الجمهورية الجزائرية الديمقراطية الشعبية
République Algérienne Démocratique et Populaire
وزارة التعليم العالي و البحث العلمي
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المدرسة الوطنية المتعددة التقنيات
Ecole Nationale Polytechnique

École Nationale Polytechnique
Département d'Électronique
Ericsson Algérie

ERICSSON

End of studies project thesis

Submitted in partial fulfillment of the requirements
for the State Engineer Degree in Electronic Engineering

Carrier Aggregation in LTE-Advanced through Software Implementation, Simulation and On-Site Data Driven Analysis

Realized by:
Mr. Hamamid Nassim
Mr. Mihoub Abderrahmane

Supervised by:
Mr. Taghi M. O. (ENP)

Publicly presented and defended on the 15th of July, 2021.

Jury members:

President	Mr. Salah Ait Cheikh	Pr	ENP
Promoter	Mr. Mohamed Oussaid Taghi	MAA	ENP
Examiner	Mr. Rachid Zergui	MAA	ENP

ENP 2021

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Mémoire de projet de fin d'études

pour l'obtention du diplôme d'Ingénieur d'État en Électronique

L'Aggrégation de Porteuses dans LTE-Advanced à travers l'Implémentation Logicielle, la Simulation, et l'Analyse de Données Collectées sur Site

Réalisé par :
M. HAMAMID Nassim
M. MIHOUB Abderrahmane

Supervisé par :
M. TAGHI M. O. (ENP)

Présenté et soutenue publiquement le 15 Juillet 2021.

Membres du jury :

Président	M. Salah AIT CHEIKH	Pr	ENP
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Examinateur	M. Rachid ZERGUI	MAA	ENP

ENP 2021

ملخص

يركز هذا العمل على تقنية ثورية في مجالات الاتصالات تحمل اسم تجميع الحوامل. و التي تعد إحدى ركائز LTE-Advanced. سيركز عملنا في البداية على تفصيل بنية LTE-A وجميع النظريات الكامنة وراء التجميع ثم ننتقل بعد ذلك إلى عمليات التنفيذ والمحاكاة التي من ناحية ، ستظهر ال "كيف" ، ولكن أيضًا المساهمة في البساطة والتكلفة التي تجلبها أدوات المحاكاة لتطوير أنظمة الاتصالات المعقدة. أخيرًا، سنجري دراسة بناءً على البيانات التي تم جمعها، ونحلل تأثير هذه التقنية على الشبكة المحلية ومستخدميها.

كلمات مفتاحية : تجميع الحوامل، LTE-Advanced، تخصيص الطيف.

Résumé

Ce travail se concentre sur une technique révolutionnaire dans le domaine de la télécommunication portant le nom de ”l’Agrégation de porteuses”. Celle-ci constitue l’un des piliers de la LTE-Advanced. Notre travail ira détailler dans un temps l’architecture de la LTE-A et toute la théorie derrière l’agrégation, pour ensuite se tourner vers des implémentations et simulations qui, d’un côté montreront le ”comment”, mais aussi l’apport en simplicité et en cout qu’apportent les outils de simulations au développement de systèmes de communications complexes. On ira enfin à travers une étude axée sur des données collectées, analyser l’impact de cette technique sur le réseau local et ses utilisateurs.

Mots clés : Agrégation de porteuses, LTE-Advanced, Allocation du spectre

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Abstract

This work focuses on a revolutionary technique in the field of telecommunications known as “Carrier Aggregation”. One of the most important LTE-Advanced features. At the beginning, our work will detail the architecture of LTE-A and all the theory behind the aggregation. Later, implementations and simulations will describe the ”know-how” and highlight the contribution in simplicity and cost-effectiveness that simulation tools bring to the development of complex communications systems. Finally, a data-driven study is presented where we analyze and discuss the impact of this technique on the local network and its users.

Keywords : Carrier Aggregation, LTE-Advanced, Spectrum allocation.

Dedication

“

To our dear parents, our families, and our friends.

”

- Abderrahmane & Nassim

Acknowledgments

First of all, we thank God the Almighty for giving us the courage, the will and the patience to carry out this work.

We thank our parents, who supported us throughout our studies' journey.

We would like to express our gratitude to our supervisor, Mr. Mohamed Oussaid TAGHI, for his consistent support, guidance and clarifications during the running of this thesis.

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Each one of us would also like to thank the other, for having the courage to embark on a relatively stranger field that has as expected seduced and benefited us a lot.

Contents

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List of Abbreviations

1G	*First Generation*
2G	*Second Generation*
3G	*Third Generation*
3GPP	*Third Generation Partnership Project*
4G	*Fourth Generation*
5G	*Fifth Generation*
CA	*Carrier Aggregation*
CC	*Component Carrier*
CDMA	*Code Division Multiple Access*
CoMP	*Coordinated Multipoint*
DL	*Downlink*
ECM	*EPS Control Management*
EDGE	*Enhanced Data-rates for GSM Evolution*
EMM	*EPS Mobility Management*
eNB	*evolved Node-B*
EPC	*Evolved Packet Core*
EPS	*Evolved Packet System*
Ev-DO	*Evolution-Data Optimized*
FDD	*Frequency Division Duplexing*
FDMA	*Frequency Division Multiple Access*
GERAN	*GSM Edge Radio Access Network*
GPRS	*General Packet Radio Service*
GSM	*Global System Mobile*

HARQ	*Hybrid Automatic Repeat reQuest*
HSPA	*High-Speed Packet Access*
ICIC	*Inter Cell Interference Coordination*
ITU	*International Telecommunication Union*
LTE	*Long Term Evolution*
LTE-A	*Long Term Evolution-Advanced*
MAC	*Medium Access Control*
MIMO	*Multiple Input Multiple Output*
NAS	*Non Access Stratum*
NMT	*Nordic Mobile Telephones*
OFDM	*Orthogonal Frequency Division Multiplexing*
OFDMA	*Orthogonal Frequency Division Multiple Access*
PAPR	*Peak-to-Average Power Ratio*
PDCP	*Packet Data Convergence Protocol*
PDN	*Packet Data Network*
PDU	*Protocol Data Unit*
PSTN	*Public Switched Telephone Network*
QAM	*Quadrature Amplitude Modulation*
RAN	*Radio Access Network*
RB	*Resource Block*
RLC	*Radio Link Control*
RNC	*Radio Network Controller*
RSRP	*Reference Signal Receive Power*
RRC	*Radio Resource Control*
SC-FDMA	*Single Carrier Frequency Division Multiple Access*
TDMA	*Time Division Multiple Access*
TTI	*Transmission Time Interval*
UE	*User Equipment*
UL	*Uplink*
UMTS	*Universal Mobile Telecommunications System*

UTRAN *UMTS Terrestrial Radio Access Network*

W-CDMA *Wideband-Code Division Multiple Access*

General Introduction

Telecommunications systems have undergone enormous development during the last two decades, this technological development has given rise to modern standards which directly impacted the quality of service (QoS) that benefit the user and which in our studied-case, will be represented by the throughput.

As the number of mobile subscribers are currently running multiple applications, simultaneously, on their smart phones that require a higher bandwidth and make users so limited to the carrier resources, their traffic has increased rapidly. As consequence, more spectrum was required.

However, due to spectrum scarcity and fragmentation, it is difficult to provide the required resources with a single frequency band. Therefore, aggregating frequency carriers that belong to different bands was proposed to utilize the radio resources across multiple carriers and expand the effective bandwidth delivered to user terminals.

This technique known as Carrier Aggregation has since, became one of the most distinct features of 4G systems including Long Term Evolution-Advanced, by increasing the efficiency of spectrum usage, and providing significant gain in mobile broadband capacity.

In order to understand, analyse, and simulate the impact of Carrier Aggregation, this thesis is organised on six chapters:

The first chapter "**Mobile communication standards**" lays out the foundations of communication systems and relates LTE-A to earlier systems, highlighting the necessity of each evolution and its added value to the field.

The second chapter "**LTE, LTE-Advanced**" covers the main concepts of LTE, followed by a brief presentation of the LTE-Advanced's enhancements.

The third chapter "**Carrier Aggregation**" is the heart of our theoretical study, it focuses on our studied LTE-A feature and presents technically the requirements, types and deployment scenarios as well as the main configuration stack.

The fourth chapter "**Matlab/Simulink implementation**" covers the Simulink modelization and simulation of the physical layer, with a smaller part that dealt with a GUI academic facility.

The fifth chapter “**Atoll implementation**” introduces the industry standard for wireless network design software and presents our work concerning a replication of a mobile operator network in ”El Harrach” region. After configurations parts, the benefits of CA on the network through simulations are shown.

The last chapter “**On-site data-driven analysis**” covers the configuration and implementation of CA in a list of predefined sites and furthermore presents a real-data driven analysis of the feature and its impact on user experience and operator’s strategy.

Chapter 1

Mobile communication standards

Introduction

The mobile communication industry started at the early 1970s, where the first network which was based on the concept of cell motif defined within the “Bell Labs” laboratories, was put into service. This technique is a technological key component of the mobile networks because it makes it possible to reuse the resources of the radio access network over several given geographic areas called cells. In this chapter, the journey of the mobile communication standards evolution from then to where it is now will be presented.

1.1 1st Generation

The 1G systems used analog communication techniques, similar to those used by traditional analog radio. The most popular systems in Europe were the Nordic Mobile Telephones (NMT) in Sweden and the Total Access Communication System (TACS) in Great Britain, while the Advanced Mobile Phone System (AMPS), a standard that uses baseband transmission, appeared in America.

Mobile 1G established the foundation of mobile, by setting up a cleared spectrum for exclusive use by mobile technologies and operator-deployed base stations to provide access for subscribers. Besides, the geographical separation allowed neighboring cells to operate on different frequencies and reusing frequencies without interference. Also, a coordinated network for seamless access and seamless mobility was established.

The main disadvantages of the 1st generation were the absence of radio communication’s encryption, all you need is a receiver on the appropriate frequency band to hear, so the absence of security, besides that the analog transmissions are inefficient at using a limited spectrum, where the 1G standards use FDMA as an access method, and a large frequency gap is required between users to avoid interference. Also, only 1 user per channel is supported.

1.2 2nd Generation

The introduction of second-generation (2G) systems in the early 1990s permitted the take-off of Mobile telecommunications as a consumer product. These systems were the first to use digital technology, which permitted more efficient use of the radio spectrum and the introduction of smaller, cheaper devices. They increased voice capacity and enabled more users.

1.2.1 GSM

The fundamental technology was developed in the Nordic countries in the 1980s, led by Ericsson, then transferred to the Groupe Special Mobile within the CEPT (Conférence Européenne des Postes de Télécommunication). The main part of further standardization of the GSM system was conducted in the European Telecommunications Standards Institute (ETSI) Special Mobile Group (SMG) until 2000 and since then by the 3rd Generation Partnership Project (3GPP) [1].

The GSM network can be split into three subsystems: the radio access network (RAN), the core network, and the management network [1].

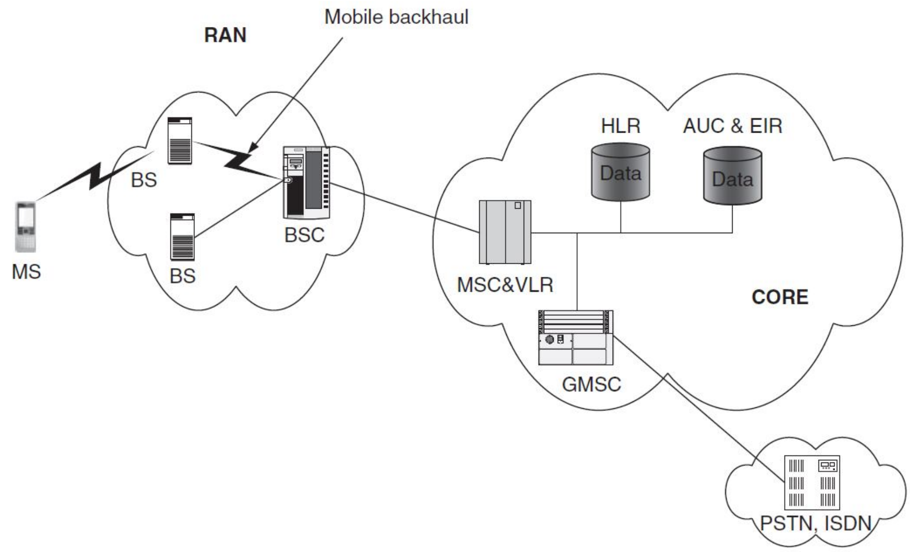


Figure 1.1: GSM system architecture [1]

The RAN contains the Base Station (BS) that receives the incoming and outgoing calls from MSs, and the Base Station Controller (BSC). While the Core Network contains the Network switch (MSC) that handles the signaling messages that set up and manage the phone calls, the subscriber identity and location database HLR, Network terminal authentication center AUC, Database of network visitors VLR, Equipment identity recorder EIR and the Operator's network operation and maintenance center OMC.

Many long-lasting concepts accompanied the 2G Evolution, as GSM was the first mobile network technology to introduce a personal chip card (SIM) that allows distinguishing between equipment mobility and subscriber mobility and also the first to impose unique addressing to all mobile users and mobile station equipment within the network.

1.2.2 GPRS

General Packet Radio Service, abbreviated to GPRS, extends the architecture of the GSM standard, to authorize the transfer of data in packets, with maximum theoretical speeds. To send packet-switched data over existing GSM networks, GPRS was designed as a packet-switched addition to the circuit-switched GSM network [2].

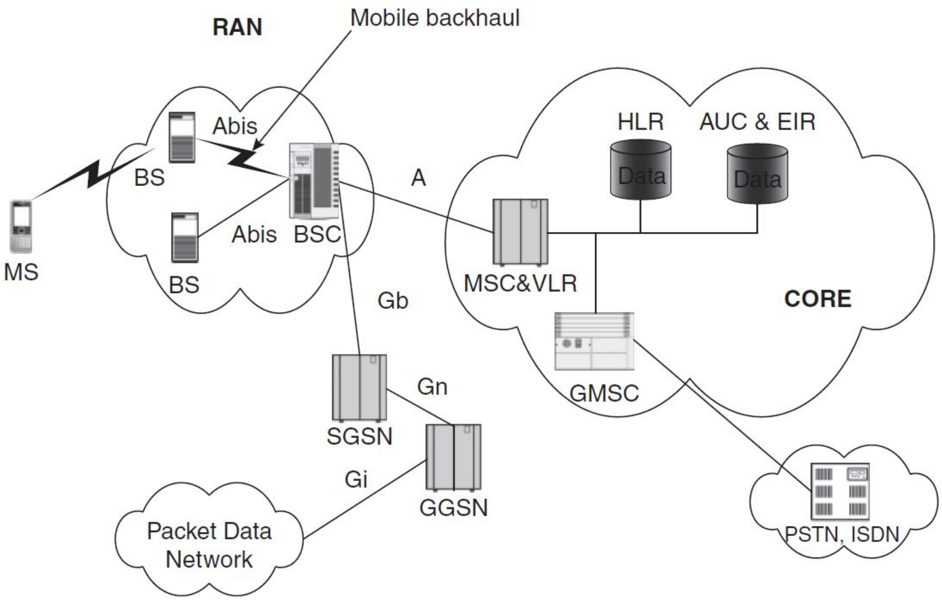


Figure 1.2: GPRS/EDGE Network [1]

Thanks to the packet transfer mode, data transmissions only use the network when necessary. The GPRS standard, therefore, makes it possible to bill the user for the volume exchanged rather than for the duration of the connection, which means in particular that he can remain connected at no additional cost.

To integrate GPRS into the existing GSM architecture, a new class of network nodes, called GPRS Support Nodes (GSNs): SGSN and GGSN, have been introduced. They are responsible for the delivery and routing of data packets between the MSs and external Packet Data Networks. Besides the introduction of new interfaces and new functionalities in the Base-station controller.

1.2.3 EDGE

Enhanced Data-rates for GSM Evolution, designated as 2.75G, introduced the combination of GMSK modulation (used in GSM) and the 8-Phase Shift Keying (8-PSK) scheme, allowing terminals to adapt their data rates to their signal quality levels. EDGE reached an approximately three times higher data rate per time slot and hence permitted a higher spectral efficiency. GPRS was then enhanced by EDGE and became EGPRS.

1.3 3rd Generation

The evolution to 3G systems came as a necessity to support demanding applications, such as high-speed internet, high-resolution videos, television mobile, and video telephony.

3G is represented by two main standards Universal Mobile Telecommunications System (UMTS) derived from GSM and widely deployed around the globe, and CDMA2000, derived from IS-95 and deployed mainly in Asia and North America. These two standards were adopted by two different competitive projects, the 3GPP and the 3GPP2 respectively. However, the 3GPP is the one responsible for evolving LTE and 5G wireless standards and refers to the different versions as 'Releases'.

The radio interfaces of these two families are based on similar technical characteristics, in particular, the code division multiple access scheme (CDMA), which enables users to share the same frequency and communicate at the same time.

1.3.1 UMTS

Also named W-CDMA (Wideband-CDMA), because it's based on this technique. The objectives of UMTS were to increase the capacity of the system for the voice service but above all to improve the support of the data services. The major difference with GSM comes at the radio interface, where it is based on direct sequence spectrum spreading.

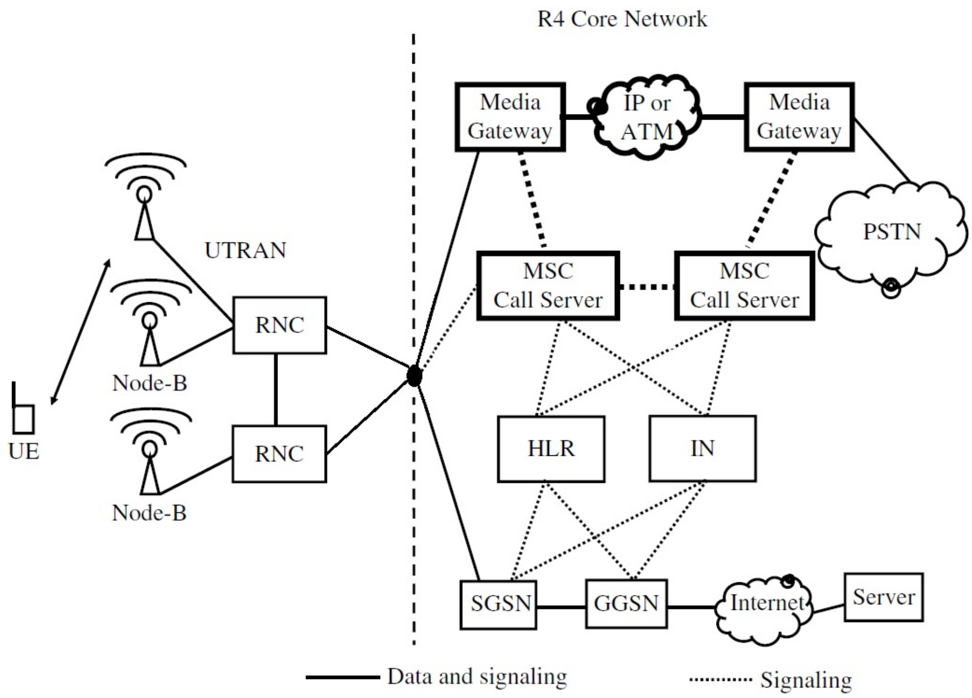


Figure 1.3: UMTS Network [2]

The introduction of UMTS is possible by keeping the same network and the same overall management (Operation, mobility, billing), the new network is combined with already existing networks. However, new frequency allocations were needed to support UMTS technology and new base stations have been installed under the name of Node B. Besides adding some elements to the network like the Radio Network Controller (RNC) which is the main element in the UTRAN (UMTS Terrestrial RAN) and the responsible for controlling the Node Bs that are connected to it, the USIM card provides enhanced features than compared to SIM card like enhanced security, and the cellphone.

Regarding the data transfer rate, UMTS has undergone several evolutions starting with:

W-CDMA

An improvement concerning the throughput can reach, under specific conditions, 384 kbit/s but in the worst case it is at least 144 kbit/s.

HSPA (HSDPA/HSUPA)

Known commercially as 3G+, 3.5G or H. HSDPA for High-Speed Downlink Packet Access, this mobile telephony protocol has undergone an evolution; it allows downloading with a data rate of 1.8 Mbits/ s, 3.6 Mbits/s, 7.2 Mbits/s, 14.4 Mbits/s. This protocol is a software enhancement that is defined by the standard WCDMA-3GPP release 5 and it concerns the user downlink to the high-speed network.

HSUPA for High-Speed Uplink Packet Access is a protocol of the UMTS family whose specifications have been proposed by 3GPP release 6, it is a complement of the previous HSDPA standard provides an upward speed of 5.8 Mbits/s (theoretical) this protocol allowed the sharing of large data (photo, video ... etc) between mobiles, and from mobile to sharing platforms on the Internet.

These protocols were defined by 3GPP to increase the possible throughputs and reduce the system latency.

HSPA+

An improved version of HSPA, known as 3G++ or H+, enhanced the UMTS network even more. With HSPA+ data rates could reach up to 42 Mbps downlink and 11.5 Mbps uplink. Since HSPA+ couldn't quite hit 4G speeds, it's also known as 3.5G.

HSPA+ is a term that brings together several technical developments, mainly represented by the use of two adjacent radio cells (DC-HSPA+). It aimed mainly at improving:

- The flow rates provided to users and the capacity of the system.
- Always-on user management. HSPA+ was standardized by 3GPP in Releases 7 (2007) and 8 (2008).

1.3.2 CDMA

The American company Qualcomm is the owner of the CDMA family technology and has developed all the CDMA systems that are standardized by the 3GPP2 organization.

CDMA2000

It is known as a 3G technology introduced by the ITU (International Telecommunication Union) it extends the 2G technology American CDMA-One (IS-95). The transition from 2G to 3G was a simple evolution, not a revolution as for European standards (GSM to UMTS).

EV-DO

Evolution-Data Optimized, an evolution of CDMA2000 that was introduced by the same 3GPP2 body but it ensures higher speeds of about 2.5 Mbits/s as theoretical speed and it allows users of data transfer services such as the Internet.

1.4 4th Generation

It was decided by network vendors and network operators that the 3GPP LTE system should become the common successor to UMTS and EV-DO [2]. The development of 4G networks followed three steps identified by the releases of 3GPP :

- releases 8 and 9 are the basis of LTE standard;
- releases 10, 11, and 12 are the basis of LTE Advanced standard;
- releases 13 and 14 are the basis of LTE Advanced Pro standard.

Figure 1.4: LTE evolution [3]

1.4.1 Motivation for LTE

Mobile data increased dramatically over voice calls in the years leading up to 2010. The figure shows measurements by Ericsson of the total traffic being handled by networks throughout the world.

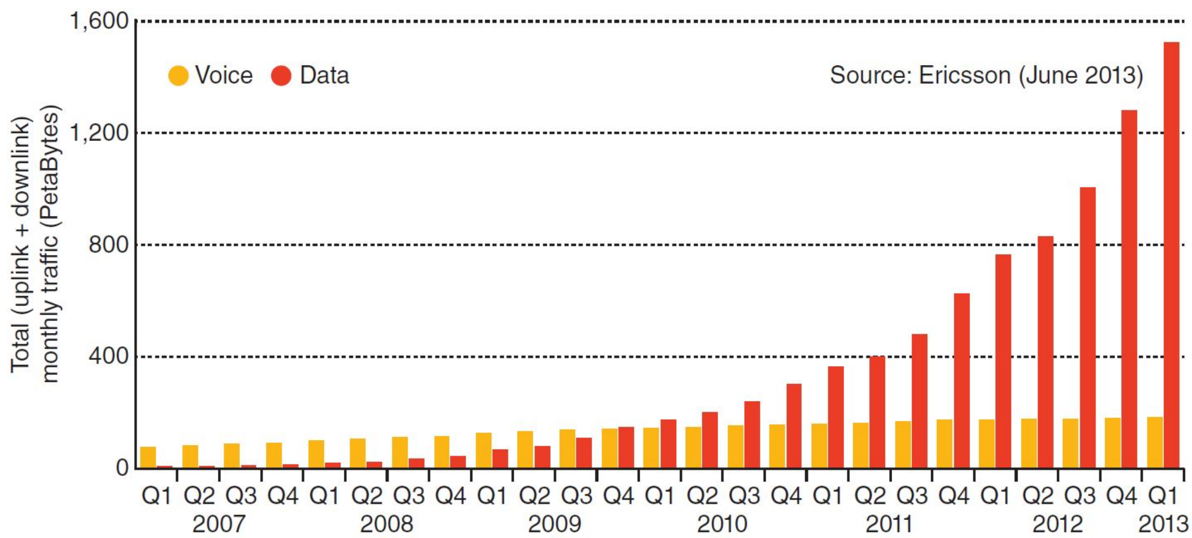


Figure 1.5: Measurements of voice and data traffic in worldwide mobile telecommunication networks, in the period from 2007 to 2013 [4]

The growth was driven by the increased availability of 3.5G communication technologies but mostly by the introduction of smartphones. These devices were more attractive, user-friendly, and permitted third-party developers to launch applications. Another key factor was the introduction of flat-rate charging schemes that permitted unlimited data downloads. That led to a situation where neither developers nor users were motivated to limit their data consumption.

As a result, 2G and 3G networks started to become congested leading to a necessity of network capacity increase. Last but not least, some technical issues have also driven the move to LTE, including the complexity of UMTS/GSM specifications, the delays introduced by 3G networks, and the difficulty to maintain two core networks (The circuit-switched domain for voice, and the packet-switched domain for data).

1.4.2 LTE architecture

The aim of 3GPP when they began a study into the long-term evolution of UMTS, was to keep their mobile communication systems competitive over timescales of 10 years and beyond. Hence, the need to deliver the high data rates and low latencies that future users would require. The figure below illustrates the resulting architecture:

LTE standard only offers services based on packet-switching (PS), and as such, only allows the transport of IP packets. In release 9, the telephone service VoLTE (Voice over LTE) is therefore provided by the network IMS (IP Multimedia Sub-system). If the VoLTE is not deployed, the mechanism CSFB (Circuit-Switched Fallback) is used to redirect the mobile to 2G/3G networks in the CS mode in the case of an incoming or outgoing telephone call [5].

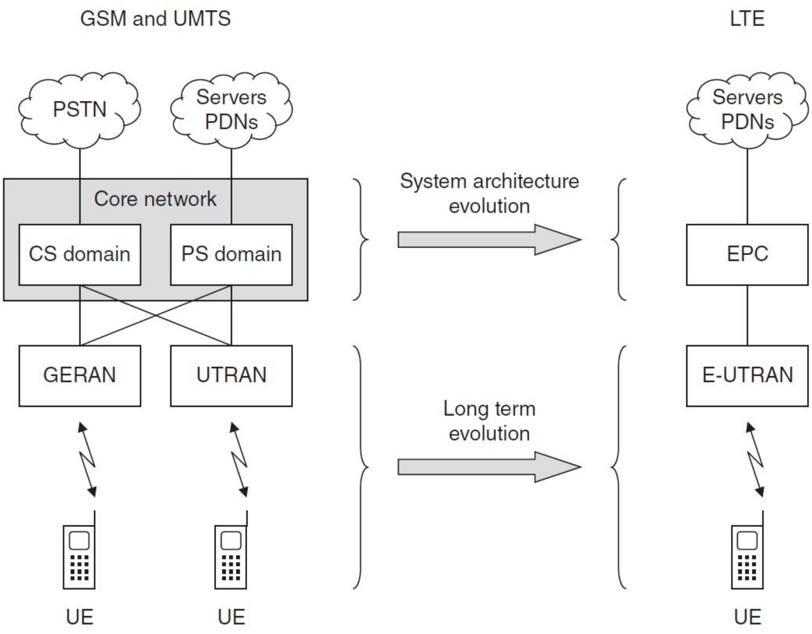


Figure 1.6: Evolution of the system architecture from GSM and UMTS to LTE [4]

While the acronym LTE refers only to the evolution of the air interface, it has however become a colloquial name for the evolved packet system (EPS) [4]. LTE will be used in this colloquial way throughout this report.

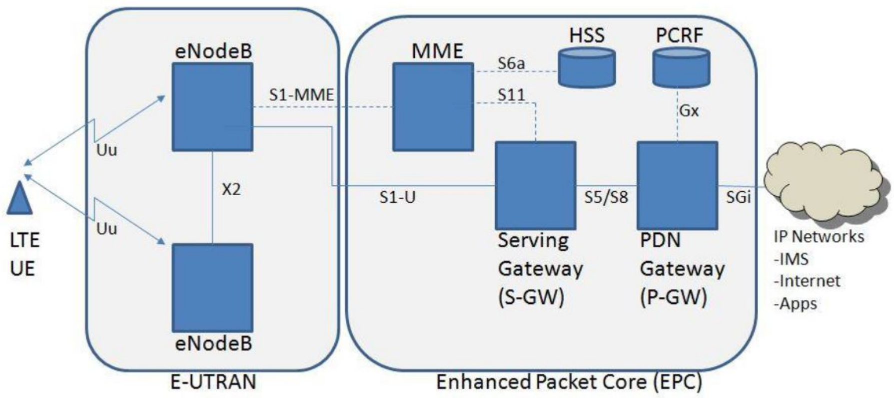


Figure 1.7: LTE architecture

UE

It can be divided into two components, namely the mobile termination (MT), which handles all the communication functions, and the terminal equipment (TE), which terminates the data streams. The universal integrated circuit card (UICC) is a smart card, colloquially known as the SIM card. It runs an application known as the universal subscriber identity module (USIM), which stores user-specific data such as the user's phone number and home network identity.

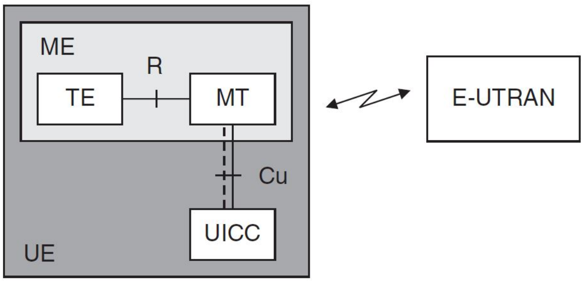


Figure 1.8: Internal architecture of the UE [6]

e-UTRAN

Unlike UTRAN where Node-B and RNC entities are present, the e-UTRAN architecture only features eNodeBs. The functions supported by the RNC have been distributed between the eNodeB and the entities of the MME / SGW core network.

The eNodeB has an S1 interface with the core network, besides a new X2 interface that has been defined between the adjacent eNodeBs, to allow them to exchange signaling information and minimize packet loss during handover, without involving the core network.

EPC

The main components of the evolved packet core:

- The home subscriber server (HSS) is a central database that contains information about all the network operator's subscribers. This is one of the few components of LTE that has been carried forward from UMTS and GSM.
- The packet data network gateway (P-GW) is the EPC's point of contact with the outside world. Through the SGi interface, each PDN gateway exchanges data with one or more external devices or packet data networks, such as the network operator's servers, the internet, or the IP multimedia subsystem.
- The serving gateway (S-GW) acts as a high-level router, and forwards data between the base station and the PDN gateway.
- The mobility management entity (MME) controls the high-level operation of the mobile, by sending it signaling messages about issues such as security and the management of data streams that are unrelated to radio communications. The MME also controls the other elements of the network, through signaling messages that are internal to the EPC.
- Policy Charging Rules Function (PCRF) provides the PGW with the charging rules necessary to differentiate the data flows and to charge them properly.

Air Interface

The major evolution in LTE compared to previous 3GPP wireless systems is the completely revised air interface [2]. In the next chapter, the main key LTE technologies that enable the use of much larger bandwidths in the downlink and the uplink directions will be described.

1.4.3 LTE-Advanced

LTE-A is an evolved version with a major enhancement of the LTE standard, it was introduced to finally satisfy the International Telecommunication Union-R 4G requirements that the LTE Rel-8 version, the one described previously, did not satisfy. LTE-Advanced is designed to be backward compatible with LTE, in the sense that an LTE mobile can communicate with a base station that is operating LTE-Advanced and vice-versa [4]. LTE-Advanced comprises several enhancements that will be covered in the next chapter.

1.4.4 LTE-Advanced Pro

The goal of LTE-A Pro standard is to increase the throughput for mobiles to reach the value of 3 Gbit/s, and to bring new functionalities like using 32-carrier aggregation [5]. Besides, introducing new technologies associated with the 5G like Massive MIMO and NB-IoT, that's why it represented a gateway for this next generation and was known as the Pre-5G.

1.5 5$^{\text{th}}$ Generation

The driving force for a new generation of technologies is generated by increasing demands from a networked human society. Those demands include more traffic volume, more devices with diverse service requirements, a better quality of user experience (QoE), and better affordability by further reducing costs. The overall objective of 5G is to provide ubiquitous connectivity for any type of device and any kind of application [1].

According to ITU-R studies, major usage scenarios for the new 5G system can be largely classified into five categories: Enhanced Mobile Broadband, Ultra-reliable and low-latency critical communications, Machine Type Communications (MTC), Enhancement of Vehicle-to-Everything V2X, and Network Operation that is enhanced with network slicing, routing, migration and interworking, and energy saving [1].

Conclusion

In this chapter, the most remarkable phases of the mobile standards history were highlighted, with the main reasons that motivated the launch of each standard and their added value to the user experience being presented. Moreover, their architectures were detailed, especially the LTE's, in order to understand the overall system structure before digging into the next chapter were the key technologies that came with the LTE, and the enhancements that came with the LTE-Advanced will be introduced.

Chapter 2

LTE, LTE-Advanced

Introduction

In December 2008, 3GPP released LTE specifications for the long-term evolution of UMTS cellular technology. This was formally known as evolved UMTS terrestrial radio access (E-UTRA) and evolved UMTS terrestrial radio access network (E-UTRAN) but now it is more commonly referred to as LTE. It is designed to support only packet-switched services, in contrast to the circuit-switched model of the previous generation cellular systems. Based on the downlink and uplink path duplexing, both frequency-division duplexing (FDD) and time-division duplexing (TDD) versions of LTE have been defined [7].

LTE technology deployment has been a success story. It showed attractive performance in the field in terms of data rates and latency and the technology acceptance has been very fast. The technologies used in this standard represented a revolution in the telecommunication field. Despite that, it didn't achieve the requirements for 4G, which were finally realized by the next step in LTE evolution, LTE-Advanced, where the data rate is set to increase even beyond 1 Gbps.

2.1 Protocol layers overview

The figure shows the protocol stack in the uplink and downlink processing, in both cases, it is split into two parts, the control and the user plane.

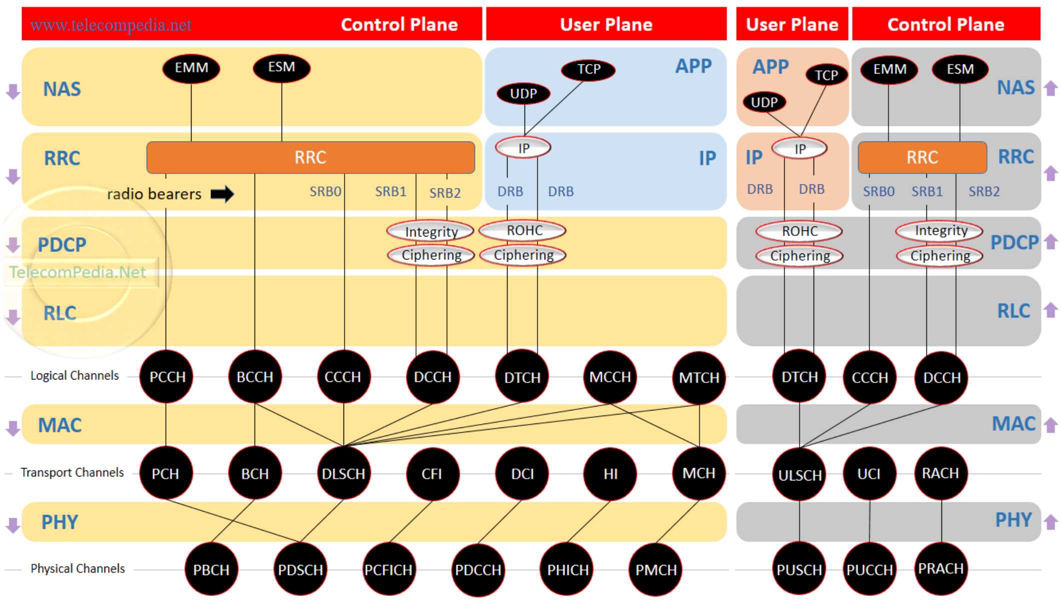


Figure 2.1: The protocol layers overview

On the control plane side, the control protocols are shown. The top layer is the NAS protocol that is used for mobility management and other purposes between the mobile device and the MME. NAS messages are tunneled through the radio network, and the eNode-B just forwards them transparently.

NAS messages are always encapsulated in Radio Resource Control (RRC) messages over the air interface. The other purpose of RRC messages is to manage the air interface connection and they are used, for example, for handover or bearer modification signaling. As a consequence, an RRC message does not necessarily have to include a NAS message.

This is different on the user data plane shown on the right of the Figure. Here, IP packets always transport user data and are sent only if an application wants to transfer data. The first unifying protocol layer to transport IP, RRC, and NAS signaling messages is the PDCP layer. As discussed in the previous section, it is responsible for encapsulating IP packets and signaling messages, for ciphering, header compression, and lossless handover support.

One layer below is the RLC. It is responsible for the segmentation and reassembly of higher-layer packets to adapt them to a packet size that can be sent over the air interface. Further, it is responsible for detecting and retransmitting lost packets (ARQ).

Just above the physical layer is the MAC. It multiplexes data from different radio bearers and ensures QoS by instructing the RLC layer about the number and the size of packets to be provided. In addition, the MAC layer is responsible for the HARQ packet retransmission functionality.

And finally, the MAC header provides fields for addressing individual mobile devices and for functionalities such as bandwidth requests and grants, power management, and timing advance control [2].

2.2 LTE physical layer

2.2.1 Time and frequency domain structure

In the time domain, LTE organizes the transmission as a sequence of radio frames of length 10 ms. Each frame is then subdivided into 10 subframes (TTI) of 1 ms length. Each subframe is composed of two slots of length 0.5 ms each. Finally, each slot consists of several OFDM symbols, either seven or six depending on whether a normal or an extended cyclic prefix is used.

In the frequency domain, there is a list of spectrum allocations ranging from 1.4 to 20MHz. The frequency spectra in LTE are formed as concatenations of resource blocks consisting of 12 subcarriers of 15 kHz, the total bandwidth of a resource block is 180 kHz. This enables transmission bandwidth configurations of from 6 to 100 resource blocks over a single frequency carrier.

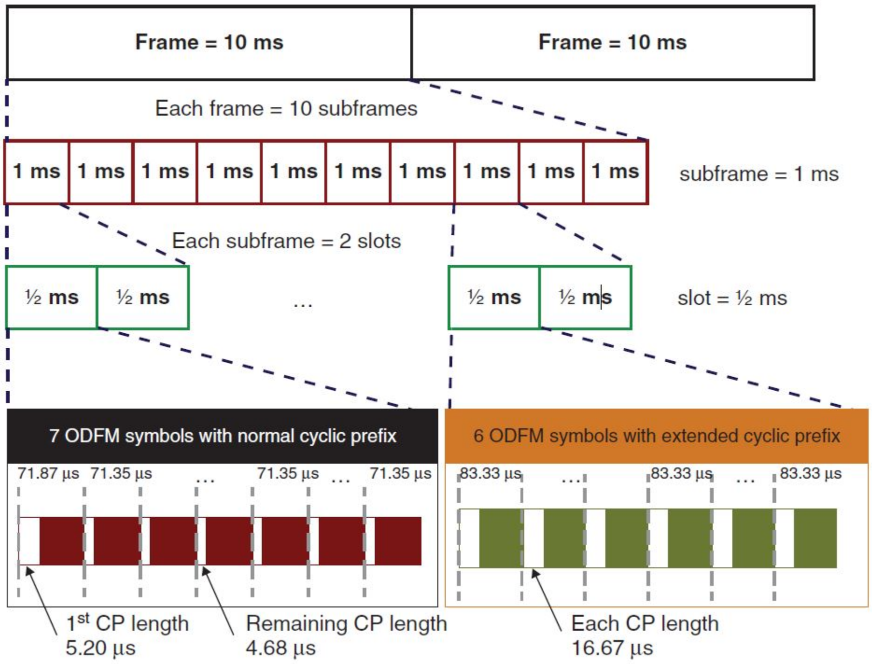


Figure 2.2: LTE time domain structure [8]

Chanenel bandwidth (MHz)	Number of resource blocks	Transmission bandwidth (MHz)
1.4	6	1.08
3	15	2.7
5	25	4.5
10	50	9
15	75	13.5
20	100	18

Table 2.1: LTE defined bandwidths

For bandwidths of 3–20MHz, the totality of resource blocks in the transmission bandwidth occupies around 90% of the channel bandwidth. In the case of 1.4 MHz, the percentage drops to around 77%. This helps reduce unwanted emissions outside the bandwidth.

2.2.2 Resource Grid

One of the most attractive features of OFDM is that it maps explicitly to a time-frequency representation for the transmitted signal. After coding and modulation, a transformed version of the complex-valued modulated signal, the physical resource element, is mapped onto a time-frequency coordinate system, the resource grid.

A resource block is defined as a group of resource elements corresponding to 12 sub-carriers or 180 kHz in the frequency domain and one 0.5ms slot in the time domain. In the case of a normal cyclic prefix with seven OFDM symbols per slot, each resource block

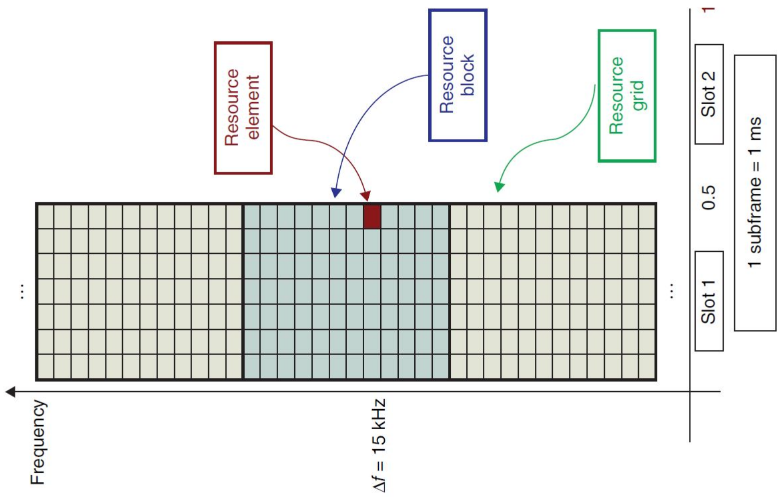


Figure 2.3: LTE resource grid

consists of 84 resource elements. In the case of an extended cyclic prefix with six OFDM symbols per slot, the resource block contains 72 resource elements. The definition of a resource block is important because it represents the smallest unit of transmission that is subject to frequency-domain scheduling.

2.3 Key technologies in LTE

2.3.1 OFDM

Orthogonal Frequency-Division Multiplexing is a technique that consists of subdividing the transmission band into N sub-channels, leading to an increase in the symbol duration. It is a technique based on the Fast Fourier Transform which makes it possible to divide the data stream to be transmitted into N sub-streams of parallel data, which will be transmitted on different orthogonal sub-bands. This technique offers high efficiency in the spectrum and power use by using N sub-carriers that are orthogonal and very close to each other.

OFDMA for Downlink Transmission

If OFDM allocates a carrier to each user and therefore allows the transmission of data from several users at the same time, OFDMA makes it possible to change the carrier for a user after a certain period of time, a concept borrowed from TDMA.

This technique allows better protection against fading because if the latter touches a frequency all user data will be lost, on the other hand with OFDMA only a small part will be affected. However, the problem of PAPR (which indicates a ratio between peak power and average power of OFDM) is still present, which is why OFDMA is only used in the downlink because the eNodeB has enough power to transmission while the user terminal (UE) has a limited autonomy thus pushing the 3GPP to use a different access method for the uplink: the SC-FDMA [2].

SC-FDMA for Uplink Transmission

Single-Carrier-FDMA is implemented in the LTE standard by essentially preceding the OFDM modulator with a DFT (Discrete Fourier Transform) precoder. This technique is known as Discrete Fourier Transform-Spread Orthogonal Frequency Division Multiplexing (DFTS-OFDM). The distinguishing feature of SC-FDM transmission is that each data symbol is essentially spread over the entire allocated bandwidth.

While OFDMA transmits several symbols in parallel on several sub-carriers spaced at 15Khz resulting in an OFDMA symbol with a duration of 66.7 s, SC-FDMA transmits only one symbol at a time (in series) but which is distributed over the set of carriers thus giving a symbol of width M $\times$ 15Khz but always of a duration of 66.7 s, really each sub-carrier carries “a sub-symbol” but visually it is as if there is only one carrier which is used hence its name.

The advantage is that the problem relating to the high PAPR disappears because it is the parallel transmission of several symbols that causes it, while with the SC-FDMA the transmission is serial which is admittedly slower but ensures a low PAPR which allows the RF amplifier of the mobile to consume a minimum of energy, which is why it was adopted for the uplink [2].

2.3.2 MIMO

3GPP Release 8 specifies and requires the use of multi-antenna techniques, also referred to as MIMO. While this functionality has also been specified for HSPA in the meantime, it is not yet widely used for this technology because of backward compatibility issues and the necessity to upgrade the hardware of already-installed UMTS base stations. With LTE, however, MIMO was natively taken into account in the design of the physical layer. This original integration coupled with the absence of intracellular interference in OFDM systems leads to the high efficiency of MIMO in the LTE system [2].

The basic idea behind MIMO techniques is about using multiple antennas at the transmitter and receiver to send several independent data streams over the same air interface channel simultaneously. to improve communication performance and data rate. It offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. In 3GPP Release 8, the use of two or four simultaneous streams is specified, 2$\times$2 MIMO in the UL, and 4$\times$4 MIMO in the DL [7].

2.3.3 Hybrid Automatic Repeat reQuest

The Hybrid ARQ scheme used in LTE is a combination of physical layer coding (Forward Error Correction) and the data link layer's repeat request mechanism (Automatic Repeat reQuest). The eNB requests retransmissions of incorrectly received data packets [7].

The eNode-B expects the mobile device to send an acknowledgment (ACK) if the data within each 1-millisecond subframe has been received correctly. A negative acknowledgment (NACK) is sent if the data could not be decoded correctly. If an ACK is received, the eNode-B removes the subframe data from its transmission buffer and sends the next chunk of data if more data is waiting in the buffer. In case a NACK is received, the eNode-B attempts to retransmit the previous data block [2].

2.3.4 Channel scheduling

Scheduling is a process through which eNodeB decides which UEs should be given resources, how many resource blocks (RBs) should be given to send or receive data to ensure the best channel transmission and maximize the system throughput. In LTE, the scheduling is fully controlled by the eNode-Bs as higher-layer radio network control instances were removed from the overall network design. This allows the network to react to changing radio conditions of each user and optimize the overall throughput, and ensure the QoS for each user, besides, the overload situations can be dealt with [2].

We distinguish three types of schedulers:

- Round Robin: The RR scheduler selects and schedules UEs in a round-robin manner, thereby creating an equal resource share. The disadvantage of this approach is that UEs with sub-optimal CQI may be allocated Physical Radio Resources (PRBs), thus reducing the overall cell throughput.

- Max CQI: The max-CQI (Channel Quality Indicator) scheduler selects the schedulable UEs based on the experienced CQI. The UEs with the highest CQI, therefore, become candidates for scheduling thereby increasing the overall cell throughput. The disadvantage of this approach is that UEs with lower CQI are denied scheduling instances, thus being starved for throughput and leading to degraded user experience.

- Proportional Fair: The PFS is expected to strike a balance between the traditional Round Robin (RR) scheduler and the max-CQI. The PFS scheduler performs in such a manner that it considers resource fairness as well as maximizing cell throughput (in addition to other possible performance metrics).

2.3.5 Adaptive Modulation and Coding

Adaptive Modulation and Coding (AMC) is used to increase the network capacity or downlink data rates. With channel station information feedback from the mobile receiver to the base station transmitter, adaptive modulation and coding can be applied to adapt to the mobile wireless channels condition to increase spectral efficiencies without increasing bit error rate in noisy channels.

Encoding a sequence of bits onto the carrier signal is obtained by adjusting its parameters, this is known as the modulation. We distinguish four modulation schemes in LTE:

- **BPSK:** One bit is sent at a time, using two symbols that can be interpreted either as initial phases of 0 and 180° or as signal amplitudes of +1 and −1.
- **QPSK:** The symbols have the same amplitude and have initial phases of 45°, 135°, 225°, and 315° which correspond to bit combinations of 00, 10, 11, and 01 respectively.
- **16-QAM:** four bits are sent at a time using 16 symbols that have different amplitudes and phases.
- **64-QAM:** six bits are sent at a time using 64 symbols that have different amplitudes and phases.

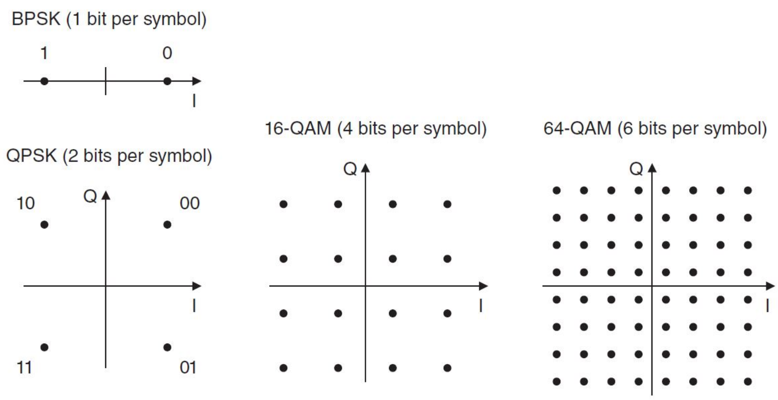


Figure 2.4: Modulation schemes used by LTE [4]

The figure 2.4 represents these four modulation schemes in a constellation diagram where the amplitude of the transmitted wave is represented by the distance of each symbol from the origin and the initial phase by the angle measured counterclockwise from the x-axis.

2.3.6 Inter Cell Interference Coordination

The first ICIC scheme was already defined in the first LTE specification, 3GPP Release 8. The idea behind what is referred to as FFR is to use only some of the subcarriers at the cell edge by transmitting with a higher power on them than on other subcarriers. Neighboring cells would do the same but for subcarriers on different frequencies thus creating less interference. Naturally, a balance has to be found between reduced interference on those subcarriers in cell-edge scenarios and the reduced number of subcarriers in such areas, which reduces the overall transmission speed for devices in such areas [2].

2.4 Basic procedures

2.4.1 Power-On sequence

The mobile begins by running the procedure for network and cell selection, which has three steps. (i) the mobile selects a public land mobile network (PLMN) that it will register with. (ii) the mobile can optionally ask the user to select a closed subscriber group (CSG) for registration. (iii) the mobile selects a cell that belongs to the selected network and if necessary to the selected CSG. In doing so, it is said to camp on the cell.

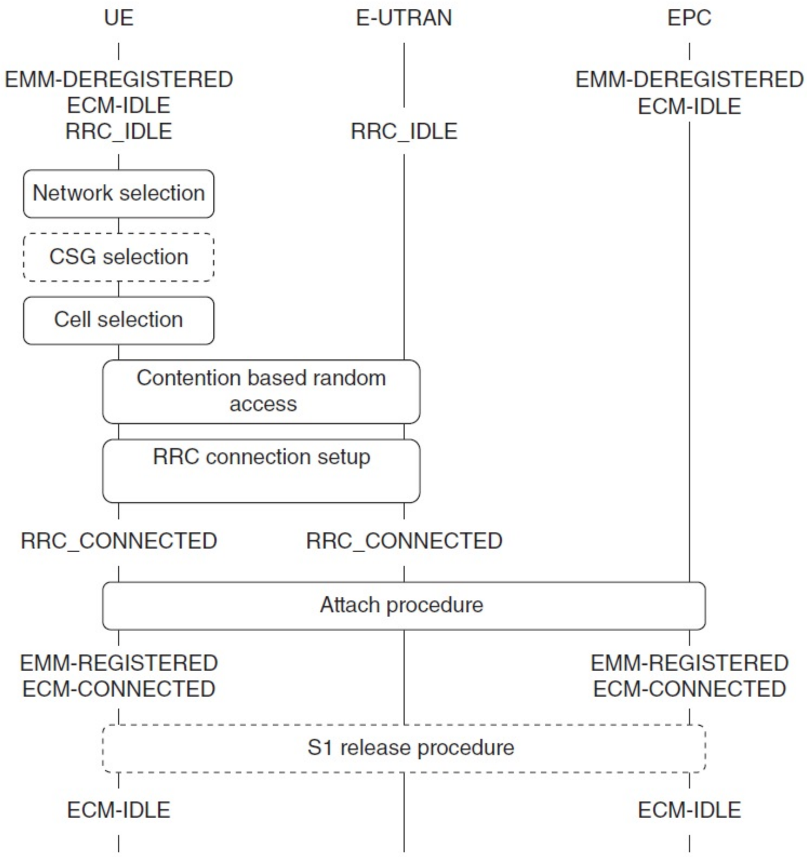


Figure 2.5: Power-On sequence [4]

The mobile then contacts the corresponding base station using the contention-based random access procedure and initiates the procedure for RRC connection establishment. During the RRC procedure, the mobile establishes a signaling connection with the selected base station and moves from RRC_IDLE into RRC_CONNECTED.

In the final step, the mobile uses the attach procedure to contact the evolved packet core. As a result of that procedure, the mobile registers its location with a mobility management entity (MME) and moves to the states EMM-REGISTERED and ECM-CONNECTED. It acquires an IP address and establishes a default bearer through which it can communicate with the outside world.

The mobile is now in the states EMM-REGISTERED, ECM-CONNECTED and RRC_CONNECTED, and will stay in those states for as long as it is exchanging data with the network. If the user does nothing, then the network can transfer the mobile into ECM-IDLE and RRC_IDLE, using a procedure known as S1 release.

2.4.2 LTE Mobility

The EPS has two main states, where mobility management needs to be handled [1]:

- ECM (EPS Connection Management) IDLE state;
- ECM-CONNECTED state.

Idle mode mobility

Cell selection and reselection are done autonomously by the UE and based on UE measurements. The UE starts receiving the broadcast channels of that cell and checks if the cell is suitable for camping, which requires that the cell is not barred and that radio quality is sufficient. After cell selection, the UE must register itself to the network.

Whenever the UE has camped to a cell, it monitors and measures the neighbor cells' broadcast channels. The decision for cell reselection is triggered when the serving cell's signal is not high enough to satisfy default QoS criteria. In the ECM-IDLE state, no signaling connection exists between the UE and the network.

CONNECTED mode mobility

In the CONNECTED state, the location of UE is known with an accuracy of eNB. The mobility in RRC connected state is entirely managed by handovers. There is a list of LTE measurement events' triggered that are configured by the network during connection setup or later on, for example, due to deteriorating signal conditions [9]:

For LTE to LTE handovers:

Event A1: The serving cell becomes better than a threshold value;
Event A2: The serving cell becomes worse than a threshold value;
Event A3: The neighbor cell becomes better than the serving cell;
Event A4: The neighbor cell becomes better than a threshold value;

Event A5: The serving becomes worse than a threshold value, neighbor becomes better than another threshold value.

For LTE to UMTS or GSM handovers:
Event B1: The inter-RAT neighbor cell becomes better than a threshold value;
Event B2: The serving cell becomes worse than threshold 1 and inter-RAT neighbor becomes better than threshold 2.

As a consequence, several mobility scenarios are supported in CONNECTED mode:

Intra-LTE Intra-eNodeB mobility
The handover may take place between cells belonging to the same eNB.

Intra-LTE inter-eNodeB mobility
The handovers happen between adjacent base stations. The most efficient one is a handover where the source eNode-B and the target eNode-B directly communicate with each other over the X2 interface. This handover is referred to as an X2 handover. If for some reason the two eNode-Bs cannot communicate with each other, for example, because they have not been configured for direct communication, the handover signaling will take place over the S1 interface, and the MME assists in the process. Such a handover is referred to as an S1 handover [2].

3GPP inter-radio access technology (inter-RAT) mobility
Involves handovers between the Evolved UTRAN and a non-LTE 3GPP access network (UTRAN or GERAN). Inter-RAT handover can be performed in both the E-UTRAN RRC connected state as well as in the E-UTRAN RRC IDLE state.

Non-3GPP inter-RAT mobility
The handover takes place between the Evolved UTRAN and a non-3GPP access network, for instance, WLAN, WiMAX, or 3GPP2 access network.

2.5 LTE-A features

2.5.1 Carrier Aggregation

The ultimate goal of LTE-Advanced is to support a maximum bandwidth of 100 MHz. This is an extremely large bandwidth, which is most unlikely to be available as a contiguous allocation in the foreseeable future. To deal with this problem, LTE-Advanced allows a mobile to transmit and receive on up to five component carriers (CCs), each of which has a maximum bandwidth of 20 MHz. This technique is known as carrier aggregation (CA) [4].

2.5.2 Enhanced Up-link Multiple Access

The original SC-FDMA was designed to work in a contiguous band. In order to support carrier aggregation in the UL as well as the DL, the LTE-Advanced adopts a modified version of SC-FDMA, which is referred to as clustered SC-FDMA.

The enhanced uplink multiple access scheme adopts clustered SC-FDMA. It is similar to SC-FDMA but it allows non-contiguous (clustered) groups of subcarriers to be allocated for transmission by a single UE, thus enabling uplink frequency-selective scheduling and better link performance [7].

2.5.3 Enhanced Multiple Antenna Transmission

In order to simplify the baseline in UE Release-8 LTE, the downlink supports a maximum of four spatial layers of transmission 4×4, and the uplink a maximum of one per UE (1×2, assuming an eNB diversity receiver). Release-10 specifies up to eight layers in the downlink to improve single-user peak data rates and improve spectrum efficiency. The UE will be specified to support up to four transmitters allowing the possibility of up to 4×4 transmission in the uplink when combined with four eNB receivers [7].

2.5.4 Relaying

Relaying is introduced in 3GPP Release-10 in order to increase the coverage and throughput. Generally, a repeater just rebroadcasts the signal whereas a relay will receive, demodulate and decode the data, apply any error correction to it, and then retransmit the signal, so signal quality is enhanced in the latter case. As shown in the figure, the LTE relay is a fixed relay, which means infrastructure without a wired backhaul connection that relays messages between the eNB and UEs. These will help (i) to provide coverage in new areas and poor coverage areas; (ii) temporary network deployment; (iii) to improve cell edge throughput; (iv) group mobility. Relaying brings the advantages like (i) cost reduction – the cost of a relay is less than the cost of an eNB; (ii) power consumption reduction as the required transmitter power in the relay is lower than the eNB [7].

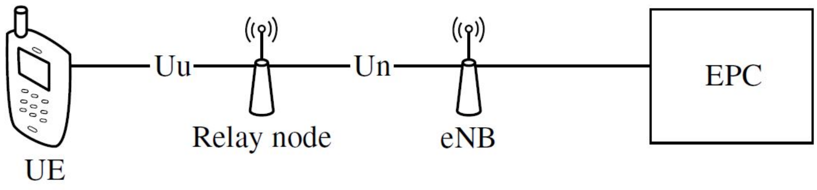


Figure 2.6: Relay node

2.5.5 Device to Device

Device-to-device (D2D) communication enables direct communication between nearby devices without routing the data paths through a network infrastructure. It is currently being specified by 3GPP in LTE Rel-12 and is recognized as one of the key technology components of the evolving 4G and 5G architecture. The cellular system infrastructure controls and assists the operation of D2D links, which will coexist with cellular communications within the same shared cellular spectrum.

2.5.6 Coordinated Multipoint

If a mobile moves away from a base station's antennas and towards the edge of a cell, then it receives a weaker signal from the serving cell and more interference from other cells that are nearby. Taken together, these two effects reduce the mobile's data rate and degrade the user's service. In a technique known as coordinated multipoint transmission and reception (CoMP), nearby antennas cooperate so as to increase the power received by a mobile at the cell edge, reduce its interference and increase its achievable data rate. In contrast, CoMP does not have much effect on the average data rate within the cell [4].

2.5.7 Heterogeneous Networks and Enhanced ICIC

Radio access networks often contain different layers of cells, such as macrocells, microcells, and picocells. A network operator can minimize interference between these layers by deploying them on different carrier frequencies. However, this technique is not always feasible as the operator may not have enough carriers available. As an alternative, a network operator can deploy different layers on the same carrier frequency, so that they occupy the same frequency band. Such a network is known as a heterogeneous network or HetNet [4].

HetNets provide two basic benefits to operators: Increase capacity in hotspots as traffic is not uniformly distributed, and improve coverage in places where macro coverage is not adequate. However, HetNets suffer from two interference problems. The first occurs if a high-power base station such as a macrocell is close to a low-power base station such as a picocell. Interference from the macrocell reduces the picocell's coverage area, so it limits the benefits that the picocell might otherwise provide. The second problem occurs if the picocell belongs to a closed subscriber group (CSG). If a nearby mobile does not belong to the closed subscriber group, then it may be unable to communicate with the macrocell because of interference from the picocell. Note the distinction between these scenarios: In the first scenario, the macrocell is the aggressor and the picocell is the victim, while the reverse is true in the second scenario [4].

While the basic ICIC FFR scheme may be beneficial in a pure macro network environment, there are no benefits in a heterogeneous network environment where several small cells are located in the coverage area of a single macrocell. In such a scenario, the coverage area of the small cells fully overlaps with the coverage area of the macro cell and thus there is no benefit from reducing the power of some of the subcarriers. This is why in 3GPP Release 10, an additional ICIC scheme, referred to as eICIC was defined.

With this scheme, the macro cell coordinates with the small cells as to which of its subframes it leaves empty in the time domain. The small cells will then use the empty macro cell subframes for their own data transmission, thus avoiding interference from the macrocell in those subframes and reciprocally not causing interference for devices being served by the macro cell. Again, a balance has to be found between the gain of reduced interference and the loss of transmission capacity in the macro cell and the small cells operating in its coverage area because of the split of subframe resources [2].

2.5.8 LTE Self-Optimizing Networks

Due to tremendous growth in cellular mobile communications and data usage, the network is becoming dense and complicated, so radio network planning and maintenance are also becoming more complicated. To address this, and to support smooth unplanned deployment of pico nodes, 3GPP has created a work item referred to as Self-configuring and Self-organizing Network (SON) to define ways to optimize and automate many labor-intensive tasks, which are specified in a series of standards including [10]. SON helps to govern a network and this includes planning, setup, and maintenance activities. It enables the network to set itself up and then manages the resources to achieve optimum performance [4].

Conclusion

This chapter presented the main concepts, technologies, and procedures of the LTE standard, besides introducing the enhancements brought by the LTE-Advanced, before focusing on one of these enhancements in the next chapter which represents the main focus of our study: carrier aggregation.

Chapter 3

Carrier Aggregation

Introduction

When LTE was launched, a carrier bandwidth of up 20 MHz was revolutionary as it was four times larger than the 5 MHz carriers used for UMTS, which was still considered ample at the time. Over the years, however, bandwidth demands per cell site continued to increase. 3GPP thus specified a way to combine several carriers into a transmission channel. This is referred to as Carrier Aggregation (CA) [2].

Whether and how many carriers can be aggregated depends on how many carriers are used at a base station site and the hardware capabilities of a mobile device, which the device signals to the network in the UE device category parameter. Carriers are usually aggregated asymmetrically as there is typically a higher demand for bandwidth in the down-link than in the up-link [2].

Each aggregated carrier is referred to as a component carrier, CC. The component carrier can have a bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz and a maximum of five component carriers can be aggregated, hence the maximum aggregated bandwidth is 100 MHz. In Release 13 LTE CA is planned to expand up to 32 CCs (potentially 640 MHz of bandwidth) and hence provide a major leap in the achievable data rates for LTE as well as in the flexibility to aggregate large numbers of carriers in different bands [1].

3.1 Types and deployment scenarios

To meet operators' spectrum scenarios, three types of carrier aggregation have been defined in 3GPP. The uplink and downlink can be configured independently. However, there are a few restrictions in FDD mode, the allocations on the uplink and downlink can be different, but the number of downlink component carriers is always greater than or equal to the number used on the uplink [4].

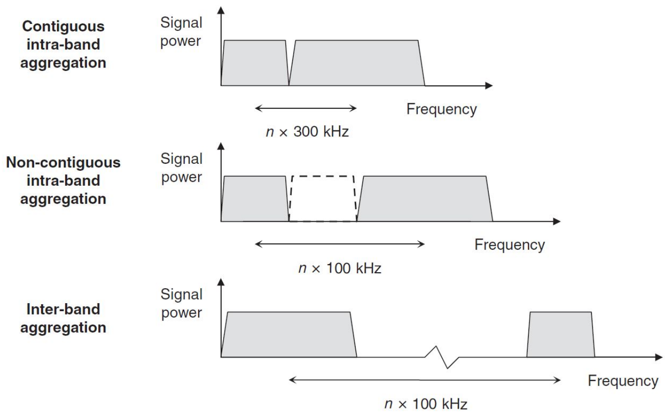


Figure 3.1: CA Types

Intra-band CA

Here, component carriers belong to a single frequency band. This is of two types:

- **Contiguous**. The aggregated carriers are adjacent to each other and center frequencies are separated by a multiple of 300 kHz, which is consistent with the orthogonality requirement so that the different sets of sub-carriers are orthogonal to each other and do not interfere [4]. The hardware implementation of this type of CA is not complicated since this type of CA can be achieved by a single RF chain. However, this type of CA is unlikely since the current spectrum is highly segmented [11].

- **Non-contiguous**. The aggregated carriers reside in the same frequency band but not adjacent to each other. This type is more realistic since the frequency bands are highly segmented. The hardware implementation of this type can simply be achieved through a single RF chain given that carriers are in the same frequency band [11].

Inter-band CA

Aggregated carriers reside in two different frequency bands and center frequencies are separated by a multiple of 100 kHz, which is the usual LTE carrier spacing [4]. The user hardware implementation for this type is the most complex since a single RF chain has limitations in terms of a certain band of interest for practical reasons [11].

Scenarios

Different deployment scenarios have been considered for the design of LTE-Advanced carrier aggregation [12]:

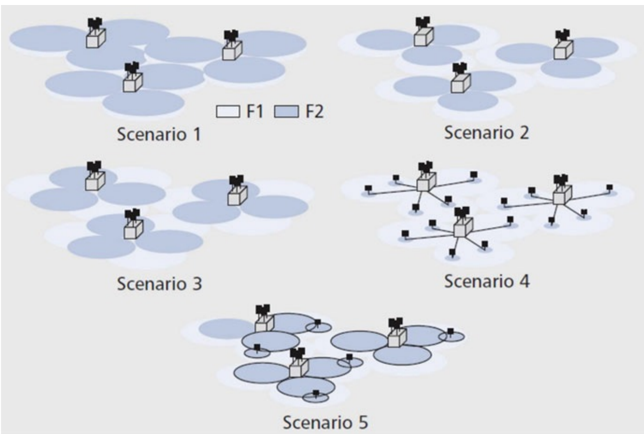


Figure 3.2: CA deployment scenarios with F2 > F1 [12]

Scenario 1: Cells with the two carrier frequencies are collocated and overlaid in the same band. Both frequencies F1 and F2 almost have the same coverage area. Carrier aggregation enables higher achievable data rates throughput the cell.

Scenario 2: Cells with the two carriers are collocated and overlaid in different bands. Different carriers have different coverage because higher frequency bands have larger path loss. Higher frequency band carriers are used to improve data rates.

Scenario 3: Cells with the two carriers are collocated in different bands. To improve the throughput of the cell edge, the antennas for cells of F2 are directed to the cell boundaries of F1. Carrier aggregation is applied for areas with overlapping coverage.

Scenario 4: Remote radio heads (RRHs) of carrier F2 are used in hot spots to improve the throughput and cells of carrier F1 are the macrocells. There are usually different bands for frequencies F1 and F2. Carrier aggregation is applied for users under the coverage area of both the RRHs and the macro-cells.

Scenario 5: Similar to scenario 2 except that to extend one of the frequencies coverage frequency-selective repeaters are deployed.

3.2 Band Classes

The table 3.1 below specifies how many component carriers a device can aggregate contiguously in a single band. This is referred to as the carrier aggregation bandwidth class [4].

CA bandwidth class	Maximum number of contiguous component carriers	Maximum aggregated bandwidth
A	1	20 MHz
B	2	20 MHz
C	2	20 - 40 MHz
D	3	40 - 60 MHz
E	4	60 - 80 MHz
F	5	80 - 100 MHz
I	8	140 - 160 MHz

Table 3.1: CA bandwidth classes [13]

The following examples show some typical carrier aggregation configurations used in practice today and their nomenclature as found in the standards [2]:
CA_3A-7A: Aggregates up to 20 MHz in band 3 (1800 MHz) and up to 20 MHz in band 7 (2600 MHz) for a combined 40 MHz channel.
CA_3C-7A: Aggregates up to 40 MHz in band 3 and up to 20 MHz in band 7 for a combined 60 MHz channel.

CA_3A-3A-7A: Aggregates up to 40 MHz (not contiguous) in band 3 and up to 20 MHz in band 7 for a combined channel of up to 60 MHz.

In Algeria, two bands are used for 4G:

- 3GPP Band 1, 2100MHz (Uplink 1920-1980 MHz, Downlink 2110-2170 MHz), also known as the IMT band. It is the world's most popular 3G UMTS frequency band. However, operators are using it for both 3G and 4G because of the lack of spectrum allocation.
- 3GPP Band 3, 1800MHz (Uplink 1710-1785 MHz, Downlink 1805-1880 MHz), where the majority of the world's network operators launched their LTE systems.

3.3 Impact of the CA

3.3.1 Protocol stack

The use of carrier aggregation is purely internal to the eNodeB. 3GPP specifications assume both carriers belong to the same eNodeB [14]. Carrier aggregation only affects the physical layer and the MAC protocol on the air interface, and the RRC, S1-AP, and X2-AP signaling protocols. There is no impact on the RLC or PDCP and no impact on data transport in the fixed network [4].

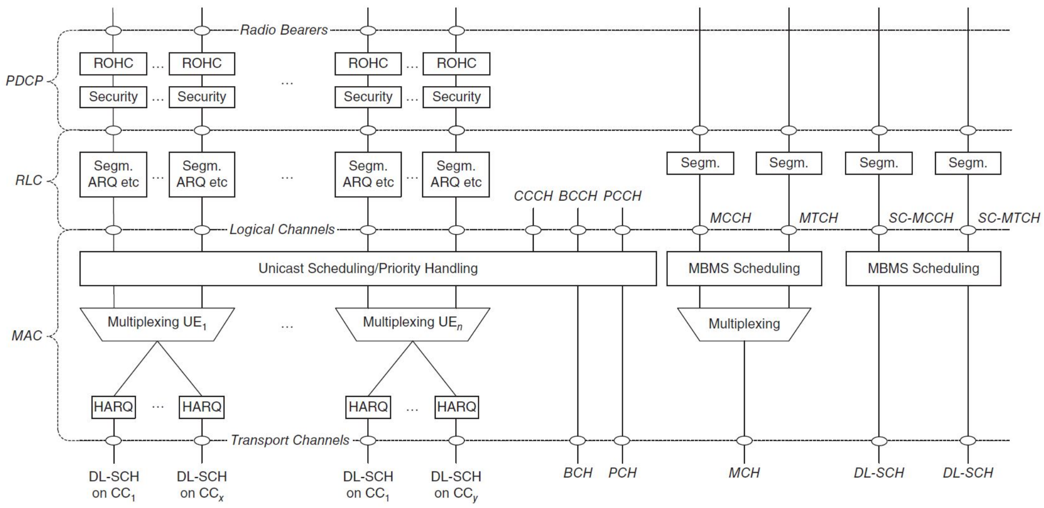


Figure 3.3: Protocol structure for DL

The MAC layer functionality will then split the data on multiple downlink carriers, often referred to as Down-link Component Carriers (DCC). The MAC layer will notify the RLC layer about transmission opportunities considering all carriers so that RLC PDUs can be formed accordingly. Each of the carriers has its own physical layer re-transmission handling, and there are separate per carrier HARQ entities [14].

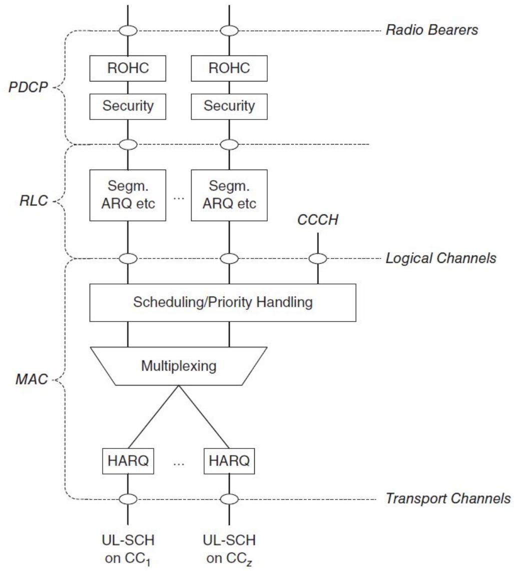


Figure 3.4: Protocol structure for UL

The scheduler functionality in the MAC layer will determine which of the component carriers should be used. This is done based on the carrier-specific quality feedback as well as other available parameters, including the load on each of the carriers. A single transport block is scheduled per component carrier in one Transmission Time Interval (TTI) to the UE, in case MIMO is in use in this carrier then two transport blocks can be scheduled per TTI on the carrier. There is a single RRC connection only per UE regardless of the number of carriers being used. The Primary Cell (PCell) is always active and may be removed or changed only with handover [14].

3.3.2 Mobility

The mobility with carrier aggregation is kept mostly unchanged, except adding a new event A6 (Neighbour becomes offset better than SCell) [9] to the handover measurement triggering events seen in the last chapter. The UE will base the mobility measurements on the PCell, this limits the needed extra measurements, and when handover is needed, the eNodeB will signal the target cell over the X2 or via the core network [14].

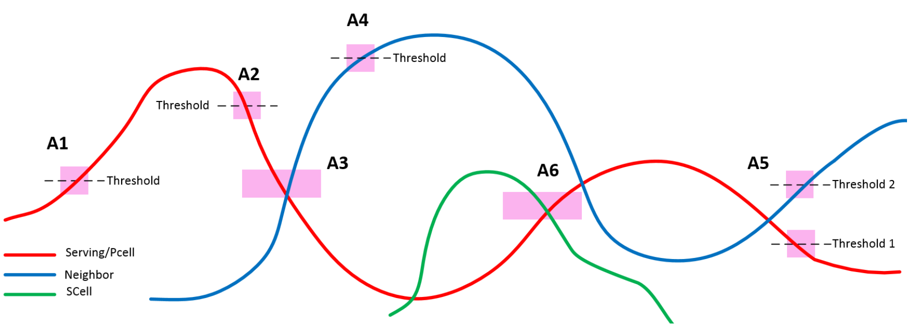


Figure 3.5: Handover triggering events

3.3.3 Performance

The gains in carrier aggregation come from the following key implications: Load balancing; Resource sharing; Frequency domain joint scheduling over more than one frequency; More bandwidth for a given uses resulting to higher peak data rate.

The peak data rate impact can be calculated by simply adding the peak data rate on each of the carriers aggregated together. An LTE UE with two receiving antennas in Release 8 can support 150 Mbps on a single carrier, thus a Release 10 UE with the capability to aggregate two downlink carriers can then support a 300 Mbps peak data rate. With four-stream MIMO the single carrier data rate in Release 8 was 300 Mbps and when increased to eight-stream MIMO, up to 600Mbps per carrier. Thus with a maximum of five carriers aggregated, the peak data rate would become 3 Gbps [14].

3.4 Configuration

LTE-Advanced CA is designed to maintain backward compatibility. Thus it is possible to construct each CC such that it is fully accessible to legacy LTE UEs. As a result, the technology developed for LTE Release 8 can be reused on aggregated LTE-Advanced CCs. From the higher layer viewpoint, each CC appears as a single cell with its own Cell ID [15].

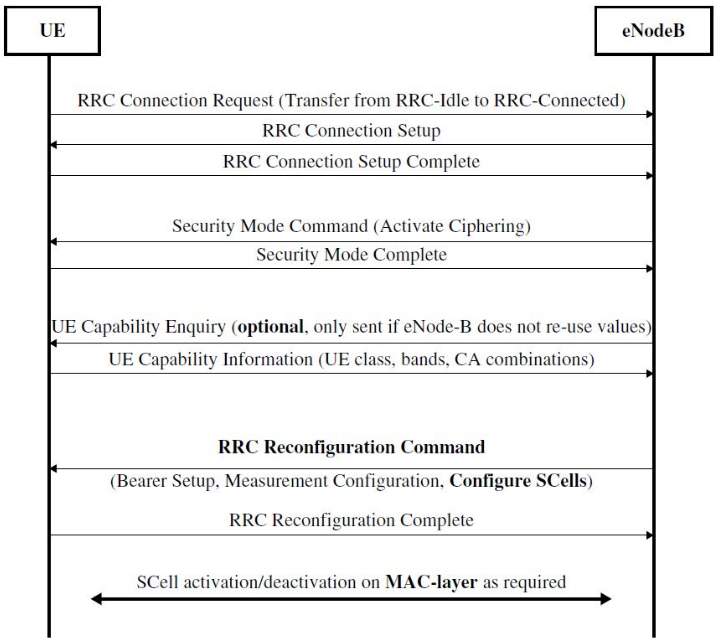


Figure 3.6: CA cofiguration [2]

If the network has not stored the device's capability description from a previous connection it sends a UECapabilityEnquiry message that the mobile device answers with a

UECapabilityInformation message. Among many other parameters, this message contains the UE category that describes the sustainable data rate the device supports, the supported frequency bands, and carrier aggregation combinations [2].

Each UE connects to one Primary Serving Cell (PCell) which is initially configured during connection establishment by following the usual legacy Release 8/9 procedures and provides all necessary control information and functions, such as non-access stratum (NAS) mobility information, security input, RRC connection maintenance, etc. Besides, up to four Secondary Serving Cells (SCells) may be configured after connection establishment, only to provide additional radio resources. The removal and reconfiguration of SCells to a UE are performed by dedicated RRC signaling [15].

Once SCells are configured with RRC messaging the eNode-B can activate them at any time on the MAC layer using a MAC-layer control element. Once the SCells are activated, scheduling of resource blocks of component carriers is done separately on each CC [2].

Power consumption can be reduced when little or no data arrives for the mobile device at the eNode-B over time. Once the transmit data buffer on the network side becomes empty the eNode-B decides to deactivate the SCells and activate them again once data arrives for the mobile device at the eNode-B. After more time has passed without data arriving for the mobile device, the eNode-B releases the RRC connection [2].

Conclusion

This chapter detailed the theoretical aspect of the Carrier Aggregation feature by presenting the different types, deployment scenarios and band classes, then introducing the impact of CA and the configuration procedure. Whereas in the next chapters the practical aspect will be tackled.

Chapter 4

Matlab/Simulink Implementation

Introduction

Throughout our theoretical study of carrier aggregation, we couldn't help but notice that there are very few works concerning a practical implementation of our studied feature, especially the physical layer that focuses on the modulation/demodulation process. We then decided to model this layer, whether it constitutes a starting point for more advanced works on CA, or simply serves as a practical example for educational purposes.

The first case was approached by implementing a modulation/demodulation system of Intra band CA (2 carriers). For the modulation sub-system, pre-defined frequencies were chosen, hence, our choice of the CA type case (Contiguous or Non-Contiguous), depending on the channel spacing we chose.

The second case (practical facility for educational purposes) was approached by building a graphical interface around a Contiguous Case Matlab Example code that we modified so it can also handle the non-contiguous one and added some parameters that we thought could enrich the study experience.

4.1 High Level Block Diagram

There are many options when it comes to CA Implementation [3], We chose a model that works both for contiguous and non contiguous aggregations, the main part that differ from the classic single carrier system consist of shifting in the frequency domain each lte frame separately and then concatenate them.

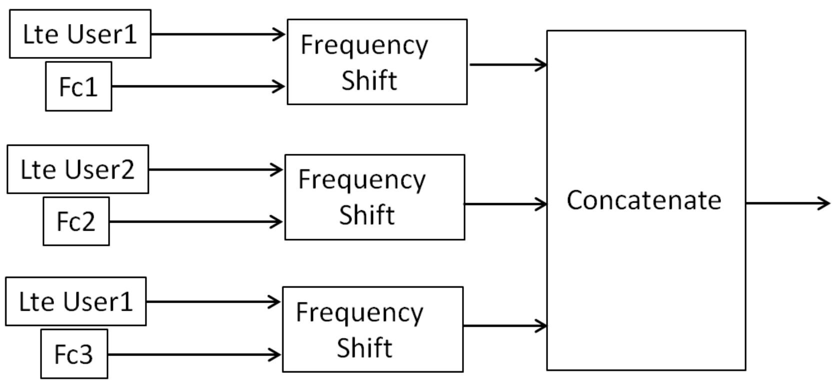


Figure 4.1: High Level Block Diagram

4.2 Simulink Implementation

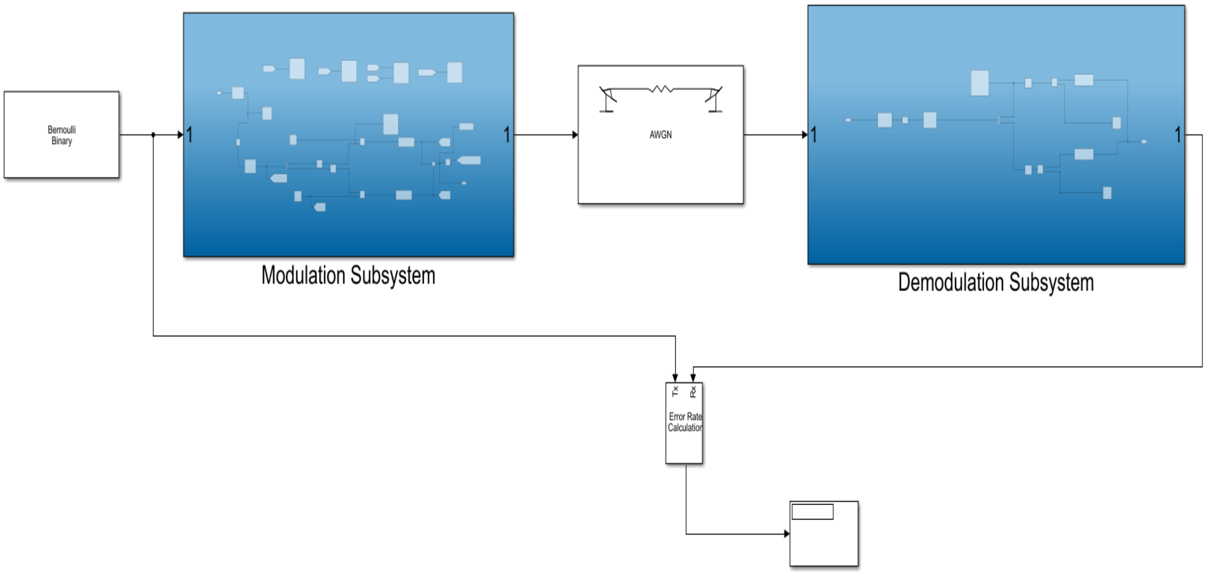


Figure 4.2: Simulink Model

4.2.1 Modulation Subsystem

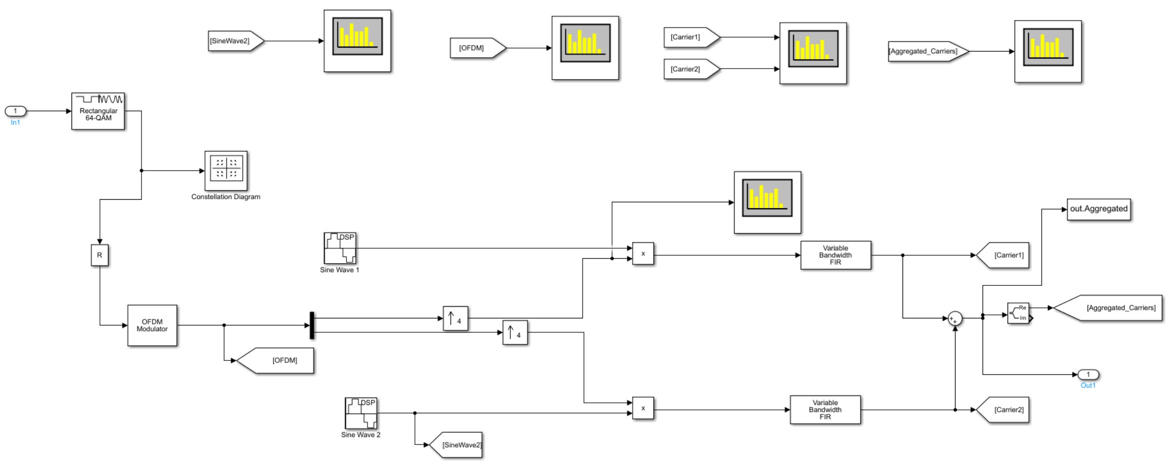


Figure 4.3: Modulation Subsystem Model

The Bernoulli Generator block generates random binary numbers under the Bernoulli distribution.

$$f(k;p) = pk + (1-p)(1-k) \quad \text{for } k \in \{0,1\}$$

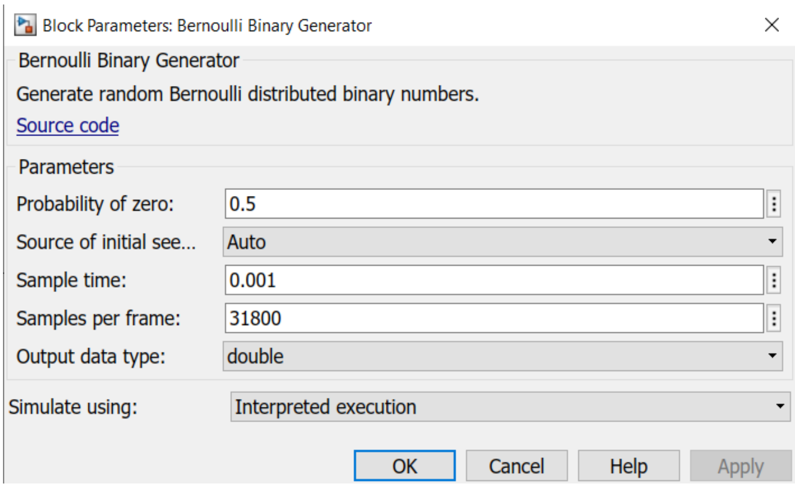


Figure 4.4: Bernoulli Generator block

Our Binary data are then modulated using the Rectangular QAM Modulator Baseband block. Parameters where chosen to suit the input data and satisfy the requirements of the next block (OFDM Modulator).

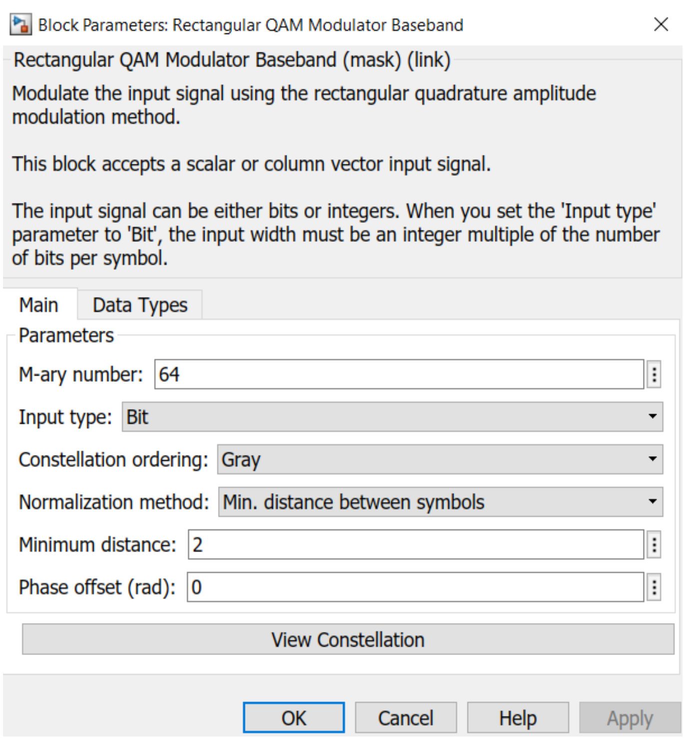


Figure 4.5: QAM modulator Block

The constellation diagram shows the resulting representation of the modulated binary data. As the amount data per frame is very high, it is without surprise that all the positions of the diagram are represented.

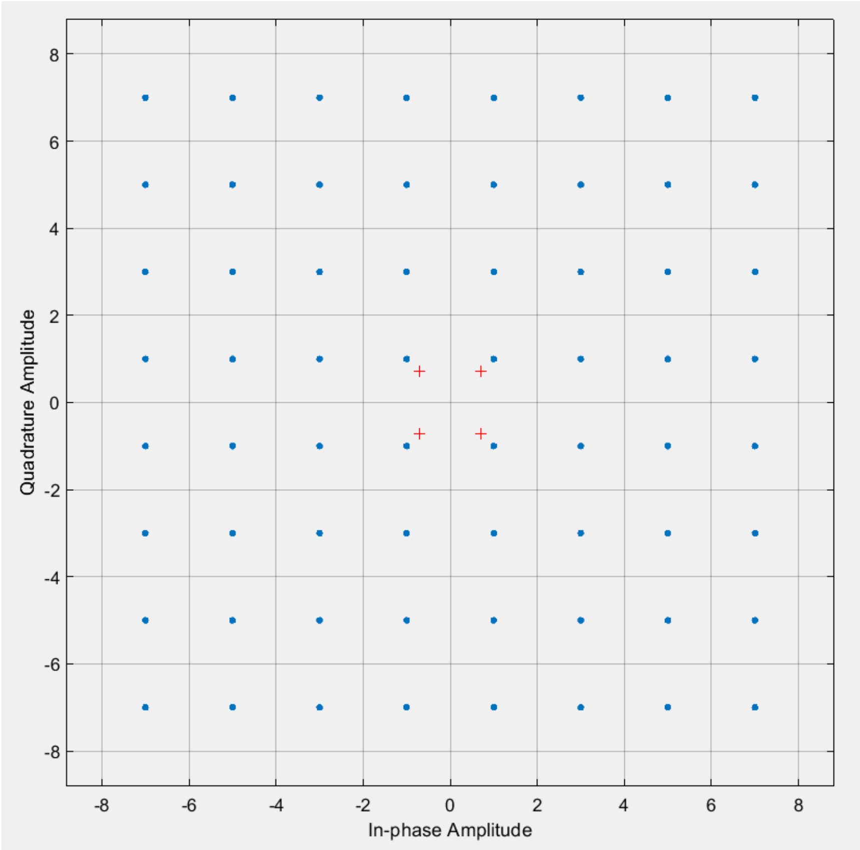


Figure 4.6: Constellation Diagram of the QAM Modulated Symbols

The QAM-modulated data are then reshaped (Serial/Parallel) and passed to the OFDM Modulator block. Standards parameters were chosen for the OFDM Modulation.

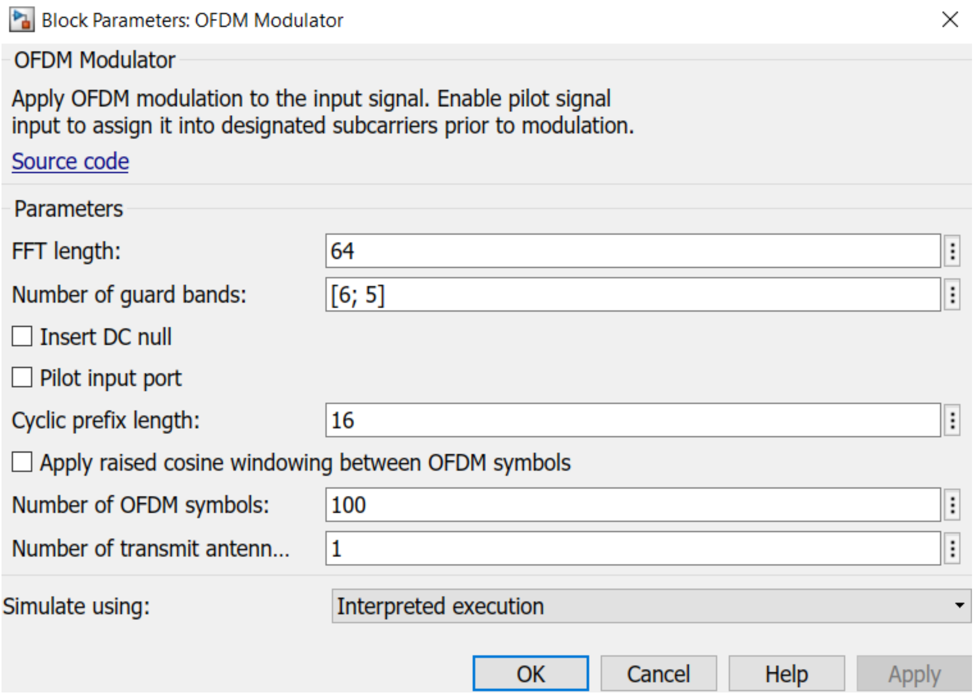


Figure 4.7: OFDM Block Parameters

As to highlight the importance of cyclic prefix we plotted next each other the spectrum analysis of Our block's output and another where cyclic prefix is disabled. This comparison clearly shows that the bandwidth of the signal is increased resulting in Inter-Symbol Interference reduction.

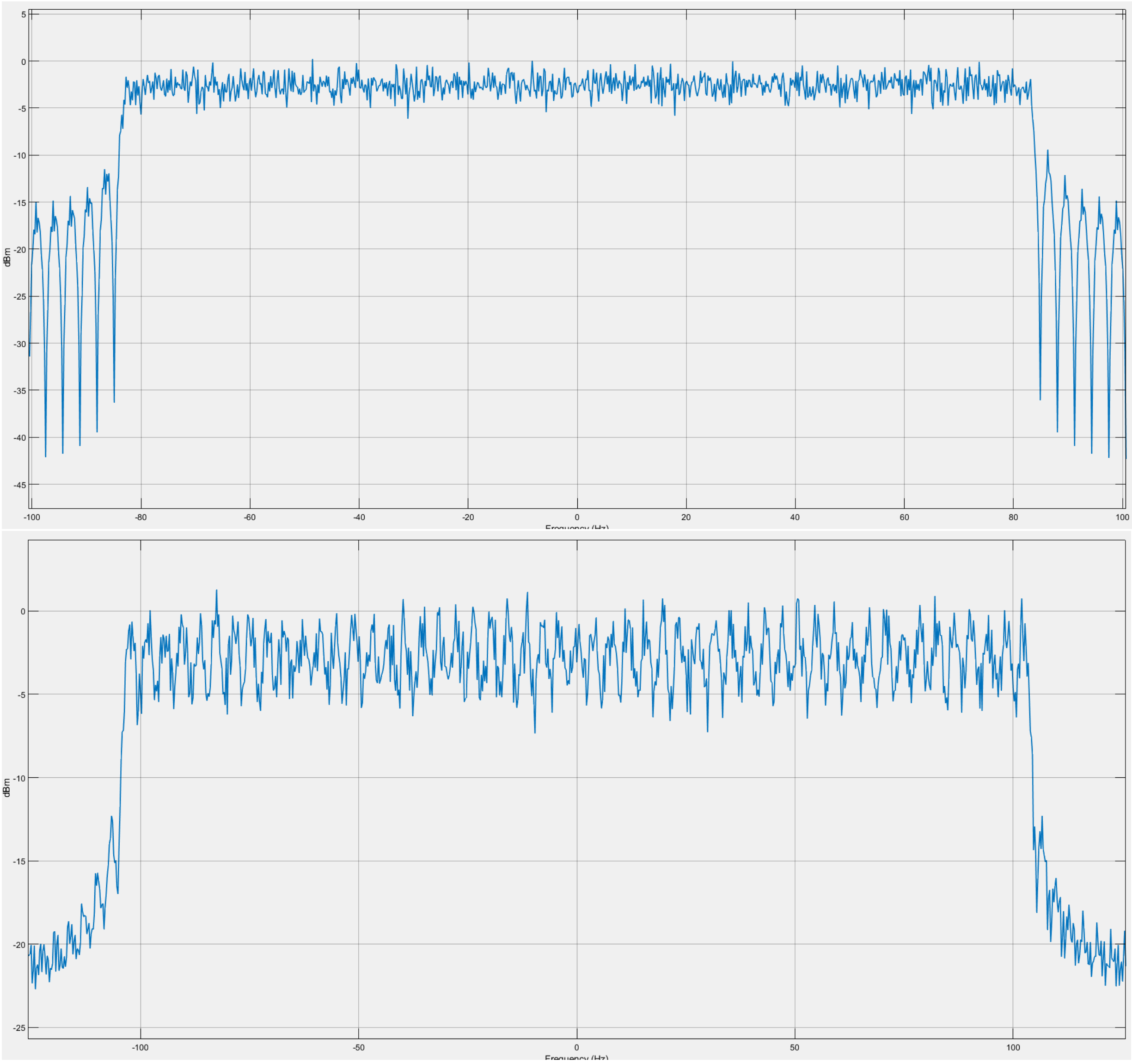


Figure 4.8: Spectrum Analysis and comparison of OFDM Block Output

Our data are then divided by a Mux Block, each sub-signal will pass through the same steps.

An oversampling is required after our modulation to ensure that the signal occupies the main fraction of the total bandwidth. For that, we use the up sampling Block.

We then move to the frequency shifting part. This is done by multiplying our signal with a higher frequency complext sinusoidal signal and filtering the result. We note that these frequencies are the same used for the demodulation process that we will explicit further bellow.

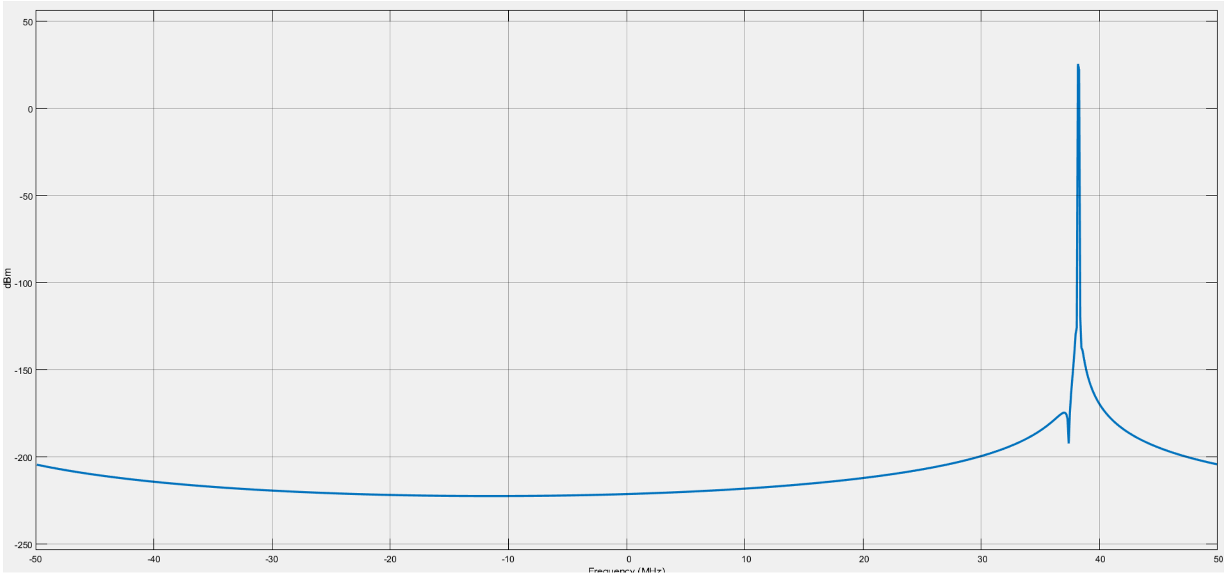


Figure 4.9: Spectrum Analysis of one of the Sinusoidal Signal

The resulting carriers which are located in different center frequencies are then simply concatenated in a final waveform that contains the 2 (or more in other cases) aggregated component carriers.

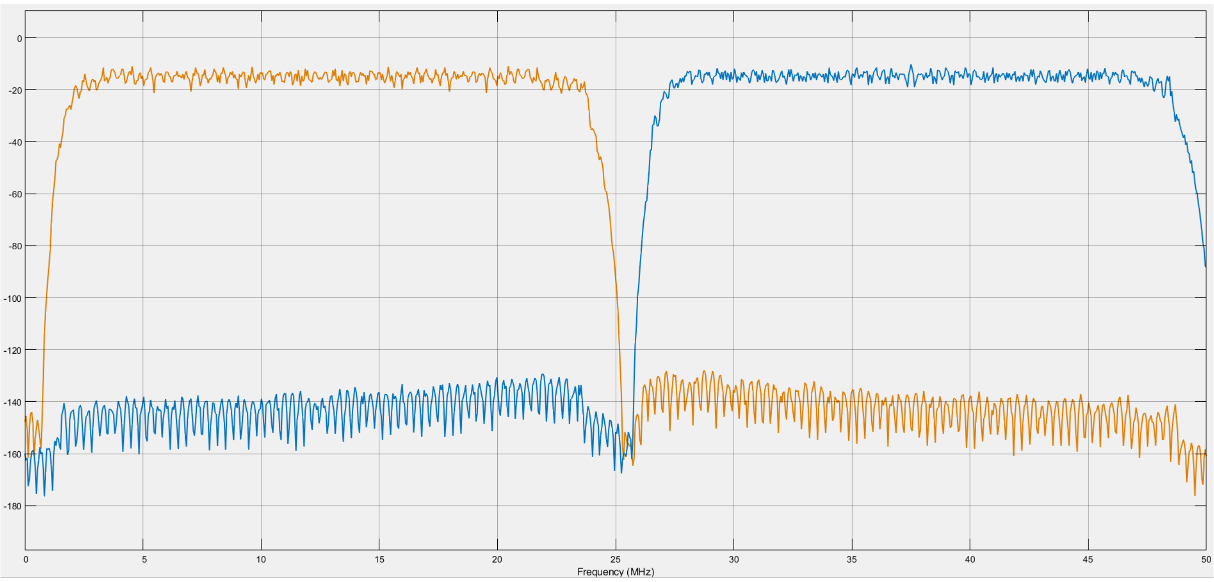


Figure 4.10: Spectrum Of The Component Carriers Before Aggregation

The Channel Spacing which is the spacing between the center frequencies equals 25MHZ, defining this case as a non-Contiguous one, being greater than the Nominal Channel spacing between two adjacent E-UTRA components carriers calculated for our case (19.8MHZ) using the formula defined in [13]

$$\text{Channel Spacing} = \left\lfloor \frac{BW_{\text{Channel (1)}} + BW_{\text{Channel (2)}} - 0.1 \left| BW_{\text{Channel (1)}} - BW_{\text{Channel (2)}} \right|}{0.6} \right\rfloor 0.3 \text{ [MHz]}$$

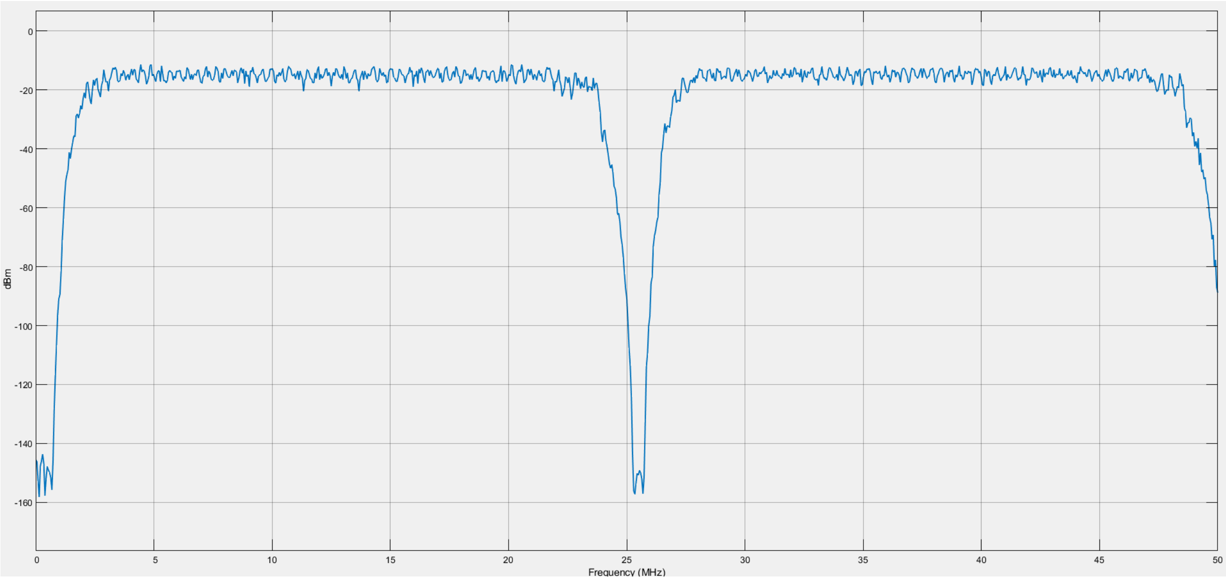


Figure 4.11: Spectrum Of The Aggregated Carriers

For the transmission, an Additive White Gaussian noise (AWGN) Channel was used with the following parameters.

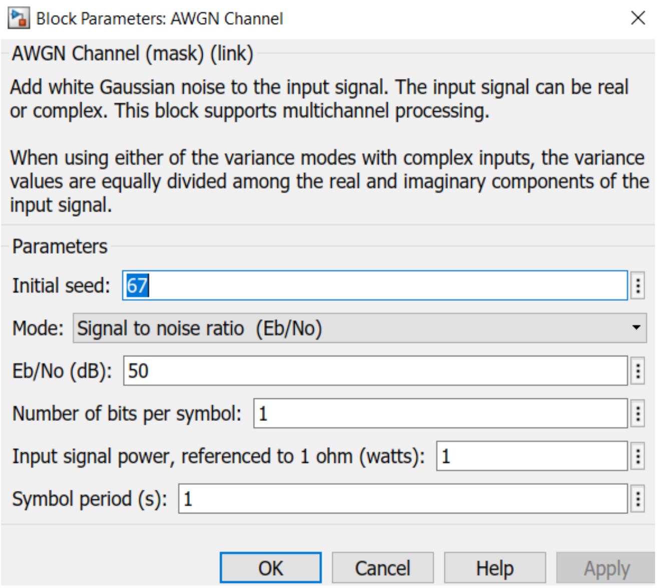


Figure 4.12: Additive White Gaussian Noise

4.2.2 Demodulation Subsystem

The demodulation Subsystem consist of an inverse flow of the modulation process. we first extract our Component of interest using a Passband FIR Filter, then we bring the resulting signal baseband. we downsample by the same sampling factor used in the modulation process and regroup our data using a mux. Finally an OFDM Demodulator followed by a Parallel to serial conversion brings our QAM modulated data back.
The final step is then to simply decode the QAM modulated symbols.

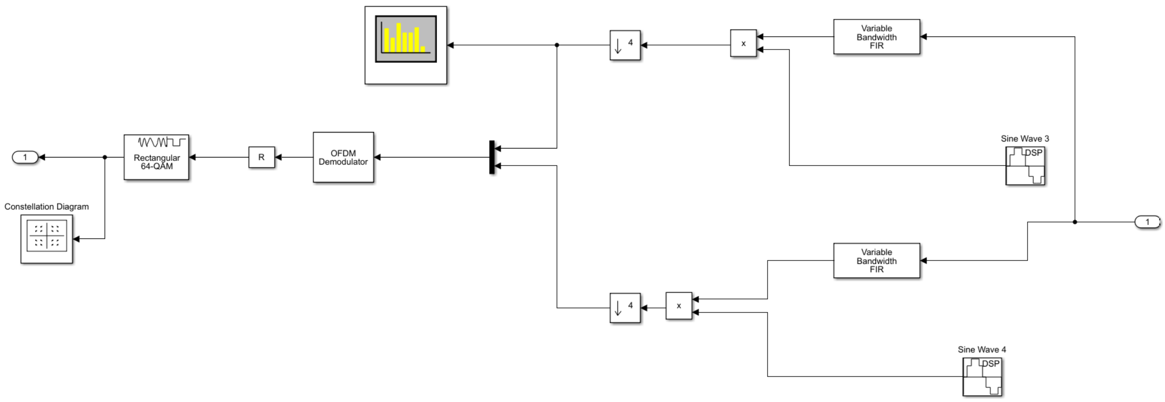


Figure 4.13: Demodulation Subsystem Model

4.3 Academic facility

The goal of this small part was to permit academics to introduce CA and explain it dynamically using a GUI. We built the Graphical User Interface using the App designer around a Mathworks example code. The reason for this choice over our simulink model resides in the large amount of functions that are available within the lte-toolbox. These functions facilitates further developements, for example, it was quite direct to add the OFDM Symbol mappin plot using the showResourceMapping function

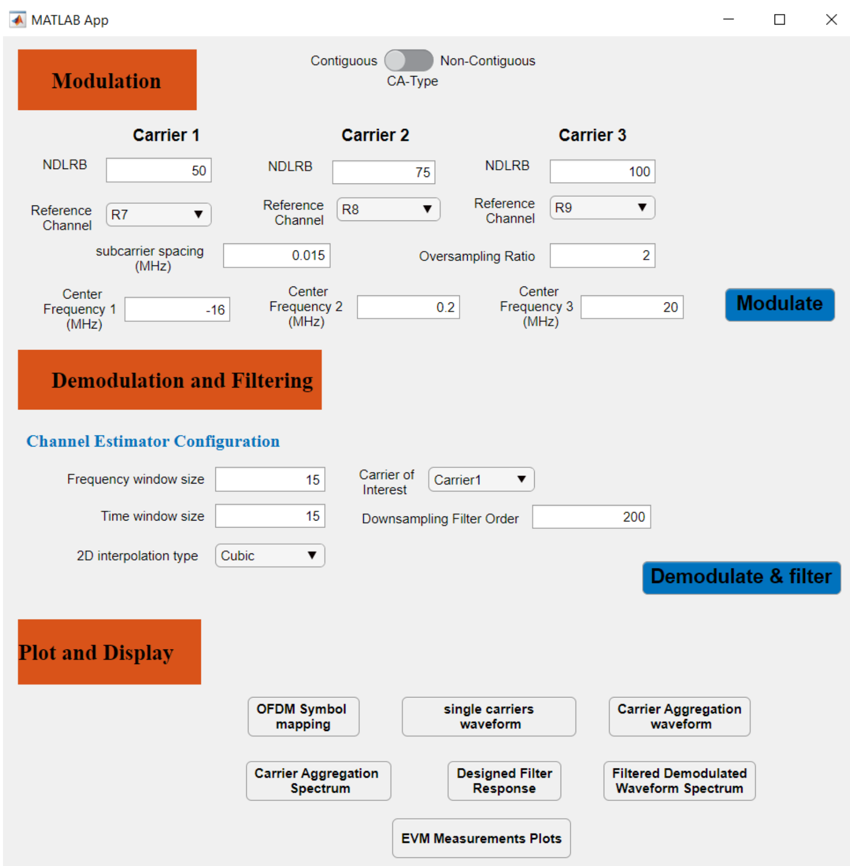


Figure 4.14: Graphical User Interface

An overview of the available resulting plots and displays is shown below.

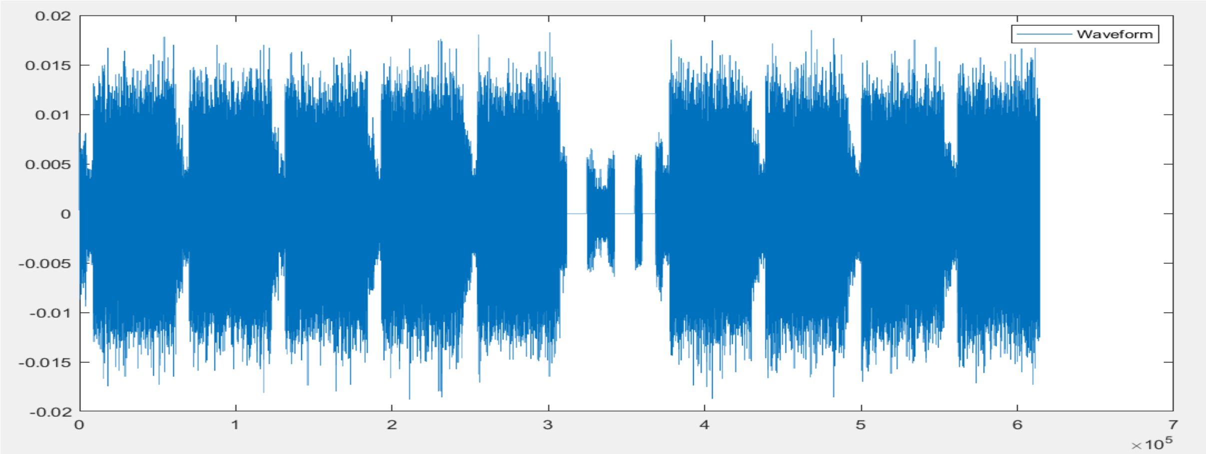


Figure 4.15: Carrier Aggregation Waveform

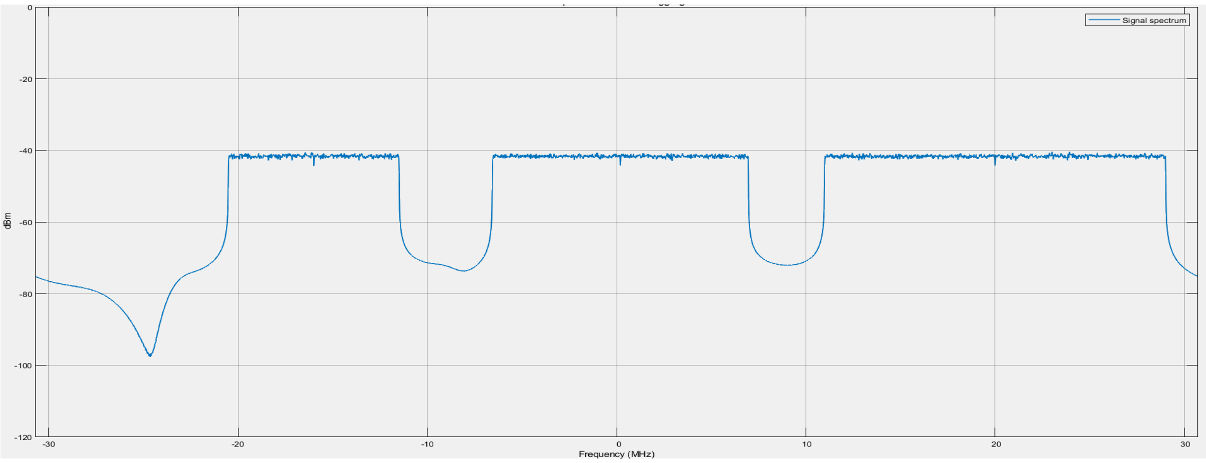


Figure 4.16: Carrier Aggregation Spectrum (GUI)

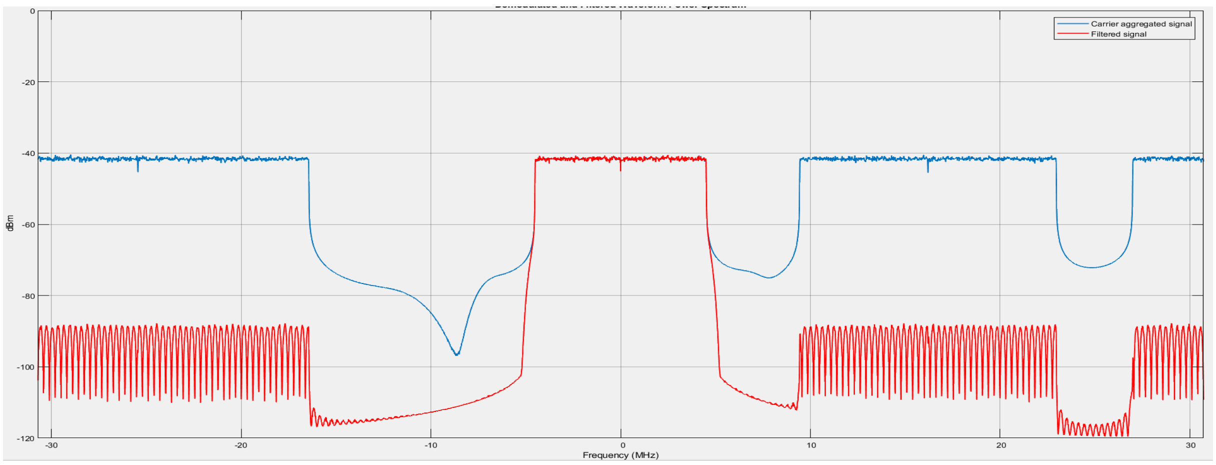


Figure 4.17: filtered Spectrum

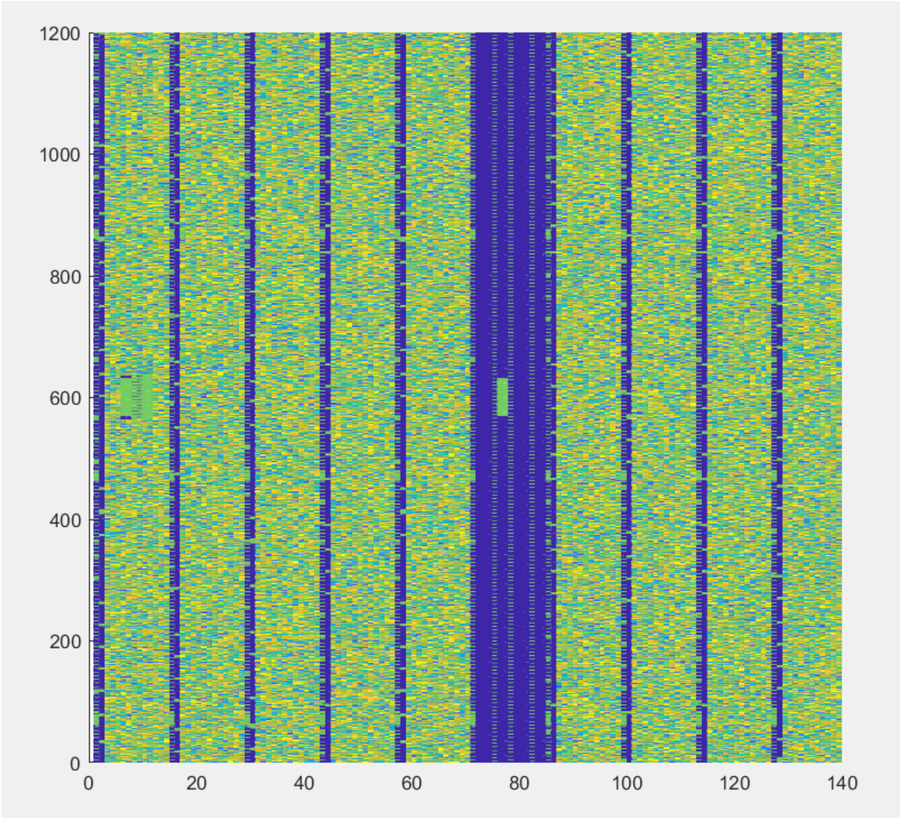


Figure 4.18: OFDM Symbol Mapping

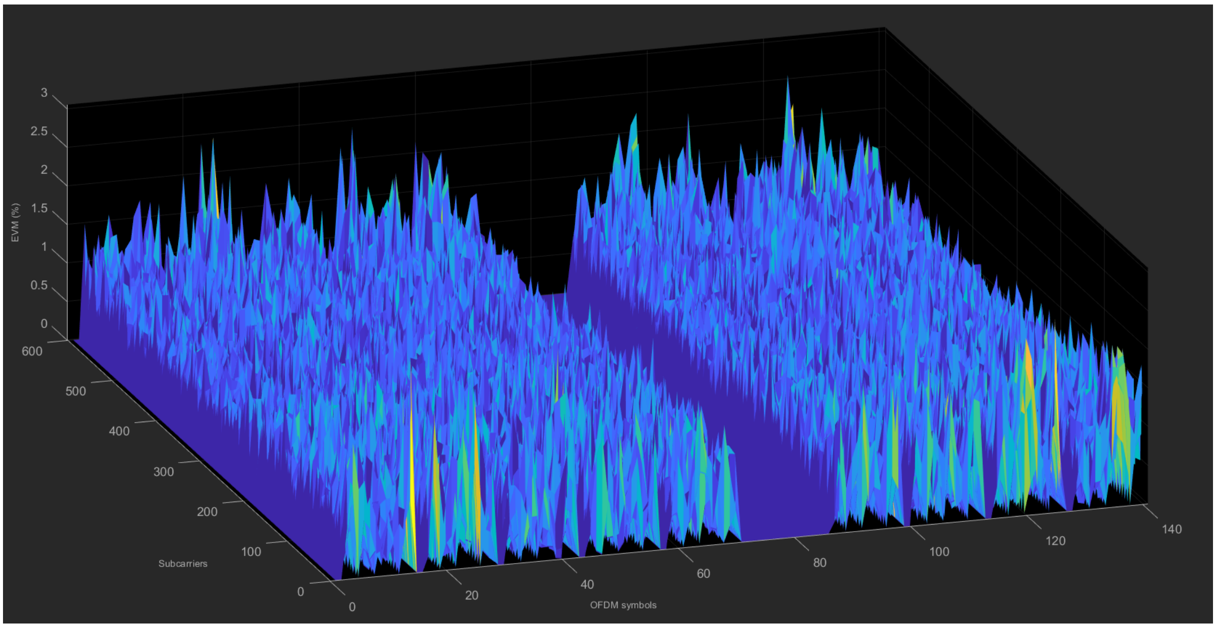


Figure 4.19: EVM - OFDM Symbols

4.4 Conclusion and Discussion

Throughout this chapter we introduced and implemented the physical layer of Carrier Aggregation on Simulink and compared it to a studied and modified Matlab system.
We can then and from our experience assimilate Matlab and Simulink as the primary and industry standard for Physical communication systems layers simulation, implementation through code generation, and performance assessment.

For modeling and simulation, we used algorithmic building blocks from the Communications System Toolbox, either as System objects or as Simulink blocks. However, and as noticed during our work, many aspects of PHY processing of mobile standards can be modeled and simulated more efficiently in MATLAB because instead of focusing on creating building complex blocks and facing rates and time delay difficulties, we can focus on introducing more advanced functionalities to a system model.

Since our system is relatively simple compared to advanced complex ones, we didn't have to take the simulation time in consideration but as mentioned in [8], various acceleration techniques are usually used in research and development departments such as the use of Parallel Processing Toolbox.

Chapter 5

Atoll Implementation

Introduction

This chapter focuses on highlighting the Carrier Aggregation benefits on the network through simulation using a multi-technology wireless network design and optimization platform known as Atoll. The software and its environment are presented briefly, then we move to the geographic data followed by sites data (positions and orientations), configuration of the Network Equipments, and finally, the parameters used for our simulation.

Throughout this chapter, we will not focus on advanced technical properties and configurations since our objective is to highlight the CA feature, thus, even if the configurations are not perfectly adjusted, they will not influence the comparative character of this part.

Atoll includes integrated single RAN–multiple RAT network design capabilities for both 3GPP and 3GPP2 radio access technologies including 5G NR, LTE, NB-IoT, UMTS, GSM, and CDMA. It provides operators and vendors with a powerful framework for designing and optimizing current and future integrated multi-technology networks. Atoll has become over the years, the industry standard for wireless network design and optimization.

5.1 The environment:

In Atoll, radio-planning projects are modeled and managed through Atoll documents (files with the ATL extension). The Atoll working environment is flexible and supports standard Windows capabilities (context menus, standard shortcuts, drag and drop... etc).

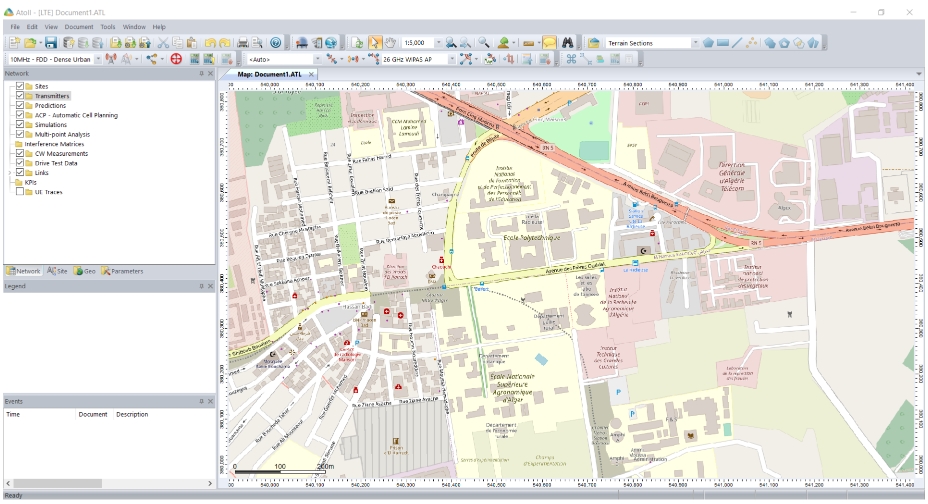


Figure 5.1: Atoll Environement

Here we highlight the main topics concerning the Atoll working environment :

5.1.1 Documents

In Atoll, radio-planning projects are modeled and managed through Atoll documents (files with the ATL extension). Each Atoll document can contain multiple technologies and assembles the following necessary information:

- Radio equipment such as sites, transmitters, antennas, repeaters, and other equipment.
- Radio data such as frequency bands, technology-specific parameters, coordinate systems.
- Geographic data such as clutter classes, clutter heights, Digital Terrain Model (DTM), population maps.

5.1.2 Atoll Work Area

The Atoll work area consists of:

- A menu bar and several toolbars that give access to Atoll functions.
- A document window that arranges by tab all the open Atoll documents, maps, data tables, and reports.
- Explorers that present a folder arrangement for data and objects contained in the Atoll document.
- Tool windows are windows providing information or data and that can be docked or floating.

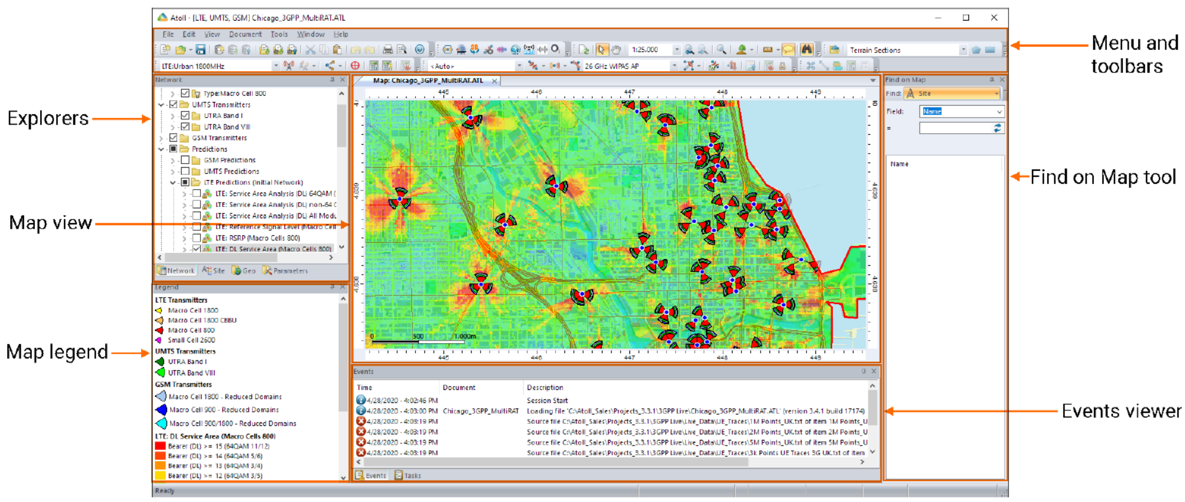


Figure 5.2: Atoll Work Area

5.2 Geographic Data

Atoll supports a wide range of geographic data types. These data play different roles in the Atoll document and are used for propagation calculations, dimensioning, statistics, or simply for display purposes.

5.2.1 Projection and Display system

A projection is a method for producing all or part of a round body on a flat sheet. This projection cannot be done without distortion, thus the cartographer must choose the characteristic (distance, direction, scale, area, or shape) which is to be shown appropriately at the expense of the other characteristics. It is therefore primordial to choose the right projection because the imported geographic data files are referenced with the same projection system.
Based on the geographic data files provided, we chose the WGS 84/ UTM zone 31N.

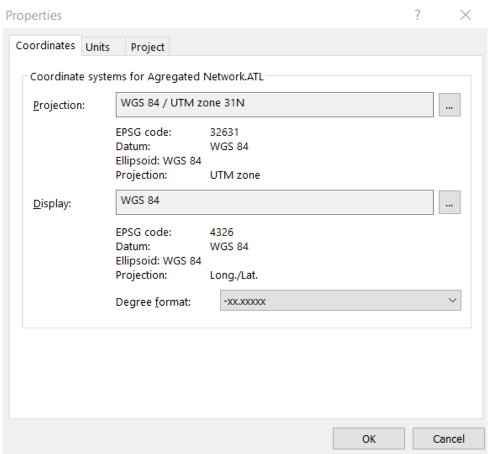


Figure 5.3: Projection System Configuration

5.2.2 Digital Terrain Models

The geographic data figure represents the elevation of the ground over sea level.

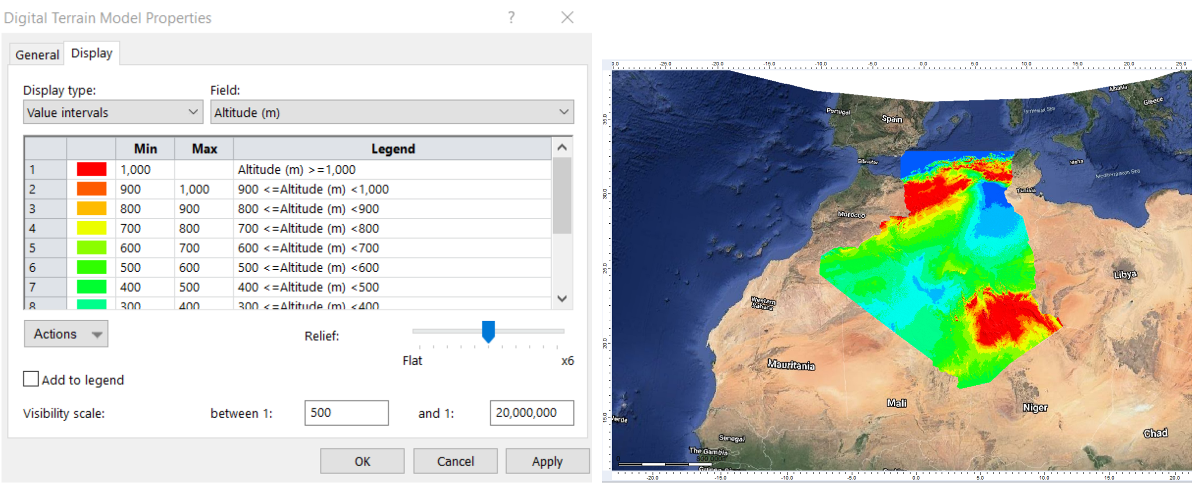


Figure 5.4: Digital Terrain Models Properties and Display

5.2.3 Clutter Classes

The geographic data file describes the type of ground use or cover. Each class (pixel) has its own propagation properties to be defined such as the C/I Standard Deviation (DL) (dB). These properties are primordial for our predictions and simulations.

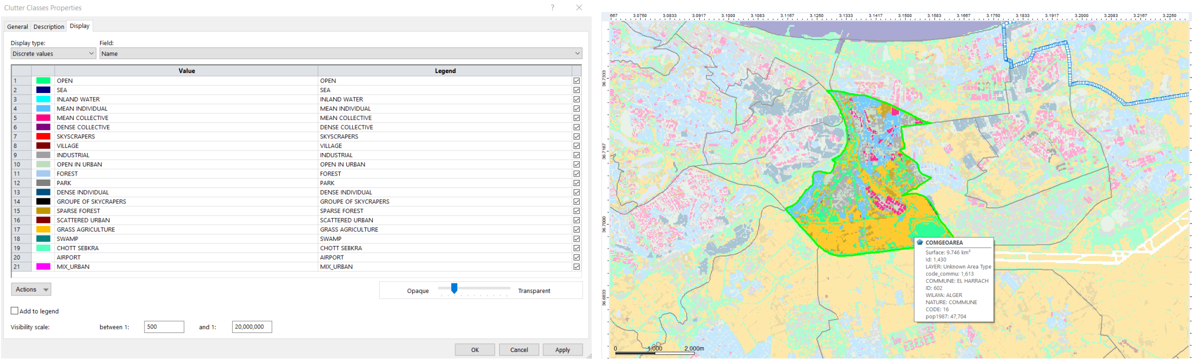


Figure 5.5: Clutter Classes Properties and Display

5.2.4 Online Map

For display purposes, we used the Google Earth online map. The highlighted zone is our focus region (El Harrach) where our campus (Ecole Nationale Polytechnique) is located.

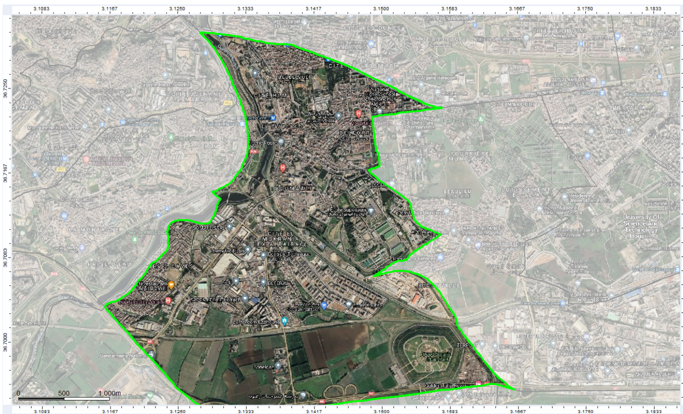


Figure 5.6: Online Map Display

5.2.5 Vectors

Additional vectors that describe and classify roads as main roads, secondary roads, highways, streets and railways.

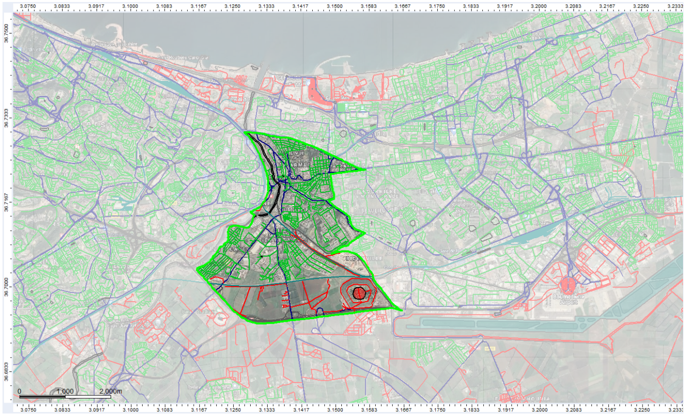


Figure 5.7: Vectors Display

5.3 Sites and Transmitters

Through the next steps, we will only conserve the online map to reduce the display volume (more clarity). Therefore, the data presented so far and the quantity of information they provide will be used in calculations and simulations.

Based on the data provided bu our tutor, we replicated the Sites positions and transmitters orientation of the Ooredoo Network which is one of three major mobile operators in Algeria.

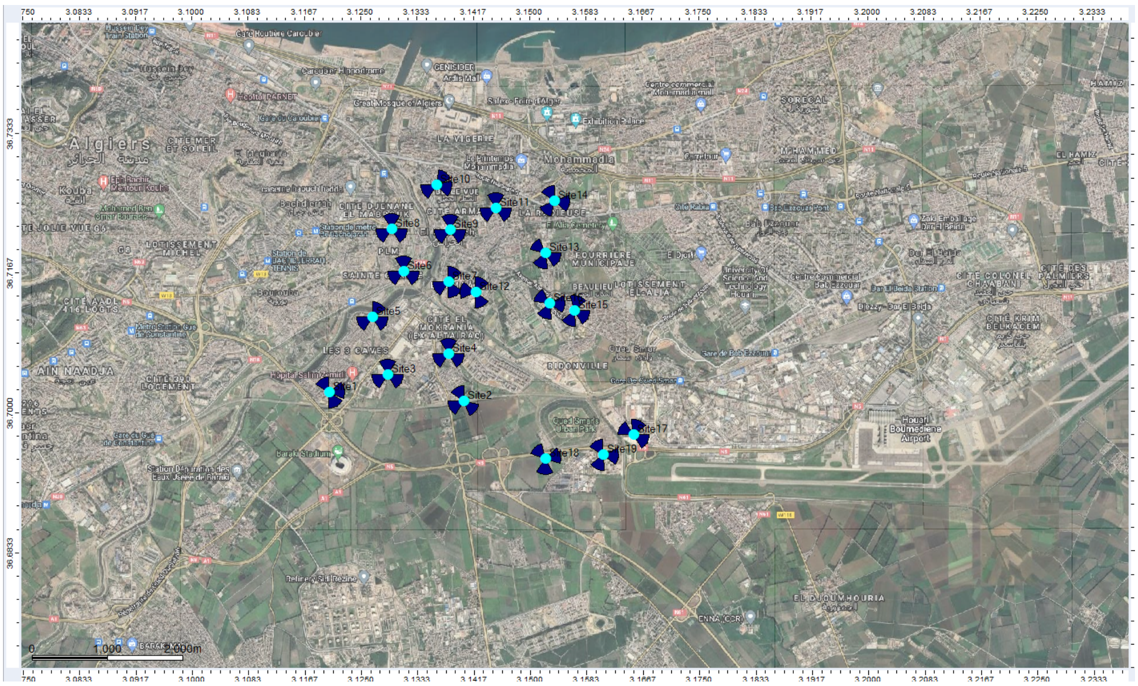


Figure 5.8: Sites Positions and Transmitters Orientation

A wide range of support for cells is available in atoll, we chose based on the location the appropriate ones, for example, if the site is above construction, we define the support as a building facade.

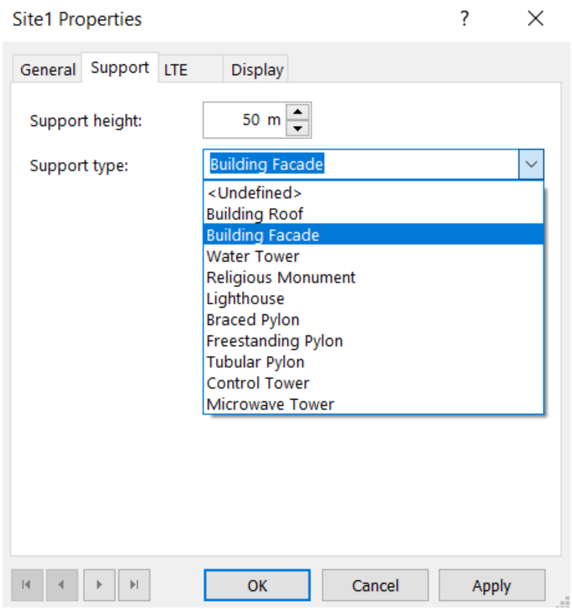


Figure 5.9: Sites Properties

5.3.1 Transmitters

The antenna used here is the PB 62 08 17 04 1800_RV4PX310B1 which is an arbitrary choice since we don't focus on network optimisation and configuration.

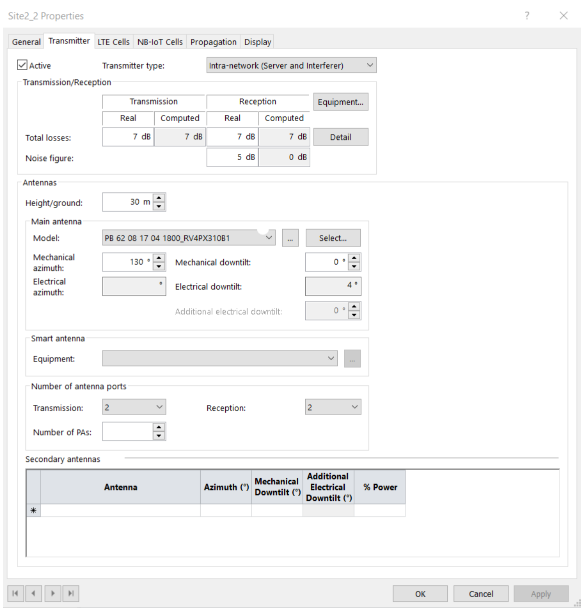


Figure 5.10: Transmitters Properties

We however considered choosing a directional antenna to conserve the regions properties. The radiation patterns of this specific antenna are shown bellow.

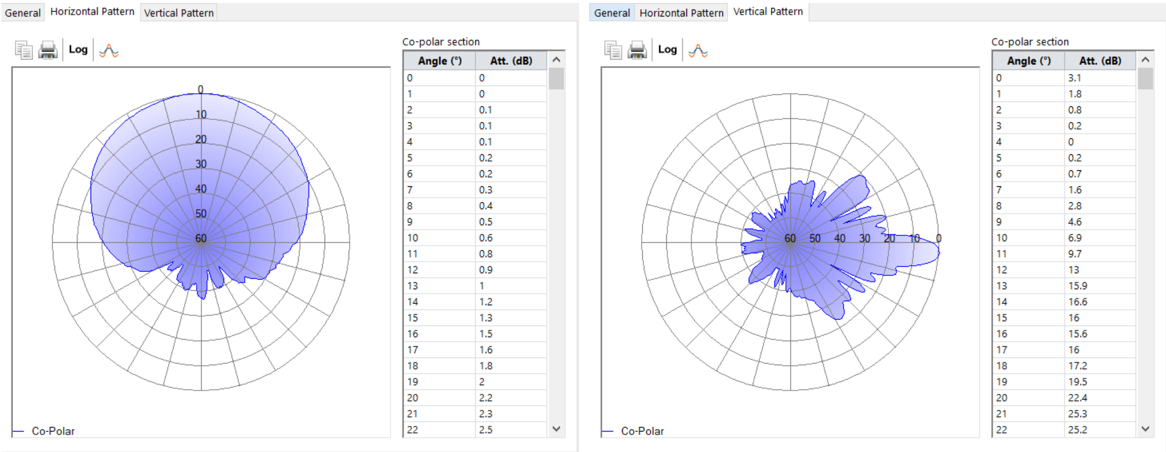


Figure 5.11: Transmitters Properties

5.3.2 Cells properties

The cells types must be configured in a way that permits each of them to be either a primary cell or a secondary one.
The frequency band chosen for our simulations is the E-UTRA Band 3 - 10MHZ.
Other secondary parameters such as the Max Power were left on default.

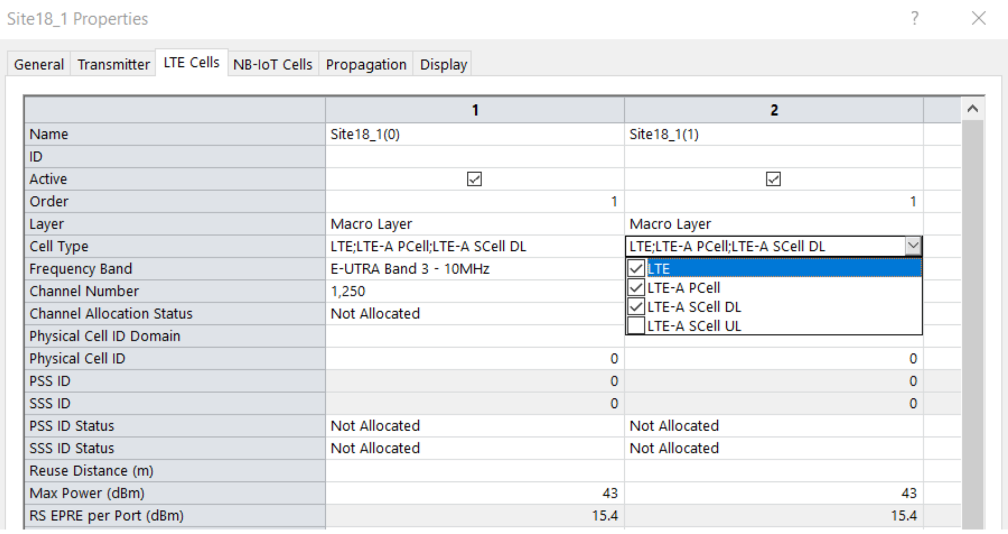


Figure 5.12: Cells Properties

5.4 Simulation results

5.4.1 Terminals and Services

We first need to modify some atoll default configurations for terminals and services.
• Enable Carrier Aggregation in the High Speed Internet Service (The one we will use for our predictions)

- Enable LTE-Advanced within the Mobile Terminal Window.
- Configure the maximum number of secondary cells for the downlink and the uplink.

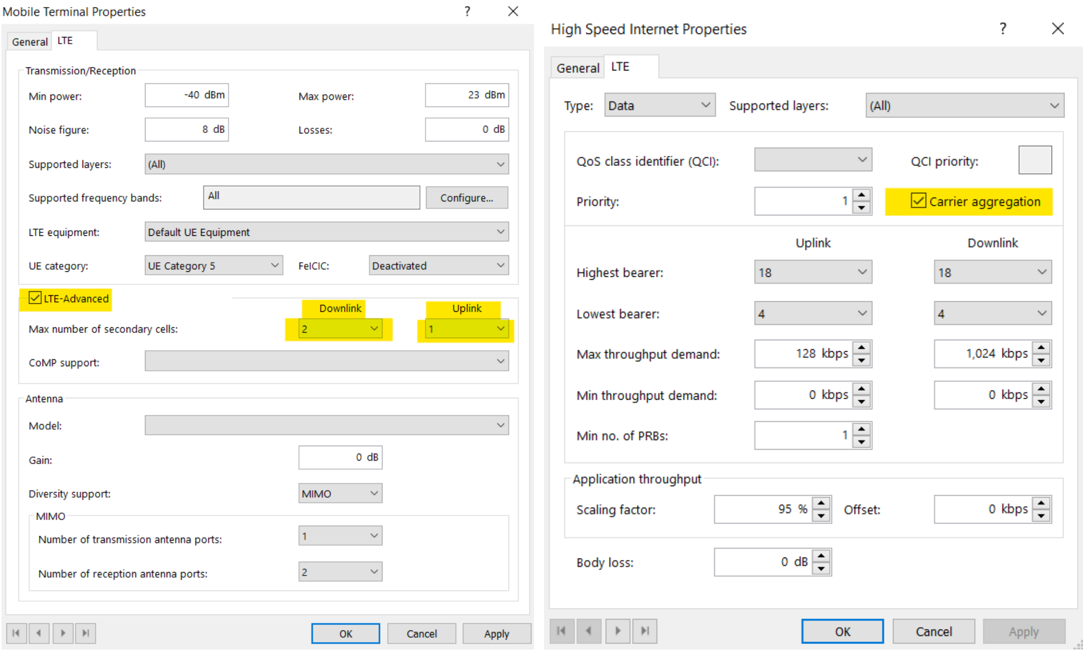


Figure 5.13: Mobile terminal

As for the simulations, We first run a point analysis simulation to highlight the aggregated efficiency then we will run a more visual one. The coverage by throughput prediction. We will there compare 2 cases, one where CA is disabled and the one where we activate the feature.

For our Simulations, We used the Standard Propagation Model (SPM) which is based on the Hata formula:

$$P_R = P_{Tx} - \left(\begin{array}{l} K_1 + K_2 \log(d) + K_3 \log\left(H_{Tx_{eff}}\right) + K_4 \text{ DiffractionLoss } + K_5 \log(d) \log\left(H_{Tx_{eff}}\right) + \\ K_6 H_{Rx_{eff}} + K_7 \log\left(H_{Rx_{eff}}\right) + K_{\text{clutter}}\, f(\text{ clutter }) + K_{\text{hill, LOS}} \end{array} \right)$$

Where

P_R the received power (dBm) P_{Tx} the transmitted power (EIRP) (dBm)
K_1 the constant offset (dB) K_2 the multiplying factor for $Log(d)$
d the distance between the receiver and the transmitter (m)
K_3 the multiplying factor for $Log(H_{Tx_{eff}})$
$H_{Tx_{eff}}$ effective height of the transmitter antenna (m)
K_4 the multiplying factor for diffraction calculation
K_5 multiplying factor for $Log(H_{Tx_{eff}}) * Log(d)$
K_6 multiplying factor for $H_{Rx_{eff}}$ $H_{Rx_{eff}}$ the mobile antenna height
K_7 the multiplying factor for $Log(H_{Rx_{eff}})$

K_{clutter} the multiplying factor for $f($ clutter $)$
$f($ clutter $)$ the average of weighted losses due to clutter
$K_{\text{hill, LOS}}$ the corrective factor for hilly regions.

Parameters were defined based on the Standard Propagation Model Guidelines [16], where Typical values for the model constants and losses (in dB) per clutter class are given.

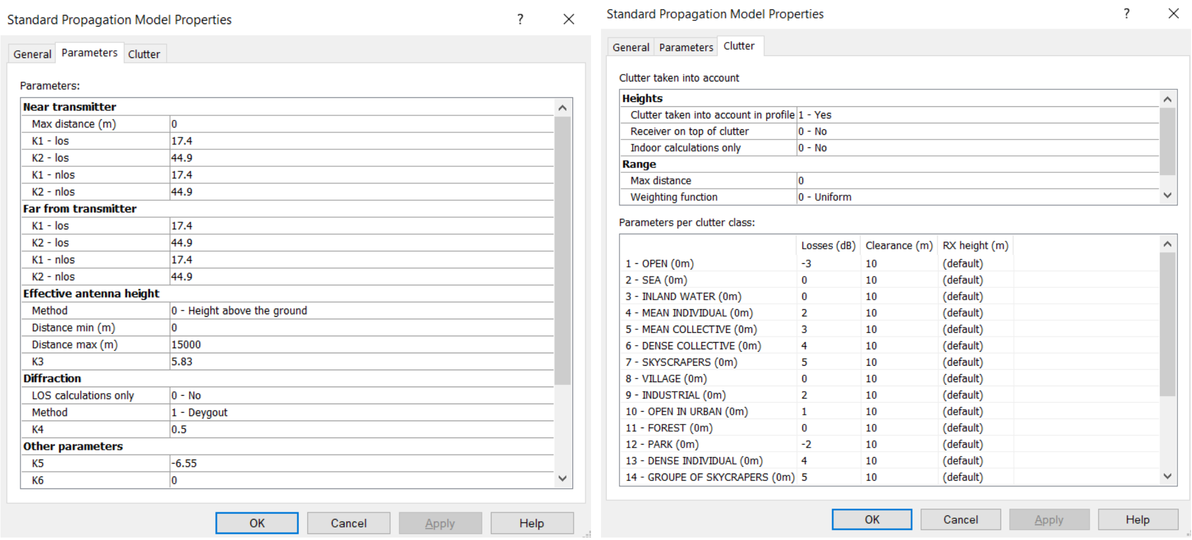


Figure 5.14: SPM Constants Propertie and Clutter Class Parameters

5.4.2 Point Analysis

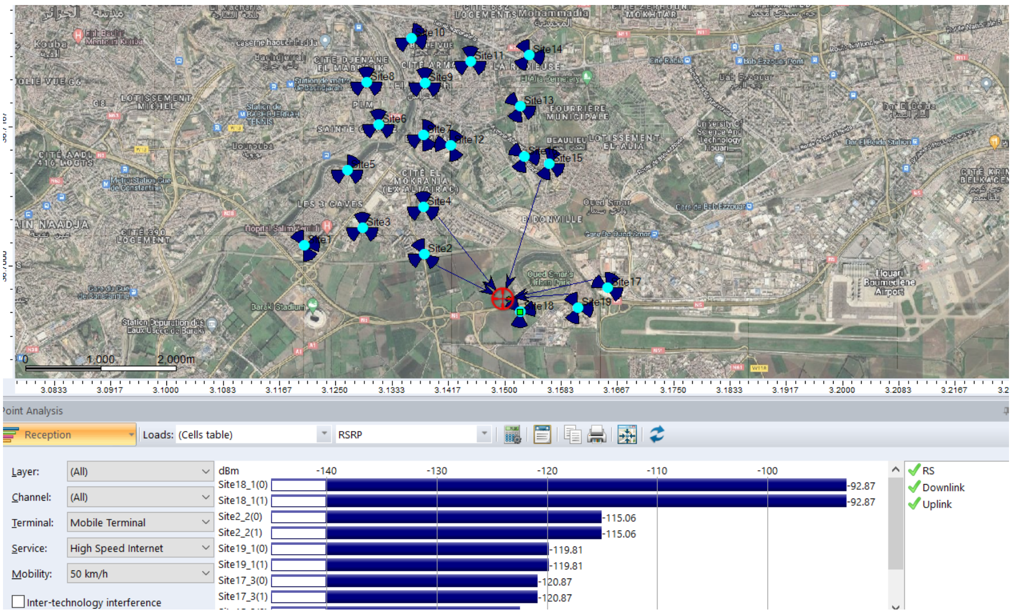


Figure 5.15: Point Analysis Simulation

The report gives more precise information than the graphical interface.

We can see that our equipment (receiver) is connected to 3 Cells,Site18_1(0) serving as the primary cell, Site18_1(1) and Site2_2(0) as secondary cells Which is the maximum number of secondary cells for the downlink we chose earlier in the mobile terminal configuration.

Site18_1(0) and Site18_1(1) shares naturally the same path losses and simulation outputs being similarly configured, sharing the same site an orientations.

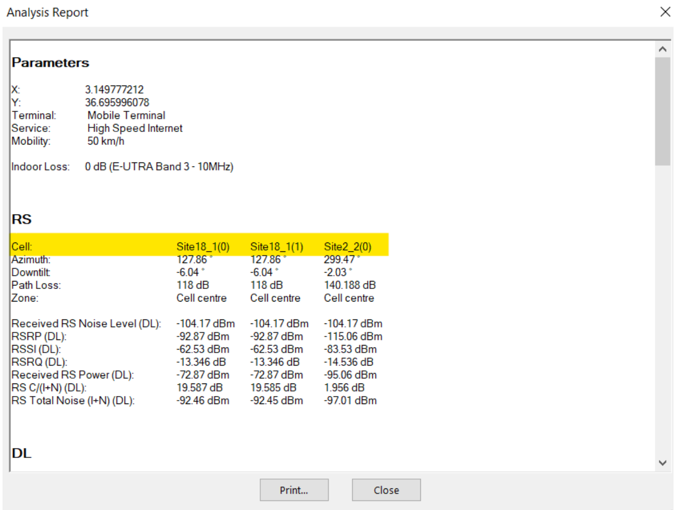


Figure 5.16: Report Analysis 1

Moving to a more consistent attribute, the RLC Channel throughput, we can see the effective value of Carrier Aggregation, going from a peak RLC of 60.82 Mbps to an aggregated peak RLC of 132.19 Mbps.

The spectral efficiency notable difference between the first secondary cell (6 bps/Hz) and the second (1bps/Hz) is justified by the Modulation scheme used.

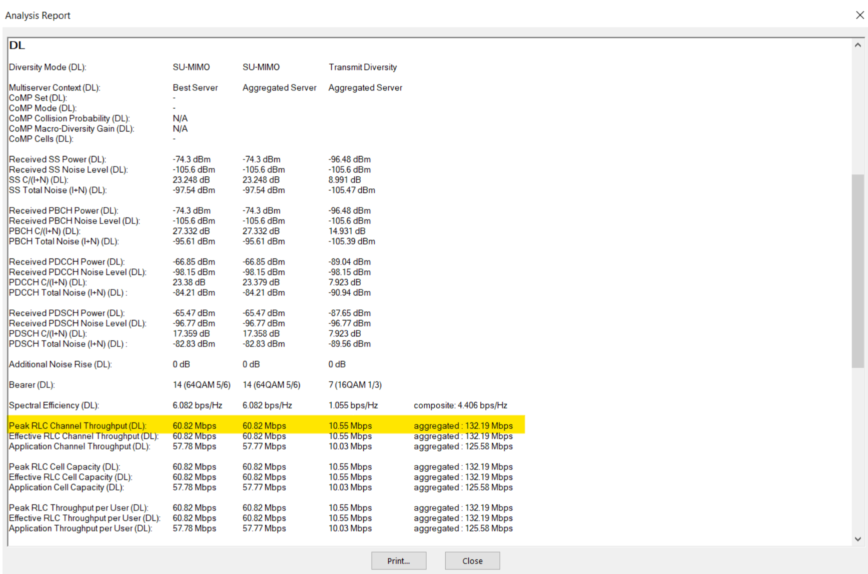
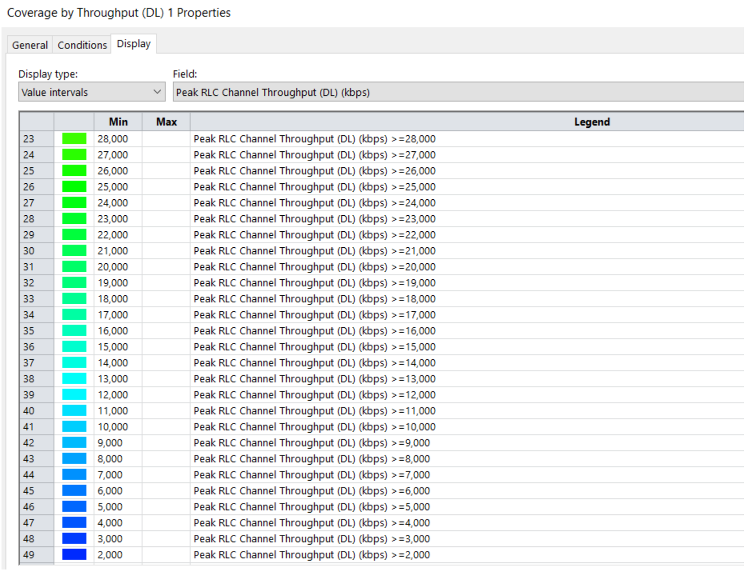


Figure 5.17: Report Analysis 2

5.4.3 Coverage by throughput

Finally, the Impact of Carrier Aggregation is remarkably visualised using the Coverage by throughput prediction, as we can clearly see the Downlink Throughput difference between the two cases. Primary and secondary cells having the same configurations and orientations, the coverage remains the same.


Coverage by Throughput (DL) 1 Properties

General | Conditions | Display

Display type: Value intervals

Field: Peak RLC Channel Throughput (DL) (kbps)

		Min	Max	Legend
23		28,000		Peak RLC Channel Throughput (DL) (kbps) >=28,000
24		27,000		Peak RLC Channel Throughput (DL) (kbps) >=27,000
25		26,000		Peak RLC Channel Throughput (DL) (kbps) >=26,000
26		25,000		Peak RLC Channel Throughput (DL) (kbps) >=25,000
27		24,000		Peak RLC Channel Throughput (DL) (kbps) >=24,000
28		23,000		Peak RLC Channel Throughput (DL) (kbps) >=23,000
29		22,000		Peak RLC Channel Throughput (DL) (kbps) >=22,000
30		21,000		Peak RLC Channel Throughput (DL) (kbps) >=21,000
31		20,000		Peak RLC Channel Throughput (DL) (kbps) >=20,000
32		19,000		Peak RLC Channel Throughput (DL) (kbps) >=19,000
33		18,000		Peak RLC Channel Throughput (DL) (kbps) >=18,000
34		17,000		Peak RLC Channel Throughput (DL) (kbps) >=17,000
35		16,000		Peak RLC Channel Throughput (DL) (kbps) >=16,000
36		15,000		Peak RLC Channel Throughput (DL) (kbps) >=15,000
37		14,000		Peak RLC Channel Throughput (DL) (kbps) >=14,000
38		13,000		Peak RLC Channel Throughput (DL) (kbps) >=13,000
39		12,000		Peak RLC Channel Throughput (DL) (kbps) >=12,000
40		11,000		Peak RLC Channel Throughput (DL) (kbps) >=11,000
41		10,000		Peak RLC Channel Throughput (DL) (kbps) >=10,000
42		9,000		Peak RLC Channel Throughput (DL) (kbps) >=9,000
43		8,000		Peak RLC Channel Throughput (DL) (kbps) >=8,000
44		7,000		Peak RLC Channel Throughput (DL) (kbps) >=7,000
45		6,000		Peak RLC Channel Throughput (DL) (kbps) >=6,000
46		5,000		Peak RLC Channel Throughput (DL) (kbps) >=5,000
47		4,000		Peak RLC Channel Throughput (DL) (kbps) >=4,000
48		3,000		Peak RLC Channel Throughput (DL) (kbps) >=3,000
49		2,000		Peak RLC Channel Throughput (DL) (kbps) >=2,000

Figure 5.18: Coverage By Throughput Display Configuration

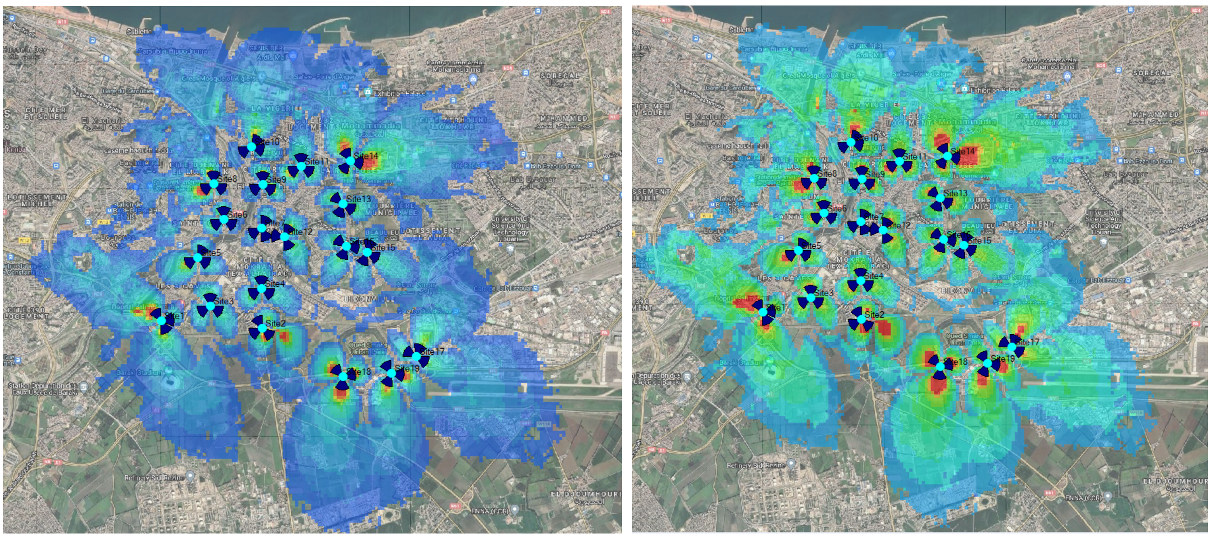


Figure 5.19: Coverage by throughput predictions

Conclusion

This chapter Introduced the Atoll software and its environment, The geographical data that constitute a basis for the propagation calculations through for example clutter classes and elevations as well as the main parameters for LTE-A configuration and steps for CA Activation.

Atoll offers a wide range of tools, predictions and simulations facilities that equip telecommunication engineers for either their planning and dimensioning works or network enhancement ones, we saw for example the Point Analysis and the Coverage Per Throughput ones. These simulations highlighted numerically and visually the drastic enhancement that CA brings to the network.

Chapter 6

On-site Analysis

Introduction

This chapter presents the implementation (Activation) procedure and configuration of CA on some sites based in Algiers through Ericsson's OSS and furthermore, presents our data-driven analysis of its impact on the network. Causes and reasons were given to properly justify the changes that occurred within our 15 days studied interval, 7 days before and after CA Activation.

6.1 Host organism

6.1.1 Ericsson International

Ericsson is a Swedish multinational networking and telecommunications company operating in more than 180 countries, it is one of the leading providers of Information and Communication Technology (ICT) to service providers. It was founded in 1876 by Lars Magnus Ericsson and was taken over by the Wallenberg family in 1960 who owns the majority of its shares.

Ericsson offers end-to-end services for all major mobile communication standards and has four main business units:

- Networks, by enabling operators to quickly offer enhanced mobile broadband to consumer customers, and providing hardware, software, and services to enable the full value of connectivity;
- Digital Services, offering solutions for service providers that help them transform their business and their network;
- Managed Services, which advances network and IT operations and optimization, and enables communications service providers (CSPs) and enterprises to run next-generation connectivity and services for their customers.
- Emerging Business, which is tasked with seeking new profitable growth for Ericsson outside its traditional core business.

6.1.2 Ericsson Algeria

Since its installation in Algeria in 2003, Ericsson carries out operations and installation of private, commercial, and industrial telecommunications equipment to Algerian operators (Algérie Télécom, Mobilis, Djezzy, and Ooredoo). Besides the maintenance of telephone systems (Antennas, Servers, etc.) for its customers in Algeria. In addition, the fulfillment, assurance, and network optimization.

Ericsson Algeria has worked on the biggest telecom projects, such as the extension of 4G in all the wilayas. Its presence in Algeria has enabled the development of 4G in a record time of two years.

6.2 Configuration

We aimed for our study sites that had their CA feature disabled, This is proper to operators strategy and we guess that they have valid reasons to do so.

Even when CA was disabled, the majority of sites had configured cell relations and parameters that we needed to modify but since the configuration and reconfiguration process implies different procedures, separate tables were sent to the Integration Team.

Throughout the configuration steps presentation, we will include rows examples from these tables and fully drop them in the annex part.

6.2.1 Cell Relations

Each Site consists of 3 primary and secondary cells that cover a specific sector, we will call them {M/1, N/2, O/3, R/4, S/5, T/6}. The goal of this part is to define EutranCell relations within the network so each M cell of each Site will have {R/4, S/5, T/6} as secondary cell candidates.

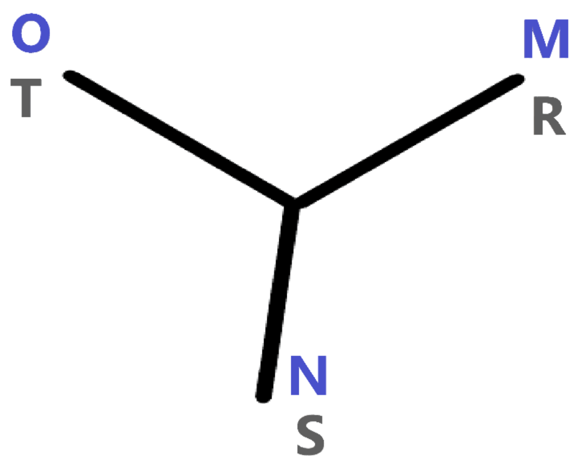


Figure 6.1: Site Sector Representation

1	IP	MO	sCellCandidate	isRemoveAllowed	verageIndicat	loadBalancing	Action
2	10.208.128.50	EUtranCellFDD=16735M,EUtranFreqRelation=150,EUtranCellRelation=6031-16735-5	1	false	2	1	create
3	10.208.132.10	EUtranCellFDD=16353M,EUtranFreqRelation=150,EUtranCellRelation=6031-16353-5	1	false	2	1	create
4	10.208.138.138	EUtranCellFDD=161391M,EUtranFreqRelation=150,EUtranCellRelation=6031-161391-5	1	false	2	1	create
5	10.208.142.86	EUtranCellFDD=16639M,EUtranFreqRelation=150,EUtranCellRelation=6031-16639-5	1	false	2	1	create
6	10.208.168.26	EUtranCellFDD=161513M,EUtranFreqRelation=150,EUtranCellRelation=6031-161513-5	1	false	2	1	create
7	10.208.128.50	EUtranCellFDD=16735M,EUtranFreqRelation=150,EUtranCellRelation=6031-16735-6	1	false	2	1	create

1	IP	MO	Attribute	Old	New
2	10.208.128.50	EUtranCellFDD=16735M,EUtranFreqRelation=150,EUtranCellRelation=6031-16735-4	sCellCandidate	2	1
3	10.208.132.10	EUtranCellFDD=16353M,EUtranFreqRelation=150,EUtranCellRelation=6031-16353-4	sCellCandidate	2	1
4	10.208.138.138	EUtranCellFDD=161391M,EUtranFreqRelation=150,EUtranCellRelation=6031-161391-4	sCellCandidate	2	1
5	10.208.142.86	EUtranCellFDD=16639M,EUtranFreqRelation=150,EUtranCellRelation=6031-16639-4	sCellCandidate	2	1

Figure 6.2: Add and Modify Cell Relations Examples

For the initial SCell selection, priority is used to determine which SCell candidate is preferred. The prioritization is enabled by setting the EUtranCellRelation.coverageIndicator attribute to indicate cell overlap.

The priority is then based on what type of overlap the cells have:

1 (Covers)
2 (Overlap)
3 (Contained_IN)
0 (None)

46	10.208.128.50	EUtranCellFDD=16735M,EUtranFreqRelation=150,EUtranCellRelation=6031-16735-4	coverageIndicator	0	1
47	10.208.132.10	EUtranCellFDD=16353M,EUtranFreqRelation=150,EUtranCellRelation=6031-16353-4	coverageIndicator	0	1

Figure 6.3: CoverageIndicator Modification

6.2.2 Parameters

To prevent drops when using Scell prioritization between scells with coverage indicator attribute set to 1 [17], blind handover must be disabled by setting covTriggerdBlindHoAllowed to false.

				Old	New
139	10.208.138.138	EUtranCellFDD=161391N	covTriggerdBlindHoAllowedBr	true	false
140	10.208.138.138	EUtranCellFDD=161391O	covTriggerdBlindHoAllowedBr	true	false
141	10.208.138.138	EUtranCellFDD=161391M	covTriggerdBlindHoAllowedBr	true	false
142	10.208.138.138	EUtranCellFDD=161391N	covTriggerdBlindHoAllowedBr	true	false
143	10.208.138.138	EUtranCellFDD=161391O	covTriggerdBlindHoAllowedBr	true	false

Figure 6.4: covTriggerdBlindHoAllowed To False

The A6 event is described as “Neighbour become offset better than S Cell”, this means that the eNodeB will replace the SCell with the best reported one.

Figure 6.5: A6 Event Visual Description

Small fluctuation around offset value can generate a lot of unnecessary a6 reports. To prevent this, the parameter called 'Hysteresis' is introduced, it's role can be illustrated as below.

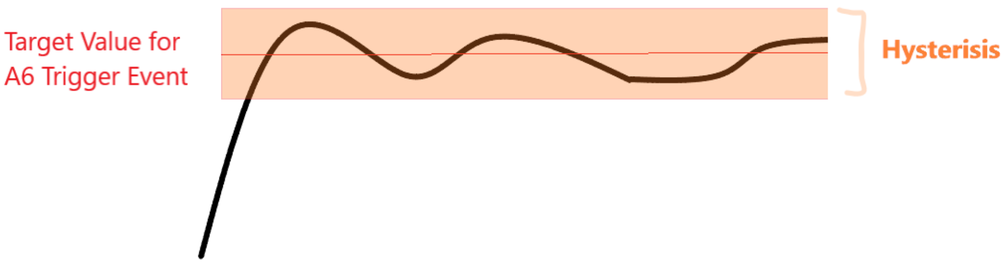


Figure 6.6: A6 Hysteresis Visual Description

9	10.208.138.138	EUtranCellFDD=161391N,UeMeasControl=1,ReportConfigSCellA6=1	a6offset	30	15
10	10.208.138.138	EUtranCellFDD=161391O,UeMeasControl=1,ReportConfigSCellA6=1	a6offset	30	15
11	10.208.138.138	EUtranCellFDD=161391R,UeMeasControl=1,ReportConfigSCellA6=1	a6offset	30	15
12	10.208.138.138	EUtranCellFDD=161391S,UeMeasControl=1,ReportConfigSCellA6=1	a6offset	30	15
13	10.208.138.138	EUtranCellFDD=161391T,UeMeasControl=1,ReportConfigSCellA6=1	a6offset	30	15
14	10.208.144.158	EUtranCellFDD=16664M,UeMeasControl=1,ReportConfigSCellA6=1	a6offset	30	15
15	10.208.144.158	EUtranCellFDD=16664N,UeMeasControl=1,ReportConfigSCellA6=1	a6offset	30	15
16	10.208.168.26	EUtranCellFDD=161513M,UeMeasControl=1,ReportConfigSCellA6=1	hysteresisA6	10	15
17	10.208.168.26	EUtranCellFDD=161513N,UeMeasControl=1,ReportConfigSCellA6=1	hysteresisA6	10	15
18	10.208.168.26	EUtranCellFDD=161513O,UeMeasControl=1,ReportConfigSCellA6=1	hysteresisA6	10	15
19	10.208.168.26	EUtranCellFDD=161513R,UeMeasControl=1,ReportConfigSCellA6=1	hysteresisA6	10	15
20	10.208.168.26	EUtranCellFDD=161513S,UeMeasControl=1,ReportConfigSCellA6=1	hysteresisA6	10	15
21	10.208.168.26	EUtranCellFDD=161513T,UeMeasControl=1,ReportConfigSCellA6=1	hysteresisA6	10	15

Figure 6.7: A6 Offset and hysteresis Modification

A1(A2) events are defined as Serving becomes better(worse) than threshold, this parameter was changed from 126 to 116 for all cells.

37	10.208.138.138	EUtranCellFDD=161391M,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116
38	10.208.138.138	EUtranCellFDD=161391N,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116
39	10.208.138.138	EUtranCellFDD=161391O,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116
40	10.208.138.138	EUtranCellFDD=161391R,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116
41	10.208.138.138	EUtranCellFDD=161391S,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116
42	10.208.138.138	EUtranCellFDD=161391T,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116
43	10.208.138.138	EUtranCellFDD=161391M,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrp	-126	-116
44	10.208.138.138	EUtranCellFDD=161391M,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116
45	10.208.138.138	EUtranCellFDD=161391N,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrp	-126	-116
46	10.208.138.138	EUtranCellFDD=161391N,UeMeasControl=1,ReportConfigSCellA1A2=1	a1a2ThresholdRsrpBidir	-140	-116

Figure 6.8: A1A2 Threshold Modification

CellSubscriptionCapacity parameter was chosen to be 25500 for primary cells and 17000 for secondary cells.

125	10.208.138.138	EUtranCellFDD=161391O	cellSubscriptionCapacity	17000	25500
126	10.208.138.138	EUtranCellFDD=161391R	cellSubscriptionCapacity	1000	17000
127	10.208.138.138	EUtranCellFDD=161391S	cellSubscriptionCapacity	1000	17000
128	10.208.138.138	EUtranCellFDD=161391T	cellSubscriptionCapacity	1000	17000
129	10.208.166.70	EUtranCellFDD=16402M	cellSubscriptionCapacity	17000	25500

Figure 6.9: Cell Capacity Modification

6.2.3 Features

Finally, the features needed are activated.
The CA feature state which has CXC4011476 as a manipulated object instance must be set to ACTIVATED.

1	IP	MO	Attribute	Old	New
2	10.208.132.10	CXC4011476	featureState	0	1
3	10.208.144.158	CXC4011476	featureState	0	1
4	10.208.146.174	CXC4011476	featureState	0	1
5	10.208.166.70	CXC4011476	featureState	0	1
6	10.208.168.26	CXC4011476	featureState	0	1

Figure 6.10: CA Feature Activation

The Dynamic SCell Selection for CA feature which has CXC4011559 as a manipulated object instance is also set to ACTIVATED. This feature follows the scheme below.

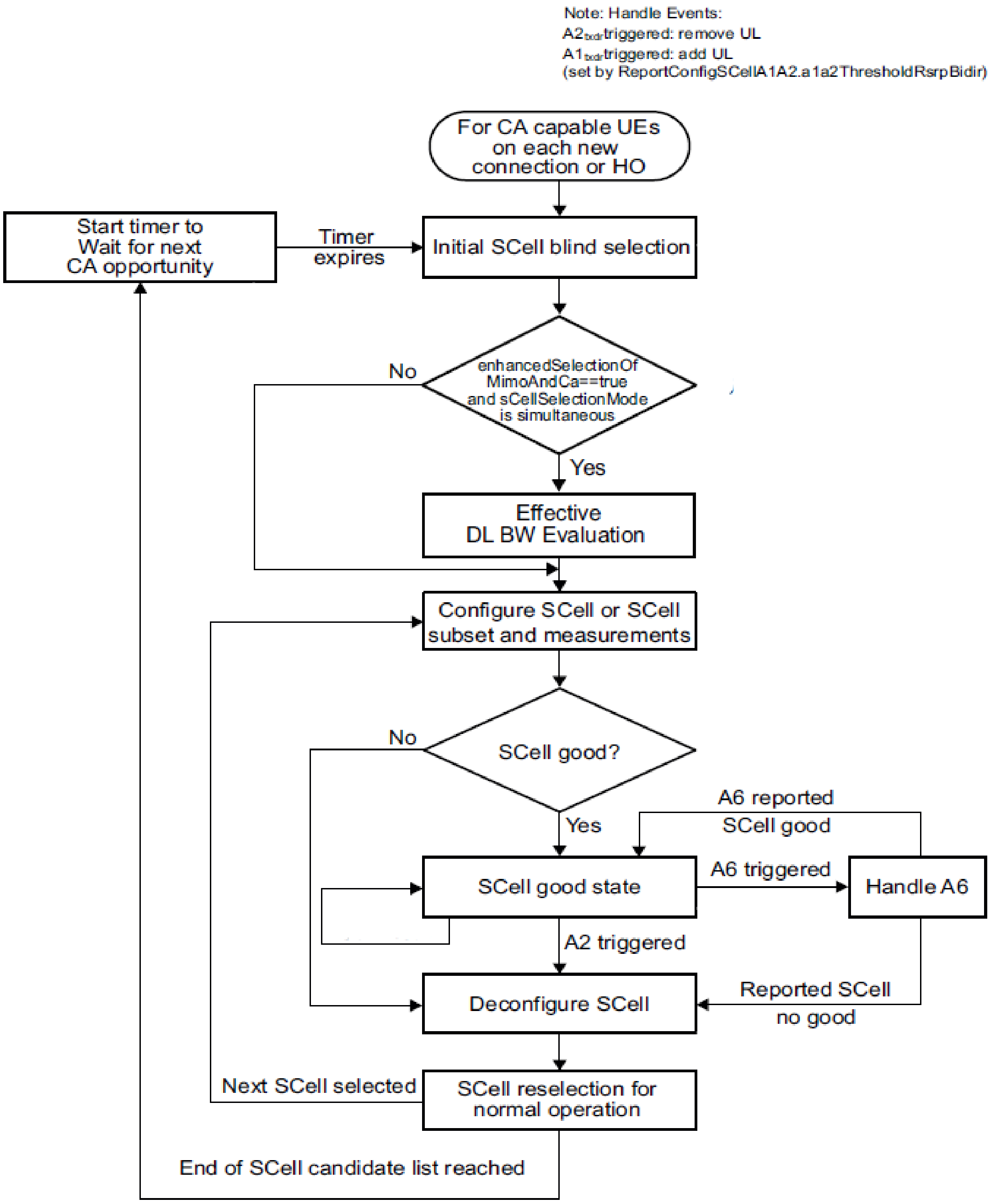


Figure 6.11: Sequence Diagram of Dynamic SCell Selection[18]

7	10.208.132.10	CXC4011559	featureState	0	1
8	10.208.144.158	CXC4011559	featureState	0	1
9	10.208.146.174	CXC4011559	featureState	0	1
10	10.208.166.70	CXC4011559	featureState	0	1
11	10.208.168.26	CXC4011559	featureState	0	1

Figure 6.12: SCell Feature Activation

6.3 Results Analysis

For the study to be valid, we needed to confirm that the cell availability did not greatly fluctuate.

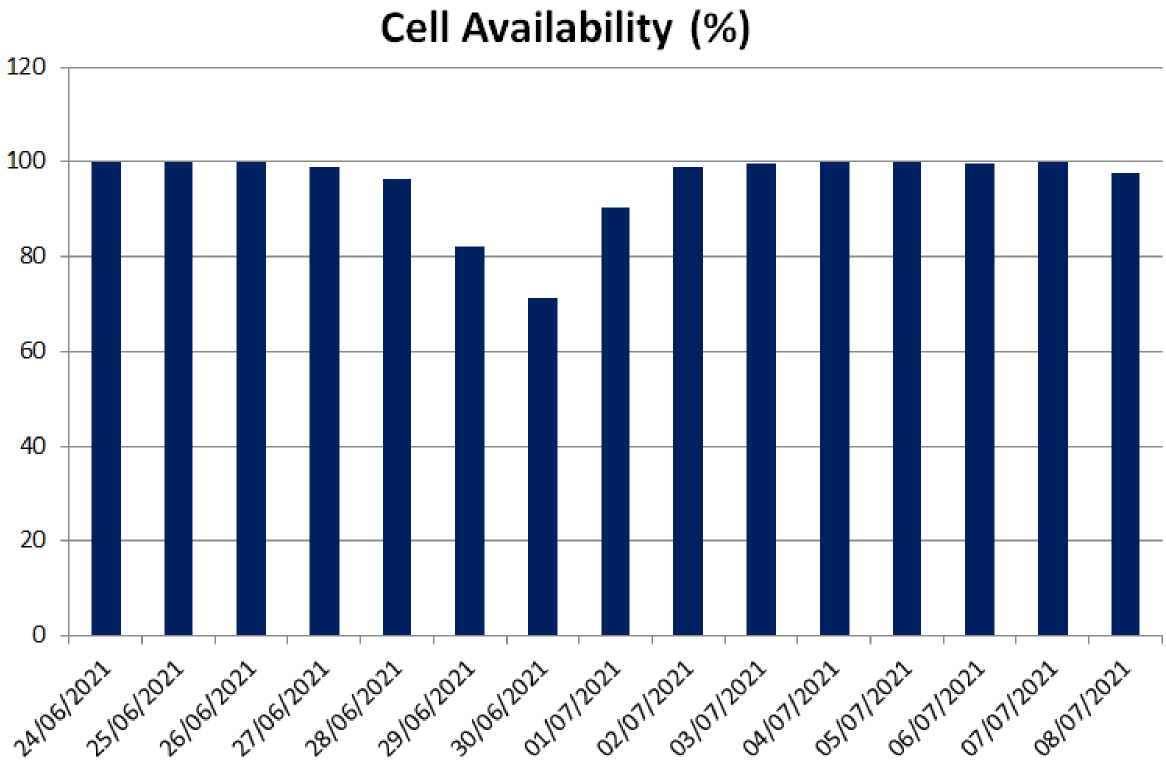


Figure 6.13: Cell Availability

We can see that except for the 29 and 30 of June where cell availability percentage dropped to around 80-75%, most of the days were around 90-99% cell availability.

That 20% drop did not considerably affect the network and we will see this through the next charts. As a consequence, The "Before-After CA" comparative character of the study was perfectly conserved.

6.3.1 Affect on the Network parameters

CA was activated on the 1 of July, this transition can be noticed through the RRC Fails and may be caused by the integration process when a Lock/Unlock Cell is done.

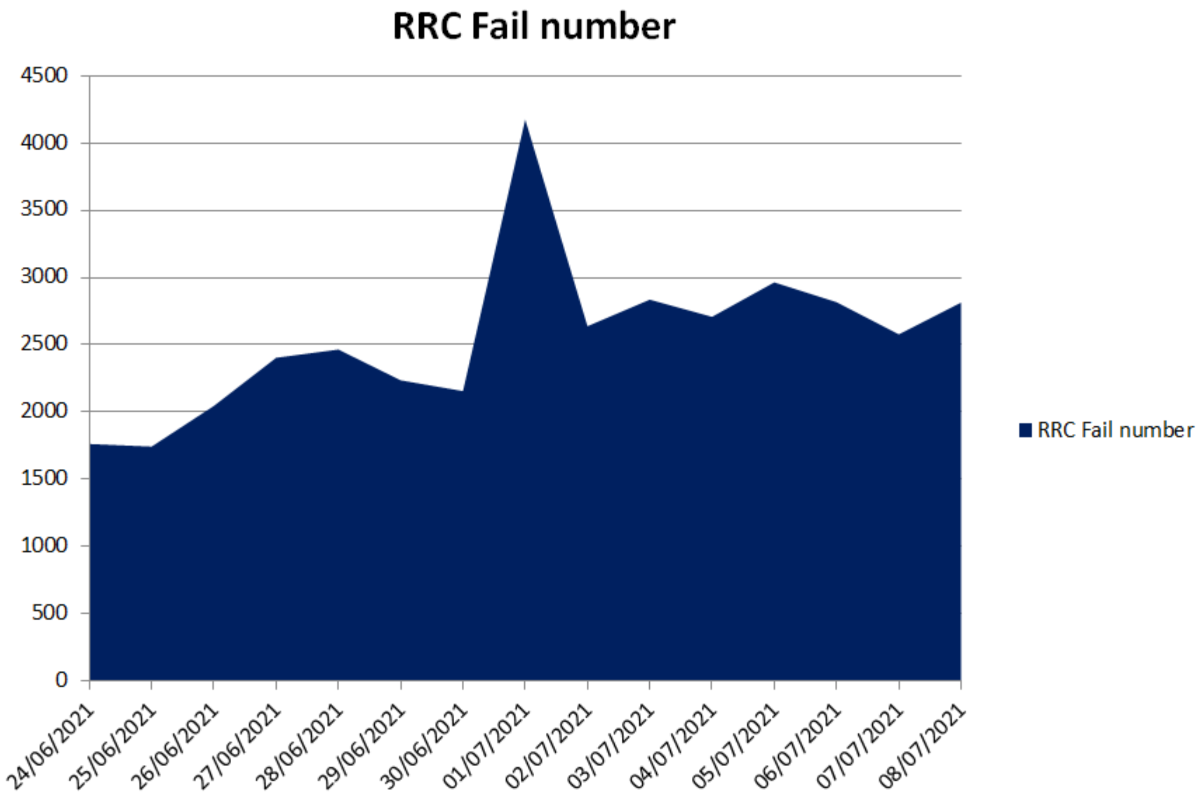


Figure 6.14: RRC Fail Number

The number of DL QAM modulations is an important revealing parameter and is proportional to the total DL volume. A dramatic overall increase was noticed and the "why" will be presented in the DL volume section later in this chapter.

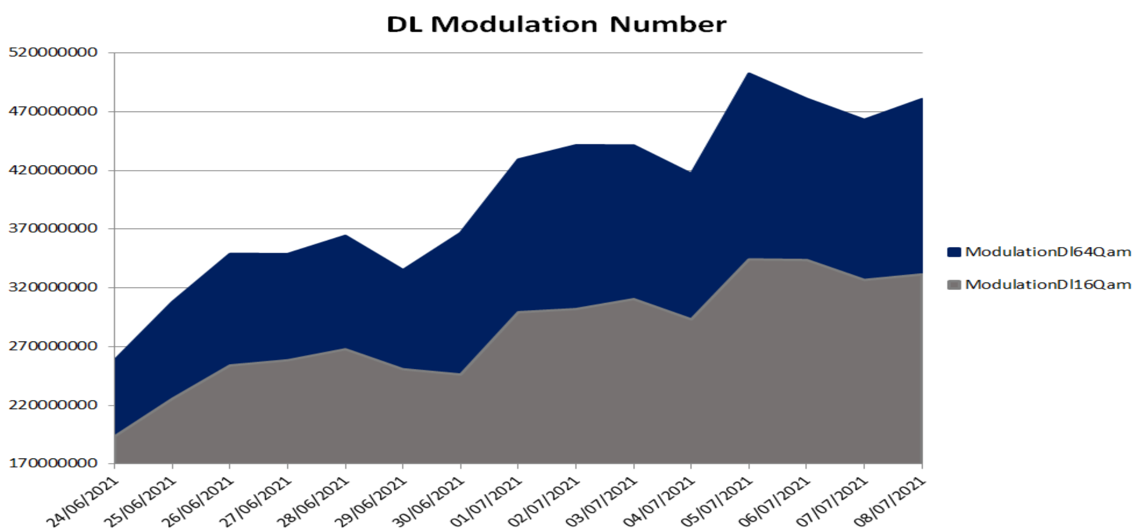


Figure 6.15: Downlink Modulation Number

Retainability is defined as the ability to retain the E-Utran Radio Bearer (ERB) once connected and was also considerably enhanced.

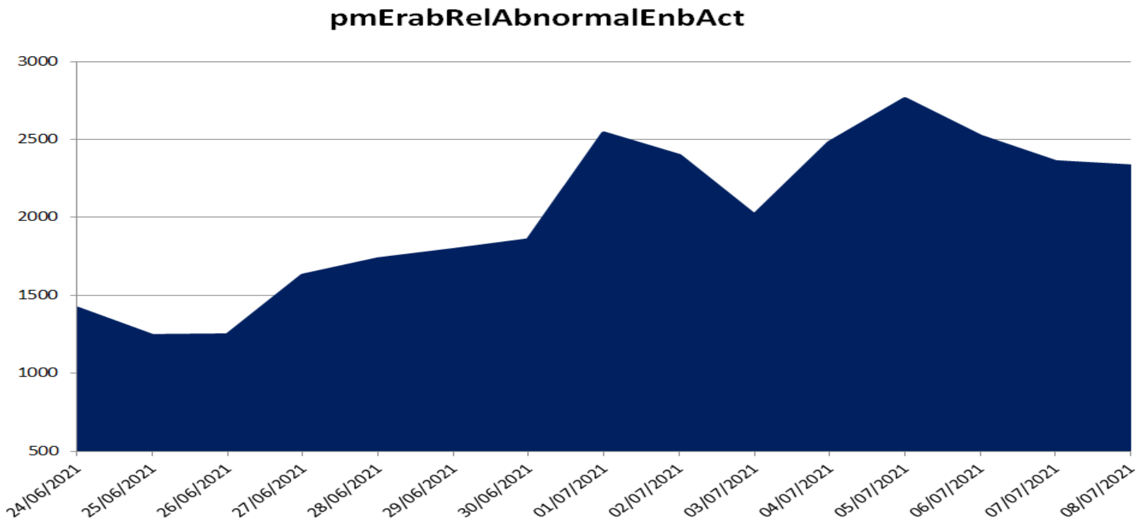


Figure 6.16: Retainability enhancement

Most of the LTE-A network parameters, however, were not affected by the CA Activation as expected.

6.3.2 Affect on the User Experience

The most important and revealing enhancement concerns the DL user throughput which literally doubled after CA Activation.

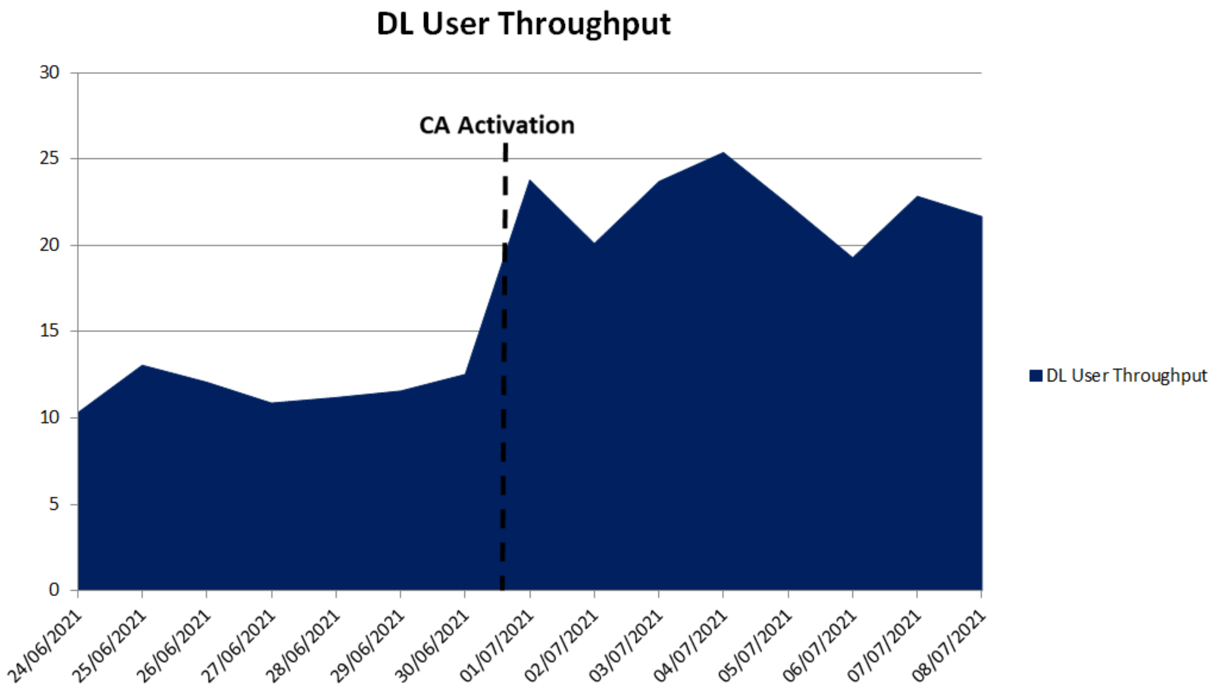


Figure 6.17: Downlink User Throughput

Some counters in the EUtranCellFDD class are specifically associated with the Carrier Aggregation feature[19] and thus have no value before activation such as the pmCaConfiguredDlSum.

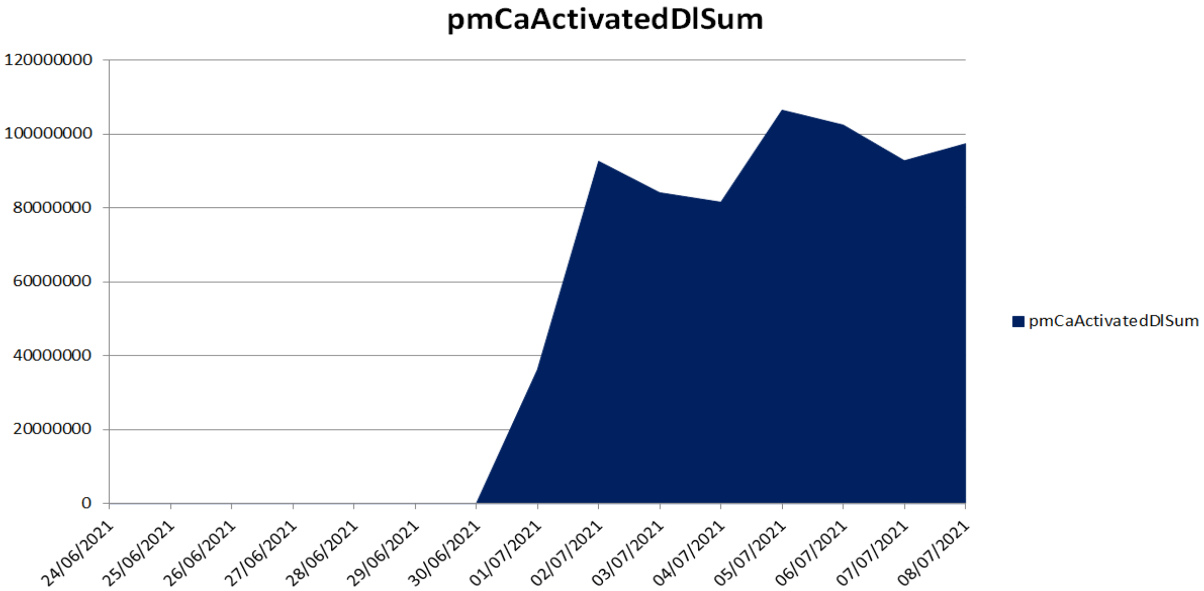


Figure 6.18: Example of CA specific counters

Last but not least, the total data volume increased dramatically, this is due to the user experience enhancement. When provided with a better connexion quality, a user tend to consume more data. Another important factor is that some mobile applications have an "auto video quality" option (youtube for example) that prefers higher resolution when the throughput permits it.

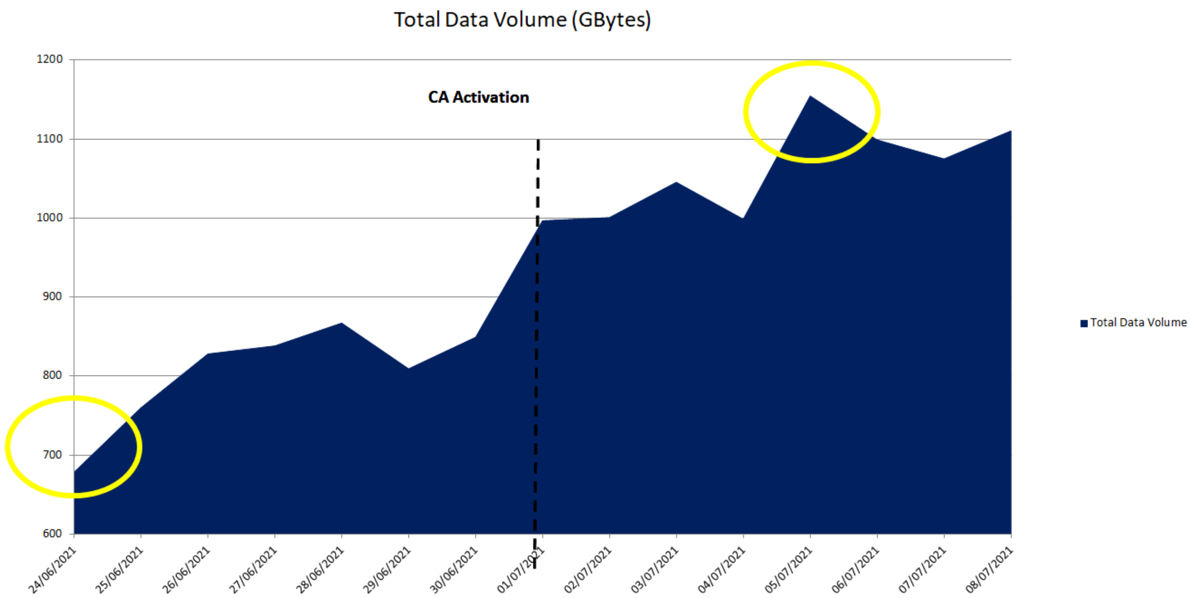


Figure 6.19: Total Data Volume

We also notice two peaks within our data volume, these two peaks find their explication in National events and their impact on user behavioral consumption. The 24^{th} of June being the last day of the baccalaureate exam and the 5th of July being the "National Independence Day of Algeria".

Conclusion and Discussion

Throughout this chapter the main configuration parameters that telecommunication engineers take into consideration when working on the CA feature were introduced and followed for CA Activation on some of Algiers sites. Upon activation and supported with real data collected, the effect of CA on the network and the quality of service were presented and discussed. Our personal analysis consists of the causes and clarifications, either technical or behavioral that we gave.

General Conclusion

From the Theoretical aspect of spectrum allocation to real-data driven analysis, passing by the physical layer implementation and network simulation, our work constitutes a global study of Carrier Aggregation's main components and affected structures, constituting consistent support and guide for further theoretical or software-based works on Carrier Aggregation.

Extensive technical challenges especially in terms of design and testing were brought by CA and the latest features but the importance and validity of software-based simulations in the telecommunications field have been more than ever put in the foreground in front of impractical cost and time-consuming experimentations for systems development.

Carrier Aggregation is one of the most important features contributing to the enhancement of the LTE-A network and its users' experiences. Increasing the utilization of the existing spectrum can significantly improve network capacity, where user equipment categories are definitely capable of handling a larger number of component carriers than used today by our local service providers, these providers if acquired new resources through new frequencies and band allocations, could drastically boost the network capabilities, taking the user experience and their income to another level.

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Appendixes

Collected Data Tables

Date	Wilaya	Cell Availability (%)	PRB usage %	DL Latency (ms)	pmErabRelAbnormalEnbAct	Mean RRC Connected User hourly
24/06/2021	Alger	99.99595185	17.79124198	5.19300153	1415	6892
25/06/2021	Alger	100	16.96555561	5.147843968	1239	7418
26/06/2021	Alger	100	19.01865026	4.830184103	1243	7786
27/06/2021	Alger	99.04024621	19.03609471	5.027165131	1626	8164
28/06/2021	Alger	96.34159301	20.34279749	4.959779638	1731	8120
29/06/2021	Alger	82.29680429	19.86785909	4.994106613	1790	7738
30/06/2021	Alger	71.1702629	20.32251075	5.009588629	1853	7792
01/07/2021	Alger	90.49328859	19.25617551	5.002222804	2538	9693
02/07/2021	Alger	98.82432209	17.42012483	5.582647764	2394	10487
03/07/2021	Alger	99.67088294	18.25479854	5.161541834	2010	9707
04/07/2021	Alger	99.97077546	17.51028386	5.228744328	2478	9999
05/07/2021	Alger	99.84114583	19.76616995	5.390069809	2758	11548
06/07/2021	Alger	99.65657698	19.59506925	5.206710931	2518	10415
07/07/2021	Alger	100	18.92775313	5.114407172	2354	10478
08/07/2021	Alger	97.80700231	19.51154312	5.234816837	2327	10445

16QAM Usage %	256QAm Usage %	64QAM Usage %	RA Contention Based SR	RA contention Free SR	ModulationDl16Qam
27.23832326	0.963416865	36.37430802	56.776431	58.30725462	193521478
26.59384812	0.93688815	36.30420781	50.37801775	55.74445788	225532650
26.46839486	1.144517944	36.36661405	53.39319021	54.37820588	253968072
27.10193355	1.372480112	36.59612764	51.81444292	57.02506404	258371107
26.76665886	1.359950058	36.42596956	45.89348285	54.97916269	267745955
27.26064007	1.186481692	36.44272865	47.38790975	49.91271324	250714151
26.18677013	1.45117583	39.01037956	52.65759685	55.09316616	246206855
26.54757408	1.460108913	38.08770707	45.12487803	57.97799195	299315716
26.43161024	2.065720006	38.64402271	40.56211157	60.13876719	301996283
26.91967372	1.935870044	38.27136651	32.96750473	57.52390057	310477123
26.58525044	1.544792038	37.81592317	41.60358262	61.08921898	293199238
26.43170419	2.063121668	38.58080379	32.32087289	57.72728558	344314383
27.17676847	1.604308662	38.02958729	39.13605212	59.60842588	343828478
26.90334442	1.797088374	38.13470499	40.83633341	61.69199718	326812912
26.73665176	2.017374539	38.78005736	43.11610227	60.92421847	331519820

Figure 20: Affect on the Network Table

ModulationDl256Qam	ModulationDl64Qam	RRC Fail number	UL User Throughput (Mbps)	UL Volume (GB)	DL Volume (GB)
6844836	258430366	1763	1.155634402	55	678
7945404	307882641	1744	1.278502446	61	760
10981815	348942915	2046	1.310250668	66	828
13084277	348882193	2404	1.327462397	66	838
13603533	364367703	2465	1.421694479	70	867
10911987	335161161	2236	1.23078313	60	809
13643891	366773864	2156	1.317526156	64	849
16462278	429427159	4174	1.609999027	87	996
23602034	441530089	2638	1.339953986	97	1000
22327290	441401478	2836	1.581164272	91	1045
17036960	417058319	2708	1.411005807	92	998
26875394	502575451	2964	1.615405113	119	1154
20297005	481133551	2817	1.291335509	88	1099
21830434	463247758	2578	1.413063612	95	1075
25014338	480851445	2814	1.703204654	102	1110

DL User Throughput	IntraFreq HOSR (%)	RRC Connection SR (%)	S1 Signaling SR (%)	ERAB Establishment SR%
10.31014063	98.13036524	99.94913215	99.92613636	99.88680069
13.06239089	97.87695914	99.95052669	99.93391918	99.90770292
12.07601148	97.76048634	99.94574178	99.92687544	99.8996209
10.87311432	97.82587171	99.94408217	99.92700228	99.8860328
11.18944708	97.74291991	99.93594511	99.89720931	99.85609283
11.57150238	97.75628613	99.94289838	99.87045782	99.86276496
12.53318202	97.82051837	99.94234869	99.91628569	99.87799817
12.58165457	97.99868876	99.81463352	99.92092826	99.89695245
11.05548366	97.5633829	99.93593568	99.92328051	99.8844732
12.37760792	97.45478966	99.9337431	99.93971045	99.90371026
13.43998953	97.69812796	99.93743228	99.95846847	99.91448918
11.39613816	97.4814872	99.93544122	99.95880112	99.9090427
10.90405601	97.69834212	99.93796409	99.94851769	99.89593925
12.71535772	97.80966711	99.93933332	99.9654646	99.92611332
11.30601784	97.7907232	99.93806068	99.95730531	99.92205314

Figure 21: Affect on the Network Table follow

Date	UL PDCP Volume (GByte)	downtime	pmCaConfiguredDlSum	pmCaScheduledDlSum	pmCaConfiguredDlSamp	Mean CA Activated User	Mean RRC Connected User
24/06/2021	0.054010366	76	0	0	0	0	287
25/06/2021	0.059300243	0	0	0	0	0	309
26/06/2021	0.064292063	0	0	0	0	0	324
27/06/2021	0.064783238	18243	0	0	0	0	340
28/06/2021	0.068964308	69539	0	0	0	0	338
29/06/2021	0.059136318	383345	0	0	0	0	322
30/06/2021	0.062563222	697449	0	0	0	0	325
01/07/2021	0.085604666	229473	782242	18933813	139035	0	404
02/07/2021	0.095207861	28442	2307946	45398258	478162	1	437
03/07/2021	0.089178134	7962	1974211	39980767	482252	1	404
04/07/2021	0.090388307	707	2117640	39570949	483707	1	417
05/07/2021	0.116537472	3843	2618912	50545238	483089	1	481
06/07/2021	0.086374169	8271	2264103	52607068	480025	1	434
07/07/2021	0.093264565	0	2307269	44920225	483852	1	437
08/07/2021	0.100068587	53053	2392953	47567415	473242	1	435

pmRrcConnLevSum	pmCaActivatedDlSum	Average CA Configured UEs	DL User Throughput	DL CA User Throughput	DL PDCP Volume (GBytes)	Total Data Volume
4962055	0	#DIV/0	10.31014063	#DIV/0	678.2217489	678.2757593
5340616	0	#DIV/0	13.06239089	#DIV/0	759.7678447	759.8271449
5605986	0	#DIV/0	12.07601148	#DIV/0	827.9121513	827.9764434
5878409	0	#DIV/0	10.87311432	#DIV/0	838.0709728	838.135756
5846560	0	#DIV/0	11.18944708	#DIV/0	867.011507	867.0804713
5571582	0	#DIV/0	11.57150238	#DIV/0	809.1337419	809.1928782
5610498	0	#DIV/0	12.53318202	#DIV/0	849.0488664	849.1114296
6978625	36233023	5.626223613	12.58165457	23.78871573	996.4791647	996.5647694
7550599	92641393	4.826703084	11.05548366	20.11134585	1000.550312	1000.64552
6988973	84107790	4.093733152	12.37760792	23.70213843	1045.224774	1045.313952
7199344	81560431	4.377939538	13.43998953	25.38213006	998.548427	998.6388153
8314664	106473317	5.42117912	11.39613816	22.38488776	1154.496931	1154.613468
7499016	102441346	4.716635592	10.90405601	19.29139109	1098.808438	1098.894812
7544145	92795404	4.76854286	12.71535772	22.84436941	1074.794368	1074.887632
7520248	97379491	5.0565102	11.30601784	21.66976193	1110.27508	1110.375149

Figure 22: Affect on the User Experience Table