subframe meant for downlink transmissions, UL represents the subframe meant for uplink transmissions, and S defines a special subframe consisting of three fields - the downlink pilot time slot (DwPTS), GP, and uplink pilot time slot (UpPTS). The length of DwPTS and UpPTS are shown in Table 1 and the total length of DwPTS, GP, and UpPTS is always 1 ms.

In E-UTRA time division duplex (TDD) the supported downlink/uplink ratios are 5 and 10 ms downlink/uplink switching-point periodicity.

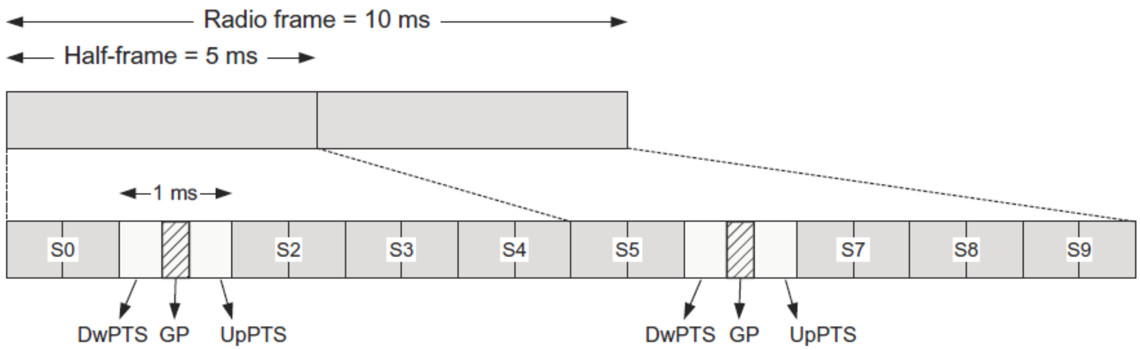


Figure 9 [4]

E-UTRA TDD Frame Configuration	Switching-Point Periodicity (ms)	Subframe Number									
		0	1	2	3	4	5	6	7	8	9
0	5	DL	S	UL	UL	UL	DL	S	UL	UL	UL
1	5	DL	S	UL	UL	DL	DL	S	UL	UL	DL
2	5	DL	S	UL	DL	DL	DL	S	UL	DL	DL
3	10	DL	S	UL	UL	UL	DL	DL	DL	DL	DL
4	10	DL	S	UL	UL	DL	DL	DL	DL	DL	DL
5	10	DL	S	UL	DL	DL	DL	DL	DL	DL	DL
6	5	DL	S	UL	UL	UL	DL	S	UL	UL	DL

Table 1 [4]

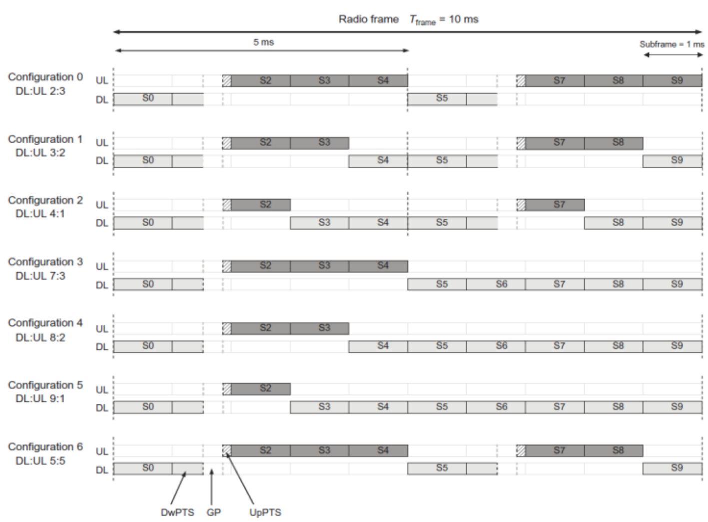


Figure 10 [4]

Special Subframe Configuration	Normal Cyclic Prefix in Downlink							Extended Cyclic Prefix in Downlink						
	DwPTS (Duration/ Number of OFDM Symbols)		GP (Number of OFDM Symbols)	UpPTS				DwPTS (Duration/ Number of OFDM Symbols)		GP (Number of OFDM Symbols)	UpPTS			
				Normal Cyclic Prefix in Uplink (Duration/ Number of OFDM Symbols)		Extended Cyclic Prefix in Uplink (Duration/ Number of OFDM Symbols)					Normal Cyclic Prefix in Uplink (Duration/ Number of OFDM Symbols)		Extended Cyclic Prefix in Uplink (Duration/ Number of OFDM Symbols)	
0	$6592T_s$	3	10					$7680T_s$	3	8				
1	$19760T_s$	9	4					$20480T_s$	8	3	$2192T_s$	1	$2560T_s$	1
2	$21952T_s$	10	3	$2192T_s$	1	$2560T_s$	1	$23040T_s$	9	2				
3	$24144T_s$	11	2					$25600T_s$	10	1				
4	$26336T_s$	12	1					$7680T_s$	3	7				
5	$6592T_s$	3	9					$20480T_s$	8	2	$4384T_s$	2	$5120T_s$	2
6	$19760T_s$	9	3					$23040T_s$	9	1				
7	$21952T_s$	10	2	$4384T_s$	2	$5120T_s$	2	$12800T_s$						
8	$24144T_s$	11	1					–	–	–	–	–	–	–
9	$13168T_s$	6	6					–	–	–	–	–	–	–

Table 2 [4]

A resource element is one subcarrier by one OFDM symbol duration and is the smallest physical resource in LTE. The minimum scheduling unit is 1ms therefore two resource blocks. The two resource blocks must be time consecutive and this is referred to as resource block pair. A carrier can have a minimum of 6 resource blocks and a maximum of 110.

A frame is 10ms and a subframe is 1ms. In the downlink, each subframe has two regions – one for control (control region) and the data region. The control region is used for L1/L2 signalling.

2.3.6 Physical Resource Block Structure

One sub-carrier over one OFDM symbol is the minimum time-frequency resource known as a resource element in LTE. In addition, a group of consecutive 12 subcarriers in frequency over one slot in time is called a Physical resource block (PRB). In LTE, each subcarrier is 15kHz. In turn, the transmission units are allocated in terms of number of PRB units.

Downlink physical channels defined in LTE are the physical broadcast channel (PBCH), physical control format indicator (PCFICH)

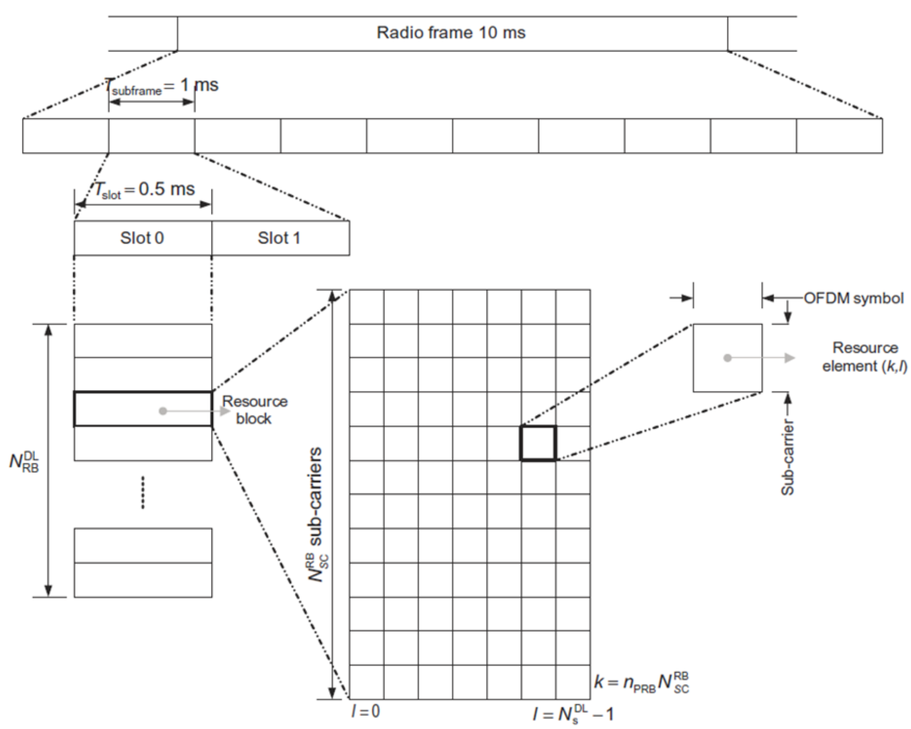


Figure 11 [4]

Physical broadcast channel (PBCH)

The master information block (MIB) part of the system information is transported using this channel. The PBCH channel is mapped to six resource blocks and the resource blocks are centred on the DC sub-carrier in subframe 0.

Physical control format indicator channel (PCFICH)

PCFICH is associated to the first orthogonal frequency division multiplexing in each downlink and has the size of the PDCCH. Its contents are the information on the number of orthogonal frequency division multiplexing symbols used for the downlink control region. The exact location of PCFICH is determined by the cell identity and system bandwidth.

Physical hybrid-ARQ indicator channel (PHICH)

The contents of this channel are the HARQ feedback regarding the uplink data transmissions.

Physical downlink control channel (PDCCH)

As the name appropriately implies the channels communicates to the user equipment about resource allocation, transport format, uplink grants and HARQ feedback. As indicated above the exact number of the orthogonal frequency division multiplexing for PDCCH is obtained in PCFICH. Multiple PDCCHs may be monitored by a UE. It also carries uplink power control commands.

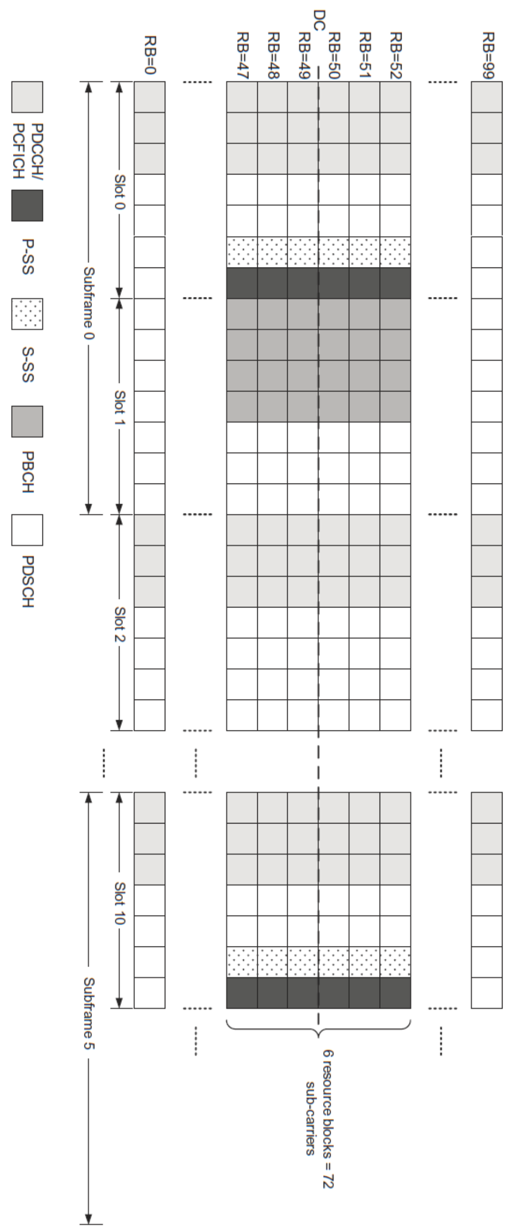
Physical downlink shared channel (PDSCH)

The PDSCH channel carries the downlink data transmission for different users in addition to upper layer signalling information.

Physical multicast channel (PMCH)

It is used to broadcast MBMS services.

Figure 12 below depicts the location of the downlink physical channels and signals in time and frequency within a type 1 frame structure.



2.3.7 Downlink Reference Signals

In LTE, the downlink reference signals types are the cell specific reference signals (CRS), demodulation reference signals (DM-RS), channel state information reference signals (CSI-RS) and positioning reference signals.

CRS are intended to be used by terminals for channel estimation for coherent demodulation of all downlink physical channels except PMCH, PDSCH in case of transmission modes 7 to 10, and the

EPDCCH control channel introduced in LTE release 11 5 CRS are also assumed to be used to acquire channel-state information (CSI) by terminals configured in transmission modes 1 to 8. Finally, terminal measurements on cell-specific reference signals are assumed to be used as the basis for cell-selection and handover decisions.

DM-RS are used for channel estimation whereas CSI-RS are used for acquisition of channel state information.

CSI-RS have a significantly lower time/frequency density, thus implying less overhead, and more flexibility compared to the cell-specific reference signals.

MBSFN reference signals are intended to be used by terminals for channel estimation for coherent demodulation in case of MCH transmission using MBSFN.

Introduced in release 10 CSI-RS are used for terminals to acquire channel state information. The CSI is used for resource scheduling, link adaption and transmission settings. CSI is used for terminals configured for transmission modes 9 and 10. Transmission modes 7 & 8 do not support CSI because they were introduced in release 7 & 8 whilst CSI is introduced in transmission modes 9 & 10. CRS can also be used to acquire CSI but CSI-RS supports up to eight layers special multiplexing.

In the time domain, CSI-RS can be configured for transmission with different periodicity, ranging from a period of 5 ms (twice every frame) to 80 ms (every eighth frame).

2.3.8 Multi-antenna

Transmission mode 1 corresponds to single-antenna transmission while the remaining transmission modes correspond to different multi-antenna transmission schemes, including transmit diversity, beam-forming, and spatial multiplexing

Transmission mode 10 was introduced in LTE release 11 to support different means of dynamic multi-point coordination and transmission.

From a terminal point-of-view, the downlink transmission in case of transmission mode 10 is identical to that of transmission mode 9 in that the terminal will see an up to eight-layers of PDSCH transmission and rely on DM-RS for channel estimation. One important difference between transmission mode 9 and transmission mode 10 lies in the acquisition and feedback of channel-state information (CSI) where transmission mode 10 allows for more elaborate multi-point measurements and feedback based on CSI processes. Transmission modes are only relevant for DL-SCH transmission.

In practice, terminals configured for transmission modes 1 to 8 can be assumed to rely on CRS to acquire CSI while, for transmission modes 9 and 10, CSI-RS should be used.

As codebook-based precoding relies on the cell specific reference signals for channel estimation, and there are at most four cell-specific reference signals in a cell, codebook-based precoding allows for a maximum of four antenna ports and, consequently, a maximum of four layers.

2.3.9 Multiple Antenna Transmission

Multiple antenna transmission is key to reaching the performance targets of LTE. The minimum number of receive/transmit antennas in LTE is specified as two. Multiple antennas can be used to offer receive diversity where the antennas collect additional energy and suppress fading. Multiple transmit antennas at the base station can be used to transmit diversity and beamforming. Beamforming improves SINR, hence the overall system capacity and coverage.

Single user MIMO (spatial multiplexing) can be used to improve overall system capacity in that multiple streams of data can be transmitted using parallel independent channels simultaneously. With Multiple User MIMO (MU-MIMO) multiple terminals can transmit on the same frequency-time resources, of course using interference suppression receiver processing, thereby improving the cell capacity.

These multiple antenna techniques are used in different scenarios, at cell edge or in a loaded cell the SINR may be low such that using spatial diversity provides limited benefits but one may opt to use beamforming instead to improve the SINR. On the hand in the high SINR regime improving the SINR has also limited benefits as the system will now be bandwidth limited rather than SINR limited. In this case it makes sense to take advantage of the good channel conditions and employ spatial diversity.

2.3.10 Spectrum

LTE can be deployed in both paired (frequency division duplexing) and unpaired (time division duplexing) spectrum. With TDD downlink and uplink transmissions happen in different non-overlapping time slots whereas with FDD the uplink and downlink transmissions happen simultaneously with the use of sufficiently separated frequencies. Prior to LTE this spectrum flexibility was used the difference being before LTE this was achieved by means of different radio technologies thereby introducing complexities in the development of dual mode terminals supporting both FDD and TDD. On the other hand, LTE supports both TDD and FDD in a single radio technology.

Different regulators in different regions or territories issue varying bandwidth and as well different frequencies, LTE supports operation in a wide range of spectrum allocations.

In the evolution of LTE, Release 9 introduced additional capabilities which include enhance beamforming, support for multicast transmission and support for network wide positioning services. In multi-cell transmission, the same information is transmitted from multiple cells and by exploiting this at the terminal, using signal power from multiple cell sites at detection, a substantial improvement in coverage can be realised. By transmitting not only identical signals from multiple cell sites (with identical coding and modulation), but also synchronizing the transmission timing between the cells, the signal at the terminal will appear exactly as a signal transmitted from a single cell site and subject to multi-path propagation. Due to the OFDM robustness to multi-path propagation, such multi-cell transmission, in 3GPP also referred to as Multicast/Broadcast Single-Frequency Network (MBSFN) transmission, will then not only improve the received signal strength, but also eliminate the inter-cell interference. The use of MBSFN places string requirements for synchronisation and time alignment of the different signal transmitted from the different cells.

By measuring on special reference signals transmitted regularly from different cell sites, the location of the terminal can be determined.

LTE release 10 was completed in late 2010 and implied enhanced LTE spectrum flexibility through carrier aggregation, further extended multi-antenna transmission, introduced support for relaying, and provided improvements around inter-cell interference coordination in heterogeneous network deployments.

With carrier aggregation (CA), where multiple component carriers are aggregated and jointly used for transmission to/from a single terminal. CA supports up to five component carriers, possibly each of different bandwidths, can be aggregated, allowing for transmission bandwidths up to 100 MHz. The component carriers do not have to be contiguous.

2.3.11 LTE Release 12

The primary goal of Rel-12 is to provide mobile operators with new options for increasing capacity, extending battery life, reducing energy consumption at the network level, maximizing cost efficiency, supporting diverse applications and traffic types, enhancing backhaul and providing customers with a richer, faster and more reliable experience [9].

Rel-12 features two Channel State Information (CSI) enhancements: 4Tx (Transmit) Precoding Matrix Index (PMI) feedback codebook enhancement and aperiodic feedback Physical Uplink Shared channel (PUSCH) mode 3-2. The CSI enhancements enable the Evolved NodeB (eNB or eNodeB) to complete delivery of data packets earlier than with legacy CSI feedback, thus improving spectral efficiency.

2.3.12 Summary

Having explored and now appreciating the targets, design goals and architecture of LTE in this chapter, we are now equipped to introduce one of the features used in LTE for ensuring consistent and fair service delivery to all users of the network especially cell edge users. Chapter 4 explores the cooperative/coordinated multipoint (CoMP) feature and how it ensures consistent user performance and network fairness.

2.4 Cooperative Multipoint (CoMP)

Even more important, in a mobile broadband system dominated by highly dynamic packet-data traffic there is frequently no data available for transmission at a given transmission point. Having statically assigned a part of the overall available spectrum to that transmission point with no possibility to use the corresponding frequency resources to provide higher instantaneous transmission capacity at neighbouring transmission points would imply an inefficient use of the available spectrum. Rather, to maximize system efficiency, as well as to enable as high as possible end-user data rates, a mobile broadband system should be deployed such that, fundamentally, all frequency resources are available for use at each transmission point.

In the case of scheduling located at a higher-level node above the eNodeB, coordination between cells of different eNodeB would, at least conceptually, be straightforward as it could be carried out at the higher-level node. However, in the LTE radio-network architecture there is no higher-level node defined, and scheduling is assumed to be carried out at the eNodeB.

Thus, the best that can be done from an LTE specification point-of-view is to introduce messages that convey information about the local scheduling strategy/status between neighbouring eNodeBs. An eNodeB can then use the information provided by neighbouring eNodeBs as input to its own scheduling process. It is important to understand though that the LTE specifications do not specify how an eNodeB should react to this information. Rather, this is up to scheduler implementation.

The main difference between CoMP and ICIC is that CoMP focused on radio-interface features and terminal functionality to assist different coordination means.

Release 11 CoMP was limited by the assumption that low latency backhaul was used for coordination thereby limiting CoMP features to either sectors of the same site or network points connected by direct low-latency links.

2.4.1 CoMP Basics

The term CoMP refers to a few different classes of schemes, as indicated above, however all the schemes consider, in one way or the other, intra- and/or inter-site interference to improved fairness and user data rates.

This technique (CoMP) may sometimes be referred to Network MIMO because of its utilisation of multiple antennas of base stations from different geographically separated sites [10], [11]. Traditionally each UE communicates with the serving cell, however with CoMP the UE communicates with many cells having differently located points forming the CoMP cooperating set (MIMO network) [7]. Not only does CoMP utilise radio resources in the time/frequency domain, it also takes advantage of spatial domain to increase spectral efficiency in terms of the number of bits/second/hertz. Beamforming makes it possible to use the spatial domain to increase the spectral efficiency [13].

CoMP schemes/types include Coordinated Scheduling/Beam-Forming (CS/CB) and Joint Processing (JP) in the downlink and joint reception & coordinated scheduling in the uplink. Most of these schemes can be categorised according to the extent of information exchange (traffic load) or coordination among cells and/or base station with UEs.

Cooperative/coordinated multipoint (CoMP) schemes dictate that base stations share user equipment data scheduling information among themselves. The information sharing in turn results in increased signalling overhead as well as complexity of the LTE network backhaul deployment. This backhaul interface in referred to as the X2 interface in LTE.

In downlink CoMP, user equipment measures and reports the channel state information (CSI) based on the experienced signal to noise and interference ratios of base stations within its vicinity. The measured CSI report is sent to the base stations in uplink transmission.

In LTE MIMO networks, the linear precoding [17-18] technique is employed as a scheme to enhance downlink performance in addition to decreasing the signalling overhead between the cells. 3GPP therefore defined a set of predefined precoding matrices to inform the possible channel states at both the transmitter and the receiver in the CoMP specifications. The Precoding Matrix Index (PMI), which is defined as the index to the preferred matrix within in a codebook matrix, is reported by UE together with Channel Quality Indicator (CQI) and MIMO Rank Indicator (RI) [15].

Rank Indication is one of the important input to eNB, in selection of the transmission layer in downlink data transmission. Even when the system is configured in transmission mode 3 (or open loop spatial multiplexing) for a particular UE and if the same UE report the Rank Indication value

1 to eNB, eNB will start sending the data in Tx diversity mode to UE. If UE report Rank Indication 2, eNB will start sending the downlink data in MIMO mode (Transmission Mode 3).

We need the RI concept in LTE because when a UE experiences a bad SNR and it would be difficult (error prone) to decode transmitted downlink data and it sends a warning to eNB by stating Rank Indication value as 1. When a good SNR is experienced the UE sends this information to eNB by indicating rank a value as 2. A UE determines the CQI and PMI parameters based on pilot measurements. The UEs then sends the CQI and PMI to their serving base stations.

The rank indicator (RI) indicates what is called the MIMO ranking, that is, the number of data streams to be transmitted in parallel for the next transmission over the MIMO channel [16]. These parameters are transmitted in a quantized manner to BS to reduce signalling overhead. By coordinating and combining signals from multiple antennas, CoMP makes it possible for UEs to enjoy consistent performance and quality when they access and share videos, photos and other high bandwidth services whether they are close to the centre of an LTE-A cell or at its outer edge.

2.4.2 Link Adaptation

Coordinated link adaptation is about using information about transmission decisions of neighbouring transmission points in the link-adaptation process, that is, in the decision with what data rate to transmit on a given resource. This is a multistep process in the scheduling and link adaptation at transmission points and is carried out at the network level.

2.4.3 Channel State Information

UEs are instructed by Base stations on how and which cells' CSI to measure using CSI Reference signal (CSI-RS) configuration messages. The UEs in turn measure the CSI and report to their servicing cells.

The channel state information includes Pre-coding Matrix Indicator (PMI), Channel Quality Indicator (CQI) and Rank Indicator (RI).

In LTE CQI is a value, ranging from 0 to 15, stating the highest modulation and coding rate (MCR) supported by a UE supporting a Block Error Rate less than 10%. The better the channel the higher the MCR used. As much as CQI heavily depends on MCR, it also relates to the signal to interference and noise ratio (SINR) of the wireless channel because Adaptive Coding and Modulation (ACM) used in LTE to ensure that the block error rate (BLER) is less than 10% has a direct relation with SINR.

The RI indicates the number of data streams (called layers in 3GPP terms) transmitted to a UE simultaneously. It therefore implies whether transmit diversity (RI=1) or spatial multiplexing (RI>1) for an n x m MIMO where n, m > 1.

PMI show how individual data streams (layers) are mapped to transmit antennas in the downlink. In LTE, a PMI code book is pre-configured at Base stations and UEs to reduce feedback overhead, hence a UE only sends a PMI index to the base station.

2.4.4 Downlink CoMP

This entails the dynamic cooperation/coordination among multiple geographically separated transmission points where a point is defined as a set of geographically co-located transmit antennas

In the downlink CoMP can be mainly classified into Coordinated Scheduling/Coordinated Beamforming (CS/CB) and Joint Processing (JP) schemes.

CS reduces inter or intra- cell interference by allocation difference resource blocks to cell edge UEs. CS is different from ICIC in that it requires more signal processing and has shorter operational period (tens to hundreds of ms in ICIC and as short as one ms in CoMP). With ICIC cells share interference information of each cell whereas in CoMP they share CSI of each user. CS is usually used in conjunction with CB hence the abbreviation CS/CB scheme.

JP in an umbrella term for Joint transmission (JT) and Dynamic Point Selection (DPS). With JT multiple cells transmit the same data to a UE using the same radio (time and frequency) resources and tight synchronisation among JT cells is required for JT to effectively operate. Also, HARQ is performed by the service cell.

In the control plane DPS is like JT and the difference manifests in the actual data transmission (data plane). The channel quality of each UE evaluated in each subframe and the cell with best quality is chosen to transmit data and other cells are muted. The other differences between JT and DPS are that there no tight synchronisation requirements with DPS and HARQ is performed at the cell that transmits data to a UE.

2.4.5 Uplink CoMP

Uplink CoMP reception may involve joint reception (JR) of the transmitted signal at multiple reception points and/or coordinated scheduling (CS) decisions among points to control interference and improve coverage.

2.4.6 CoMP Deployment Scenarios and Operation

Deployments of LTE systems are initially mostly homogeneous, that is, macrocells. In homogeneous networks, all base stations in the LTE network are of the same power class and type [12]. In LTE Release 8 the multiple input multiple output (MIMO) transmissions are performed independent of each neighbouring base stations. Inter-cell interference coordination (ICIC) is implemented by having coordination messages exchanged between base stations using the X2 interface. The aim of ICIC is to have a scheduler at one cell providing information on the current or anticipated interference situation at its neighbours. The backhaul technology (fibre, microwave, copper, etc) used introduces a constraint regarding the latency with which these coordination messages can be exchanged through the X2 interface. Thus because of the varied distance between base stations and backhaul technology or media, latencies are not always guaranteed to be low. One of the differences between ICIC and CoMP schemes is the ICIC was designed for semi-static coordination while CoMP schemes are designed to for dynamic coordination which require lower latency guarantees.

On the other hand, LTE networks can be based on heterogeneous deployments. Here the macro-cells constitute the basis of the networks coverage, however low power nodes are also deployed within the macro-cell coverage to increase capacity. The low-power nodes can be pico-cell, micro-cell or relay nodes. This presents a challenge of harsh interference between the macro-cell and low power nodes in heterogeneous networks due to the proximity of the macro-cells and low power nodes and different power classes.

Recently the deployment of LTE that has gained acceptance or popularity is having the base station functions divided into what is called the baseband unit (BBU) functionality and the remote radio head (RRH) functionality. The BBU is responsible for all baseband processing and scheduling whilst the RRH carries out the radio frequency functions. Such RRH operations include filtering, power amplification and frequency up-conversion. In terms of location the BBU can be situated in a different place to the RRH, for instance the BBU may be in a building basement while the RRH will be close to the antenna. The BBU and RRH are connected using optic fibre. An inherent advantage of this setup is that of suppressing antenna feeder losses since the power amplifier is close to the antenna. Also by having the RRHs from BBU enables either centralized BBUs to jointly manage the operations of several radio sites or the exchange of very low-latency coordination messages between BBUs responsible for their own site. RRH deployments therefore facilitate the fast coordination between transmission/reception points that is required for coordinated multipoint (CoMP). The effectiveness of the CoMP technology is conditioned on constraints which include capacity and latency and these in turn dictate on the specific type of CoMP processing architecture to be used and therefore expected performance.

Due to the varied LTE deployment architectures and backhaul characteristics, the 3GPP has homed on the below deployment topologies.

1. Coordination between the cells (sectors) controlled by the same macro base station (where no backhaul connection is needed)

2. Coordination between cells belonging to different radio sites from a macro network

3. Coordination between a macro-cell and low power transmit/receive points within its coverage, each point controlling its own cell (with its own cell identity)

4. The same deployment as the latter, except that the low-power transmit/receive points constitute distributed antennas (via RRHs) of the macro-cell, and are thus all associated with the macro-cell identity

Scenarios 1 and 2 are targeted for homogeneous scenarios (Figure. 13a), and scenarios 3 and 4 are targeted for heterogeneous scenarios (Figure. 13b). Note that different operators will have different priorities regarding the CoMP deployment scenarios, leading to different implementation considerations.

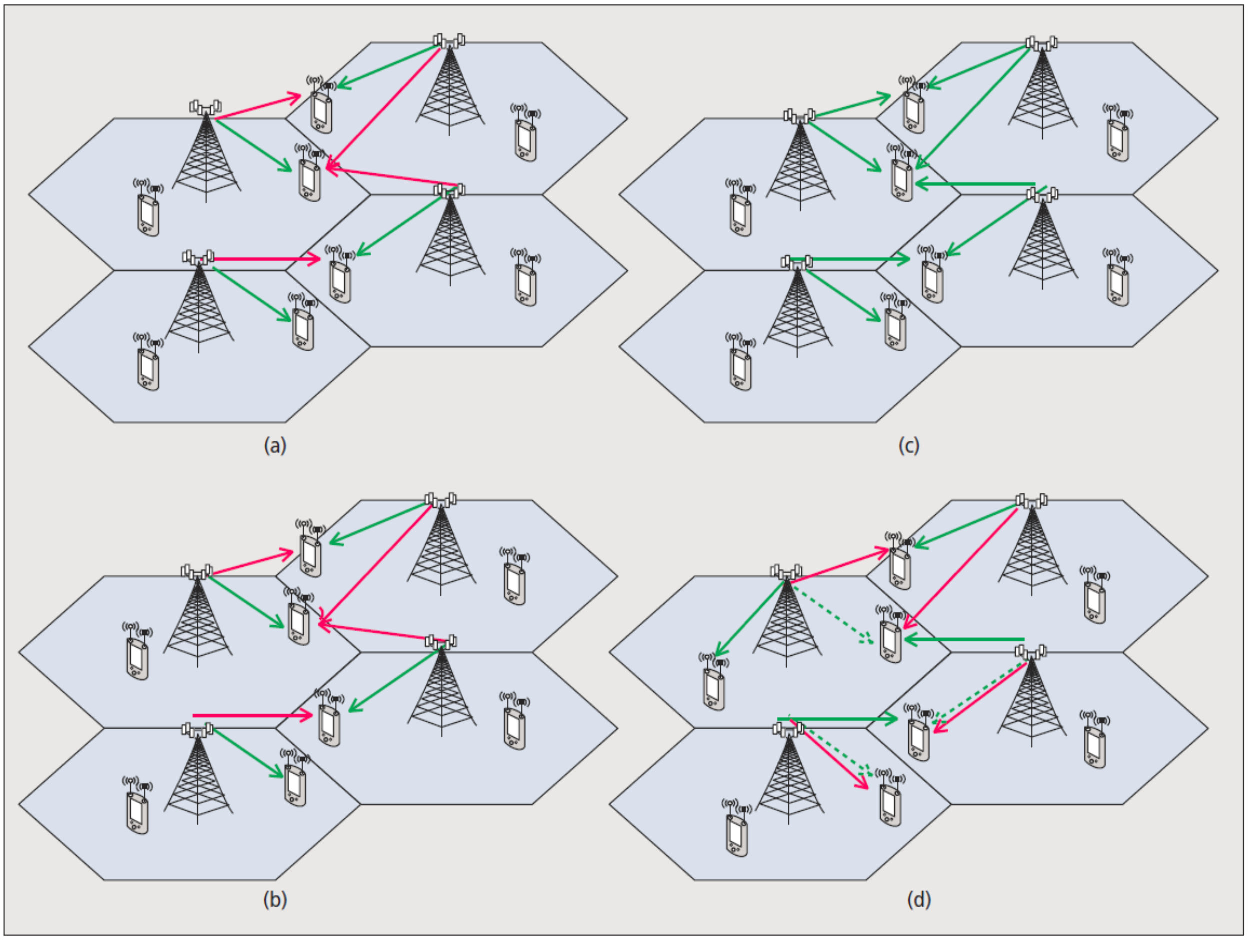


Figure 12 [11]

2.4.7 Performance

A common measure of system performance is “spectral efficiency,” which is the system throughput per MHz of spectrum in each cell of the system.

In this work, the main performance measure we will consider in throughput. The major objective of cooperative multipoint is to enhance performance in terms of throughput by way of improving the CQI of cell edge users. These are the users who experience severe interference because they are at the boundary of two or more cells. It is this destructive interference that degrades performance of these cell edge users.

Other important performance indicators, technically termed Key performance indicators (KPIs) include RRC/S1 Signalling/ E-RAB Success Rate, Call drop Rate and Intra-freq HO out Success Rate. These ensure a consistent user experience, that is, no network timeouts or disruptions which mostly affect user experience and thereby annoying to users.

2.4.8 Summary

Having looked at the CoMP feature we are now able to design experiments and evaluate its performance benefits by evaluating its effectiveness on both the downlink and uplink in LTE.

Chapter 3 explains the experimental design.

2.5 Chapter summary

Tools used in ensuring reliable transmission of information over a channel were introduced in this chapter. Shannon provided a mathematical tool for calculating or determining the maximum channel capacity for error free transmission. On the other hand, coding is another tool at our disposal for ensuring that we approach the maximum channel capacity as determined by Shannon. It was determined that the signal to interference and noise ratio to a critical constraint in achieving high channel capacities. A peek at Information theory, OFDM as technologies used in LTE we reviewed. Armed with these key technologies LTE and the LTE feature which improves cell edge user throughput were then dissected.

In Chapter 3 measurement/experimental setup for evaluating the effectiveness of CoMP is designed and explained. We will look at the necessary switches for enabling CoMP using Scenario 2 [17]

Chapter 3

3 Measurement/Experimental Setup

The LTE-Advanced Release 12 homogenous network in Zambia is using the 2330-2350MHz spectrum i.e. 20MHz bandwidth with time division duplexing (TDD). For our purposes, we will conduct measurements at points shown in Figure 15 and measure the Channel Quality Indicators (CQI) as measured by the UEs with and without CoMP enabled in the network. The CQIs are related to the other things like SINR. The cells are backhauled to the core infrastructure using optic fibre links. Each site has three sectors at heights of 36m.

In release 12, 3GPP expanded CoMP to not only be used within a single eNodeB (Intra-site) as in release 11 but also to be used in inter-site in Release 12 [17]. In this campaign, we evaluate 3GPP Scenario 2, which is inter-Macro eNodeB & Non-ideal backhaul.

The UE measures the channel state information (CSI) and because we are using TDD, channel reciprocity is exploited by the Base station/eNodeB.

We will be using drive test handsets to measure and record CQI values. The handsets are also capable of measuring UDP throughputs using iPerf [18] and other KPIs as highlighted above.

The following procedure will be used during the measurement campaign (Huawei equipment parameters are also included).

3.1 DL CoMP

1. Selecting an eNodeB to centrally schedule resources (EuCoSchCfg)
2. Enable Sounding reference signals (SRS) (TDLBFD-002003)
3. Set the switches for Intra- and inter- eNodeB DL CoMP with relaxed backhaul (TDLAOFD-081411)
4. Set eNodeB measurement information reporting to 3, 6 and 15ms (TDLAOFD-081411)
5. Enable Rank reporting for spatial multiplexing (RankRapidRptSwitch) (EnAperiodicCqiRptSwitch)
6. Use the default (1), the number of UE for centralised control (TDLAOFD-081411)

7. Use ideal backhaul by setting the appropriate switches.

8. First, enable JT on its own and we will call this Setup 1.

9. Second, enable DPS only

10. Enable CS/CB [CellBfMimoParaCfg (MIMO_BF_ADAPTIVE)]

3.2 UL CoMP

1. JR/CS

Note: the feature switches/parameters are as per Huawei's implementation of CoMP as specified by 3GPP. The switch values will be varied and enabled or disabled to enable and/or tune CoMP features.

3.3 Field Trials

On 28th February 2017 at 10h45, we activated 3 LTE liquid sites, 100009_Chalala_Rockfield, 100008_ARTHURWINA and 100010_MWAIWAKE.

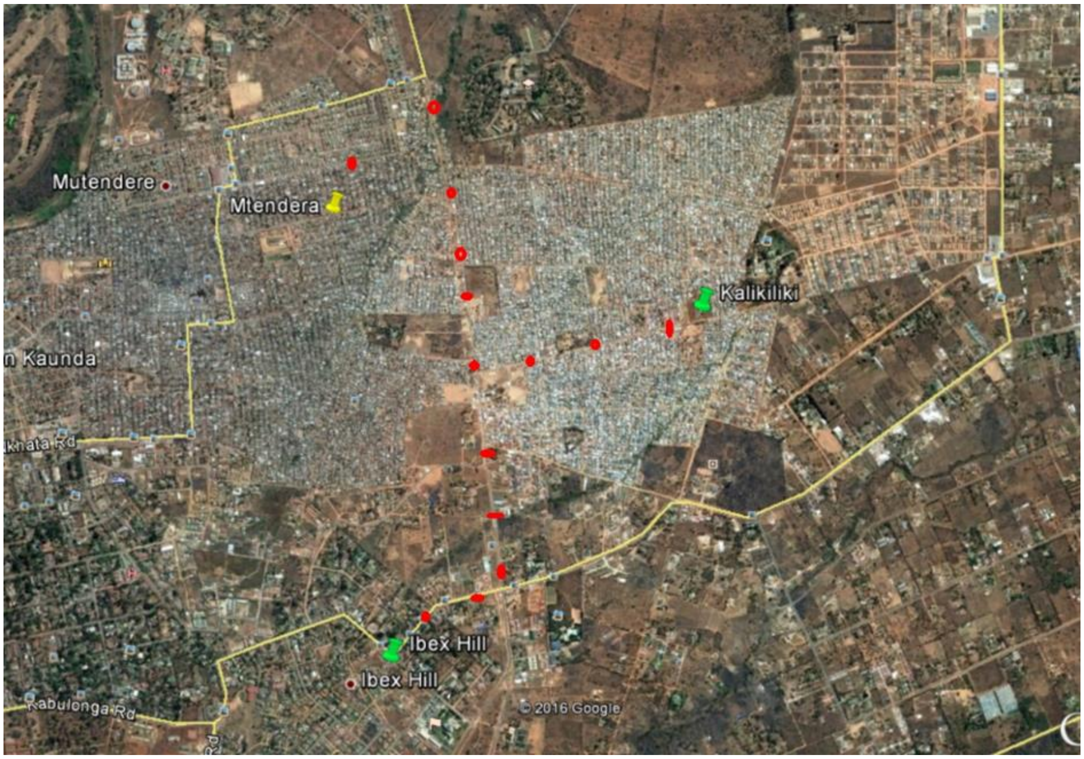


Figure 13

Chapter 4

4 Research Output

4.1 Analysis and KPIs

The overall main KPIs of those sites are shown as below compared with 6 days before and 6 days after implementation of DL ComP feature. The graphed KPIs are extracted in PDF format from the Huawei U2000 OSS.

4.1.1 RRC/S1 Signalling/ E-RAB Success Rate (%)

RRC/S1 Signalling/ E-RAB Success Rate (%) after change is slightly better than that of before. An E-UTRAN radio access bearer (E-RAB) is a bearer on the access stratum (AS) for carrying service data of UEs. An E-RAB release is a process of releasing the bearer resources for UEs, and it represents the capability of a cell to release bearer resources for UEs. One E-RAB release is counted once.

Accessibility KPIs are used to measure the probability that a user accesses the network and requests services in the given operating conditions. The service provided by the E-UTRAN is defined as EPS/E-RABs. (EPS is short for evolved packet system, and E-RAB is short for E-UTRAN radio access bearer). Radio Resource Control (RRC) connections and System Architecture Evolution (SAE) setups are the main procedures whose performance is measured by accessibility KPIs.

According to 3GPP TS 36.331, the RRC connection setup procedure is triggered by different causes, which are identified in the "establishmentCause" field in an RRC Connection Request message as emergency, highPriorityAccess, mt-Access, mo-Signaling, mo-Data, or delayTolerantAccess-v1020. The UE sets the establishmentCause in accordance with the information it receives from upper layers. The mo-signaling cause is a signalling-related cause. All other causes are service-related causes. The accessibility KPI evaluates the RRC setup success rate using service-related causes in a cell or radio network.

The RRC Setup Success Rate (Service) KPI is calculated based on the counters measured at the eNodeB when the eNodeB receives an RRC Connection Request message from the UE, as shown in Figure 14. The number of RRC connection attempts is collected by the eNodeB at measurement point A, and the number of successful RRC connections is counted at measurement point C.

Figure 14 Measurement points for RRC connection setup

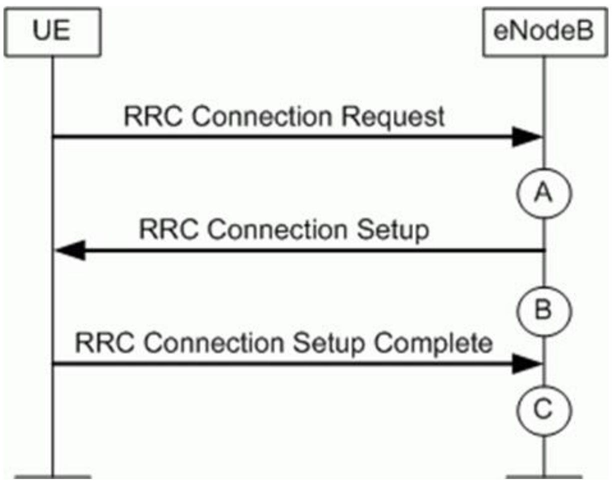


Figure 14 [19]

An E-RAB is the access layer bearer for carrying service data of a UE. The E-RAB setup success rate in a cell directly represents the capability of the cell to provide E-RAB connections for UEs. The E-RAB.Est.Cell function subset measures the number of E-RAB setup attempts and number of successful E-RAB setups for each service with a specific QoS Class Identifier (QCI) in a cell. The setup of one E-RAB is counted once. Figure 14 shows the measurement points of an E-RAB setup procedure during a non-handover process. Figure 15 shows the measurement points of an E-RAB setup procedure initiated by the target eNodeB during a handover.

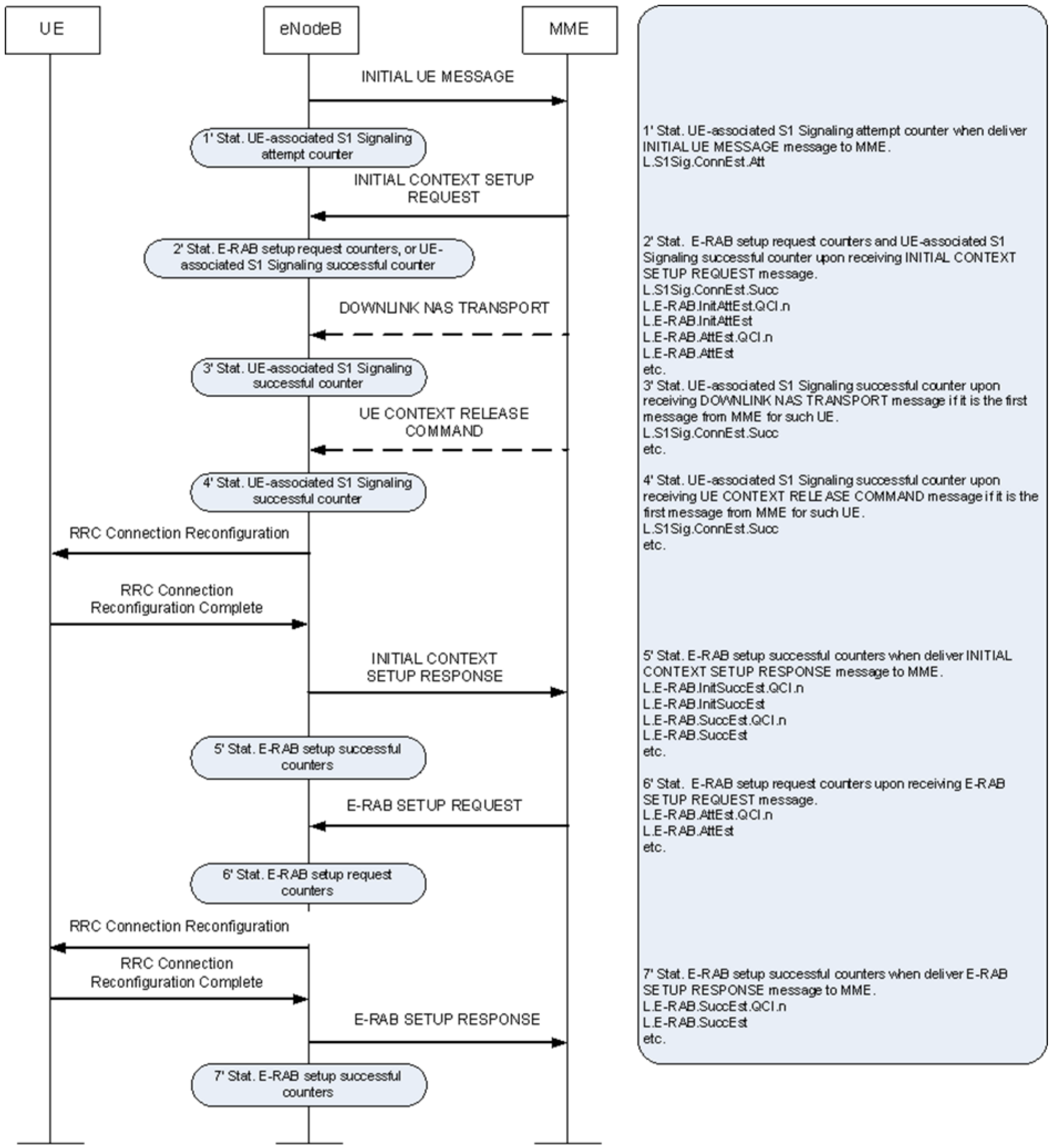
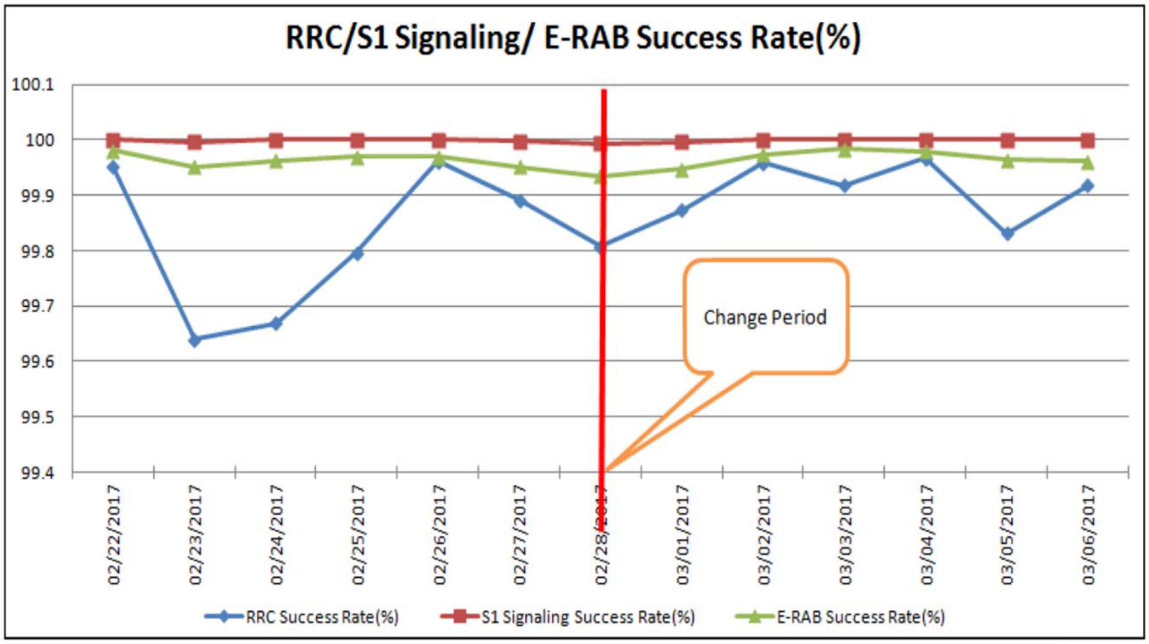

UE
eNodeB
MME
INITIAL UE MESSAGE
1' Stat. UE-associated S1 Signaling attempt counter
INITIAL CONTEXT SETUP REQUEST
2' Stat. E-RAB setup request counters, or UE-associated S1 Signaling successful counter
DOWNLINK NAS TRANSPORT
3' Stat. UE-associated S1 Signaling successful counter
UE CONTEXT RELEASE COMMAND
4' Stat. UE-associated S1 Signaling successful counter
RRC Connection Reconfiguration
RRC Connection Reconfiguration Complete
INITIAL CONTEXT SETUP RESPONSE
5' Stat. E-RAB setup successful counters
E-RAB SETUP REQUEST
6' Stat. E-RAB setup request counters
RRC Connection Reconfiguration
RRC Connection Reconfiguration Complete
E-RAB SETUP RESPONSE
7' Stat. E-RAB setup successful counters
1' Stat. UE-associated S1 Signaling attempt counter when deliver INITIAL UE MESSAGE message to MME.
L.S1Sig.ConnEst.Att
2' Stat. E-RAB setup request counters and UE-associated S1 Signaling successful counter upon receiving INITIAL CONTEXT SETUP REQUEST message.
L.S1Sig.ConnEst.Succ
L.E-RAB.InitAttEst.QCI.n
L.E-RAB.InitAttEst
L.E-RAB.AttEst.QCI.n
L.E-RAB.AttEst
etc.
3' Stat. UE-associated S1 Signaling successful counter upon receiving DOWNLINK NAS TRANSPORT message if it is the first message from MME for such UE.
L.S1Sig.ConnEst.Succ
etc.
4' Stat. UE-associated S1 Signaling successful counter upon receiving UE CONTEXT RELEASE COMMAND message if it is the first message from MME for such UE.
L.S1Sig.ConnEst.Succ
etc.
5' Stat. E-RAB setup successful counters when deliver INITIAL CONTEXT SETUP RESPONSE message to MME.
L.E-RAB.InitSuccEst.QCI.n
L.E-RAB.InitSuccEst
L.E-RAB.SuccEst.QCI.n
L.E-RAB.SuccEst
etc.
6' Stat. E-RAB setup request counters upon receiving E-RAB SETUP REQUEST message.
L.E-RAB.AttEst.QCI.n
L.E-RAB.AttEst
etc.
7' Stat. E-RAB setup successful counters when deliver E-RAB SETUP RESPONSE message to MME.
L.E-RAB.SuccEst.QCI.n
L.E-RAB.SuccEst
etc.

Figure 15



4.1.2 Call drop Rate (%)

Call drop Rate (%) after change is slightly better than that of before.

The Call Drop Rate KPI indicates the call drop rate of the VoIP services in a cell or radio network. A VoIP call drop occurs when the VoIP E-RAB is abnormally released. Each E-RAB is associated with QoS information. Usually, the QCI of VoIP services is 1.

An E-RAB consists of a radio bearer and a corresponding S1 bearer. Any abnormal release of either bearer causes a call drop. A release is defined as abnormal by its release cause according to 3GPP TS 36.413.

Abnormal E-RAB releases can be classified into the following two scenarios, as shown in Figure 16.

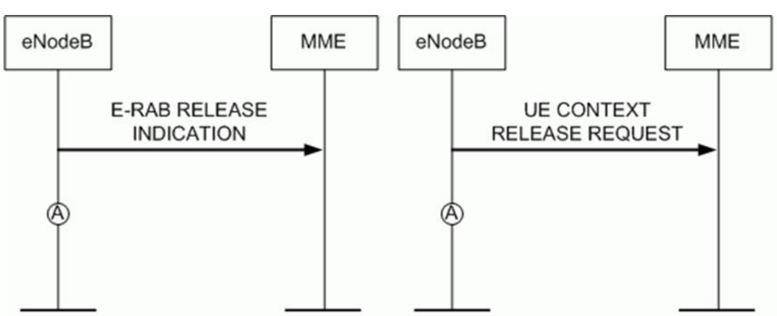
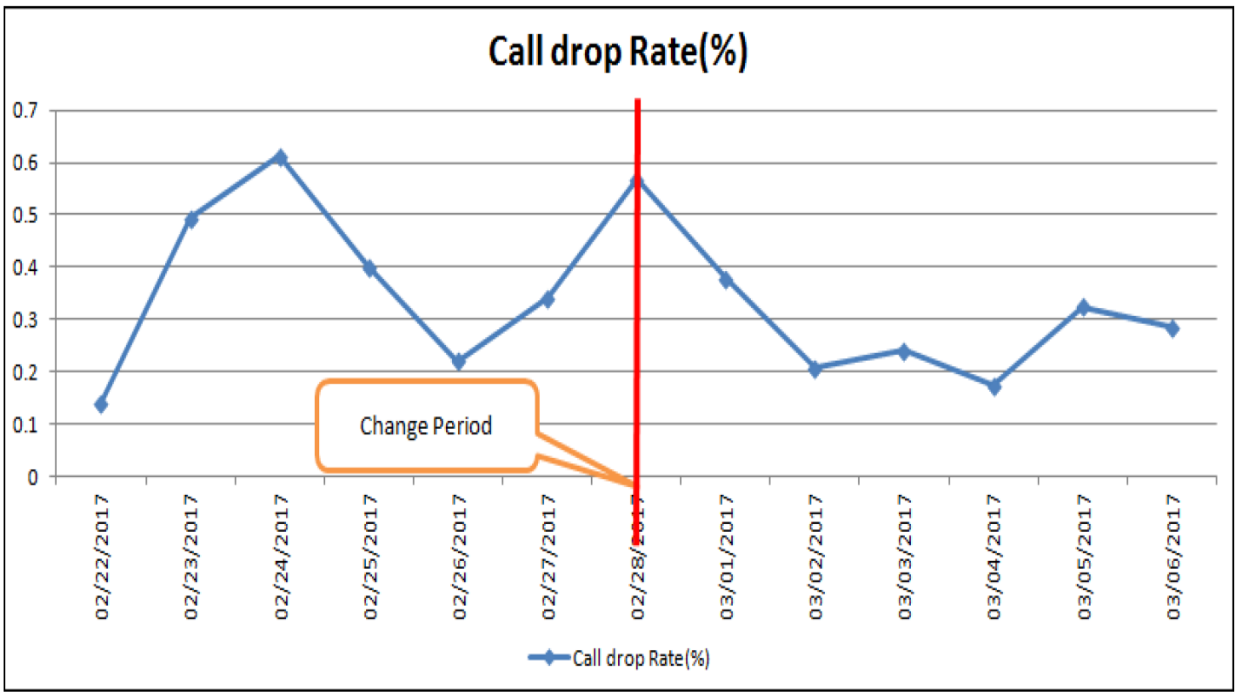


Figure 16 [10]

Scenario 1: When the eNodeB sends an E-RAB Release Indication message to the MME, the abnormal E-RAB release counter is incremented if the bearer to be released carries data and the release cause is not "Normal Release", "Detach", "User Inactivity", "CS Fallback triggered", "UE Not Available for PS Service", or "Inter-RAT Redirection".

Scenario 2: When the eNodeB sends a UE Context Release Request message to the MME, the abnormal E-RAB release counter is incremented if the bearer to be released carries data and the release cause is not "Normal Release", "Detach", "User Inactivity", "CS fallback triggered", "UE Not Available For PS Service", "Inter-RAT redirection", "Time Critical Handover", "Handover Cancelled".



4.1.3 DL Throughput /DL User Edge Throughput (Kbps)

DL Throughput and DL User Edge Throughput after change is better than that of before.

The User Downlink Average Throughput KPI indicates the average downlink UE throughput in a cell. According to 3GPP TS 32.450, the throughput measurement needs to remove the data scheduled in the last TTI before the downlink buffer is empty, as shown in Figure 17.

Figure 17 Downlink throughput measurement defined in 3GPP TS 32.450

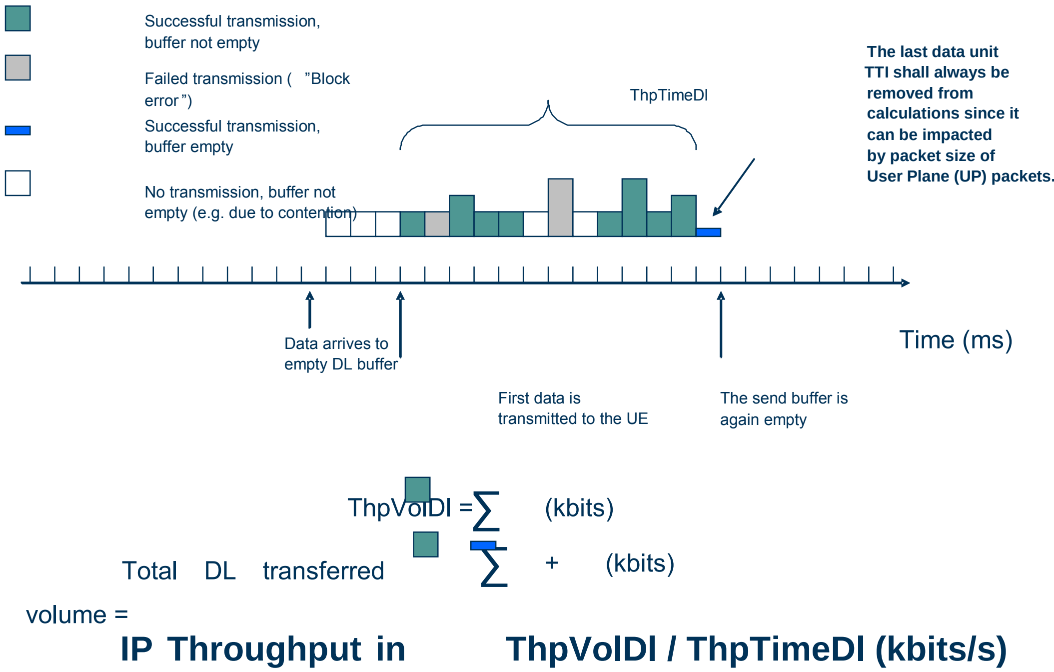
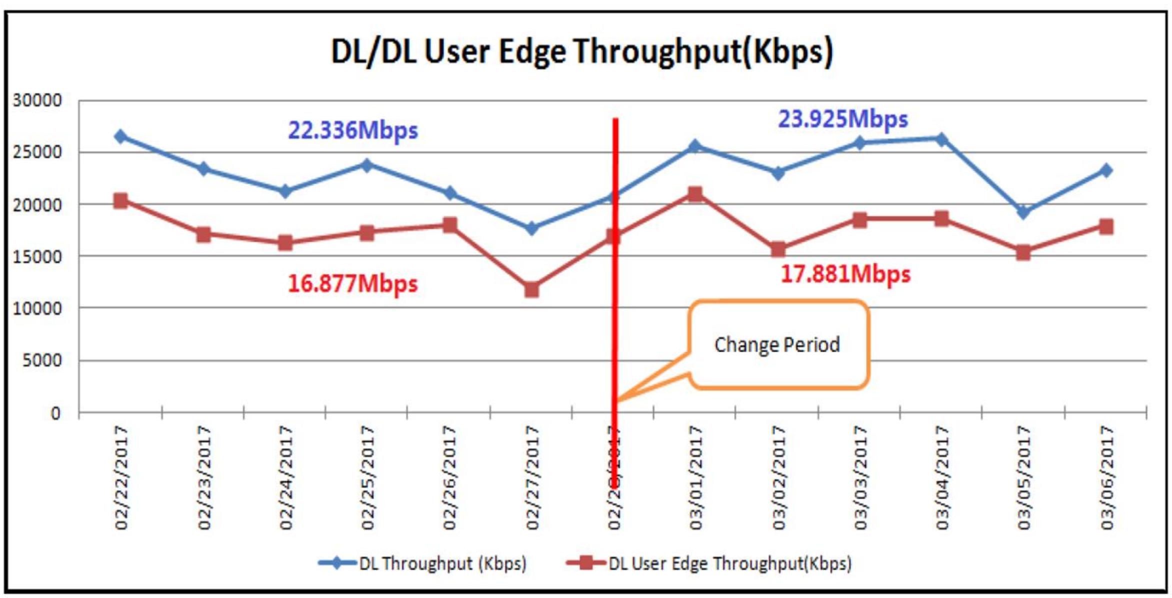


Figure 17 [20]



Below are the detailed results:

Date	DL Throughput (Kbps)	Average DL Throughput (Kbps)	DL User Edge Throughput(Kbps)	Average DL User Edge Throughput(Kbps)
02/22/2017	26553.7283	22336.91579	20462.36217	16877.38725
02/23/2017	23430.03518		17184.47967	
02/24/2017	21321.71126		16341.60194	
02/25/2017	23872.64598		17300.6037	
02/26/2017	21143.9347		18061.96917	
02/27/2017	17699.43929		11913.30686	
02/28/2017	20765.29733		16942.6834	
03/01/2017	25664.49374	23925.037	21052.22683	17881.79476
03/02/2017	23037.27641		15702.08625	
03/03/2017	25924.88001		18540.27446	
03/04/2017	26343.43908		18650.34856	
03/05/2017	19268.9543		15426.15054	
03/06/2017	23311.17848		17919.68195	

Improvement by (%)	7.109850044	5.951202622

DL Throughput and DL User Edge Throughput after change is better than that of before by 7.10% and 5.95% respectively.

4.1.4 Intra-freq HO out Success Rate (%)

Intra-freq HO out Success Rate (%) after change is almost the same as that of before.

The Intra-Frequency Handover Out Success Rate KPI indicates the success rate of intra-frequency handovers (HOs) from the local cell to neighbouring E-UTRAN cells. The intra-frequency HOs are classified into intra- and inter-eNodeB HOs.

Intra-eNodeB Outgoing HO

Intra-eNodeB outgoing HOs can be further classified into HO with RRC connection reestablishment and HO without RRC connection reestablishment.

Intra-eNodeB outgoing HO without RRC connection reestablishment

Figure 18 illustrates an intra-eNodeB outgoing HO without RRC connection reestablishment, and the source and target cells operate at the same frequency. When the eNodeB sends an RRC

Connection Reconfiguration message containing the handover command to the UE, the eNodeB counts the number of intra-eNodeB intra-frequency HO outgoing execution attempts in the source cell at point B. When the eNodeB receives an RRC Connection Reconfiguration Complete message from the UE, the eNodeB counts the number of successful intra-eNodeB intra-frequency outgoing HO executions in the source cell at point C. Figure 18 Intra-eNodeB outgoing HO without RRC connection reestablishment

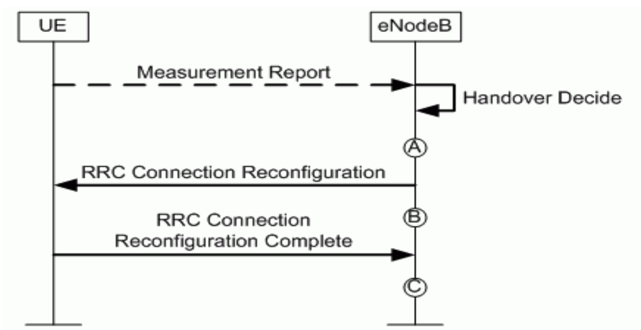


Figure 18

Intra-eNodeB outgoing HO with RRC connection reestablishment

Figure 19 illustrates an intra-eNodeB outgoing HO with RRC connection reestablishment, and the source and target cells operate at the same frequency. When the eNodeB sends an RRC Connection Reconfiguration message containing the handover command to the UE, the eNodeB counts the number of intra-eNodeB intra-frequency outgoing HO execution attempts in the source cell at point B. When the eNodeB receives an RRC Connection Reestablishment Complete message from the UE, the eNodeB counts the number of successful intra-eNodeB intra-frequency outgoing HO executions in the source cell at point C.

Figure 19 Intra-eNodeB outgoing HO with RRC connection reestablishment.

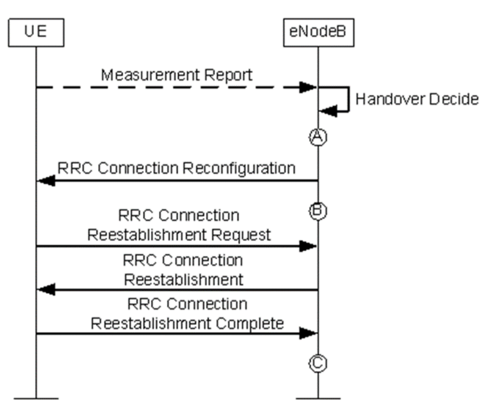
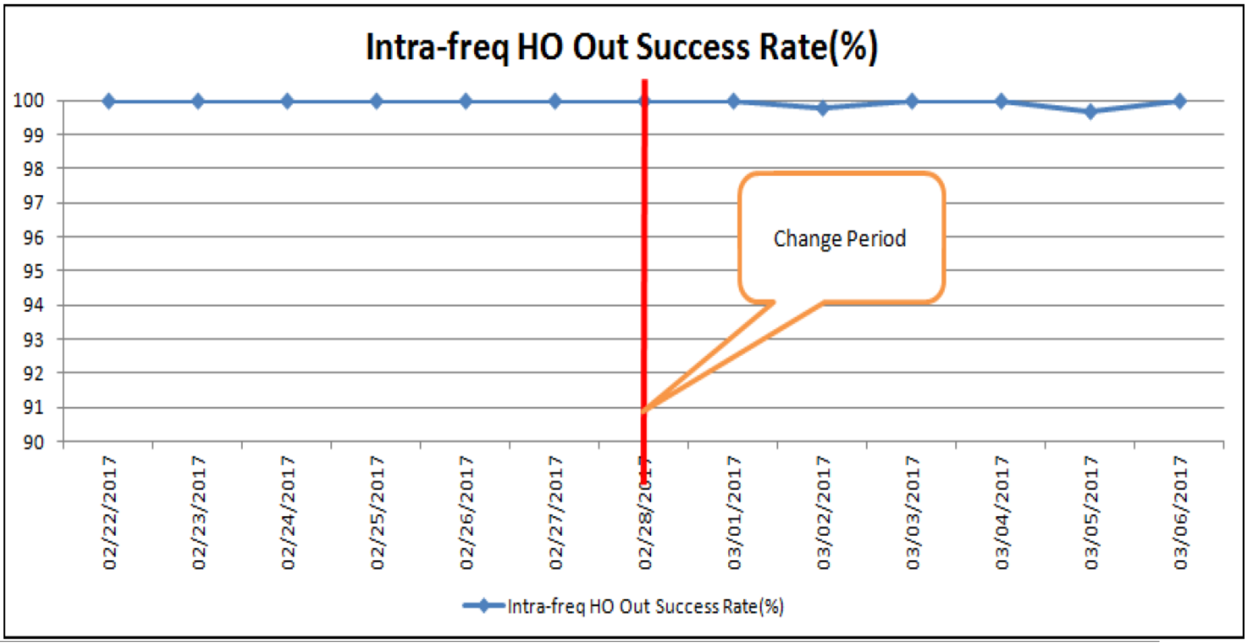


Figure 19



4.2 Summary

The results shared in this chapter clearly show that using CoMP does improve cell edge user performance. The KPIs we used to quantitatively provide visibility into the so call "user experience". That is, E-RAB success rate indicates that a user can at least access service. Throughput shows what the bandwidth (in bps) what a user can reach. The call drop rate and intra-frequency is an indication of service continuity.

Chapter 5

5 Conclusion and Recommendations

5.1 Conclusion

From the drive tests measurements, it is concluded that after activating DL CoMP feature for the 3 sites, data throughput was significantly improved, that is, the DL throughput and DL Edge user's throughput.

It is therefore evident from the measurement results that the cooperative multipoint feature improves data throughput for users (especially cell edge users who experience a lot of interference) as well as providing a better user experience in terms of call drop rate reduction. As evidenced by the measurement results carried over twelve days the overall main KPIs of those sites with the CoMP feature enabled, the performance of the network significant improved.

However, since this is a live commercial network we had to be cautious in terms disrupting customers' services, that is, not to cause significant downtime. We therefore could not manage all CoMP parameters as to evaluate the maximum performance improvement we can achieve with this feature.

Some of the parameters are specified in the 3GPP TS 36.331 and 3GPP TS 36.413 specification documents. For example, in our measurements we only used ideal backhaul which is 10Gigabits in capacity using optic fibre. Given time and opportunity it will be interesting to compare the results of ideal and non-ideal backhaul, when HARQ is activated and deactivated, etc.

Also, dependent on the proximity of the base stations it is also interesting to measure the backhaul overhead load when more cells are added into clusters. This is also dependent on the initial phase of RF planning which determines the extent of coverage overlap among the cells.

Even with these parameters enabled or disabled, the parameters also have extensive options associated with them leading us to the recommendations made below.

5.2 Recommendation

I recommend that since the CoMP feature has a lot switches involved a test bed is very crucial in extensively playing around with the switched/parameters and their associated options to provide "best practices" reports or documents as what is produced by other internet bodies like the IETF, Regional Network Organizations, e.g. AFNOG, RIPE, NANOG, etc. Such best practices documents will point out the main parameters and recommended options and option values for different LTE network deployment scenarios.

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