FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
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MASTER'S THESIS

IMPLEMENTATION AND EVALUATION OF CARRIER AGGREGATION (CA) FOR EXPERIMENTAL LIVE MOBILE NETWORK

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ABSTRACT

Carrier Aggregation (CA) has become a key technology component in LTE since its introduction in LTE Release 10, also known as LTE-Advanced. CA allows to combine up to five backward compatible LTE carriers to be used for multicarrier transmission in both downlink and uplink. CA provides increased throughputs, additional capacity and possibilities for load balancing.

This thesis presents the main features of LTE Carrier Aggregation. Furthermore, CA performance is evaluated in an experimental live mobile network. Thus, CA was previously implemented at 5G Test Network (5GTN) of University of Oulu by upgrading the base stations software. The objective was to test whether CA is capable of delivering the performance theoretically expected.

Network performance was measured for both single carrier connection and if using CA. Performance is presented in terms of throughput and only downlink CA was tested.

Even though performance results did not achieve the theoretical expectations, it has been proven that CA provides higher throughputs compared to the non-CA scenario.

Key words: Carrier Aggregation, CA, LTE, eNodeB, throughput.

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FOREWORD

The present work represents the culmination of my Master’s Degree in Telecommunication Engineering at Universitat Politècnica de València (UPV), likewise it concludes my stay in Finland via the Erasmus exchange Programme. This thesis was conducted at the Centre for Wireless Communications (CWC) at University of Oulu, between March 2019 and July 2019. The theoretical part was finished later on in Spain, in March 2021, due to work.

First of all, I would like to thank my technical supervisor Dr.Sc.(Tech.) Ville Niemelä for his excellent support and guidance. His advice and feedback were really helpful during the entire project.

I am grateful to my supervisor Prof. Ari Pouttu for supervising this thesis and for suggesting the topic. I really appreciate the opportunity to base my thesis on this topic and have a first-hand experience with a live mobile network.

I would also like to thank my supervisor from my home university (UPV), Dra. Marta Cabedo Fabrés, for the help provided in this thesis. I do appreciate the trust placed in me.

Finally, I am really grateful to my family and friends for their enormous support and encouragement during my studies. Especially, I would like to thank my parents for their sacrifice and patience put on me during all my studies.

Valencia, March, 17 2021

Rubén Cano Menaches

LIST OF ABBREVIATIONS AND SYMBOLS

Symbols

Δ	Change in a given variable
*	Multiplication
λ	Wavelength
f_c	Carrier frequency

Abbreviations

3GPP	3rd Generation Partnership Project
5GTN	5G Test Network
ARQ	Automatic Repeat reQuest
ATBC	Aggregated Transmission Bandwidth Configuration
AuC	Authentication Centre
BCS	Bandwidth Combination Set
BW	Bandwidth
CA	Carrier Aggregation
CAGR	Compound Annual Growth Rate
CC	Component Carrier
CIF	Carrier Indicator Field
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CR	Coding Rate
CWC	Centre for Wireless Communications
D2D	Device-to-Device
DL	Downlink
DL-SCH	Downlink Shared Channel
DRX	Discontinuous Reception
E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
eNB	Evolved Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System
FDD	Frequency Division Duplexing
GERAN	GSM EDGE Radio Access Network
GP	Guard Period
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat request
HLR	Home Location Register
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
IP	Internet Protocol

ITU	International Telecommunication Union
KPI	Key Performance Indicator
LAA	Licenced Assisted Access
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MTC	Machine-Type Communication
NAS	Non-Access Stratum
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
P-GW	Packet Data Network Gateway
PAPR	Peak-to-Average Power Ratio
PCC	Primary Component Carrier
PCell	Primary Cell
PCI	Physical Cell ID
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PHY	Physical Layer
PRB	Physical Resource Block
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
RLC	Radio Link Control
RNC	Radio Network Controller
ROHC	Robust Header Compression
RRC	Radio Resource Control
RRH	Remote Radio Head
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RX	Reception/Receiver
S-GW	Serving Gateway
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SAE	System Architecture Evolution
SCC	Secondary Component Carrier
SCell	Secondary Cell
SDU	Service Data Unit
SNR	Signal-to-Noise Ratio
TB	Transport Block

TBS	Transport Block Size
TDD	Time Division Duplexing
TM	Transmission Mode
TTI	Transmission Time Interval
TX	Transmission/Transmitter
UE	User Equipment
UL	Uplink
UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunications System
UPV	Universitat Politècnica de València
UTRAN	UMTS Terrestrial Radio Access Network
VNI	Visual Networking Index
Wi-Fi	Wireless Fidelity
WCDMA	Wideband Code Division Multiple Access
WIMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

1 INTRODUCTION

Mobile communication has become an everyday commodity. During the last decades, it has evolved from being an expensive technology for a few selected individuals to today's widespread systems used by a majority of the world's population. [1]

Mobile communications technologies are typically divided into generations. Until now, there have been five generations of mobile communication systems, each associated with a specific set of technologies and a specific set of supported use cases, see Figure 1. [1] The most recent one, the fifth generation (5G) of mobile networks, is slowly expanding around the world. Nevertheless, 4G is the world's dominant mobile technology at present, supporting more than half (52%) of global connections in the last year. [2]

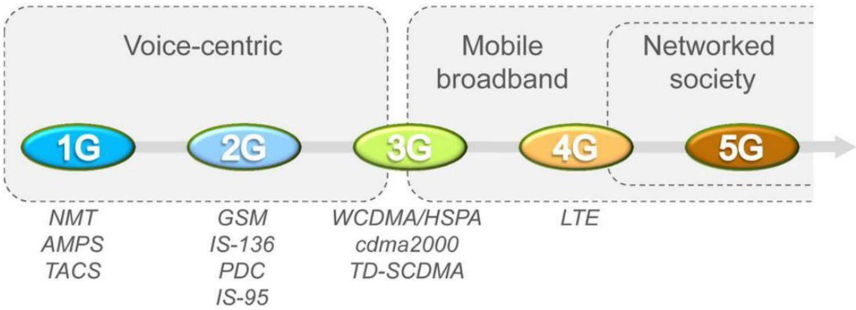

Figure 1. Cellular generations. [1]

Unlike previous 1G/2G generations which were voice centric, 3G and 4G mobile systems focus on broadband data services. In the last years, mobile broadband services are undergoing a period of tremendous growth triggering a huge increase in data traffic. [3] According to *Cisco Mobile VNI Forecast 2017-2022*, overall mobile data traffic is expected to grow to 77 exabytes per month by 2022, a seven-fold increase over 2017. Mobile data traffic will grow at a CAGR (Compound annual growth rate) of 46% from 2017 to 2022, see Figure 2. [4]

Figure 2. Global Mobile Data Traffic, 2017 to 2022. [4]

Mobile operators are continuously pursuing cost-effective and efficient solutions to meet the high data demand requirements of their subscribers. Limited spectrum allocations and non-contiguous spectrum chunks continue to pose challenges for mobile operators supporting large amount of data across their networks. Along with the increase in video and social media content, the challenges increase exponentially. [5]

Carrier Aggregation (CA) is a solution developed to deal with these challenges within the mobile ecosystem. [5]

1.1 Objectives and Research Scope

This thesis focuses on studying the practical performance of a key feature introduced in LTE-Advanced (LTE Release 10): Carrier Aggregation.

The main research questions considered in this work are the following. In practice, is Carrier Aggregation capable of delivering the performance theoretically expected? What is the performance gain if comparing to LTE Release 8? In this thesis, CA performance is evaluated in an experimental live mobile network. The performance of a radio network is typically evaluated with throughput measurements, which is also the method employed in this thesis.

CA offers different implementation possibilities in terms of number of component carriers (CC) or band combinations, depending on the available frequency bands and the capabilities of the end user's device and the operator's network. Currently, uplink CA is quite constrained due to transmitter implementation challenges in the User Equipment (UE), only being supported by the latest high-end devices. This thesis focuses on evaluating downlink CA performance. Although the standards allow combination of up to 5CC with CA, the scenario presented when conducting this work only allowed to test 2CC CA.

1.2 Structure of the Thesis

The following work is composed of a theoretical first part, covered in Section 2 and Section 3, and a practical second part presented in Section 4.

An overview on LTE is provided in Section 2. Firstly, the Evolved Packet System (EPS) architecture is described. Secondly, the LTE air interface aspects are discussed in Section 2.2, including multiple access techniques, modulation and coding schemes (MSC), duplex schemes, MIMO and LTE operating bands. The RAN protocol architecture is presented in Section 2.3. Lastly, Section 2.4 describes the evolution of LTE through the different LTE releases, providing a theoretical peak throughput comparation.

Section 3 focuses on the principal topic of this thesis: Carrier Aggregation. An overview of CA is provided at the beginning of the section. Then, the different deployment scenarios for CA are presented in Section 3.1. The impact of CA on the LTE protocol stack is briefly described in Section 3.2. CA configuration procedure is explained in Section 3.3. Lastly, sections 3.4 and 3.5 cover possible E-UTRA CA configurations and performance expectations of CA, respectively.

The practical part of this thesis is covered in Section 4, where LTE CA implementation and subsequent evaluation for an experimental live network are described. Firstly, the measurement setup is presented in Section 4.1. Performance measurements are provided in Section 4.2, measuring network performance for both single carrier connection and if using CA. The results are evaluated and compared with the theoretical expectations.

Finally, Section 5 concludes the thesis and provides some proposals for future research.

2 LTE

LTE (Long Term Evolution) or the E-UTRAN (Evolved Universal Terrestrial Radio Access Network), introduced in 3GPP Release 8, is the access network of the Evolved Packet System (EPS). [6]

As can be seen in Figure 3, EPS refers to the evolution of UMTS/HSPA networks. The EPS is made up of the E-UTRAN and the EPC (Evolved Packet Core), which are commonly known as LTE and SAE (System Architecture Evolution) respectively. [7] However, LTE is also typically used to represent both radio and core network evolution (LTE and SAE).

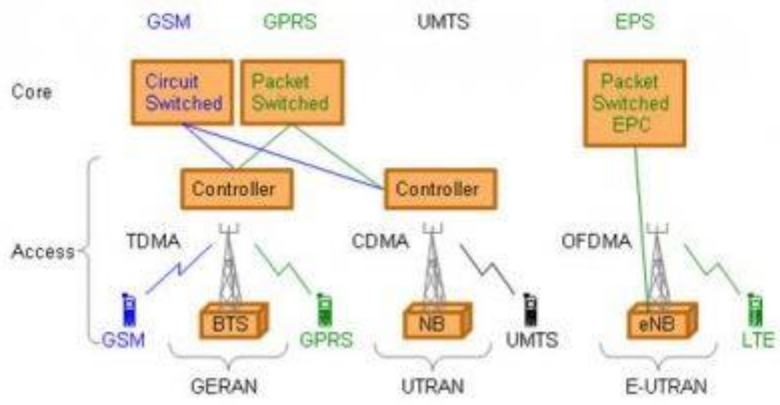

Figure 3. Network solutions from GSM to LTE. [6]

E-UTRAN focuses on the evolution of the Radio Access Network whereas EPC looks into the needs of the core network. [7] EPS is defined in 3GPP Release 8, which was completed in December 2008, with enhancements in the following LTE releases, introducing additional functionalities and capabilities in different areas. [1]

The Long-Term Evolution is often called as “4G”. Nevertheless, LTE release 10, also referred to as LTE-Advanced, is the true 4G evolution step, with the first release of LTE (Release 8) being labeled as “3,9G”. [8]

LTE technology is purely IP based and, unlike 3G networks, has no support for circuit-switched voice. Mobile broadband services were the focus, with strict requirements on high data rates, low latency, and high capacity. Other important considerations were spectrum and bandwidth flexibility, improved mobility and commonality between FDD (Frequency Division Duplex) and TDD (Time Division Duplex) operation modes. Also, a new core network architecture (EPC) was developed to replace the architecture used by GSM and UMTS. [1]

As will be discussed in Section 2.4, since its commercial introduction in 2009, LTE has evolved significantly in terms of data rates, capacity, spectrum and deployment flexibility, and application cases. From initial macrocell deployments with peak data rates of 300 Mbit/s in 20 MHz of contiguous and licensed spectrum, the evolution of LTE in release 13 (LTE-Advanced Pro) can achieve up to Gbit/s peak data rates in optimal circumstances with enhancements in terms of multi antenna techniques, multisite coordination, exploitation of fragmented as well as unlicensed spectrum and heterogeneous deployments. Furthermore, the evolution of LTE has spread the range of uses beyond mobile broadband by, for example, improving support for massive machine-type (MTC) communication or introducing direct device-to-device (D2D) communication. [1]

2.1 Evolved Packet System (EPS) architecture

The EPS is a simplified architecture (i.e., some intermediate network elements were removed or combined together) with an all-IP network support for higher throughput, lower latency radio access and improved mobility between multiple heterogeneous access networks including evolved universal terrestrial radio access (E-UTRA), 3GPP legacy systems (e.g., GERAN or UTRAN), as well as non-3GPP systems, such as Wi-Fi and CDMA2000. [9]

The EPS architecture can be seen in Figure 4, it can be represented by functional entities and the interfaces between them (also named reference points), over which interoperability is achieved. [9]

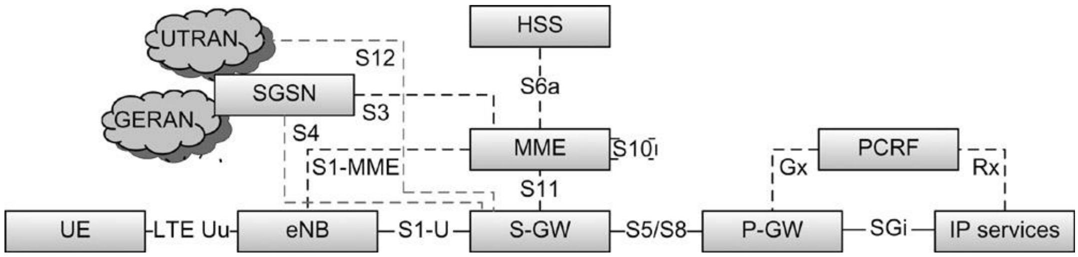

Figure 4. EPS architecture. [9]

As already mentioned, the overall LTE architecture has two distinct components, which are described in the following sections: the access network (E-UTRAN) and the core network (EPC). [9]

2.1.1 E-UTRAN

The LTE access network is simply a network of base stations, evolved NodeBs (eNBs), generating a flat architecture (Figure 5). Unlike previous 2G/3G technologies, LTE has integrated the radio controller function (RNC) into the eNB, which was responsible for controlling the Node Bs (NBs) connected to it. The eNBs are typically inter-connected via the X2-interface and towards the core network by the S1-interface. The UE (User Equipment) is directly connected to the E-UTRAN (eNB) via the LTE Uu interface. [6][9]

The reason for distributing the intelligence amongst the base-stations in LTE is to speed up the connection set-up and reduce the time required for a handover. For an end-user the connection set-up time for a real time data session is in many cases crucial, especially in on-line gaming. [6]

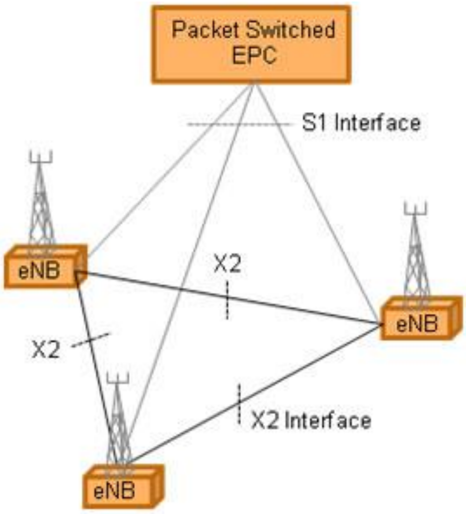

Figure 5. E-UTRAN. [6]

All the functions performed and the services provided by the E-UTRAN reside in the eNB, which can be responsible for managing multiple cells. The eNodeB is responsible for all radio-related functions, header compression, security and connectivity to the EPC. [9]

2.1.2 Evolved Packet Core (EPC)

The EPC is the latest evolution of the 3GPP core network architecture. It was designed to have a "flat architecture". Few network nodes are involved in the handling of the traffic and protocol conversion is avoided which allows to handle the data traffic efficiently from performance and costs perspective. [10]

The user data (also known as user plane) and the signaling (also known as control plane) is handled separately to make the scaling independent. This functional split allows the operators to dimension and adapt their network easily. [10]

The EPC architecture can be seen in Figure 4, it is interconnected with the E-UTRAN (eNB) through the S1 interface. The S1-MME interface interconnects the access network with the Mobility Management Entity (MME) while the S1-U is the interface between the E-UTRAN and the Serving Gateway (S-GW). The most important functional entities which compose the EPC are introduced below:

Mobility Management Entity (MME) is the main control node in the EPC. It deals with the control plane and is not involved in the user plane. The MME handles the signaling related to mobility and security between the E-UTRAN and the core network. It is responsible for the tracking and the paging of UE in idle-mode and is the entity that selects the most appropriate S-GW and P-GW for routing the user data. It is the termination point of the Non-Access Stratum (NAS), see Section 2.4. [10][11]

Home Subscriber Server (HSS) is a database server which stores user subscription information. [7] It also plays a role in mobility management, call and session setup, user authentication and access authorization. It is based on the pre -3GPP Release 4- Home Location Register (HLR) and Authentication Centre (AuC). [10][11]

The gateways **(Serving GW and PDN-GW)** deal with the user plane. They transport the IP data traffic between the User Equipment (UE) and the external networks. [10]

Serving Gateway (S-GW) interconnects the access network and the EPC. Its main purpose is routing the UE incoming and outgoing IP packets as well as to act as the mobility anchor for inter-eNodeB handovers and between LTE and other 3GPP accesses. It is logically connected to the other gateway, the PDN GW. [10][11]

Packet Data Network Gateway (P-GW or PDN-GW) is the point of interconnect between the EPC and the external IP networks, called packet data networks (PDN). The P-GW routes packets to and from the PDNs. The UE may have connectivity with more than one P-GW for accessing multiple PDNs. The PDN-GW also performs various functions such as IP address/IP prefix allocation or policy control and charging. [10][11]

These functional entities are specified independently by 3GPP, but in practice some of them may be implemented in a "single box", such as a combined MME and HSS or a combined SGW and PGW. [11]

2.2 LTE Air Interface

LTE operates on an air interface based on orthogonal frequency division multiplexing (OFDM) technology. The OFDM transmission scheme can be seen as a kind of multi-carrier transmission, which converts the allocated frequency band into multiple flat fading subcarriers. OFDM has many advantages including its robustness against multipath fading and interference. Several other radio access technologies use OFDM as well, for example WLAN and WiMAX. [8][11]

OFDM can be also used as a multiple-access scheme in LTE, allowing for simultaneous frequency-separated transmissions to/from multiple terminals (see Figure 6). [8] The LTE air interface, termed as E-UTRA, uses orthogonal frequency division multiple access (OFDMA) scheme on the downlink (DL) and a slight variation on the uplink (UL), the latter referred to as single-carrier frequency division multiple access (SC-FDMA). [11] SC-FDMA is used on the UL to compensate for an OFDMA drawback, which has a high peak to average power ratio (PAPR) in the transmitter. High PAPR requires expensive and inefficient power amplifiers with high requirements on linearity, which means higher cost of the terminal and shorter battery life. [12]

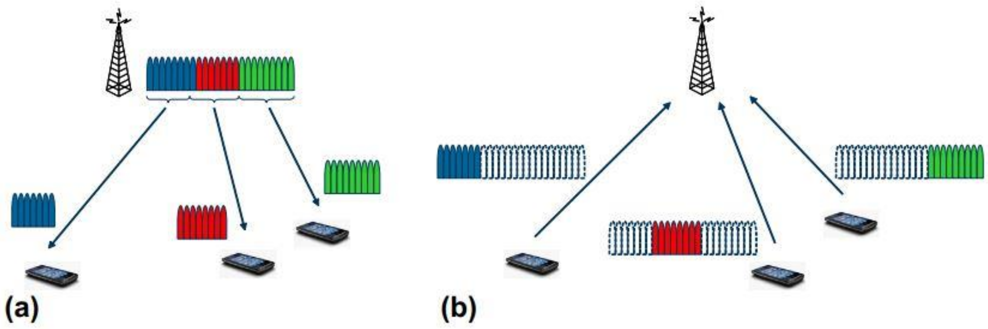

Figure 6. OFDM as a multiple-access scheme: a) downlink and b) uplink. [8]

Spectrum flexibility is an important requirement in LTE, in this sense LTE specifications allow for the allocation of channel bands of 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. Furthermore, LTE supports both FDD and TDD modes for transmission on paired and unpaired spectrum, which are presented in Section 2.2.3. [11]

2.2.1 OFDM as a user-multiplexing scheme

As already mentioned, the multiuser access mechanism used in LTE is based on the OFDM concept, where the allocated frequency band for the network is split into many adjacent narrowband subcarriers. Each subcarrier is handled (almost) individually carrying a portion of the signal from the time domain in the case of OFDMA on downlink and from the frequency domain in the case of SC-FDMA on uplink. Figure 7 shows a comparison between OFDMA and SC-FDMA schemes. [11][13]

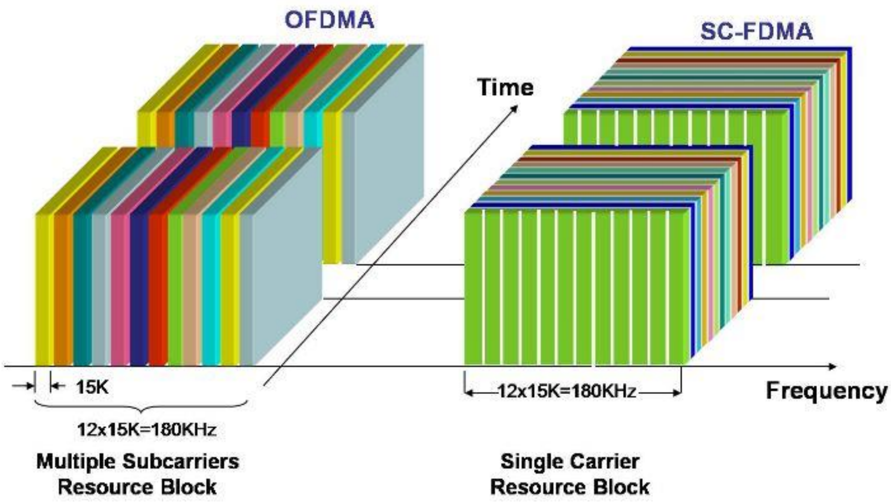

Figure 7. OFDMA vs SC-FDMA. [14]

The number of available subcarriers depends on the transmission bandwidth allocated for the network. The subcarrier spacing is 15 kHz to maintain the orthogonality between them and a maximum of 1200 different subcarriers can be allocated. Not all the subcarriers need to be transmitted to/from the base station but the exact number depends on the amount of spectrum allocated by the operator (1.4, 3, 5, 10, 15, or 20 MHz). [11]

The subcarriers are allocated to a connection in units of 12 adjacent subcarriers (180 kHz), called physical resource blocks (PRBs) or resource blocks (RBs), which last for 0.5 ms in the time domain. [11]

The allocation of PRBs is handled by a scheduling function at the eNodeB. A PRB is the smallest element of resource allocation assigned by the base station scheduler, however the minimum scheduling unit in LTE consists of two time-consecutive resource blocks referred to as a *resource-block pair*. The number of PRBs and the number of subcarriers that LTE has provided for various channel bandwidths are given in Table 1. [1][11]

The smallest modulation structure within a PRB is the Resource Element (RE), which is one 15 kHz subcarrier by one symbol and carries 2 (QPSK), 4 (16QAM) or 6 (64QAM) bits depending on the modulation scheme (see Section 2.2.2). The number of symbols within a PRB

(6 or 7) depends on the Cyclic Prefix (CP) in use. When a normal CP is used, the Resource Block contains seven symbols. Thereby, 12 consecutive subcarriers in the frequency domain and 6 or 7 symbols in the time domain form each Resource Block. Figure 8 shows the structure of a PRB using normal CP. [11]

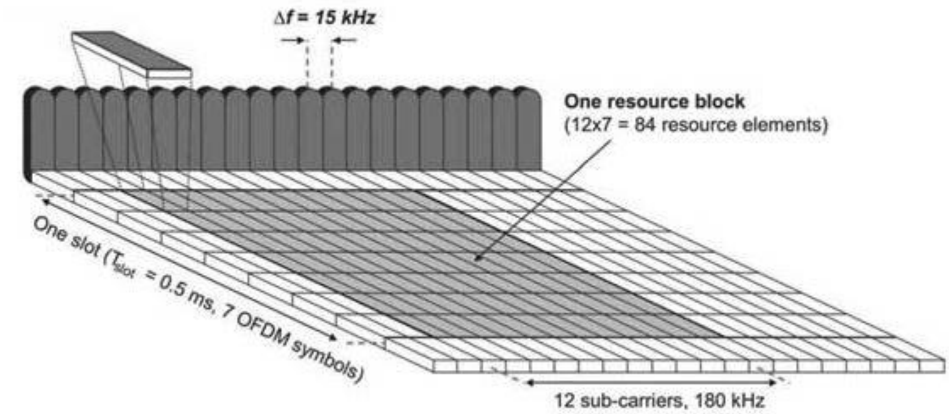

Figure 8. LTE Resource Block. [15]

Available channel bandwidth (MHz)	1.4	3	5	10	15	20
Number of occupied subcarriers	72	180	300	600	900	1,200
Number of PRBs	6	15	25	50	75	100

Table 1. Number of Resource Blocks with Channel Bandwidth. [11]

2.2.2 Modulation and Coding Schemes (MCS)

Modulation refers to the process of modifying the properties of a carrier signal with a modulating signal that contains information to be transmitted. By using higher order modulation, it is possible to transmit more bits per symbol and hence increase the bit rate. Conversely, the lower modulation order results in lower data rates but require less SNR (Signal-to-Noise Ratio) to operate, allowing larger coverage area and operation in poor channel conditions. [11]

The modulation schemes supported by LTE Release 8 are QPSK, 16-QAM and 64-QAM. 256-QAM was added for the downlink in LTE release 13. The modulated signal has 2^m states and each symbol carries *m* bits. QPSK is the lowest order modulation scheme being capable to transmit 2 bits per symbol, whereas 256-QAM can transmit 8 bits per symbol. Figure 9 shows modulation schemes used in LTE. [11]

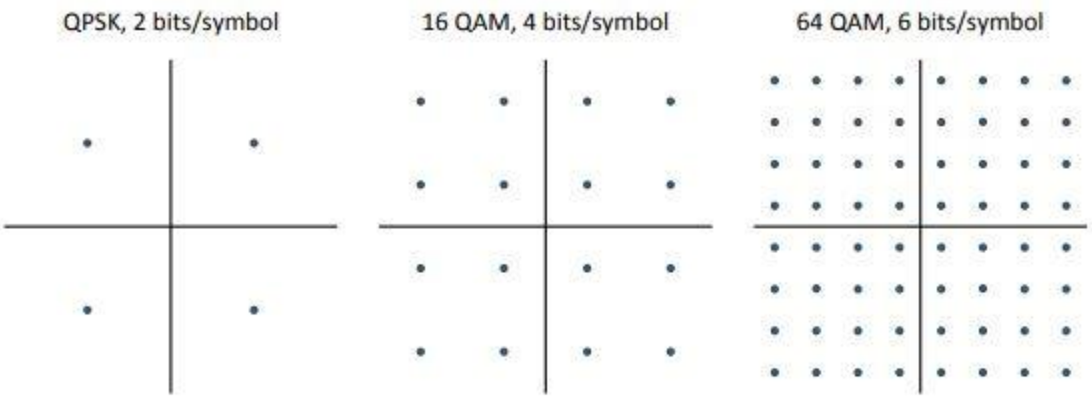

Figure 9. LTE modulation schemes. [16]

LTE uses the Modulation and Coding Scheme (MCS) index to specify the modulation and the effective coding used on the channel. The selection of the modulation scheme is held adaptively by the eNodeB based on UL measurements and the CQI (channel quality indicator) signaled by the UE. The CQI conveys the downlink channel quality to the eNodeB, based on SNR measurements of the channel. The UE can report the CQI to the base station either periodically or aperiodically. [11]

The MCS index ranges from 0 to 31 and determines the modulation order and the transport block size (see Table 2). The Transport Block Size (TBS) refers to the amount of useful information transmitted at the physical layer and is directly related with the data rate. [11]

MCS Index I_{MCS}	**Modulation Order** Q_m	**TBS Index** I_{TBS}
0	2	0
1	2	1
2	2	2
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	4	9
11	4	10
12	4	11
13	4	12
14	4	13
15	4	14
16	4	15
17	6	15

18	6	16
19	6	17
20	6	18
21	6	19
22	6	20
23	6	21
24	6	22
25	6	23
26	6	24
27	6	25
28	6	26
29	2	Reserved
30	4	
31	6	

Table 2. Modulation and TBS index table. [11]

2.2.3 Duplex Schemes

In addition to the flexibility in transmission bandwidth, LTE also supports operation in both FDD and TDD duplex modes, supporting operation in both paired and unpaired spectrums. LTE specifications have defined two slightly different frame structures for the FDD and TDD modes, type 1 for FDD and type 2 for TDD. Licensed-assisted access (LAA) was added in release 13, allowing for operation in unlicensed spectrum, for this reason frame structure type 3 was also introduced. The different LTE frame structures types are represented in Figure 10 and explained below. [1][11]

The time-domain frame structure is, in most aspects, the same for all three frame structures. However, there are some differences, especially the presence of a "special subframe" in the case of frame structure type 2, which is used to provide the necessary guard time for downlink–uplink switching. [1]

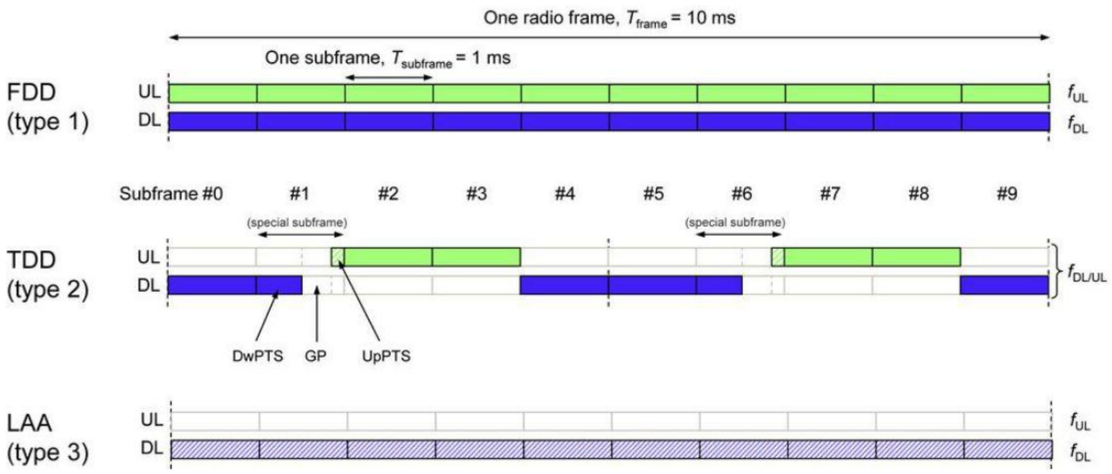

Figure 10. Uplink/downlink time-frequency structure in case of FDD and TDD. [1]

FREQUENCY-DIVISION DUPLEX (FDD)

In the case of FDD operation (frame structure type 1) different carrier frequencies are used for uplink and downlink, denoted f_{ul} and f_{dl} in the upper part of Figure 10. The FDD frame is made up of 20 slots of 0.5 ms each and two adjacent slots form a subframe (1 ms). Therefore, during each frame, there are ten uplink subframes and ten downlink subframes, where uplink and downlink transmissions can occur simultaneously within a cell. Transmission/reception filters, known as duplex filters, are employed to achieve isolation between DL/UL transmissions. [1][11]

TIME-DIVISION DUPLEX (TDD)

In the case of TDD operation (frame structure type 2), there is a single carrier frequency where uplink and downlink transmissions are carried on separately in the time domain. As seen in Figure 10, in each frame some subframes are allocated for uplink transmissions and some subframes are allocated for downlink transmission. The switch between downlink and uplink occurs in a special subframe (subframe 1 and, for some uplink–downlink configurations, also subframe 6). The special subframe consists of three parts: a downlink part (DwPTS), a guard period (GP), and an uplink part (UpPTS). [1]

Different uplink-downlink configurations are defined to support different asymmetries in terms of the amount of resources -that is, subframes- allocated for uplink and downlink transmission. Downlink transmissions are always allocated in subframes 0 and 5 while subframe 2 is always allocated for uplink transmissions. The remaining subframes (except the special subframe) can be flexibly allocated either for downlink or uplink transmission depending on the load on each link. [1]

2.2.4 MIMO

Multiple Input Multiple Output (MIMO) is a key technology in LTE based on the use of multiple antennas at the receiver and/or the transmitter to increase the overall bitrate or to improve the robustness of data transmission. [8] Generally, a MIMO system consists of m transmit antennas and n receive antennas as can be seen in Figure 11 below. [17]

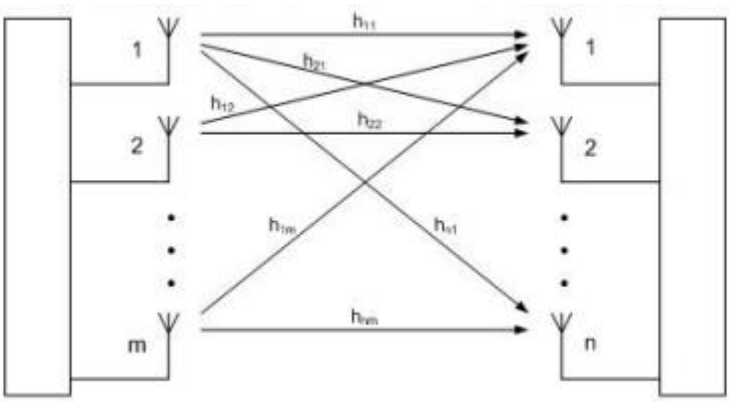

Figure 11. MIMO system with m TX and n RX antennas. [17]

LTE Release 8 supports 2 x 2 MIMO and 4 x 4 MIMO for downlink, while for the uplink, MIMO was not introduced until LTE Release 10, where 4 x 4 uplink MIMO and 8 x 8 downlink MIMO were defined. [18] MIMO can be used in different ways. The most common use cases are *Transmit diversity* and *Spatial multiplexing*, which are described below.

Transmit diversity is a traditional implementation to improve the S/N (Signal to Noise ratio) when the signal quality is poor. In this scenario, the same data stream is transmitted through two or more antennas to decrease the effect of fading at the channel. The system capacity is increased by ensuring the integrity of the signal but the data rate is not improved. [18]

Spatial multiplexing (sometimes referred as MIMO) is another transmission scheme which significantly increase the system throughput. In this implementation, different data streams are transmitted on two (or more) TX antennas and received by two (or more) RX antennas. This does not necessarily make the transmission more robust since data streams are not duplicated, but it increases considerably the data rate compared to a single antenna scenario. [19]

Spatial multiplexing can be used when S/N and channel conditions are good. For situations with low S/N it is better to use other type of multi-antenna schemes to instead increase the S/N, i.e. by means of TX-diversity. To adjust the type of multi-antenna transmission scheme a number of different Transmission Modes (TM) has been defined. [19] Table 3 shows the different transmission modes defined for the downlink in Release 12.

Downlink Transmission modes in LTE Release 12		
Transmission modes	**Description**	**Comment**
1	Single transmit antenna	single antenna port port 0
2	Transmit diversity	2 or 4 antennas ports 0,1 (…3)
3	Open loop spatial multiplexing with cyclic delay diversity (CDD)	2 or 4 antennas ports 0,1 (…3)
4	Closed loop spatial multiplexing	2 or 4 antennas ports 0,1 (…3)
5	Multi-user MIMO	2 or 4 antennas ports 0,1 (…3)
6	Closed loop spatial multiplexing using a single transmission layer	1 layer (rank 1), 2 or 4 antennas ports 0,1 (…3)
7	Beamforming	single antenna port, port 5 (virtual antenna port, actual antenna configuration depends on implementation)
8	Dual-layer beamforming	dual-layer transmission, antenna ports 7 and 8
9	8 layer transmission	Up to 8 layers, antenna ports 7 - 14
10	8 layer transmission	Up to 8 layers, antenna ports 7 - 14

Table 3. MIMO Transmission modes in LTE Release 12. [17]

2.2.5 Spectrum allocation

Until the Release 16 (June 2019), the standards have identified 78 bands for LTE operation, 47 for FDD and 31 for TDD in licensed and unlicensed spectrum. LTE frequency bands can be seen in [20].

In the place where this work has been carried out (Oulu, Finland), the available frequency bands are the following: Band 1 (2.1 GHz) Band 7 (2.6 GHz), Band 28 (700 MHz) and Band 42 (3.5 GHz), which are presented in Table 4. Band 1, Band 7 and Band 28 are defined for FDD operation while Band 42 operates in TDD. Table 4 describes the maximum bandwidths in each band defined by 3GPP releases. The used bandwidths in the actual measurements are smaller due to limitations in frequency licences.

Band	Name	Downlink (MHz)			Bandwidth DL/UL (MHz)	Uplink (MHz)			Duplex spacing (MHz)	3GPP release
		Low	Middle	High		Low	Middle	High		
1	2100	2110	2140	2170	60	1920	1950	1980	190	8
7	2600	2620	2655	2690	70	2500	2535	2570	120	8
28	700 APT	758	780.5	803	45	703	725.5	748	55	11.1
42	3500	3400	3500	3600	200	-				10

Table 4. LTE frequency bands. [20]

2.3 RAN Protocol Architecture

Keeping in mind the overall LTE network architecture, the RAN protocol architecture for the user and control planes is discussed below. Figure 12 illustrates the RAN protocol stack (although the MME is not part of the RAN, it is included in the figure for completeness). As seen in Figure 12, the protocol entities are to a large extent common for the user and control planes. [1]

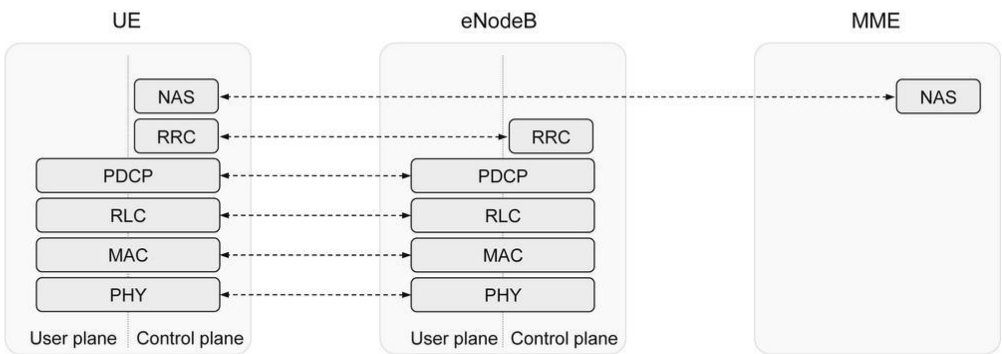

Figure 12. RAN protocol stack in LTE. [1]

The different RAN protocol entities are described below. Generally, the Non-Access Stratum (NAS) and the Radio Resource Control (RRC) entities belong to Layer 3, whereas PDCP, RLC and MAC are considered as Layer 2 sublayers. The physical layer (PHY) corresponds to Layer 1. [1]

PACKET-DATA CONVERGENCE PROTOCOL

The Packet data convergence protocol (PDCP) sublayer performs IP header compression, reducing the number of bits to transmit over the radio interface. LTE uses a standardized header-compression algorithm, known as Robust Header Compression (ROHC), also used in other mobile-communication technologies. PDCP also performs ciphering to protect the data against eavesdropping. For the control plane, PDCP is responsible for integrity protection, ensuring that control messages are originated from the correct source. On the receiver side, the PDCP performs the corresponding deciphering and decompression operations. [1]

RADIO-LINK CONTROL

One of the main functions performed by the RLC sublayer is the segmentation/concatenation of IP packets, also known as RLC SDUs, from the PDCP into RLC PDUs. In general, the data entity from/to a higher protocol layer is known as a service data unit (SDU) and the corresponding entity to/from a lower protocol layer entity is called a protocol data unit (PDU). RLC is also responsible of handling retransmissions of erroneously received PDUs and removal of duplicated PDUs. Although the RLC is capable of handling transmission errors as due to noise or unpredictable channel variations, error-free delivery is in most cases handled by the MAC sublayer hybrid-ARQ protocol. Ensuring in-sequence delivery of SDUs to upper layers is also performed by RLC. [1]

MEDIUM-ACCESS CONTROL

MAC entity performs multiplexing of logical channels (described below), hybrid-ARQ retransmissions, and uplink and downlink scheduling. It is also responsible for multiplexing/demultiplexing data over multiple component carriers when carrier aggregation is used (see Section 3.3). [1]

The MAC serves the RLC in the form of logical channels. A logical channel is defined by the type of information it carries. Logical channels can be classified as control channels, which carry control information and configuration for operating an LTE system, or as a traffic channel, used for the user data. [1]

On the other hand, the MAC layer uses services from the physical layer in the form of Transport Channels. A transport channel defines how the information is transmitted over the radio interface. The information on a transport channel is organized into transport blocks. Each transport block includes a transport format (TF) associated, which contains information about the transport-block size, the modulation and coding scheme, and the antenna mapping. [1]

MAC is responsible for the multiplexing of the different logical channels and mapping of the logical channels to the appropriate transport channels. Figures 13 and 14 show the mapping between logical channels and transport channels for the downlink and for the uplink respectively. DL-SCH for the downlink and UL-SCH for the uplink are the main transport channels. [1]

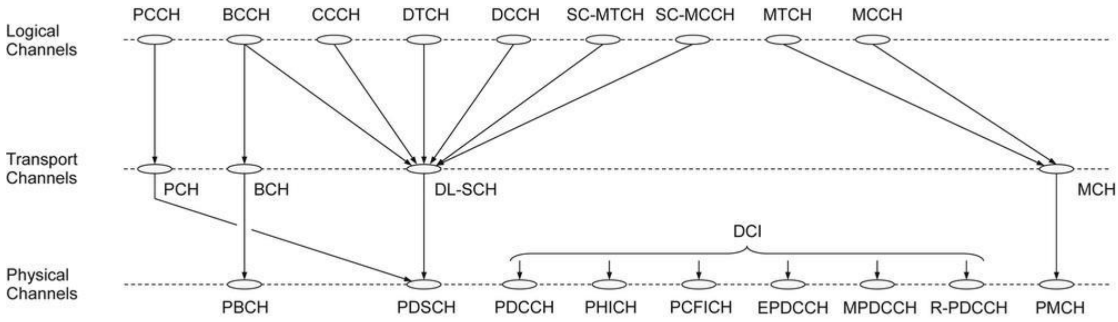

Figure 13. Downlink channel mapping. [1]

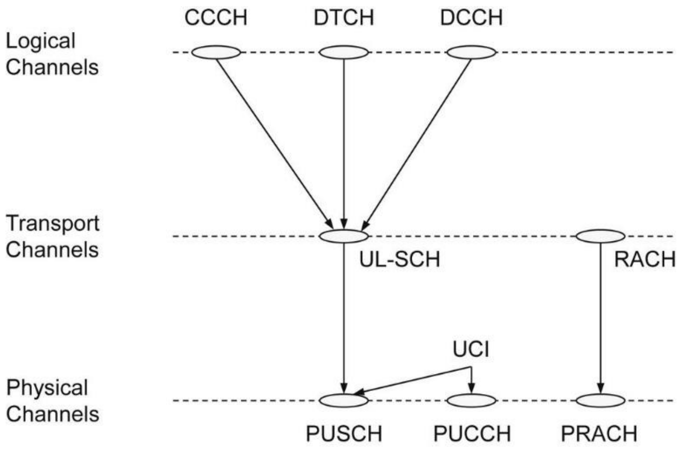

Figure 14. Uplink channel mapping. [1]

PHYSICAL LAYER

The physical layer (PHY) is at the bottom of the protocol stack and carries 1-ms subframes which contain a transport block (TB). [11] Physical layer functions include coding, physical-layer hybrid-ARQ processing, modulation, multi-antenna processing and mapping of the signal to the appropriate physical time-frequency resources. It is also responsible for the mapping of transport channels to physical channels (Figures 13 and 14). [1]

2.4 From LTE to LTE Advanced Pro

Significant improvements have been done from the first LTE system design, released in 2009, which was considered a pre-4G system. LTE Release 10 enhanced LTE capabilities to fulfill the International Telecommunication Union's (ITU) requirements for 4G systems. The resulting system, branded as LTE-Advanced, can provide peak data rates up to 3 Gbps on downlink and 1.5 Gbps on uplink by means of Carrier Aggregation and enhanced multi-antenna techniques added in LTE Release 10. LTE Release 13 enhanced the LTE-Advanced system by adding new features to go beyond 4G and constituting a part of the 5G framework. LTE Release 13 and 14 are known as LTE-Advanced Pro. Table 5 provides a comparison of those key evolution steps. [11]

System Branding	LTE	LTE-Advanced	LTE-Advanced Pro
3GPP Release	Release 8	Release 10*	Release 13 and beyond
Freezing date	March 2009	June 2011	March 2016
Main purpose	Provide high throughput for MBB, prepare mobile system for evolution towards 4G	Fulfill IMT-Advanced requirements for 4G system	Mark evolution point with significant improvements to the LTE-Advanced
Key features	OFDMA, DL MIMO (4 × 4), Modulation with up to 64QAM, Flat architecture (eNodeB), Flexible system BW (1.4–20 MHz)	CA (extending system BW to 100 MHz), Enhanced DL MIMO (8 × 8), UL MIMO (4 × 4), small cells, HetNet, eICIC, SON, CoMP, ePDCCH	DC, LAA, LWA, Modulation 256QAM, EB/FD-MIMO, D2D, V2X, NB-IoT, eMTC

Table 5. Comparison of LTE System Evolution Steps. [11]

*LTE-Advanced is defined in 3GPP as Release 10, but it also covers the enhancements from Release 11 and Release 12.

One of the key system's performance indicators is its maximum throughput, which is also the main topic of this Thesis. In this sense, below are provided simplified calculations taken from [11] to show how those peak data rates are achieved. This also serves to show how the LTE system has evolved and what parameters and new features influence those calculations. The throughputs below are only calculated for the DL. [11]

2.4.1 LTE Release 8

Assuming the following configuration [11]:

Max. number of spatial layers: NoLayers = 4 (MIMO 4 x 4);
Max. modulation*:* Mod = 64 QAM;
Max. coding rate: CR = 0.9258 (LTE MCS Index 13);
Max. BW size: BW = 20 MHz (channel BW);
Max. occupied bandwidth size: BWoccupied = 18 MHz (occupied by OFDMA subcarriers)

Considering the following PHY-layer signaling overhead: Overhead = 25%

The maximum LTE Release 8 throughput can be calculated in the following way:

Bandwidth efficiency:

BWeff = BWocuppied/BW = 18 MHz/20 MHz = 0.9 [11] (1)

Maximum DL spectral efficiency for a single stream:

SE_Layer = Log2(Mod) * CR * BWeff = 6 * 0.9258 * 0.9 = ~ 5 bps/Hz [11] (2)

Total maximum DL spectral efficiency:

$$\text{Total\_SE} = \text{NoLayers} * \text{SE\_Layer} = 4 * 5 = 20 \text{ bps/Hz [11]} \quad (3)$$

Spectral efficiency considering the PHY-layer overhead:

$$\text{Effective\_SE} = \text{Total\_SE} * (1 - \text{Overhead}) = 20 * (1 - 0.25) = 15 \text{ bps/Hz [11]} \quad (4)$$

Maximum DL throughput:

$$\text{DLthpt} = \text{Effective\_SE} * \text{BW} = 15 \text{ bps/Hz} * 20 \text{ MHz} = 300 \text{ Mbps [11]} \quad (5)$$

2.4.2 LTE-Advanced Release 10

Considering the above calculation as a baseline, the improvements done in LTE-Advanced are included in the following ways:

The number of antennas and thus spatial layers were increased to 8 (4 in the LTE Release 8). Thus, the maximum spectral efficiency has increased by a factor of 2: NoLayersImprovement = 2. [11]

The maximum BW size was increased by a factor of 5, due to carrier aggregation with 5 component carriers:

$$\text{BW\_LTEA} = 5 * 20 \text{ MHz} = 100 \text{ MHz [11]} \quad (6)$$

Therefore, the maximum throughput of LTE-Advanced can be calculated as:

Effective spectral efficiency:

$$\begin{aligned}\text{Effective\_SE\_LTEA} &= \text{Effective\_SE} * \text{NoLayersImprovement} \\ &= 15 * 2 = 30 \text{ bps/Hz [11]}\end{aligned} \quad (7)$$

Maximum DL throughput:

$$\begin{aligned}\text{DLthrpt} &= \text{Effective\_SE\_LTEA} * \text{BW\_LTEA} \\ &= 30 \text{ bps/Hz} * 100 \text{ MHz} = 3 \text{ Gbps [11]}\end{aligned} \quad (8)$$

2.4.3 LTE-Advanced Pro Release 13

Finally, considering the LTE-Advanced Pro improvements, the maximum throughput could be improved by the following ways:

The maximum modulation scheme was improved to 256 QAM, which improves maximum spectral efficiency by a factor of 8/6 (a maximum of 8 bits/symbol can be transmitted instead of 6 bits/symbol using 64-QAM): Mod_Improvement = 8/6. [11]

The maximum spectrum BW size could be increased to 640 MHz due to massive CA (32 component carriers of 20 MHz each). However, the possibility of using 32 CCs is not likely to happen in the nearest future since it depends on UE capabilities, thus: BW_LTEAPro = 100 MHz. [11]

Therefore, for the calculation of the maximum throughput for LTE-Advanced Pro it is only considered the modulation improvement:

Effective spectral efficiency:

$$\text{Effective\_SE\_LTEAPro} = \text{Effective\_SE\_LTEA} * \text{Mod\_Improvement} = 30 \text{ bps/Hz} * 8/6 = 40 \text{ bps/Hz [11]} \quad (9)$$

Maximum DL throughput:

$$\text{DLthrpt} = \text{Effective\_SE\_LTEAPro} * \text{BW\_LTEAPro} = 40 \text{ bps/Hz} * 100 \text{ MHz} = 4 \text{ Gbps [11]} \quad (10)$$

In the case of calculating the theoretical maximum throughput including 32 CCs:

Max. theoretical throughput*:*

$$\text{DLthrpt\_theoretical} = 40 \text{ bps/Hz} * 640 \text{ MHz} = 25.6 \text{ Gbps [11]} \quad (11)$$

Table 6 summarizes the above considerations.

System	LTE	LTE-Advanced	LTE-Advanced Pro
Max. system BW	20 MHz	100 MHz	100 MHz, 640 MHz*
Max. DL modulation	64QAM	64QAM	256QAM
Max. DL number of spatial layers	4	8	8
Max. DL spectral efficiency	15 bps/Hz	30 bps/Hz	40 bps/Hz
Max. DL throughput	300 Mbps	3,000 Mbps (3 Gbps)	4,000 Mbps (4 Gbps), 25,600 Mbps (25.6 Gbps)**

Table 6. Comparison of the Systems' Key Parameters and Throughputs. [11]

3 CARRIER AGGREGATION

Carrier aggregation is a key feature introduced in LTE release 10 (LTE-Advanced) with enhancements in the following releases. Carrier aggregation allows a mobile to transmit and receive on a number of aggregated carriers, where each carrier is named a component carrier (CC) and can have a bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz. Up to five component carriers, possibly each with different bandwidth can be aggregated, allowing for transmission bandwidths of up to 100 MHz. Even though release 13 allows the aggregation of 32 CCs, defined CA schemes only support five CCs aggregation. Each component carrier can also be accessed by an LTE device from earlier releases, that is, component carriers are *backward compatible*. [1]

Aggregated component carriers do not need to be contiguous in the frequency domain. In this sense, three different cases can be identified depending on the frequency location of the different component carriers [1] (see Figure 15):

Intra-band contiguous: In this scenario, the different component carriers are allocated contiguously in the same frequency band. The frequency spacing between the center frequencies of aggregated RF carriers is a multiple of 300 kHz in order to be compatible with LTE Rel-8/9 frequency raster of 100 kHz and preserve orthogonality of the subcarriers with 15 kHz spacing. [9]

Intra-band non-contiguous: In this scenario, the aggregated carriers are in the same frequency band but they are not adjacent. [9]

Inter-band non-contiguous: In this type of carrier aggregation the aggregated components belong to different frequency bands. [9]

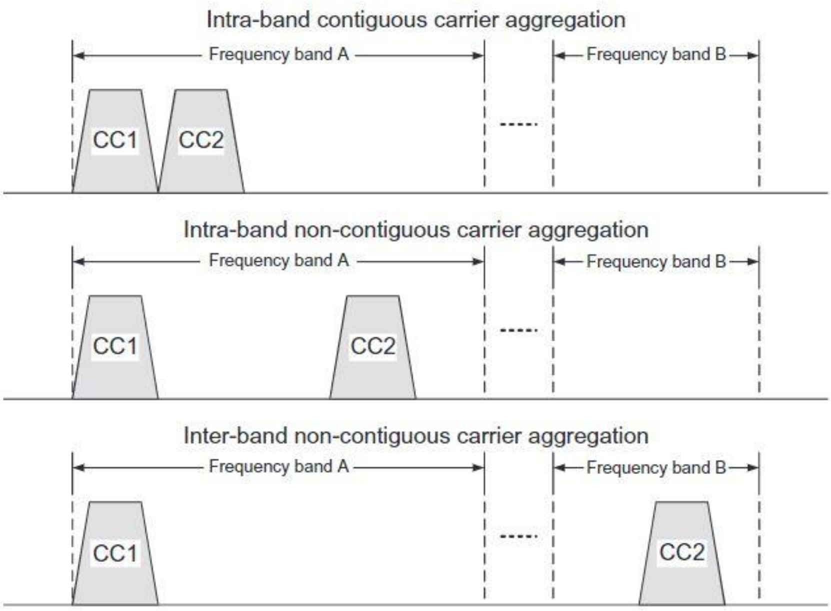

Figure 15. Carrier aggregation scenarios. [9]

The possibility to aggregate nonadjacent component carriers allows mobile operators with a fragmented spectrum to provide higher data-rate services based on the availability of a wide overall bandwidth, although they do not possess a single wideband spectrum allocation. There is no difference between the three different cases presented in Figure 15, except from an RF point of view. The complexity of RF implementation is vastly different. Thus, although spectrum aggregation is supported by the physical layer and protocol specifications, the actual implementation is quite constrained, only supporting a limited number of aggregation scenarios. [1]

In LTE-Advanced carrier aggregation terminology, a component carrier (CC) is generally referred to as serving cell, is assigned its own physical cell identifier (PCI), and is managed as a serving cell by the higher layers. The number of downlink/uplink component carriers may be different, but the number on the uplink must be equal or smaller than that on the downlink. In general, a different number of component carriers can be aggregated for downlink and uplink. Depending on its capabilities, the UE may support carrier aggregation only in the downlink or in both directions (see Section 3.5). [9]

Carrier aggregation is supported for all frame structures, TDD and FDD (as well as type 3, LAA, for aggregation of licensed and unlicensed spectrum). In FDD mode, each serving cell comprises two different carrier frequencies for downlink and uplink transmissions, whereas for TDD systems, a serving cell is composed by a single-carrier frequency where downlink and uplink transmission occur in different transmission time intervals. In release 10, all aggregated component carriers must have the same duplex mode and, in case of TDD, the same uplink-downlink configuration across the component carriers. [1][9]

In release 11, different uplink-downlink configurations across the component carriers can be used by TDD devices. Release 12 further enhanced carrier aggregation by allowing aggregation between FDD and TDD to enable efficient utilization of an operator overall spectrum. Aggregation across different duplex schemes can also be used to improve the uplink coverage of TDD with the possibility for continuous uplink transmission on the FDD carrier. Figure 16 shows the evolution of carrier aggregation through the different releases. [1]

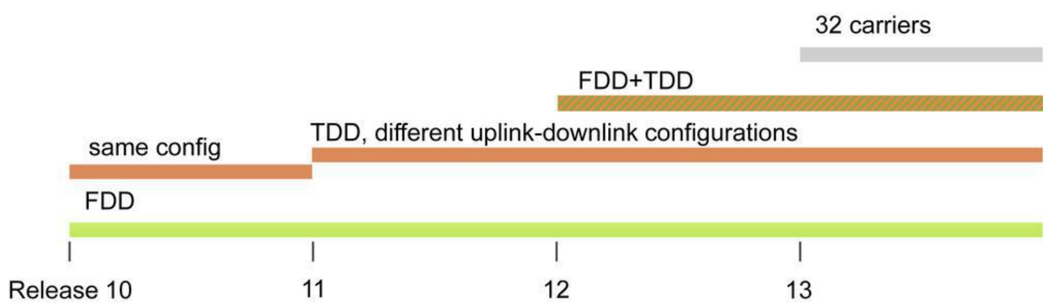

Figure 16. Evolution of carrier aggregation. [1]

3.1 Deployment scenarios

Carrier Aggregation enables various network deployment possibilities. Generally, carrier aggregation is employed to increase data rates for users within overlapped areas of the cells. Nevertheless, CA can also be used to mitigate inter-cell interference in heterogenous networks. Below are presented different network deployment scenarios considered during the development of LTE-Advanced for carrier aggregation operation. Although the cases are exemplified with two component carriers, the concept can be generalized to any number of component carriers. [9]

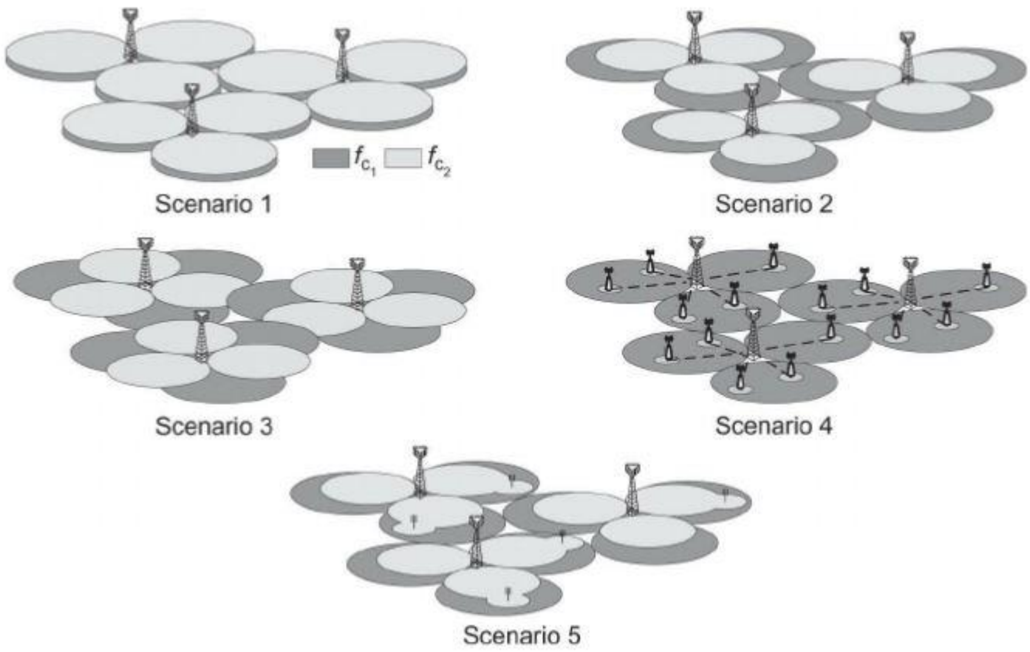

Figure 17. Carrier aggregation deployment scenarios. [9]

Deployment Scenario 1: In this scenario, cells with carrier frequencies f_{c_1} and f_{c_2} are collocated and their coverage is overlaid. Frequencies f_{c_1} and f_{c_2} are in the same frequency band thus providing approximately the same coverage area due to similar path loss characteristics. This carrier aggregation scenario is used to achieve higher data rates within the overlapped coverage area. Mobility can be supported by any of the carrier frequencies. [9]

Deployment Scenario 2: In this case, the cells comprising carrier frequencies f_{c_1} and $f_{c_2}$are collocated and overlapped but the frequencies belong to different frequency bands. The coverage provided by both frequencies is different, experiencing larger path losses with the higher frequency. In this scenario, the lower frequency band typically supports mobility. The component carrier in the higher frequency band provides smaller coverage area and is used to improve the throughput where both cells are overlapped. [9]

Deployment Scenario 3: In this scenario, cells with carrier frequencies f_{c_1} and f_{c_2} are collocated and the frequencies are in different bands. The antennas transmitting at f_{c_2} are directed to the cell boundaries of f_{c_1}, improving the cell-edge data rates. Mobility is supported by the lower frequency and carrier aggregation can be used within the overlaid cells. [9]

Deployment scenario 4: In this case, cell with carrier frequency f_{c_1} provides macro coverage, whereas remote radio heads (RRHs) with f_{c_2} are used to improve throughput at hot spots. Mobility is supported by the cell with larger coverage area. Carrier aggregation can be employed within the coverage of RRHs. [9]

Deployment Scenario 5: This scenario is similar to the second case, where additional frequency-selective repeaters or distributed antenna systems are deployed to extend the coverage for one of the carrier frequencies. [9]

3.2 Overall protocol structure

Carrier aggregation is basically duplicating the MAC and PHY processing for each component carrier while keeping RLC and above identical to the non-aggregation case (see Figure 18). [1]

In presence of carrier aggregation, one RLC entity may handle data transmitted across multiple component carriers. The MAC entity distributes data from each flow across the component carriers. Each component carrier has its own hybrid-ARQ entity, implying that hybrid-ARQ retransmissions must use the same component carrier as the original transmission. RLC retransmissions, on the other hand, may occur on a different component carrier than the original transmission since CA is invisible above the MAC layer. The RLC also handles reordering across component carriers to ensure in-sequence in case a radio bearer is transmitted on multiple component carriers. [1]

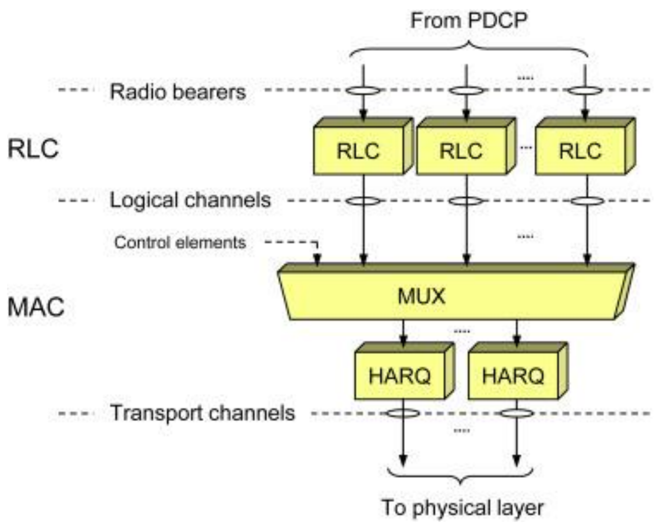

Figure 18. LTE-Advanced protocol structure. [1]

3.3 CA configuration, activation and deactivation

In practice, carrier aggregation is implemented in the following way. When a device moves from ‘RRC_idle’ to ‘RRC_connected’ state, only a single carrier is used, which is referred to as Primary Component Carrier (PCC) and is provided by the Primary Cell (PCell). During this procedure, if the network had not stored the device’s capability information from a previous connection it sends a ‘UECapabilityEnquiry’ message. In reponse, the mobile sends a ‘UECapabilityInformation’ message. This message includes, among many other parameters, the UE category that describes the sustainable data rate supported by the device, the supported frequency bands and the supported carrier aggregation configurations. [21]

Once the communication between the network and the device is established, additional component carriers can be configured. [1] These are referred to as Secondary Component Carriers (SCCs) and are provided by the Secondary Cells (SCells). Adding SCells during the connection setup procedure can take less than 100 milliseconds. Whether additional carriers are added to a connection or not, is network implementation specific. Typically, carrier aggregation is attempted when the base station detects that larger amounts of data need to be transferred. [21]

Generally, SCell configuration includes the setup of signal quality measurements. SCells are configured after 'RRC_Reconfiguration_Complete' message. Figure 19 shows how CA is configured in practice. Once SCells are configured, the eNodeB can activate them at any time on the MAC layer using a MAC-layer control element. The SCells then become available for use eight subframes after, i.e. after 8 milliseconds. [21]

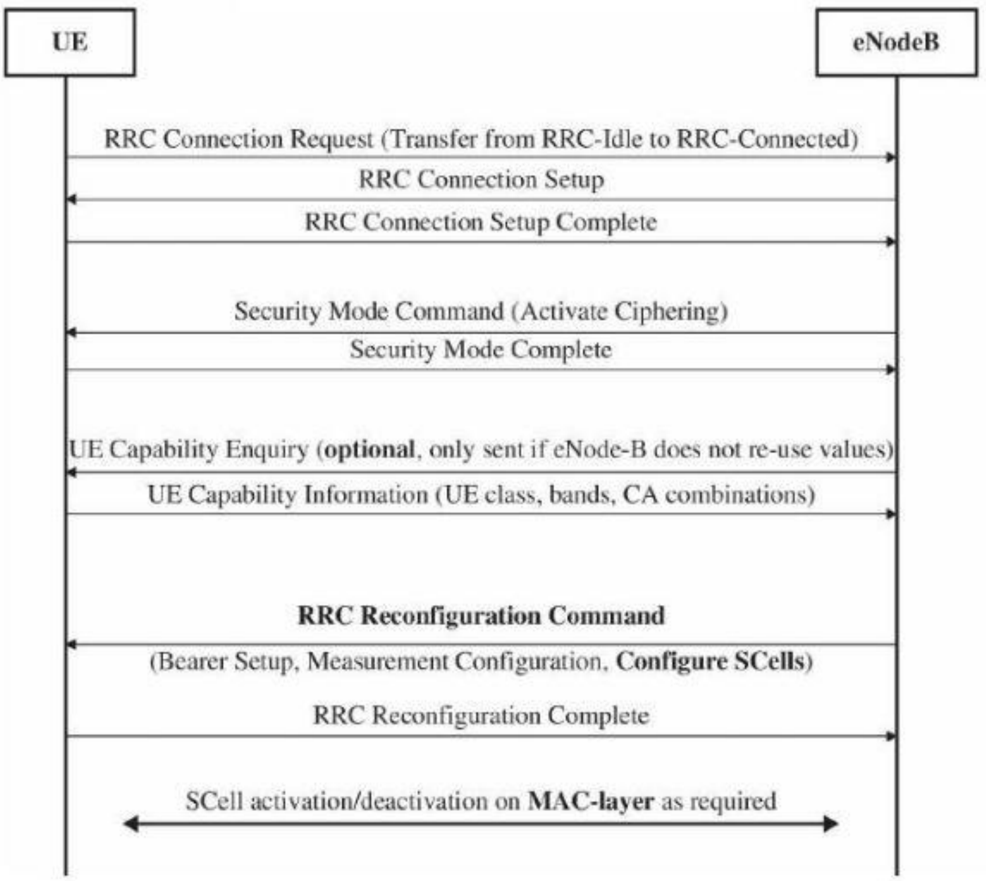

Figure 19. CA configuration during RRC connection establishment. [21]

Once the SCells are activated, each component carrier may be independently scheduled with individual scheduling assignments/grants per component carrier. The scheduling assignment/grant can either be transmitted on the same carrier as data (self-scheduling) or on another component carrier (cross-carrier scheduling). Both possibilities are illustrated in Figure 20. [1]

In case of self-scheduling, downlink scheduling assignments are valid for the component carrier in which they are transmitted. For uplink grants, each uplink component carrier has an associated downlink component carrier, provided as part of the system information. In this sense, the device knows to which uplink component carrier the uplink grant relates to. [1]

When using cross-carrier scheduling, downlink PDSCH or uplink PUSCH are transmitted on a component carrier different that which PDCCH is transmitted upon. The Carrier Indicator Field (CIF) was included on the PDCCH to inform about the component carrier used for the

PDSCH or PUSCH. Whether cross-carrier scheduling is used or not is configured using higher-layer signaling. [1]

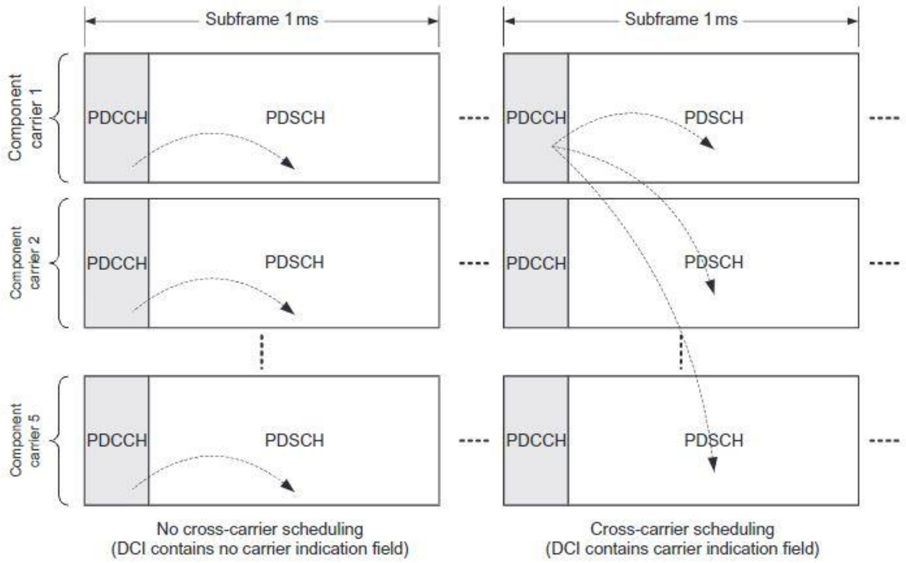

Figure 20. Self-scheduling and cross-carrier scheduling. [9]

From a power-consumption perspective, it is beneficial to receive as few component carriers as possible. For this reason, carrier aggregation use is separated into a slow configuration phase during which some parameters need to be communicated in an 'RRC_Reconfiguration' message and a fast SCell activation/deactivation procedure. This way, power can be conserved while resources on the PCell are sufficient to transfer data to the mobile and bandwidth can be quickly increased when becomes necessary. On a deactivated SCell, the UE neither receives downlink signals nor transmits any uplink signal. Activation and deactivation of SCells is performed independently for each cell by the eNB with activation/deactivation command in the form of a MAC control element. Also, SCells may be automatically by means of a deactivation timer (see Figure 21). Activation/deactivation is not applicable to the PCell since it is required to always remain activated when the UE has an RRC connection to the network. [1][21]

Additionally, the discontinuous reception (DRX) mode was defined in LTE Rel-8/9 as a means to reduce the device power consumption. During DRX mode, the UE stops listening to the PCell continuously to save even more battery. This holds equally well for CA operation. If one or more SCells are configured for a UE in addition to the PCell, the same DRX mode is applied to all serving cells. [1]

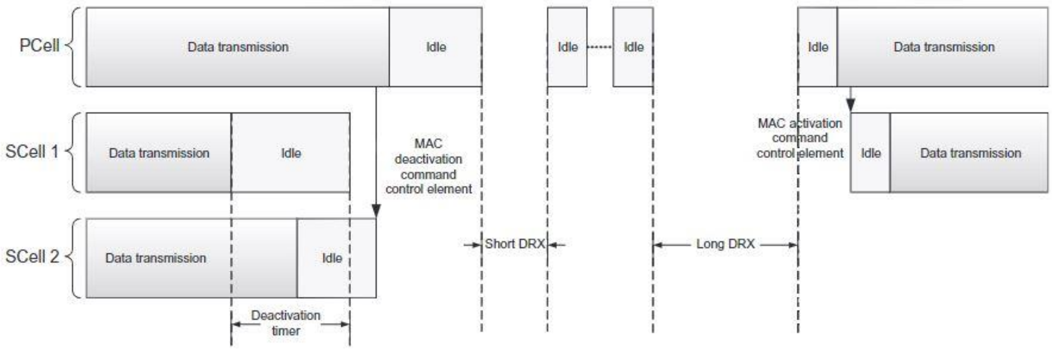

Figure 21. DRX and SCell activation/deactivation. [9]

3.4 E-UTRA CA Configurations (Rel-15 Dec 2018)

Carrier aggregation configuration indicates a combination of E-UTRA operating band(s) and CA bandwidth class(es). A CA bandwidth class is defined by the aggregated transmission bandwidth configuration (ATBC) and the maximum number of component carriers (CC) a device can aggregate contiguously in a single band. Table 7 shows supported bandwidth classes in LTE Rel-15. [22]

ATBC Aggregated Transmission Bandwidth Configuration

$N_{RB,agg}$ Number of aggregated resource blocks within the fully allocated Aggregated Channel bandwidth

Class	ATBC $N_{RB,agg}$	MHz	Maximum number of CC
A	N <= 100	20	1
B	25 < N <= 100	20	2
C	100 < N <= 200	40	2
D	200 < N <= 300	60	3
E	300 < N <= 400	80	4
F	400 < N <= 500	100	5
I	700 < N <= 800	160	8

Table 7. CA bandwidth class. [23]

ATBC denotes the total number of aggregated physical resource blocks. [22] For example, CA Bandwidth Class B indicates 25 < $N_{RB,agg}$ <= 100. It means that total aggregated PRBs should be greater than 25 (5 MHz) and lower or equal than 100 (20MHz). In this way, CA Bandwidth Class B allows to aggregate up to 100 PRBs for a maximum of two aggregated component carriers.

A UE may simultaneously receive or transmit on one or multiple CCs depending on its capabilities. The band combinations and bandwidth classes a UE supports are reported to network by the UE via ‘UE Capability Information’ message. [24]

Following is the example for 2CC Inter-Band Carrier Aggregation supportability: DL 4A_17A, UL 4A. In this scenario, the device allows aggregation of 2 CCs on the downlink, 1CC in Band 4 and 1CC in Band 17, whereas only 1 CC is supported on the uplink in Band 4. Each CC can use up to 20 MHz of bandwidth, indicated by CA Bandwidth Class A. [24]

```
nonCriticalExtension
   rf-Parameters-v1020
      supportedBandCombination-r10: 1 item
         Item 0
            BandCombinationParameters-r10: 2 items
               Item 0
                  BandParameters-r10
                     bandEUTRA-r10: 4
                     bandParametersUL-r10: 1 item
                        Item 0
                           CA-MIMO-ParametersUL-r10
                              ca-BandwidthClassUL-r10: a
                     bandParametersDL-r10: 1 item
                        Item 0
                           CA-MIMO-ParametersDL-r10
                              ca-BandwidthClassDL-r10: a
                              supportedMIMO-CapabilityDL-r10: twoLayers
               Item 1
                  BandParameters-r10
                     bandEUTRA-r10: 17
                     bandParametersDL-r10: 1 item
                        Item 0
                           CA-MIMO-ParametersDL-r10
                              ca-BandwidthClassDL-r10: a
                              supportedMIMO-CapabilityDL-r10: twoLayers
```

Figure 22. 2CC inter-band CA supportability [24]

More than a thousand of different CA configurations have been defined in LTE Rel-15, which can be seen in [23]. However, in the place where the project is carried out only a few frequency bands are available. Therefore, this work will focus on the CA configurations for these bands. The frequency bands to test will be the following: Band 28 (700MHz), Band 1 (2.1GHz), Band 7 (2.6GHz) and Band 42 (3.5GHz). Tables 8-15 show the different CA configurations for these frequency bands for Inter-band and Intra-band CA:

- CA Inter-band (2 bands)

Configuration		BCS	Band	Name	Bandwidth [MHz]						Max aggregated bandwidth [MHz]	3GPP Release
DL	UL				1.4	3	5	10	15	20		
1A-28A	1A-28A	0	1	2100			✓	✓	✓	✓	40	12.6
			28	700 APT			✓	✓	✓	✓		
1A-28A (1)	1A-28A	1	1	2100			✓	✓			20	12.6
			28	700 APT			✓	✓				
		0	1	2100	1A-1A BCS 0						60	14.4

1A-1A-28A			28	700 APT			✓	✓	✓	✓		
1A-7A	1A-7A	0	1	2100			✓	✓	✓	✓	40	12.5
			7	2600				✓	✓	✓		
1A-7A (1)	1A-7A	1	1	2100			✓	✓	✓	✓	40	15.0
			7	2600			✓	✓	✓	✓		
1A-1A-7A		0	1	2100	1A-1A BCS 0						60	15.0
			7	2600			✓	✓	✓	✓		
1A-7A-7A	1A-7A	0	1	2100			✓	✓	✓	✓	60	14.1
			7	2600	7A-7A BCS 3							
1A-7A-7A (1)		1	1	2100			✓	✓	✓	✓	60	15.2
			7	2600	7A-7A BCS 1							
1A-7C	1A-7A 7C	0	1	2100			✓	✓	✓	✓	60	13.3
			7	2600	7C BCS 2							
1A-7C (1)	1A-7A 7C	1	1	2100			✓	✓	✓	✓	60	14.2
			7	2600	7C BCS 1							
1A-42A	1A-42A	0	1	2100			✓	✓	✓	✓	40	12.5
			42	TD 3500			✓	✓	✓	✓		
1A-42A-42A	1A-42A	0	1	2100			✓	✓	✓	✓	60	15.0
			42	TD 3500	42A-42A BCS 0							
1A-42C	1A-42A 1A-42C 42C	0	1	2100			✓	✓	✓	✓	60	12.5
			42	TD 3500	42C BCS 0							
1A-42A-42C	1A-42A	0	1	2100			✓	✓	✓	✓	80	15.0
			42	TD 3500	42A-42C BCS0							
1A-42C-42C	1A-42A	0	1	2100			✓	✓	✓	✓	100	15.0
			42	TD 3500	42C-42C BCS 0							
1A-42D	1A-42A	0	1	2100			✓	✓	✓	✓	80	15.0
			42	TD 3500	42D BCS0							
1A-42E	1A-42A	0	1	2100			✓	✓	✓	✓	100	15.0
			42	TD 3500	42E BCS 0							
7A-28A	7A-28A	0	7	2600			✓	✓	✓	✓	35	12.2
			28	700 APT			✓	✓	✓			
		1	7	2600			✓	✓	✓	✓	40	13.0

7A-28A (1)	7A-28A		28	700 APT			✓	✓	✓	✓		
7B-28A		0	7	2600	7B BCS 0						40	13.0
			28	700 APT			✓	✓	✓	✓		
7C-28A	7A-28A 7C	0	7	2600	7C BCS 2						60	13.0
			28	700 APT			✓	✓	✓	✓		
7C-28A (1)	7A-28A 7C	1	7	2600	7C BCS 1						60	15.0
			28	700 APT			✓	✓	✓	✓		
7A-42A		0	7	2600			✓	✓	✓	✓	40	13.2
			42	TD 3500			✓	✓	✓	✓		
7A-42A-42A		0	7	2600			✓	✓	✓	✓	60	13.2
			42	TD 3500	42A-42A BCS 0							
28A-42A	28A-42A	0	28	700 APT			✓	✓	✓	✓	40	13.2
			42	TD 3500			✓	✓	✓	✓		
28A-42C	28A-42A 42C	0	28	700 APT			✓	✓	✓	✓	60	13.2
			42	TD 3500	42C BCS 0							
28A-42D		0	28	700 APT			✓	✓			70	15.3
			42	TD 3500	42D BCS 0							

Table 8. CA Inter-band configurations (2 bands). [23]

- CA Inter-band (3 bands)

Configuration		BCS	Band	Name	Bandwidth [MHz]						Max aggregated bandwidth [MHz]	3GPP Release
DL	UL				1.4	3	5	10	15	20		
1A-7A-28A	1A-7A 1A-28A 7A-28A	0	1	2100			✓	✓	✓	✓	55	13.0
			7	2600				✓	✓	✓		
			28	700 APT			✓	✓	✓			
1A-7A-28A (1)	1A-7A 1A-28A 7A-28A	1	1	2100			✓	✓	✓	✓	60	13.3
			7	2600				✓	✓	✓		
			28	700 APT				✓	✓	✓		

1A-7A-28A (2)	1A-7A 1A-28A 7A-28A	2	1	2100			✓	✓	✓	✓	60	14.4
			7	2600				✓	✓	✓		
			28	700 APT			✓	✓	✓	✓		
1A-7C-28A	1A-7A 1A-28A 7A-28A	0	1	2100			✓	✓	✓	✓	80	13.3
			7	2600	7C BCS 2							
			28	700 APT				✓	✓	✓		
1A-7A-42A		0	1	2100			✓	✓	✓	✓	60	14.1
			7	2600				✓	✓	✓		
			42	TD 3500			✓	✓	✓	✓		
1A-28A-42A	1A-28A 1A-42A 28A-42A	0	1	2100			✓	✓	✓	✓	50	14.1
			28	700 APT			✓	✓				
			42	TD 3500			✓	✓	✓	✓		
1A-28A-42C	1A-28A 1A-42A 28A-42A	0	1	2100			✓	✓	✓	✓	70	14.2
			28	700 APT			✓	✓				
			42	TD 3500	42C BCS 0							

Table 9. CA Inter-band configurations (2 bands). [23]

- CA Intra-band

BAND 1 (2100 MHz)
Non-contiguous carriers

Configuration		BCS	Band	Name	Allowed channel bandwidth [MHz]					Max aggregated bandwidth [MHz]	3GPP Release
DL	UL				CC1	CC2	CC3	CC4	CC5		
1A-1A		0	1	2100	5, 10, 15, 20	5, 10, 15, 20				40	14.4

Table 10. Band 1 Intra-band Non-contiguous CA. [23]

Contiguous carriers

Configuration DL	Configuration UL	BCS	Band	Name	Allowed channel bandwidth [MHz] CC1	CC2	CC3	CC4	CC5	Max aggregated bandwidth [MHz]	3GPP Release
1C	1C	0	1	2100	15	15				40	10
					20	20					
1C (1)	1C	1	1	2100	5, 10, 15	20				40	14.4
					20	5, 10, 15, 20					

Table 11. Band 1 Intra-band Contiguous CA. [23]

BAND 7 (2600 MHz)
Non-contiguous carriers

Configuration DL	Configuration UL	BCS	Band	Name	Allowed channel bandwidth [MHz] CC1	CC2	CC3	CC4	CC5	Max aggregated bandwidth [MHz]	3GPP Release
7A-7A		0	7	2600	5	15				40	12.2
					10	10,15					
					15	15, 20					
					20	20					
7A-7A (1)		1	7	2600	5, 10, 15, 20	5, 10, 15, 20				40	13.2
7A-7A (2)		2	7	2600	5, 10, 15, 20	5, 10				30	14.0
7A-7A (3)		3	7	2600	10, 15, 20	10, 15, 20				40	14.1

Table 12. Band 7 Intra-band Non-contiguous CA. [23]

Contiguous carriers

Configuration DL	Configuration UL	BCS	Band	Name	Allowed channel bandwidth [MHz] CC1	CC2	CC3	CC4	CC5	Max aggregated bandwidth [MHz]	3GPP Release
7B		0	7	2600	15	5				20	13.0
7C	7C	0	7	2600	15	15				40	11.2
					20	20					
7C (1)	7C	1	7	2600	10	20				40	12.4
					15	15, 20					
					20	10, 15, 20					
7C (2)	7C	2	7	2600	15	10, 15				40	13.0
					20	15, 20					

Table 13. Band 7 Intra-band Contiguous CA. [23]

BAND 28 (700 MHz)
Contiguous carriers

Configuration		BCS	Band	Name	Allowed channel bandwidth [MHz]					Max aggregated bandwidth [MHz]	3GPP Release
DL	UL				CC1	CC2	CC3	CC4	CC5		
28C		0	28	700 APT	5	20				30	15.2
					10	15, 20					
					15	10, 15					
					20	5, 10					

Table 14. Band 28 Intra-band Contiguous CA. [23]

BAND 42 (3500 MHz)
Non-contiguous carriers

Configuration		BCS	Band	Name	Allowed channel bandwidth [MHz]					Max aggregated bandwidth [MHz]	3GPP Release
DL	UL				CC1	CC2	CC3	CC4	CC5		
42A-42A		0	42	TD 3500	5, 10, 15, 20	5, 10, 15, 20				40	12.4
42A-42C	42C	0	42	TD 3500	5, 10, 15, 20	42C BCS 0				60	13.0
					42C BCS 0	5, 10, 15, 20					
42A-42D		0	42	TD 3500	5, 10, 15, 20	42D BCS 0				80	13.2
					42D BCS 0	5, 10, 15, 20					
42C-42C	42C	0	42	TD 3500	42C BCS0	42C BCS 0				80	13.2

Table 15. Band 42 Intra-band Non-contiguous CA. [23]

Contiguous carriers

Configuration		BCS	Band	Name	Allowed channel bandwidth [MHz]					Max aggregated bandwidth [MHz]	3GPP Release
DL	UL				CC1	CC2	CC3	CC4	CC5		
42C	42C	0	42	TD 3500	5, 10, 15, 20	20				40	12.4
					20	5, 10, 15, 20					

42C (1)	42C	1	42	TD 3500	10, 15, 20	20				40	13.4
					20	10, 15					
42D	42C	0	42	TD 3500	5, 10, 15, 20	20	20			60	13.0
					20	20	5, 10, 15, 20				
42D (1)	42C	1	42	TD 3500	10, 15, 20	20	20			60	14.0
					20	20	10, 15				
42E	42C	0	42	TD 3500	5, 10, 15, 20	20	20	20		80	13.2
					20	20	20	5, 10, 15, 20			
42F	42C	0	42	TD 3500	5, 10, 15, 20	20	20	20	20	100	14.1
					20	20	20	20	5, 10, 15, 20		

Table 16. Band 42 Intra-band Contiguous CA. [23]

3.5 CA Performance

Carrier aggregation provides performance gains in the following ways. On the one hand, it increases the theoretical peak data rate through increasing the transmission bandwidth. On the other hand, from a network capacity point of view, carrier aggregation is very useful for dynamically scheduling the downlink traffic of many simultaneous users. [21]

The theoretical peak data rate depends on the capabilities and the software version at the base station site and the capabilities of user's device. Section 3.5.1 describes the difference between terminals in terms of device capabilities. While in Section 3.5.2 are presented the theoretical peak data rates depending on the capabilities supported by the device.

3.5.1 Device capabilities

To support different scenarios with different capabilities in terms of data rates, as well as to allow for market differentiation in terms of low- and high-end terminals with different prices, not all terminals support all capabilities. Terminals from earlier releases of the standard will not support features introduced in later versions of LTE. For example, a Release-10 device will be able to transmit/receive on multiple component carriers whereas release-8/9 terminals will do so on only a single carrier, since carrier aggregation was introduced in LTE release 10. Also, a device may be capable of three component carriers in the downlink but only a single component carrier in the uplink. Hence, during the connection setup, the device indicates not only which release of LTE it supports, but also its capabilities within the release. Figure 23 shows some examples of different carrier aggregation capabilities. [1]

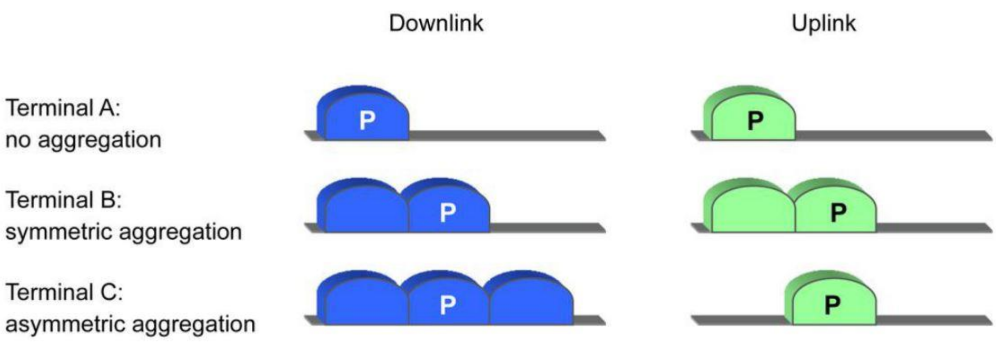

Figure 23. Examples of carrier aggregation capabilities ("P" denotes PCC). [1]

Although the different parameters could be specified separately, to limit the number of combinations and avoid a parameter combination, a set of physical-layer capabilities are lumped together forming a UE category (UE, User Equipment, is the term used in 3GPP to denote a terminal). LTE release 8/9 specified five different UE categories, ranging from the low-end category 1 not supporting spatial multiplexing to the high-end category 5 supporting the full set of features in the release-8/9 physical layer specifications. The UE categories specified up to Release 11 are summarized in Table 17 in a simplified form (for the full set of details, see [25]). [1]

UE Category		Max. Data Rate		Min. Number of DL CCs	DL MIMO Layers	Highest Modulation	
		DL	UL			DL	UL
Rel 8	1	~ 10 Mbps	~ 5 Mbps	1	1	64 QAM	16 QAM
	2	~ 50 Mbps	~ 25 Mbps		2		
	3	~ 100 Mbps	~ 50 Mbps				
	4	~ 150 Mbps	~ 50 Mbps				
	5	~ 300 Mbps	~ 75 Mbps				64 QAM
Rel 10	6	~ 300 Mbps	~ 50 Mbps	1 or 2	2 or 4		16 QAM
	7	~ 300 Mbps	~ 100 Mbps				
	8	~ 3000 Mbps	~ 1500 Mbps	5	8		64 QAM
Rel 11	9	~ 450 Mbps	~ 50 Mbps	2 or 3	2 or 4		16 QAM
	10	~ 450 Mbps	~ 100 Mbps				
	11	~ 600 Mbps	~ 50 Mbps	2, 3 or 4		256 QAM	
	12	~ 600 Mbps	~ 100 Mbps				

Table 17. UE categories combined. [26]

There is a single UE category up to Rel 11 which combines both DL and UL device capabilities. However, in Rel 12, this single category definition was decoupled into two individual categories (see Figure 24), where ue-CategoryDL defines the DL throughput performance and ue-CategoryUL defines the UL throughput performance. Different combinations of ue-CategoryDL and ue-CategoryUL are supported to allow for more flexibility in terms of choosing the DL and UL requirements. These categories can be seen in [25]. [26]

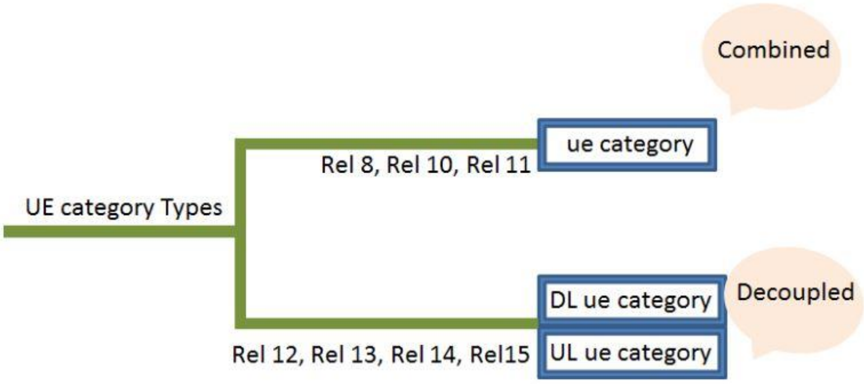

Figure 24. UE category types. [26]

LTE release 10 introduced new features such as carrier aggregation and uplink spatial multiplexing, calling for additional capability signaling compared to release 8/9. Defining new categories for each combination of the maximum number of component carriers and the maximum degree of spatial multiplexing could be done in principle, however, the number of categories might become very large and the categories a terminal supports may be frequency-band dependent. Therefore, the maximum number of component carriers and degree of spatial multiplexing supported, both in uplink and downlink, are signaled separately from the category number. In this case, a release-10/11 device may declare itself as, for example, category 4 but capable of uplink spatial multiplexing. Thereby, categories 1-5 may have different meaning for a release-8/9 and a later release terminal, depending on the separately declared capabilities. The duplexing schemes supported, the support of UE-specific reference signals for FDD in release 8 or whether the terminal supports other radio-access technologies as GSM or WCDMA, is also declared separately from the UE category. Furthermore, to be able to operate in release-8/9 networks, a later LTE release device has to be able to indicate both release-8/9 and later releases categories. [1]

3.5.2 Theoretical expectations

The theoretical maximum throughputs through the different LTE releases were calculated in Section 2.4. In general, the data rate depends on the modulation scheme, the allocated bandwidth (or allocated PRBs), the channel encoding and the number of transmission layers (MIMO). Figure 25 illustrates the theoretical downlink peak data rates for different bandwidths and MIMO schemes with 64-QAM modulation scheme. If using 256-QAM, 4 Gbps data rates could be achieved with MIMO 8 x 8 and 100 MHz of bandwidth. In practice, peak data rates can be achieved only in excellent radio conditions and with very low number of other UEs in the same network.

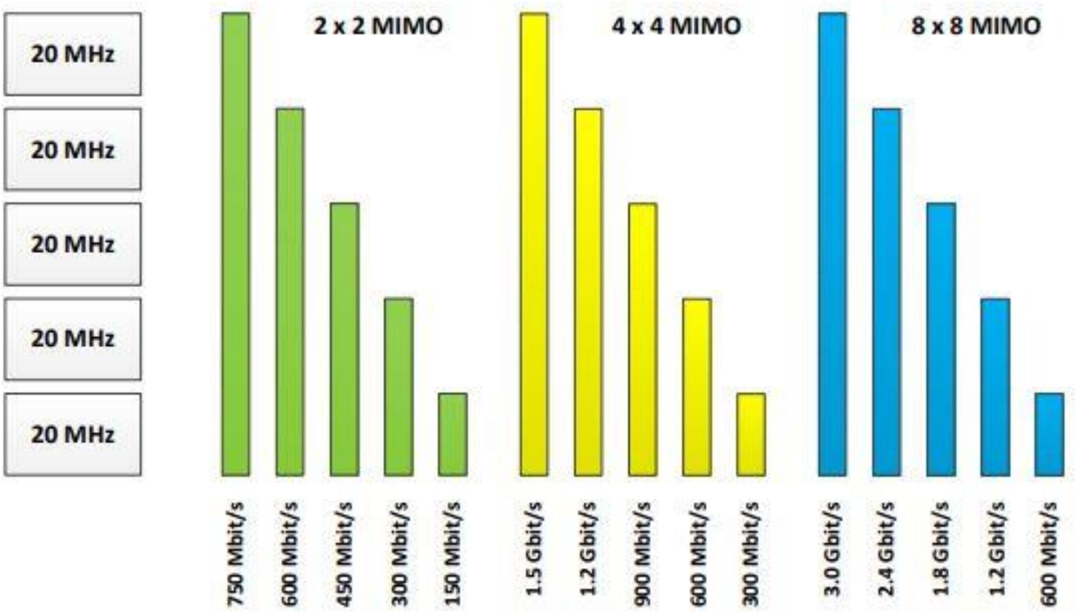

Figure 25. Theoretical maximum data rates in downlink depending on available bandwidth and MIMO scheme. [16]

The theoretical peak throughput can be calculated using the Transport Block Size. The data from the MAC layer delivered to the physical layer in LTE is basically referred to as transport block (TB), which is transmitted in one transmission time interval (TTI) of 1 ms. The TBS is determined by the number of Physical Resource Blocks ($\mathrm{N_{PRB}}$) and the MCS. Table 7.1.7.1-1 from 3GPP 36.213 shows the mapping from the MCS Index ($\mathrm{I_{MCS}}$) to TBS Index ($\mathrm{I_{TBS}}$), see Section 2.3.4. The TBS is finally derived from $\mathrm{I_{TBS}}$ along with the number of PRBs allocated, N_{PRB} (Table 7.1.7.2.1-1 from 3GPP 36.213). TBS is expressed in number of bits transmitted/received in one TTI (1 ms), hence the throughput can be obtained multiplying the TBS value by a factor of 1000. [9]

4 PERFORMANCE EVALUATION

One of the main advantages of Carrier Aggregation is that it allows to increase the bandwidth, and thereby increasing the data rate, which provides a significant upgrade to the radio network performance. CA performance has already been proven in some live networks [16], [27] and in early laboratory and field tests [28].

In this study, LTE CA performance is evaluated at 5G Test Network (5GTN) of University of Oulu, Finland [29]. Measurements were taken in stationary outdoor location with LOS (line of sight) and good radio conditions. The CA performance is presented in terms of throughput, comparing a CA scenario with the non-aggregation case. The original idea was to test 3CC aggregation since at the place where the work was carried out there are 3 frequency bands available with overlaid coverage. However, at the time of the experiments, the UEs used for the tests only allowed 2CC aggregation for the available band combinations.

The results obtained are discussed and compared with the theoretical expectations at the end of Section 4.2.1 and Section 4.2.2. Also, few proposals are presented for future research.

4.1 Measurement Setup

The 5GTN has the infrastructure for accessing to 5G as well as earlier 3GPP technologies as LTE. Testing 5G Carrier Aggregation was originally an objective of this thesis, but due to a lack of 5G devices it was not conducted.

The radio network under study has two eNodeBs, one operating in TDD mode and the other with FDD operation. The FDD base station has two radio frequencies; 700 MHz (Band 28) and 2600 MHz (Band 7). On the other hand, the TDD eNodeB operates in Band 42 (3500 MHz). However, only for the TDD frequency it is available the maximum LTE bandwidth of 20 MHz, corresponding to 100 PRBs. The available bandwidths for Band 28 and Band 7 are 5 MHz and 10 MHz, respectively. The cells are co-located and overlaid, having two cells per carrier frequency. The network deployment corresponds to the Scenario 2 in Section 3.1, where lower frequency band (700 MHz) provides better coverage. Thereby, 35 MHz of bandwidth could be theoretically aggregated amongst the three frequency bands.

First, both base stations software version was upgraded to allow CA operation within the network. Carrier Aggregation was enabled and configured through a software, allowing aggregation amongst the three carrier frequencies within the overlapped cells. The network was parametrized in such way that any cell could act as Primary Cell (PCell). In practice, the cell with lower carrier frequency (700 MHz) typically performs as PCell.

The TDD eNodeB used in measurements utilized transmission power of 43 dBm, while the eNodeB operating in FDD mode was configured with 39 dBm of transmission power for 700 MHz cells and 44 dBm for 2600 MHz cells. The network employed 2 x 2 MIMO and if possible by the UE, 64QAM scheme for downlink transmission.

The CA measurements were conducted with Samsung S8 and Essential Phone PH-1 devices, the first one being a UE Category 9 capable device and the latter DL UE Category 13 and UL UE Category 5. However, the following issues were found when carrying out the measurements. On one hand, the band combination specifications do not allow aggregation of the three available bands (Band 7, 28 and 42) all together, Section 3.4 shows band combination defined by 3GPP. On the other hand, the Samsung S8 does not allow operating in Band 42 (3500 MHz) whereas the Essential Phone, being a Release 12 device, only allows aggregation amongst Band 7 and Band 28 (within the available frequency bands). Band combinations including Band 42 and Band 7/Band 28 were defined in Release 13 onwards (see Table 7, Section 3.4). This way, the maximum aggregated bandwidth when testing CA will be 15 MHz (5 MHz in Band 28 and 10 MHz in Band 7). In the non-aggregation scenario, 20 MHz of bandwidth can be employed in Band 42.

4.2 Performance Measurements

In this section LTE Carrier Aggregation performance is evaluated in terms of throughput and compared with a non-aggregation scenario. The measurement software used was Nemo Handy from Keysight [30], in which you can select the desired frequency band/s to connect to the network and see the main parameters. Throughput measurements were obtained through a SpeedTest software from Ookla [31].

The eNodeB is located in a suburban area, with low profile buildings. All the measurements were taken from the same outdoor and stationary location, around 40 meters from the base stations with LOS, thus having good radio conditions. The radio conditions can be determined by measuring the Reference Signal Received Power (RSRP) and the Signal to Noise Ratio (SNR). RSRP represents the average power received from a single Reference signal, ranging typically around -44 dBm (good) to -140 dBm (bad). The SNR/SINR, is the ratio between the wanted signal and the unwanted noise. Another parameter typically used for evaluating the signal quality is the Reference Signal Received Quality (RSRQ), which indicates the quality of the received signal. Table 18 illustrates the typical values for the above parameters. [32]

	Parameter	**SINR (dB)**	**RSRQ (dBm)**	**RSRP (dBm)**
Signal Quality	**Excellent**	> 12.5	> -5	> -84
	Good	10 to 12.5	-6 to -10	-85 to -102
	Fair	7 to 10	-6 to -10	-103 to -111
	Poor	< 7	< -11	< -112

Table 18. LTE signal quality parameters. [32]

4.2.1 Single band measurements

In order to evaluate LTE performance without Carrier Aggregation, each frequency band has been tested separately. Band 7 (2600 MHz), Band 28 (700 MHz) and Band 42 (3500 MHz) have been tested. The measurements were conducted with the Essential Phone PH-1 device since Samsung S8 does not allow operation in Band 42. A comparison between the three frequency bands is provided at the end of this section. It should be noted that during the measurements the number of other simultaneous users in the same network is not measured or controlled. In addition, the fixed network capacity is shared with university's wifi users and the routing between the base station and EPC was done to perform the fixed ethernet connections which may have an impact on the measured performances.

BAND 7 (2600 MHz)

The DL available bandwidth in Band 7 was 10 MHz. It can be seen from Nemo Handy software along with other network parameters. The 'Serving PCI' field indicates the cell to which the device is connected, in this case to cell 70. While ‘PC Bandwidth’ field (right Figure below), denotes the maximum available bandwidth for DL.

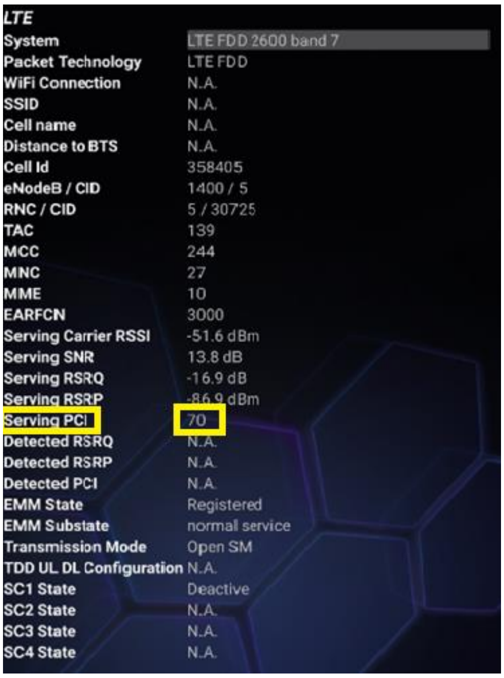

Figure 26. Network parameters B7.

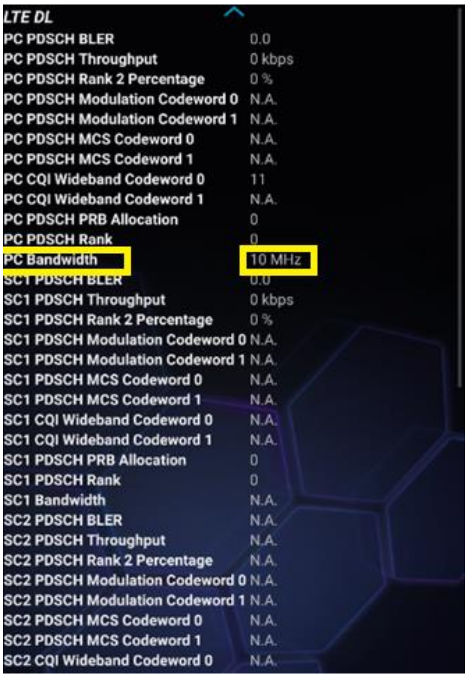

Figure 27. Network parameters B7.

The signal quality experienced in Band 7 is shown below.

Figure 28. Signal quality B7.

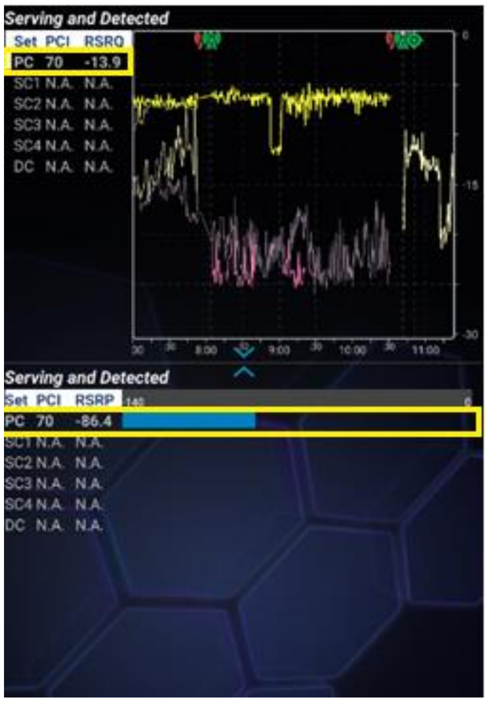

Figure 29. Signal quality B7.

The throughput obtained for Band 7 can be seen in Figure 30.

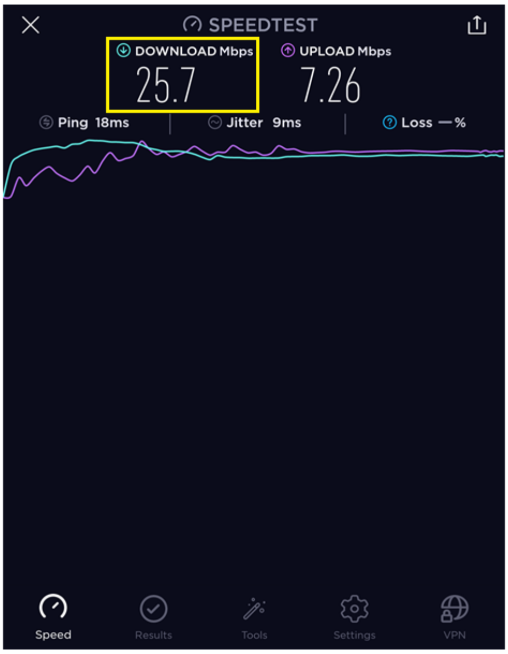

Figure 30. Throughput B7.

BAND 28 (700 MHz)

In Band 28, the available bandwidth is 5 MHz. The device is connected to cell with PCI 50. It can be seen in Figures 31 and 32 below.

Figure 31. Network parameters B28.

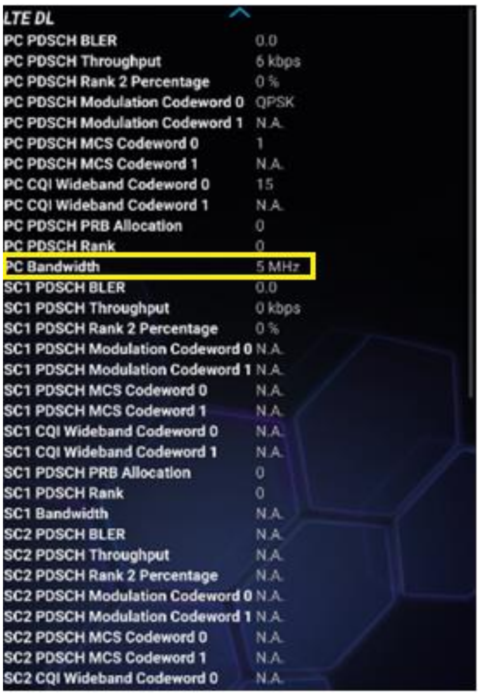

Figure 32. Network parameters B28.

Figures 33 and 34 show the signal quality in Band 28.

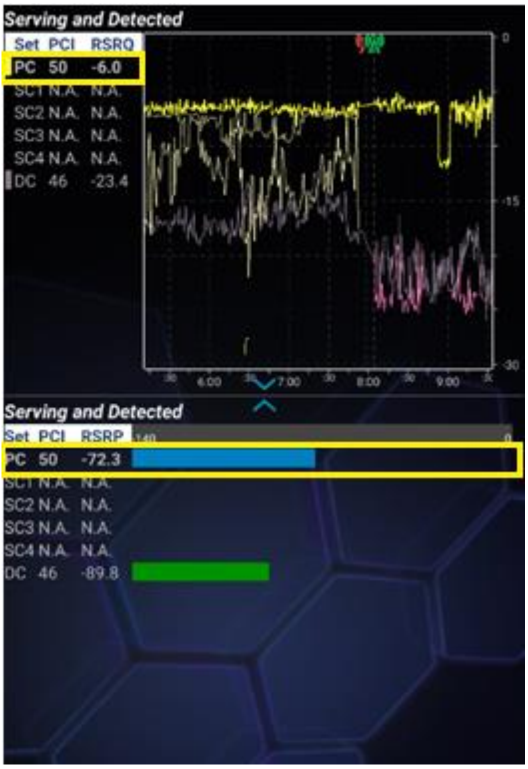

Figure 33. Signal quality B28.

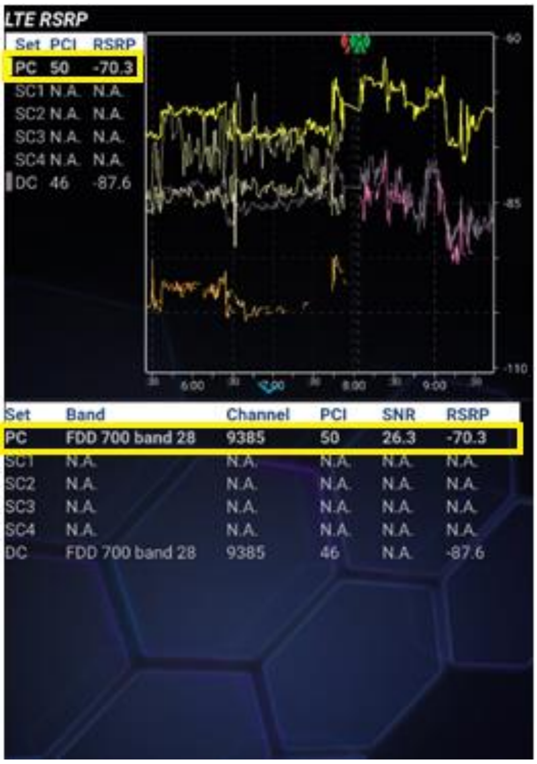

Figure 34. Signal quality B28.

And the throughput obtained through the speed test is the following:

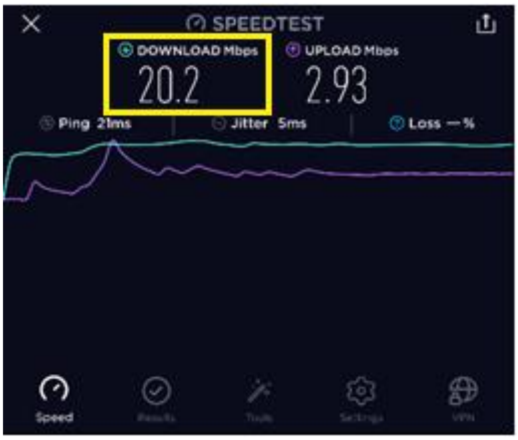

Figure 35. Throughput B28.

BAND 42 (3500 MHz)

In Band 42, it is available the maximum LTE bandwidth, this is, 20 MHz. Figures 36 and 37 show the network parameters upon connection to the network in Band 42.

Figure 36. Network parameters B42.

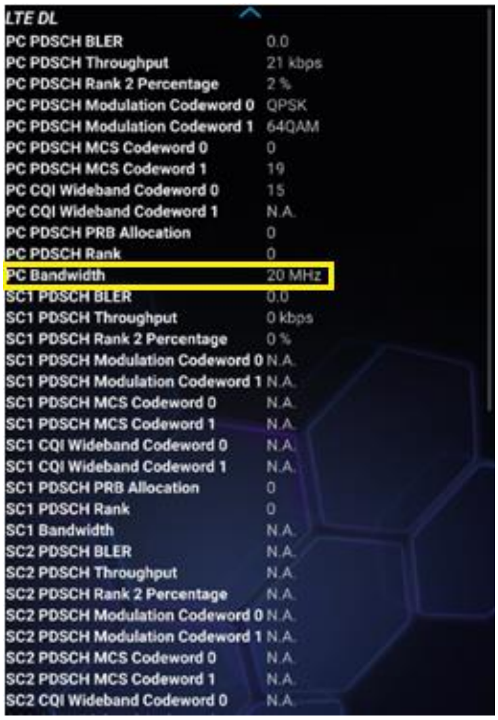

Figure 37. Network parameters B42.

The signal quality measurements in Band 42 show the following results.

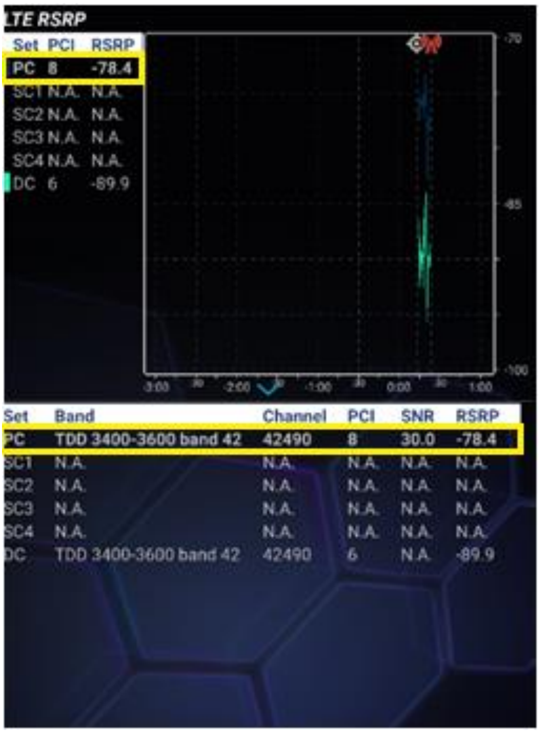

Figure 38. Signal quality B42.

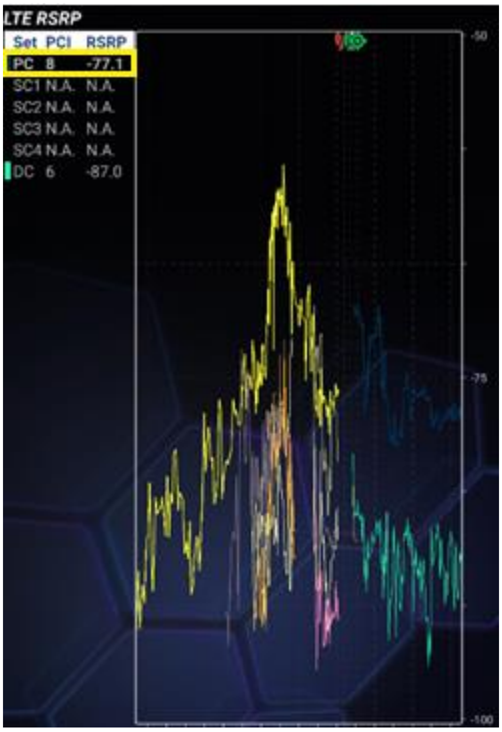

Figure 39. Signal quality B42.

And the experienced throughput can be seen below.

Figure 40. Throughput B42.

SUMMARY NON-AGGREGATION SCENARIOS

LTE performance without CA has been tested for the different frequency bands by connecting to the corresponding cell in the network. The main parameters for each connection are gathered in Table 19. The evaluated performance would correspond to an LTE Release 8/9 scenario in Section 2.5, where the maximum available bandwidth is 20 MHz. Theoretically, the LTE Release 8 peak throughput is 300 Mbps, employing 20 MHz of bandwidth, 64-QAM modulation and MIMO 4x4. Section 3.5.2 shows the LTE theoretical throughput for downlink depending on the number of layers (MIMO scheme) and the transmission bandwidth.

Frequency Band	700 MHz (Band 28)	2600 MHz (Band 7)	3500 MHz (Band 42)
PCI	50	70	8
Duplex mode	FDD	FDD	TDD
Bandwidth (MHz)	5	10	20
MIMO scheme	2 x 2	2 x 2	2 x 2
Modulation	64 QAM	64 QAM	64 QAM
RSRP (dBm)	-71	-86.5	-78

SNR (dB)	26.5	18	30
Throughput (Mbps)	20	26	63
Theoretical peak throughput (Mbps)	37.5	75	150
Percentage of the theoretical peak throughput (%)	53.33	34.66	42

Table 19. LTE single band measurements (without CA).

As can be seen in Table 19, the real throughputs obtained for the different frequency bands do not match the theoretical expectations, being the best case the one in Band 28 (700 MHz), which reaches the 53% of the theoretical value. If analyzing the values from Table 19, it can be noted that, regardless of the bandwidth used, the better signal quality the higher the bit rate experienced. The poorer signal quality (although good enough if comparing with values from Table 18) corresponds to Band 7 (2600 MHz), where only a 34% of the theoretical peak throughput is achieved. As already commented, the modulation and MIMO schemes employed depend on the channel quality, allowing to use higher order modulation and greater number of layers as better the signal is. As expected, the highest throughput value was obtained from Band 42 (3500 MHz) using 20 MHz of bandwidth. The 63 Mbps measured correspond to a 42% of the theoretical maximum value for 20 MHz of bandwidth and MIMO 2 x 2. It should be noted that the LTE Release 8/9 theoretical peak data rate cannot be achieved since the UE employed only allows up to MIMO 2 x 2.

4.2.2 Carrier Aggregation measurements

In addition to other benefits, carrier aggregation offers the possibility to increase the LTE transmission bandwidth and thus, the bitrate. 3GPP has defined a large number of different CA configurations (see Section 3.4), this is, different band combinations for CA operation. However, defined CA schemes depend on the capabilities at the base station side (number of available carriers, software version, etc.) and the UE capabilities (UE category, band combinations supported), see Section 3.5.1. Thereby, in order to take benefit from the latest LTE improvements, the most recent software version at eNodeB and the latest UEs are needed as well.

As commented at the beginning of this section, actual standards do not allow combination of the three available bands all together, which makes unfeasible testing 3CC aggregation. Additionally, FDD-TDD aggregation was introduced in Release 12 (see Section 3), nevertheless band combinations are Release independent (newer Releases add new combinations to those already defined). The UE employed, being a “Release 12 device” (UE DL Category 13) does not allow combination of Band 7+Band 42 and Band 28+42. This could be because these combinations were defined more recently, in Release 13 (see Section 3.4).

As described in Section 3.3, the following procedure is used to transfer UE radio access capability information from the UE to E-UTRAN. [33]

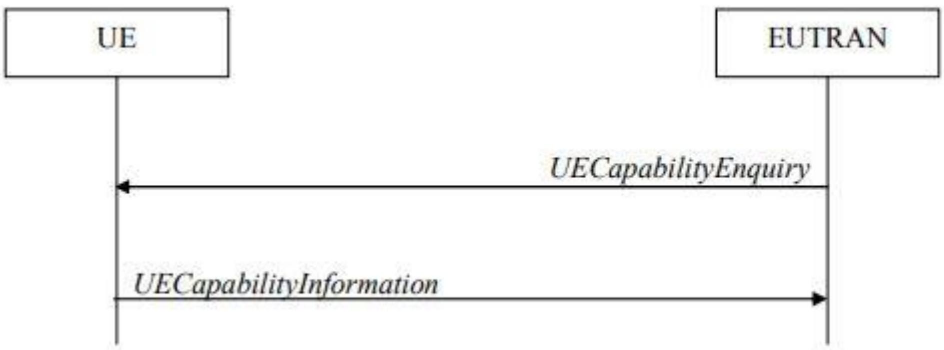

Figure 41. UE Capability Transfer. [33]

E-UTRAN initiates the procedure to a UE in RRC_CONNECTED when it needs (additional) UE radio access capability information. The 'UECapabilityEnquiry' message is used to request the transfer of UE radio access capabilities for E-UTRA as well as for other RATs. Along with other requested capabilities, the 'UECapabilityEnquiry' message include the following fields if the network allows CA operation: 'requestedMaxCCsDL', 'requestedMaxCCsUL'. These fields indicate the maximum number of CCs for which the UE is requested to provide supported CA band combinations and non-CA bands. [33]

This way, upon connection to the network, the 'UECapabilityEnquiry' message received at the UE is as follows:

Figure 42. UECapabilityEnquiry message.

From Figure 42, it can be seen the network requesting the UE to provide supported band combination for a maximum of 2CC.

UE replies the network via 'UECapabilityInformation' message, reporting the radio access capabilities requested by the E-UTRAN. It includes, along with other radio parameters, the supported LTE bands for non-CA operation as well as supported band combinations if the UE supports CA. [33] The Figures below show the 'UECapabilityInformation' message from the tested UE (Essential Phone-1) to the network (5GTN).

Figure 43. Band Combinations 1.

Figure 44. Band Combinations 2.

Figure 45. Band Combinations 3.

Figure 46. Band Combinations 4.

From Figures 43-46 it can be seen the UE supported band combinations, section 3.4 describes the terminology used for the different CA configurations. Each value within the 'supportedBandCombination-r10' field defines a CA configuration, composed by an E-UTRA operating band (denoted by 'bandEUTRA-r10' field) and a CA Bandwidth Class (denoted by 'ca-BandwidthClass-r10' field), the latter indicating the maximum contiguous aggregated bandwidth.

For the case under study, the used UE supports non-CA operation in Band 7, Band 28 and Band 42 (values 1-3 in Figure 43), corresponding to 7A, 28A and 42A CA configurations, respectively. This allows to use up to 20MHz of bandwidth in each frequency band. Regarding CA operation, the device supports the following band combinations. Band 7 + Band 28 inter-band CA (values 4.1-4.2 and 5.1-5.2 in Figure 44), which corresponds to 7A-28A CA configuration. The difference between values 4 and 5 is that the first uses Band 28 for the uplink while value 5 shows uplink operation in Band 7. In Figure 45 it can be seen Band 42 intra-band CA supportability (non-contiguous, values 6.1-6.2; contiguous, value 7), corresponding to 42A-42A and 42C CA configurations, respectively. Band 7 intra-band CA supportability is represented in Figure 46 (non-contiguous, values 8.1-8.2; contiguous, values 9 and 10). Value 8 represents 7A-7A CA configuration, while values 9 and 10 correspond to 7C and 7B CA configurations, respectively. Also, it can be seen up to 2 x 2 MIMO supportability for any band combination, indicated by 'supportedMIMOcapabilityDL-r10' field (highlighted in red in Figures 42-45).

Summarizing, this scenario allows to test Carrier Aggregation with up to 2CC on the downlink. On the uplink, the device does not allow CA. On the other side, the available bandwidth at the base station, makes unfeasible to test intra-band CA. Thereby, CA have been tested by aggregating 1CC in Band 7 and 1CC in Band 28, corresponding to 7A-28A CA configuration.

The following network parameters can be seen on Nemo Handy when enabling LTE operation in Band 7 and Band 28.

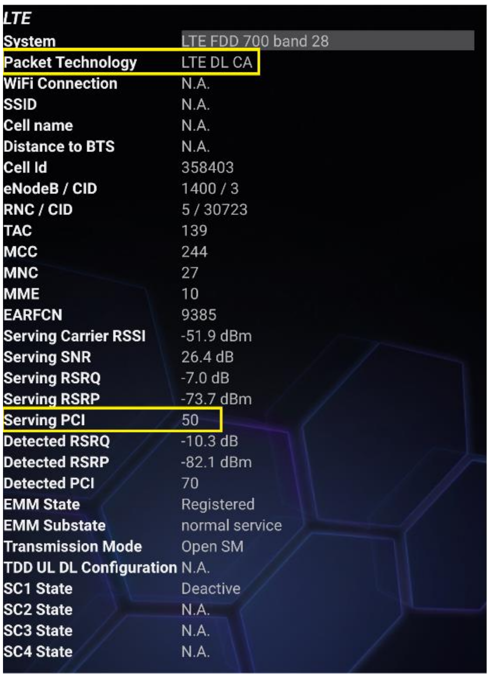

Figure 47. LTE CA network parameters 1.

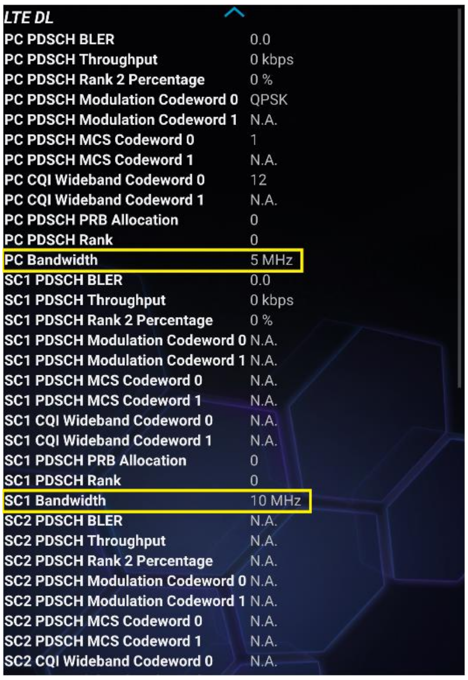

Figure 48. LTE CA network parameters 2.

It can be seen from Figure 47 above that the 'Packet Technology' field has been changed to 'LTE DL CA'. The cell at 700 MHz performs as Primary Cell, as indicated in the 'Serving PCI' field. The cell at 2600 MHz is configured as Secondary Cell. Both PCell and SCell available bandwidths are shown in Figure 48. In Band 28, 5 MHz of bandwidth can be used while 10 MHz are available in Band 7. Therefore, 15 MHz of bandwidth can be aggregated through Carrier Aggregation.

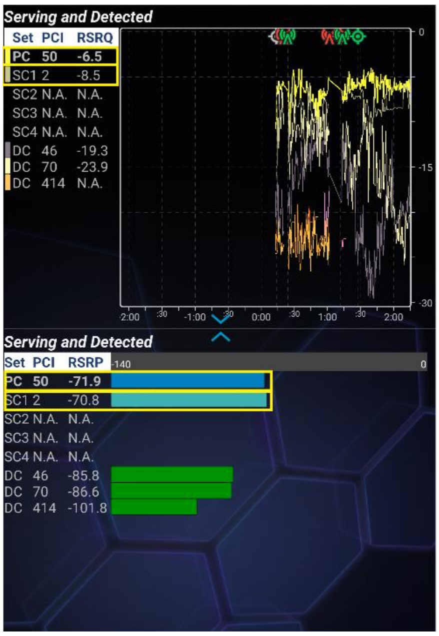

Figure 49. CA signal quality 1.

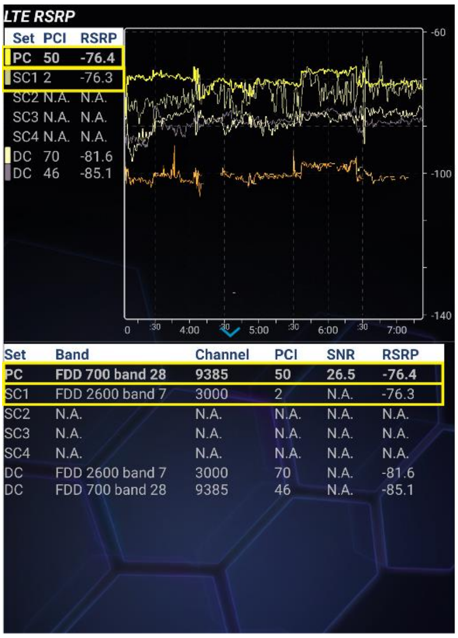

Figure 50. CA signal quality 2.

Figures 49 and 50 show signal quality measurements for the different serving cells. Both PCell and SCell signals are good if comparing with Table 18 values. This scenario results in the following experienced data rate.

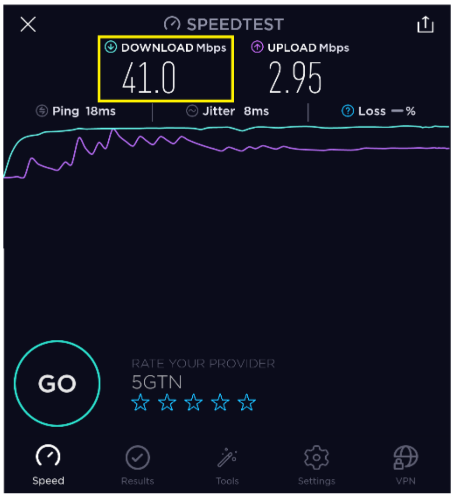

Figure 51. CA throughput.

The throughput obtained is 41 Mbps, which is below theoretical expectations. Theoretically, employing 15 MHz of bandwidth, 64-QAM modulation and MIMO 2 x 2, it could be achieved 112.5 Mbps. Table 20 summarizes the main parameters of this CA scenario.

	Primary Cell	Secondary Cell	CA operation
Frequency Band	700 MHz (Band 28)	2600 MHz (Band 7)	Band 7 + Band 28
PCI	50	2	
Duplex mode	FDD	FDD	FDD
Bandwidth (MHz)	5	10	15
MIMO scheme	2 x 2	2 x 2	-
Modulation	64 QAM	64 QAM	-
RSRP (dBm)	-76.4	-76.3	-
SNR (dB)	26.5	18	-
Throughput (Mbps)	-	-	41
Theoretical peak throughput (Mbps)	-	-	112.5
Percentage of the theoretical peak throughput (%)	-	-	36.4

Table 20. LTE CA measurements.

Although the data rate obtained is below the expectations, it must be noted that when using a single band connection to the network with Band 7 or Band 28 (section 4.2.1), this is no-CA, the throughput obtained is much lower than the one obtained when combining both bands through CA. Carrier Aggregation clearly provides throughput gains in comparison to the non-CA case. It is illustrated in Table 21.

	700 MHz (Band 28)	2600 MHz (Band 7)	CA B28+B7
Bandwidth (MHz)	5	10	15
Throughput (Mbps)	20	26	41
CA throughput gain over single band connection (%)	105	57	-

Table 21. Single carrier connection and CA throughput comparison.

5 CONCLUSIONS

This work presented a study on performance of LTE Release 10 feature referred as Carrier Aggregation. The literature part provides an overall description on Long Term Evolution technology. LTE aspects directly involved in CA performance has been described, which include Modulation and Coding Schemes (MSC) and Multiple Input Multiple Output (MIMO). LTE evolution through the different LTE releases has been presented, providing a peak throughput comparison from each LTE version. The characteristics and functionalities of Carrier Aggregation constitute the main part of the literature review. The CA performance was evaluated in live mobile network with field measurements and results have been compared with the theoretical expectations.

5.1 Objectives and Results

The principal objective for this thesis was to evaluate the practical CA performance in an experimental live mobile network. Carrier Aggregation performance has already been tested in live LTE networks in few studies, this work contributes as one more reference to evaluate the end user performance and how it is achieved. CA downlink performance was evaluated using commercial user equipment, from the perspective of a stationary LTE-Advanced user. Additionally, LTE Release 8/9 performance was evaluated through single band measurements and compared with a Carrier Aggregation scenario.

It can be concluded that CA provides a significant upgrade to the radio network, allowing to increase the transmission bandwidth and thereby the data rate. The results showed that when combining both Band 28 (700 MHz) and Band 7 (2600MHz) through CA, the throughput obtained is much higher than when using a single carrier connection in these bands. As expected, the throughput experienced is proportional to the transmission bandwidth. For the case under study, CA throughput gain was 105% over Band 28 single connection. While the throughput gain if comparing to a single connection in Band 7 was 57%. It should be noted that available bandwidth in Band 28 and Band 7 is 5MHz and 10MHz, respectively.

However, throughput results did not match theoretical expectations for both single carrier connection and if using CA. For 2CC CA using 15MHz of aggregated bandwidth with MIMO 2 x 2 and 64QAM it was achieved 36% of the theoretical value, 112.5Mbps. While for the non-aggregation scenario, the best case corresponds to Band 28, achieving 53% of 37.5Mbps with 5MHz of bandwidth, MIMO 2 x 2 and 64QAM.

Carrier Aggregation has already been evaluated for live mobile networks in [16] and [27]. In those studies, CA peak throughput results were close to the theoretical values, reaching 95% of the theoretical peak throughput in [16] and 86% in [27]. The results obtained in this thesis, however, are quite far from those mentioned above. Some reasons could be that there were other UEs generating traffic or testing against a server located in internet. Also, theoretical peak throughputs are calculated for Spatial Multiplexing MIMO scheme. It could be that MIMO was not performing in that way, and thus not providing a throughput gain.

Regardless, in commercial live mobile networks, theoretical peak data rates are not easily achieved. Data rates can be visible to the end user, unlike the technology behind these data rates. When using Carrier Aggregation, the user does not know the number of component carriers operating, neither that CA is being even used. This thesis proved that the end user will benefit from CA operation.

5.2 Future work

In this thesis, Carrier Aggregation has been evaluated for two component carriers, being the only aggregation scenario supported by the device. However, the network under study supports aggregation of 3CC within the available frequency bands. Currently, there are already mobiles which support three carriers. Therefore, testing 3CC Carrier Aggregation at 5GTN would be the clear next step. Also, CA testing have been done employing two FDD component carriers. Adding a component carrier in Band 42, which operates in TDD mode, would be a good opportunity to test FDD-TDD Carrier Aggregation. Aggregation across different duplex schemes can be used to improve the uplink coverage of TDD with the possibility for continuous uplink transmission on the FDD carrier.

Carrier Aggregation measurements were taken in stationary outdoor location with LOS and good radio conditions. Future work could include performance evaluation in different radio conditions. Different modulation and MIMO schemes can be employed depending on the channel quality, allowing to use higher order modulation and greater number of layers as better the signal is. Generally, the poorer the signal quality the lower the data rate. In poor signal strength situation, Carrier Aggregation can help to improve the throughput.

Higher order MIMO and modulation and coding schemes are already being implemented in devices. In downlink, 3GPP specifications have defined up to 8 x 8 MIMO and 256-QAM modulation scheme. A comparison between different transmission schemes could be conducted in the future.

Uplink CA was not evaluated in this thesis and it would be another point to study. Although there are defined CA configurations for aggregating component carriers on the uplink, the implementation is quite constrained due to the transmission power limit of the user equipment. Nevertheless, uplink CA is also interesting from the system performance point of view and its behavior would offer attractive study items.

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