Sudan University of Science & Technology

College of Postgraduate Studies

Optimization of 4G by Advanced Carrier Aggregation Strategies

تحسين الجيل الرابع من خلال استراتيجيات تجميع الناقل

This thesis is submitted in partial Fulfillment for the requirement of M.Sc. in Communication Engineering

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الآية

بسم الله الرحمن الرحيم

قال تعالى:

{فَقُلْتُ اسْتَغْفِرُوا رَبَّكُمْ إِنَّهُ كَانَ غَفَّارًا (10) يُرْسِلِ السَّمَاءَ عَلَيْكُم مِّدْرَارًا (11) وَيُمْدِدْكُمْ بِأَمْوَالٍ وَبَنِينَ وَيَجْعَل لَّكُمْ جَنَّاتٍ وَيَجْعَل لَّكُمْ أَنْهَارًا (12)}

صدق الله العظيم

(سورة نوح)

Dedication

I dedicate this work to the memory of my father and to my mother, my husband, my children and my family for their endless love, support and encouragement. Thanks for always being here for me.

ACKNOWLEDGEMENT

I believe in Allah who has drown me with this uncounted blessing and shown me right way to go on with this life.

I would like to thank my advisor **Dr. Ibrahim Khider** for his excellent support and guidance. His insightful comments and feedback were helpful during the entire project.

I am grateful to my mother for her support and help in my Master's was invaluable.

I would like to express my thank to my husband and my children for his support and patience over this year and especially during this project.

I am grateful to my friends (Reham) and family for their support during my studies.

Abstract

In long term evolution-advanced (LTE-A) networks, the carrier aggregation technique is incorporated for user equipment's to simultaneously aggregate multiple component carriers (CCs) for achieving higher transmission rate. By combining five component carriers, each of 20 MHz, we can extend the bandwidth to 100 MHz and hence also can achieve high data rates of the order of 1Gbps. Many research works for LTE-A systems with carrier aggregation configuration is carried out in this project we will study the performance of carrier aggregation for various optimization steps and further evolution seen in future.

المستخلص

في الشبكات التطوير طويل الأمد المتقدمة يتم دمج تقنية تجميع الموجات الناقلة للمستخدم لتجميع عدة موجات ناقلة المكون في وقت واحد للزيادة في معدل الأرسال. من خلال الجمع بين خمسة ناقلات المكون, كل واحدة 20 ميغاهرتز, ويمكننا زيادة عرض النطاق الترددي الى 100 ميغاهرتز وبالتالي أيضا يمكننا تحقيق معدلات بيانات عالية تصل الى 1 قيقاهرتز. يتم أجراء العديد من الأعمال البحثية لأنظمة التطوير طويل الأمد المتقدمة مع ترتيب تجميع النواقل في هذا البحث وسوف ندرس أداء تجم ريع النواقل لمختلف خطوات التحسين. وهناك المزيد من التطور سيدرس في المستقبل.

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List of Abbreviations

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACK	Acknowledgement
BS	Base Station
CA	Carrier Aggregation
CC	Component Carrier
CDMA	Code Davison Multiple Access
COMP	Coordinated multipoint transmission and reception
CPE	Customer Premises Equipment
CSG	Closed Subscriber Group
DARPA	Defence Advanced Research Projects Agency
DFT	Discrete Fourier Transform
DL	Downlink
DSP	Digital signal processing

EDGE	Enhanced Data Rates for Global Evolution
eNodeB	Evolved Node B
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
FDD	Frequency division duplexing
FDMA	Frequency division multiple access
FFT	Fast Fourier Transform
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HeNB	Home enhanced-node-B
HetNet	Heterogeneous Networks
HSPA	High Speed Packet Access
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunications
IP	Internet Protocol
ITU	International Telecommunication Union
LPNs	Low Power Nodes
LTE	Long Term Evolution

LTE-A	Long Term Evolution Advanced
MIMO	Multiple Input Multiple Output
MS	Mobile Station
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PCC	Primary Component Carrier
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SC-FDMA	Single Carrier Frequency Division Multiple Access
SNR	Signal to Noise Ratio
SINR	Signal to Interference Pulse Noise Ratio
SON	Self Optimizing Network
TDD	Time division duplexing
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System

UTRAN	Universal Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity

Chapter One

Introduction

1.1 Preface

The global mobile data traffic has grown tremendously during the last few years and the growth is expected to continue in the future. In the coming years, the emphasis will be in providing video and voice services over packet switched mobile networks [1].

It has been estimated that mobile video streaming will increase 13-fold between 2014 and 2019. There will be increased demand in high capacity mobile networks. At the same time it is more cost efficient to provide the Internet services wirelessly, which will increase the number of mobile data users. While the 3GPP (Third Generation Partnership Project) Release 8 Long Term Evolution (LTE) networks have been deployed rapidly, more advanced solutions are needed.

LTE-Advanced Carrier Aggregation (CA) is one possible solution for the operators to manage global mobile network traffic growth. CA is a technique that is capable of combining multiple LTE carriers. It enables deploying high capacity and performance radio networks. The network vendors and operators have been increasingly interested on CA recently. The technology has already been trialed and implemented in several countries [1].

Carrier Aggregation is one of the major features of LTE-Advanced. All operators are moving towards CA as this feature helps to maintain the quality of network and increase the user experience in terms of data rates, peak user throughput and reduce latency. CA allows mobile network operators to combine a number of separate LTE carriers. This enables them to increase the peak user, data rates and overall capacity of their networks and to exploit fragmented spectrum allocations [2].

1.2 Problem statement

In recent years, the number of users using intelligent hand-held equipment increases significantly due to rapid development of information and communication technologies and novel applications. There are tremendous demands of wireless services with high bandwidth, such as view video, listen to audio, browse the internet and other services offered by services vendors to make life more convenient. However, it is very difficult to achieve such high data rates using conventional Communication methods without increasing the bandwidth [3]. This motivation to develop new techniques to achieve high data speed, high function and economical wireless network.

1.3 Objective

This thesis focuses on studying the practical performance of one of the key features of LTE-Advanced Carrier Aggregation. Also it has many objectives are:

-To study and implement CA in LTE-A.

-To simulate and Evaluate CA in LTE-A.

- To achieve high bandwidth transmissions.

- To facilitate efficient use fragmented spectrum.

-To increase data rate.

1.4 Proposed Solution

In order to meet the high data rate demand to support various services on internet, the ITU started the standardization process. In response to the requirements laid by ITU, the third generation partnership project introduced a new technique as carrier aggregation. This process can be sensing the unused carriers or spectrum and combine them with the PCC.

1.5 Methodology

The methodology of the techniques are introduced and investigated through mathematical model. The Simulation code written in MATLAB to investigate the optimization of the use of Carrier Aggregation techniques.

1.6 Thesis Outlines

This thesis plan is divided into five chapters their outlines are as follows chapters:

Chapter 1: Introduction. This chapter presents main information of the project.

Chapter 2: Literature review. This chapter provides a literature review on LTE, LTE-Advanced, Carrier Aggregation, OFDMA and SC-OFDMA.

Chapter 3: Optimization of Carrier Aggregation techniques. This chapter about Carrier Aggregation that is one of the key features in LTE-A and it is also the primary topic of this paper. Also the chapter discussed the mathematical expressions of CA.

Chapter 4: Simulation and result. This chapter presents the simulation and discussed the reliability and significance of the results

Chapter5: Conclusion and recommendation. This chapter concludes the thesis and provides proposals for further research.

Chapter Two

Literature Review

2.1 Introduction

In the field of mobile communications, a "generation" generally refers to a change in the fundamental nature of the service, non-backwards-compatible transmission technology, higher peak bit rates, new frequency bands, wider channel frequency bandwidth in Hertz, and higher capacity for many simultaneous data transfers (higher system spectral efficiency in bit/second/Hertz/site).

Wireless communications have evolved from the so-called second generation (2G) systems of the early 1990s, which first introduced digital cellular technology, through the deployment of third generation (3G) systems with their higher speed data networks to the much-anticipated fourth generation (4G) technology developed today (shown in figure 2.1).

The 4G of wireless cellular systems has been a topic of interest for quite a long time, the first two commercially available technologies billed, as 4G were the Wi-MAX standard (offered in the U.S. by Sprint) and the LTE standard [7].

When talking about 4G, things can get a little confusing. Basically, there is 4G and 4G LTE. Many people consider LTE to be true 4G technology. Generally, if a cellular provider describes a 4G network without mentioning LTE, they are probably talking about a High-Speed Packet Access (HSPA) network. The HSPA network is a faster version of the 3G GSM network. While not as fast as an LTE network, it is still faster than a 3G network.

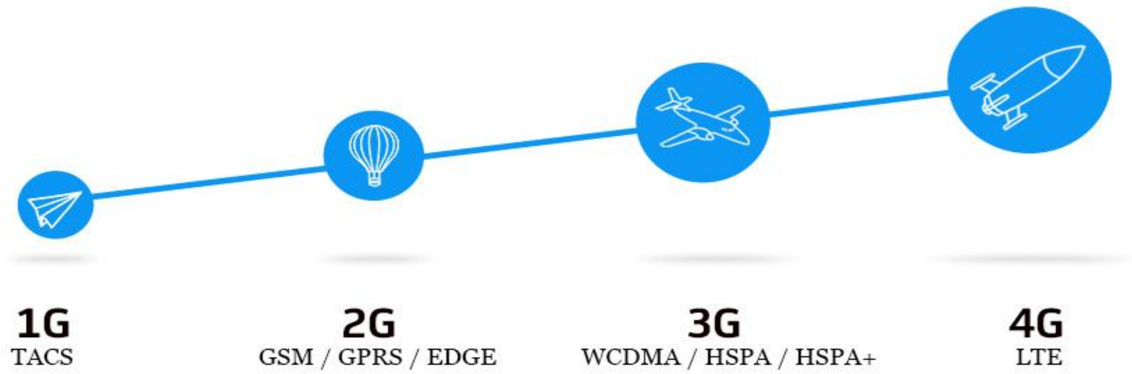


Figure 2.1 Evolution of radio access technologies

2.2 Long Term Evolution (LTE)

The 4G system was originally envisioned by the Defence Advanced Research Projects Agency (DARPA). The DARPA selected the distributed architecture and end-to-end Internet protocol (IP), and believed at an early stage in peer-to-peer networking in which every mobile device would be both a transceiver and a router for other devices in the network, eliminating the spoke-and-hub weakness of 2G and 3G cellular systems. Since the 2.5G GPRS system, cellular systems have provided dual infrastructures: packet switched nodes for data services, and circuit switched nodes for voice calls [7].

In 4G systems, the circuit-switched infrastructure is abandoned and only a packet-switched network is provided, while 2.5G and 3G systems require both packet-switched and circuit-switched network nodes, i.e. two infrastructures in parallel. This means that in 4G, traditional voice calls are replaced by IP telephony.

Long Term Evolution (LTE) is a standard for high-speed wireless communication for mobile devices and data terminals. It is based on the GSM/EDGE and UMTS/HSPA technologies. It increases the capacity and speed using a different radio interface together with core network improvements. The standard is developed by the 3GPP (3rd Generation Partnership Project) and is specified in its Release 8 document series, with minor enhancements described in Release 9.

LTE introduced new system architecture and multiple access techniques, which improved the system performance. LTE is also fully packet switched technology. Due to extensive changes, the terminals that support only earlier 3GPP generations cannot access to LTE network. However, LTE has good interoperability capabilities towards HSPA, WCDMA and GSM [11].

LTE is the natural upgrade path for carriers with both GSM/UMTS networks and CDMA2000 networks. The different LTE frequencies and bands used in different countries mean that only multi-band phones can use LTE in all countries where it is supported.

Compared to earlier generations, LTE aimed for increasing spectral efficiency 2–4 times. That required new multiple access schemes. With streamlined architecture and improved spectral efficiency, the targets for data rates were also higher than before: 100 Mbit/s for the downlink and 50 Mbit/s for the uplink. Also, the frequency allocation was specified to be more flexible.

LTE is commonly marketed as 4G LTE, but it does not meet the technical criteria of a 4G wireless service, as specified in the 3GPP Release 8 and 9 document series, for LTE Advanced. The requirements were originally set forth by the ITU-R organization in the IMT Advanced specification. However, due to marketing pressures and the significant advancements that WiMAX, Evolved High Speed Packet Access and LTE bring to the original 3G technologies, ITU later decided that LTE together with the technologies can be called 4G technologies, ITU has defined them as "True 4G" [11].

LTE isn’t as much a technology as it is the path followed to achieve 4G speeds. As it stands, most of the time when your phone displays the “4G” symbol in the upper right corner, it doesn’t really mean it. When the ITU-R set the minimum speeds for 4G, they were a bit unreachable, despite the amount of money tech manufacturers put into achieving them. In response, the regulating body decided that LTE, the name given to the technology used in pursuit of those standards, could be labeled as 4G if it provided a substantial improvement over the 3G technology.

LTE is a registered trademark owned by ETSI (European Telecommunications Standards Institute) for the wireless data communications technology and a development of the GSM/UMTS standards. However, other nations and companies do play an active role in the LTE project. The goal of LTE was to increase the capacity and speed of wireless data networks using new DSP (digital signal processing) techniques and modulations that were developed around the turn of the millennium. A further goal was the redesign and simplification of the network architecture to an IP-based system with significantly reduced transfer latency compared to the 3G architecture. The LTE wireless interface is incompatible with 2G and 3G networks, so that it must be operated on a separate radio spectrum.

LTE was first proposed by NTT DoCoMo of Japan in 2004, and studies on the new standard officially commenced in 2005. In May 2007, the LTE/SAE Trial Initiative (LSTI) alliance was founded as a global collaboration between vendors and operators with the goal of verifying and promoting the new standard to ensure the global introduction of the technology as quickly as possible.

The LTE standard was finalized in December 2008, and the first publicly available LTE service was launched by TeliaSonera in Oslo and Stockholm on December 14, 2009 as a data connection with a USB modem. The LTE services were launched by major North American carriers as well, with the Samsung SCH-r900 being the world's first LTE Mobile phone starting on September 21, 2010 and Samsung Galaxy Indulge being the world's first LTE smartphone starting on February 10, 2011 both offered by MetroPCS and HTC ThunderBolt offered by Verizon starting on March 17 being the second LTE smartphone to be sold commercially. In Canada, Rogers Wireless was the first to launch LTE network on July 7, 2011 offering the Sierra Wireless AirCard 313U USB mobile broadband modem, known as the "LTE Rocket stick"(shown in figure 2.2) then followed closely by mobile devices from both HTC and Samsung. Initially, CDMA operators planned to upgrade to rival standards called UMB and WiMAX, but all the major CDMA operators (such as Verizon, Sprint and MetroPCS in the United States, Bell and Telus in Canada, au by KDDI in Japan, SK Telecom in South Korea and China Telecom/China Unicom in China) have announced that they intend to migrate to LTE after all. The evolution of LTE is LTE Advanced, which was standardized in March 2011. Services were commencing in 2013. Additional evolution known as LTE Advanced Pro have been approved in year 2015.

LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz and supports both frequency The LTE specification provides downlink peak rates of 300 Mbit/s, uplink peak rates of 75 Mbit/s and QoS provisions permitting a transfer latency of less than 5ms in the radio access network. LTE can manage fast-moving mobiles and supports multi-cast and broadcast streams. Frequency division duplexing (FDD) and time-division duplexing (TDD). The IP-based network architecture, called the Evolved Packet Core (EPC) designed to replace the GPRS Core Network, supports seamless handovers for both voice and data to cell towers with older network technology such as GSM, UMTS and CDMA2000. The simpler architecture results in lower operating costs (for example, each E-UTRA cell will support up to four times the data and voice capacity supported by HSPA).

Figure 2.2 LTE Rocket Stick

LTE is short for a very technical process for high-speed data for phones and other mobile devices. By the intensities growth in the user demand six technologies were submitted seeking for approvals international 4G communications standard 3GPP‟s candidate's LTE-Advanced, the backward-compatible enhancement of LTE Release8 that is fully specified in 3GPP Release10. By backward compatibility it is meant that it should be possible to deploy LTE-Advanced in a spectrum already occupied by LTE with no impact on the existing LTE terminals.

2.3 LTE-Advanced (LTE-A)

In LTE-Advanced focus is on higher capacity. The driving force to further develop LTE towards LTE–Advanced - LTE Release10 was to provide higher bit rates in a cost-efficient way and at the same time completely fulfill the requirements set by ITU for IMT Advanced, also referred to as 4G.

Increased peak data rate, DL 3Gbps, UL 1.5Gbps (shown in table 2.1), higher spectral efficiency, from a maximum of 16bps/Hz in R8 to 30bps/Hz in R10, increased number of simultaneously active subscribers and improved performance at cell edges, e.g. for DL 2x2 MIMO at least 2.40 bps/Hz/cell [15].

Table 2.1 LTE-Advanced Enhancement

	Uplink/downlink	**LTE**	**LTE-Advanced**
Peak data rate	DL	300 Mbps	3Gbps
	UL	75 Mbps	1.5Gbps
Peak spectral efficiency [bps/Hz]	DL	15	30
	UL	3.75	15

2.3.1 LTE-Advanced Features

1. Wider bandwidths, enabled by carrier aggregation.

2. Higher efficiency enabled by enhanced uplink multiple accesses and enhanced multiple antenna transmission (advanced MIMO techniques).

3. Coordinated multipoint transmission and reception (CoMP).

4. Relaying.

5. Support for heterogeneous networks.

6. LTE self-optimizing network (SON) enhancements.

7. Home enhanced-node-B (HeNB) mobility enhancements.

8. Fixed wireless customer premises equipment (CPE) RF requirements.

- **Carrier Aggregation:**

  For LTE-Advanced to fully utilize the wider bandwidths of up to 100MHz, while keeping backward compatibility with LTE, a carrier aggregation scheme has been proposed. Carrier aggregation consists of grouping several LTE Component Carriers (CCs) (e.g. of up to 20 MHz) [13].

- **Multiple Input Multiple Output (MIMO):**

  MIMO is a key technique in any modern cellular system that refers to the use of multiple antennas at both the transmitter and receiver sides. It describes the possibility to have multiple Transmitter and receiver antennas.

  4G cellular systems will have to provide a large number of users with very high data transmission rates, and MIMO is a very useful tool towards increasing the spectral efficiency of the wireless transmission, adding additional diversity against fading, shaping the overall antenna beam in specific direction and achieving very high Bandwidth utilization without reduction in the power efficiency.

- **LTE Self-Optimizing Network Enhancements:**

  Today's cellular systems are very much centrally planned, and the addition of new nodes to the network involves expensive and time-consuming worksite visits for optimization, and other deployment challenges. The intent of SON is to substantially reduce the effort required to introduce new nodes and manage the network. There are implications for radio planning as well as for the operations and maintenance (O&M) interface to the base station. The main aspects of SON can be summarized as follows:

a. Self-configuration: the one-time process of automating a specific event, such as the introduction of a new femto cell, by making use of the O&M interface and the network management module.

b. Self-optimization: the continuous process of using environmental data, such as UE and base station measurements, to optimize the current network settings within the constraints set by the configuration process.

c. Self-healing: The process of recovering from an exceptional event caused by unusual circumstances, such as dramatically changing interference conditions or the detection of a Ping-Pong situation in which a UE continuously switches between macro and femto cells.

- **Fixed Wireless Customer Premises Equipment (CPE):**

Customer premises equipment in the context of the 3GPP specifications refers to a UE in a fixed location. The main advantage of the CPE is that it can be optimally located using a higher performance antenna, and it is defined with a higher output power of up to 27dBm compared with 23dBm for a standard UE.

- **Home ENodeBs Mobility Enhancements:**

Another category of network enhancement is the femto cell or home eNodeB (HeNB). Although the femto cell concept is not unique to LTE or LTE-Advanced, an opportunity exists for LTE to incorporate this technology from the start rather than retrospectively designing it into legacy systems such as UMTS and GSM. Operators must decide whether the femto cell will be deployed for closed subscriber group (CSG) UE or for open access. Although in the co-channel CSG case, the probability that areas of dense femto cell deployment will block macro cells becomes an issue. Despite this issue, studies have shown that increases in average data rates and capacity are possible with femto cells over what can be achieved from the macro network. On the other hand, femto cells do not provide the mobility of macro cellular systems, and differences exist in the use models. For these reasons, femto cell and hotspot deployments should be considered complimentary to rather than competitive with macro cells and microcells [13].

- **Relaying:**

Another method of improving coverage in difficult conditions is the use of relaying. The main use cases for relays are to improve urban or indoor throughput, to add dead zone coverage, or to extend coverage in rural areas. The concept of relaying is not new but the level of sophistication continues to grow. The most basic and legacy relay method is the use of a radio repeater, which receives, amplifies and then retransmits the downlink and uplink signals to overcome areas of poor coverage.

In general, repeaters can improve coverage but do not substantially increase capacity in order to increase the capacity along with coverage. Release10 intends to address the support of heterogeneous networks Deployment method one of the most LTE-Advanced key technologies.

- **Homogenous and Heterogeneous Networks:**

Traditionally the deployment of cellular mobile network was homogenous deployment (shown in figure 2.3). A homogeneous cellular system is a network of base-stations in a planned layout and a collection of user terminals, in which all the base-stations have similar transmit power levels, antenna patterns, receiver noise floors, and similar backhaul connectivity to the (packet) data network. Moreover, all base stations offer unrestricted access to user terminals in the network, and serve roughly the same number of user terminals, all of which carry similar data flows with similar QoS requirements [13].

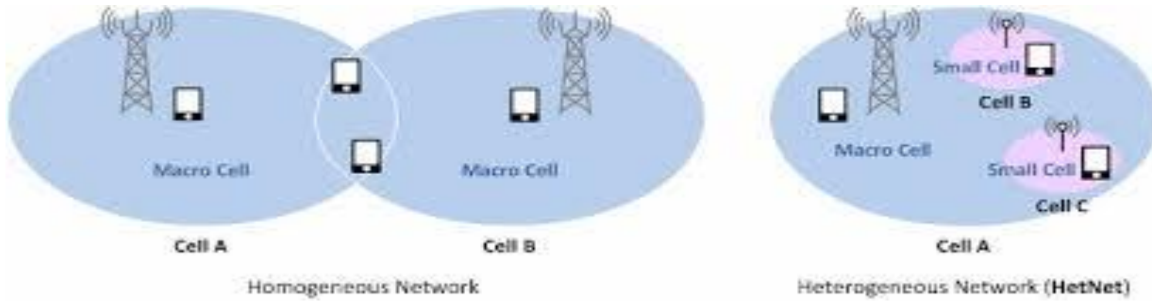


Figure 2.3 Homogeneous and Heterogeneous Networks

The locations of the macro base-stations are carefully chosen by network planers, and the base-station settings are properly configured to maximize the coverage and control the interference between base stations.

As the traffic demand grows and the RF environment changes, the network relies on cell splitting or additional carriers to overcome capacity and link budget limitations and maintain uniform user experience. However, this deployment process is complex and iterative. Moreover, site acquisition for macro base-stations with towers becomes more difficult in dense urban areas.

A more flexible deployment model is needed for operators to improve broadband user experience in a ubiquitous and cost-effective way.

There are several approaches that can be taken to meet traffic and data rate demands on a high level, the key options to expand network capacity include:

1. Improving the macro layer.

2. Densification the macro layer.

3. Complementing the macro layer with low power nodes, thereby creating a heterogeneous network.

Additional frequency resources can increase capacity easily but it is difficult for operators to get them because of the finite nature of the network.

One of the promising and cost-effective approaches to resolve this issue is heterogeneous

Networks (HetNet) where Low Power Nodes (LPNs) (e.g. Micro/Pico/Home eNodeB and Relay node) are deployed throughout a Macro cell layout.

Here is the table 2.3 shown the compression of performance requirements for LTE and LTE-A.

Table 2.3 Compression between LTE and LTE-A

System Performance		**LTE**	**LTE-A**
Peak data rate	**UL**	100Mbps/ 20Mhz	1000Mbps/ 100Mhz
	DL	50Mbps/ 20Mhz	500Mbps/ 100Mhz
Control plane delay	**Idle to connected**	<100ms	<50ms
	Dormant to active	<50ms	<10ms
User plan delay (without load)		<5ms	Lower than that of LTE
Peak spectrum efficiency [bps/Hz]	**UL**	3.75 (64 QAM SISO)	15 (up to 4x4 MIMO)
	DL	15 (4x4 MIMO)	30 (up to 8x8 MIMO)
Physical layer	**UL**	SC-FDMA	SC-FDMA
	DL	OFDMA	OFDMA

2.4 Physical layer

The basic principle in LTE physical layer is that resources are shared dynamically among the users No user receives dedicated resources. The principle is comparable to one in the Internet and packet switched networks in general. There is a variety of techniques for multiple users to simultaneously access the radio system [1]. LTE multiple access method differs from earlier 3GPP generations. Downlink multiple accesses in LTE is based on Orthogonal Frequency Division Multiple Access (OFDMA) and uplink multiple accesses is based on Single Carrier Frequency Division Multiple Access (SC-FDMA) [6].

2.4.1 Orthogonal Frequency Division Multiplexing (OFDMA)

In OFDM (Orthogonal Frequency Division Multiplexing) systems the original bandwidth is subdivided into multiple subcarriers. Each of this subcarrier can them be individually modulated. Typically, in OFDM systems we can have hundreds of subcarriers with a content spacing between them (15 KHz on the LTE case). Since the multiple subcarriers in OFDM are transmitted in parallel, it's possible for each one to transmit with a lower symbol rate. That improves robustness on the technology for mobile propagation conditions [8].

The chain to generate an OFDM signal starts by paralyzing the symbols that need to be transmitted, after they are modulated (in LTE the modulation can be QPSK, 16AQM, 64QAM). Them they are used as input bands for an inverse fast Fourier transform operation. This operation produces OFDM symbols, which will be transmitted. Notice that a conversion from the frequency to the time domain was made when the IFFT was used. Before the transmission, however, a cyclic prefix is including in the OFDM symbols in order to avoid intersymbol interference. This cyclic prefix in LTE has 5.2us on the first symbol, 4.7us for the rest of them and an extended cyclic prefix for larger cells.

On the receiving side of the OFDMA system we should expect an FFT operation that will them convert the symbol to the frequency domain again.

The main difference between an OFDM and an OFDMA (Orthogonal Frequency Division

Multiple Access) system if the fact that in the OFDM the user is allocated on the time domain only while using an OFDMA system the user would be allocated by both time and frequency (shown in figure 2.4). This is useful for LTE since it makes possible to exploit frequency dependence scheduling. For instance, it would be possible to exploit the fact that user 1 might have a better radio link quality on some specific bandwidth area of the available bandwidth.

OFDMA is used on the downing, but since it presents a high Peak-to-average Power Ratio it is not possible to use it on the uplink. For the uplink SC-FDMA will be used.

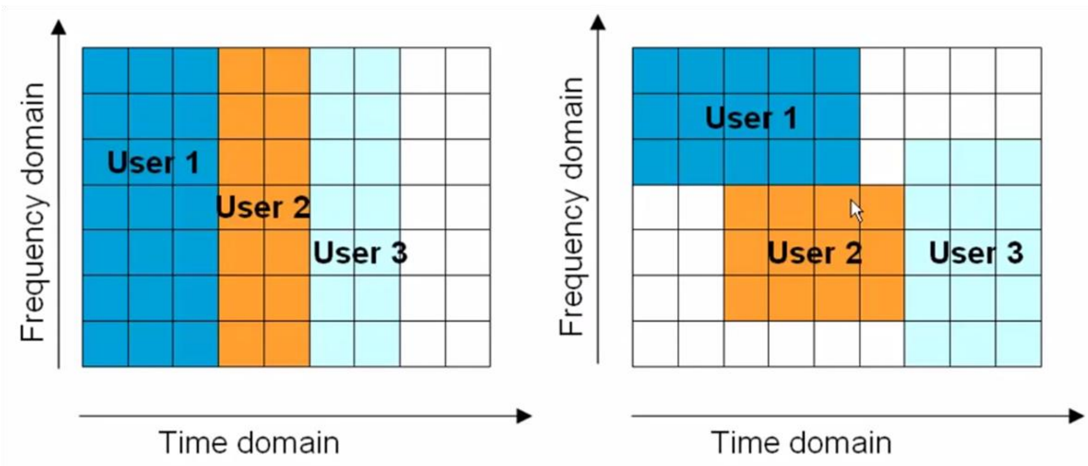


Figure 2.4 OFDMA and OFDM

The motivation for OFDMA:

- Good performance in frequency selective fading channels.
- Low complexity of base-band receiver.
- Good spectral properties and handling of multiple bandwidths.
- Link adaptation and frequency domain scheduling.
- Compatibility with advanced receiver and antenna technologies.

The challenges of OFDMA:

- Tolerance for frequency offset. 15 kHz subcarrier spacing is used in LTE to overcome this issue.

- The high peak-to-average ratio of transmitted signal. This requires linear amplifiers in transmitters, which have low power conversion efficiency and therefore are not suitable for LTE uplink.

2.4.2 Signal Carrier Frequency Division Multiple Access (SC-FDMA)

It is not possible to use OFDMA on the uplink since, as told before, it presents a high Peak-to-average Power Ratio. SC-FDMA (Single Carrier FDMA) presents the benefit of a single carrier multiplexing of having a lower Peak-to-average Power Ratio. On SC-FDMA before applying the IFFT the symbols are pre-coded by a DFT (Discrete Fourier Transform). This way each subcarrier after de IFFT will contain part of each symbol. Looking to the figure 2.5 bellow it is possible to see the difference between SC-FDMA and OFDMS. Also, it is possible to notice that the intersymbol interference will be reduced since all subcarriers on a period represent the same symbol [8].

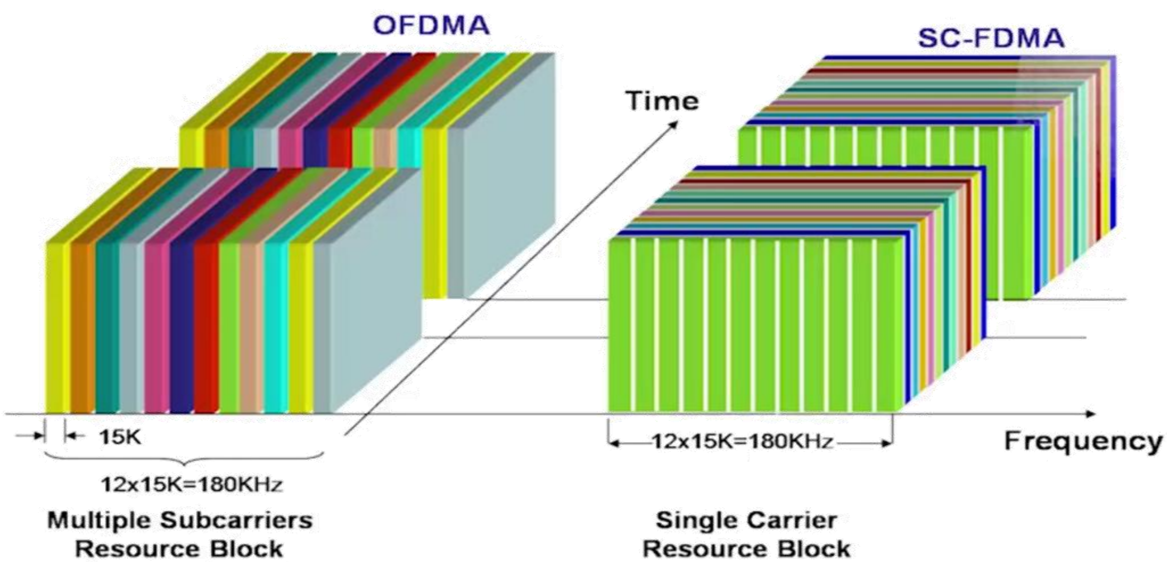


Figure 2.5 OFDMA VS SC-FDMA

2.5 Carrier Aggregation (CA)

Carrier aggregation is one of the most features of 4G systems including LTE-A. It allows scalable expansion of effective bandwidth through concurrent utilization of radio resource across multiple carriers to be delivered to user terminal. These carriers may be of different bandwidths and may be in the same or different bands to operators by combining the deployment of new radio equipment and additional spectrum operators are able to increase capacity. So CA technology can support very high data rate transmission over wide frequency bandwidth [15].

In CA, where multiple component carriers are aggregated and jointly used transmission to/from a single terminal [18]. There are up to five component carriers, possibly each of different bandwidth, which can be aggregated, allowing for transmission bandwidth up to 100MHz (shown in figure 2.6) backwards compatibility where, each CC use release8 structure. Hence, to release 8/9 terminal, each CC will appear as an LTE release 8 carriers, while a carrier aggregation capable terminal can exploit the total aggregated bandwidth, enabling higher data aggregated for downlink and uplink.

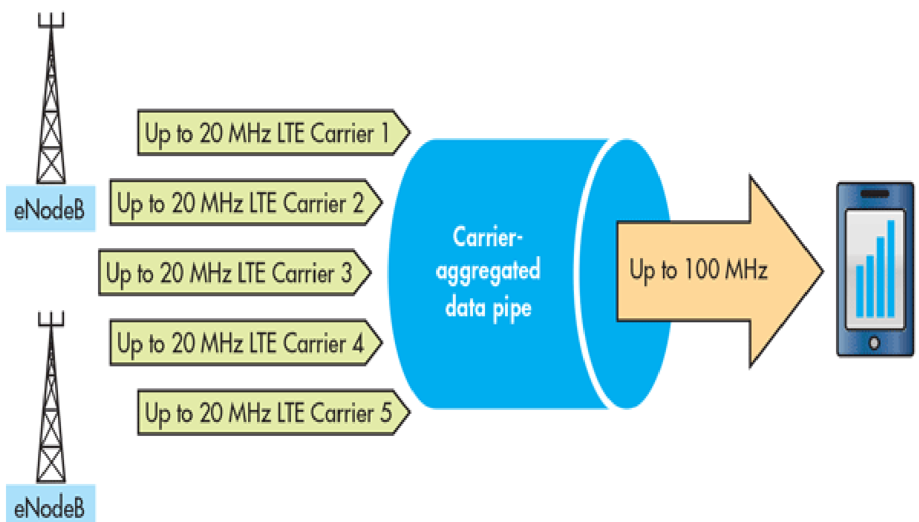


Figure 2.6 Carrier aggregation combines multiple LTE component carriers

2.5.1 Carrier Aggregation Classification

Carrier aggregations are classified as intra band contiguous carrier aggregation, intra band non-contiguous carrier aggregation and inter band non-contiguous carrier aggregation. They are also classified as symmetric and asymmetric carrier aggregation depending on the number of component carriers in the uplink and downlink [6] (shown in figure 2.7).

- Intra band contiguous carrier aggregation: In this, both the component carriers are in same frequency band and continuous to each other in frequency domain.
- Intra band non-contiguous carrier aggregation: Here both the component carriers are in same band of frequency, but they are not adjacent or continuous in the frequency domain.
- Inter band non-contiguous carrier aggregation: In this case, the component carriers are from different bands of frequency and hence they will be always non continuous if the number of component carriers in both the uplink and downlink is same then it is said to symmetric carrier aggregation. If the number of component carriers in downlink is more than that of uplink or vice versa then it is said to be asymmetric carrier aggregation.

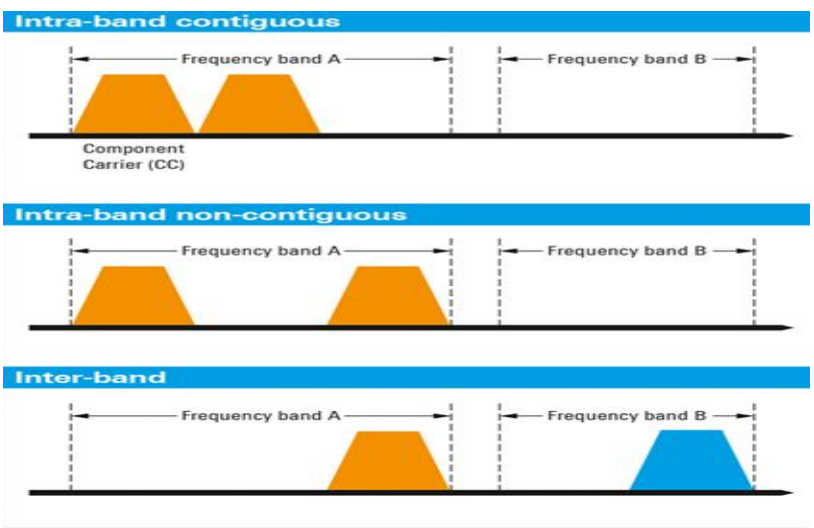


Figure 2.7 Classification of Carrier aggregations

2.5.2 Carrier Aggregation bandwidth

When aggregating carriers for an LTE signal, there are several definitions required for the bandwidth of the combined channels. As there as several bandwidths that need to be described, it is necessary to define them to reduce confusion.

In the process of spectrum aggregation, it should be taken into consideration that both the aggregated carriers in LTE and the wider channel in LTE-A have different bandwidth consequently there are several method of aggregation, e.g. 30MHz= 20MHz + 10MHz = 20MHz+ 5MHz + 5MHz. In order to reduce the design complexity of transceiver, a concept is proposed called bandwidth factor, which indicted the multiple relationship between bandwidth of aggregated carriers in LTE, e.g. when the bandwidth factor is 2, the only solution can be chosen is that 30MHz= 20MHz + 10MHz, for 20 is twice large 10. Obviously, the proposal bandwidth factor can the restrict the method of aggregation successfully and reduce the deign complexity of transceiver greatly [8].

2.5.3 Aggregation of licensed and non-licensed spectrum

Today's LTE networks are deployed in licensed spectrum bands. However, ever-increasing demands for capacity will require network operators to exploit all possible spectrum resources available to them. Among these are large tranches of unlicensed spectrum, including roughly 500MHz available in many regions of the world in the 5GHz band. This spectrum is not dedicated to individual network operators in the same way as licensed spectrum, and it is used by other technologies, such as Wi-Fi, as a result of which its occupancy is somewhat variable and unpredictable. Nonetheless, this is a valuable resource [3].

One possible approach to harnessing unlicensed spectrum is to use Carrier Aggregation. Connections could be anchored in reliable, licensed spectrum, to provide reliable mobility management, while unlicensed spectrum is used opportunistically to boost throughput and capacity where and when it is available.

The wide bandwidth, low power and limited propagation of the 5GHz band make it well suited to small, high capacity cells set in a backdrop of wide area coverage provided by lower frequency licensed band macro cells. Dynamic Channel Allocation could be used to minimise the impact between LTE and Wi-Fi in unlicensed bands. Carrier Aggregation for unlicensed bands is a candidate for 3GPP standards beyond Release 12 [3] [6].

Chapter Three

Methodology

Carrier aggregation is used in LTE-Advanced in order to increase the bandwidth, and thereby increase the bit rate. Since it is important to keep backward compatibility with R8 and R9 UEs the aggregation is based on R8/R9 carriers. Carrier aggregation can be used for both FDD and TDD. Figure 3.1shown an example where FDD is used [17].

CA is one key enabler of LTE-A to meet IMT-A requirement in terms of peak data rates it is demanded feature from a network operator perspective, since it enables also the aggregation of different spectrum fragment.

Figure 3.1 Carrier Aggregation (FDD); The LTE-Advanced UE can be allocated DL and UL resources on the aggregated resource consisting of two or more Component Carriers (CC), the R8/R9 UEs can be allocated resources on any ONE of the CCs. The CCs can be of different bandwidths.

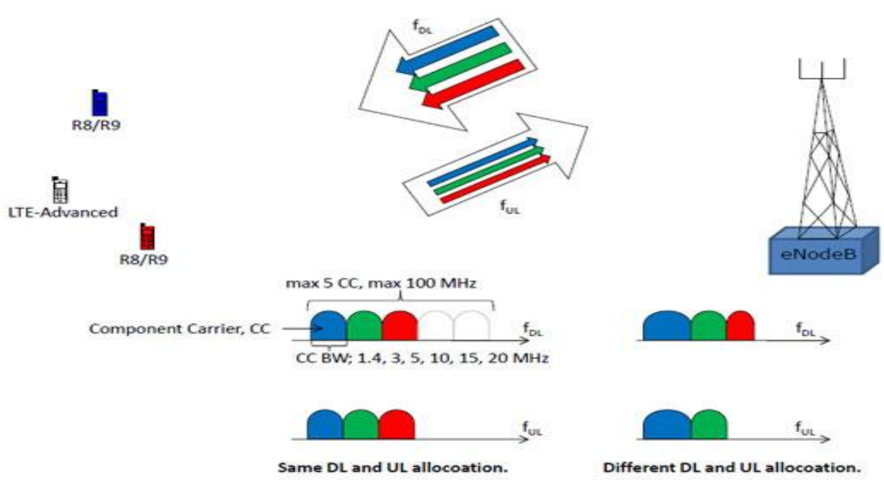


Figure 3.1 Frequency Division Duplex

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 FDD the number of aggregated carriers can be different in DL and UL. However, the number of UL component carriers is always equal to or lower than the number of DL component carriers. The individual component carriers can also be of different bandwidths. For TDD the number of CCs as well as the bandwidths of each CC will normally be the same for DL and UL [17].

3GPP is currently worked on TDD and FDD carrier aggregation is used in LTE to boost the UE's data rate. This can be achieved by user equipment receiving or transmitting data on pieces of spectrum that is spread out in different frequency bands.

In case of FDD operation there are two carriers, one for UL transmission and other for DL transmission. In other case of TDD operation there is a single frequency only one UL and DL transmission are separated in time domain on a cell base [15] (shown in figure 3.2).

The ability to aggregate the two types of spectrum TDD carriers and FDD carriers has many potential benefits. For example, TDD spectrum could be used to supplement FDD spectrum to provide additional throughput and capacity on the downlink. Conversely, FDD spectrum, which is generally at lower frequencies than TDD spectrum, could be used to achieve greater range on a TDD uplink, which is often the limiting factor for TDD coverage.

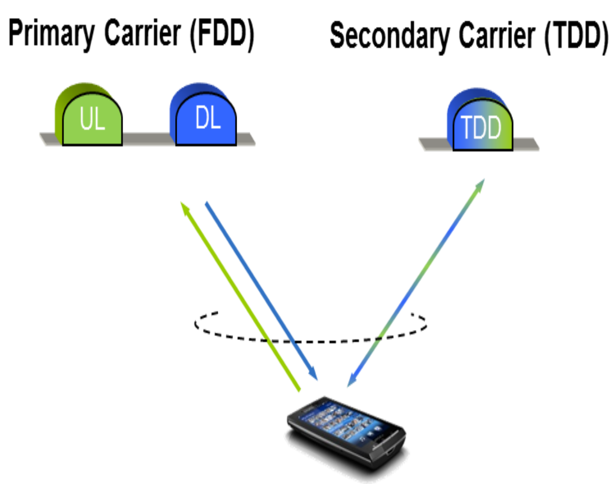


Figure 3.2Frequency/Time duplex

3.1 Carrier Aggregation Scenario

On the scenario can be determine the main idea of carrier aggregation there are two mobile handset on with carrier aggregation other without carrier aggregation, the height of mobile station (MS) in 2m and the height of base station (BS) is 30m.

We can see the figure 3.3 Of the scenario without carrier aggregation has one band with maximum 20MHZ and the other with carrier aggregation has 3 bands of 20MHz for each bands which means (20 + 20 + 20 =60MHz).

Three times as the without CA can use the band from more than one BS shown in figure below

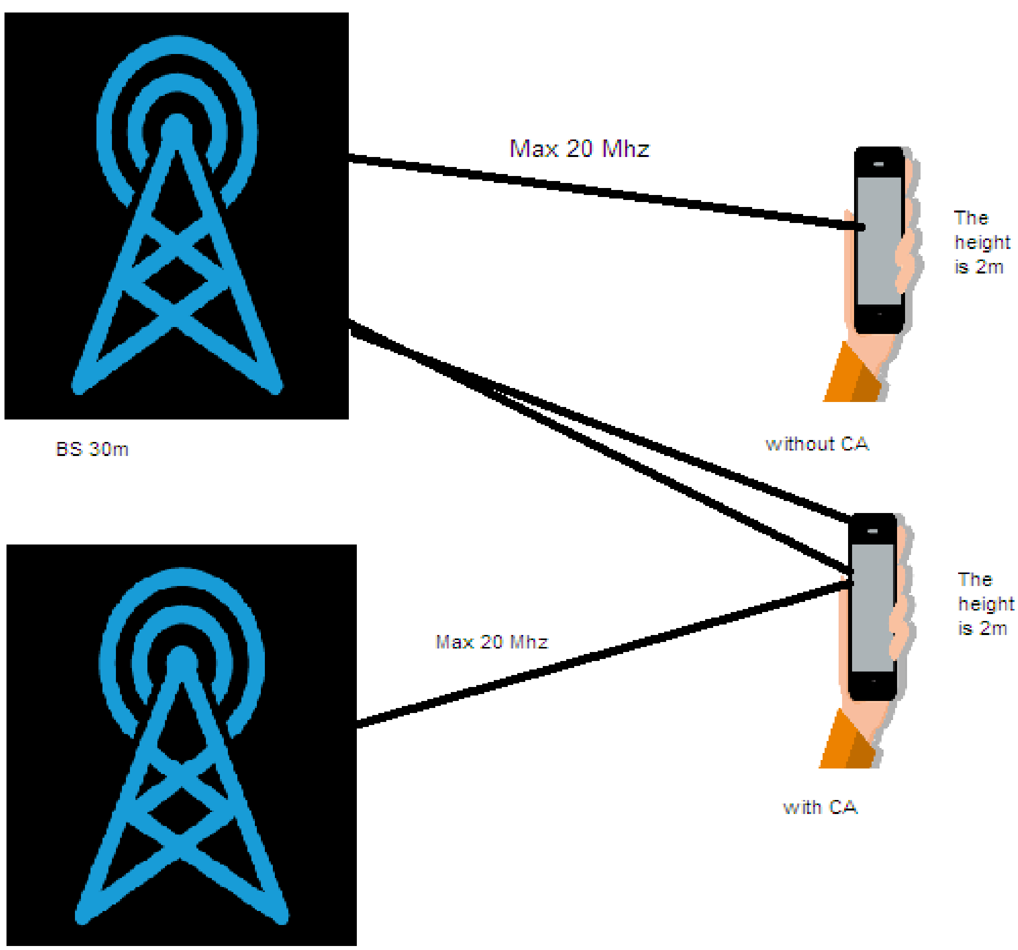


Figure 3.3 Simulation Scenario

3.2 Signal-to-Interference-Plus-Noise Ratio (SINR)

In information theory and telecommunication engineering, the **signal-to-interference-plus-noise ratio** (**SINR**[]) also known as the **signal-to-noise-plus-interference ratio** (**SNIR**) is a quantity used to give theoretical upper bounds on channel capacity (or the rate of information transfer) in wireless communication systems such as networks. Analogous to the SNR used often in wired communications systems, the SINR is defined as the power of a certain signal of interest divided by the sum of the interference power (from all the other interfering signals) and the power of some background noise. If the power of noise term is zero, then the SINR reduces to the signal-to-interference ratio (SIR). Conversely, zero interference reduces the SINR to the signal-to-noise ratio (SNR), which is used less often when developing mathematical models of wireless networks such as cellular networks [19].

The complexity and randomness of certain types of wireless networks and signal propagation has motivated the use of stochastic geometry models in order to model the SINR, particularly for cellular or mobile phone networks.

$$\boldsymbol{SINR = \frac{P}{I+N}} \tag{3.1}$$

Where

P: Power of the received signal

I: Interface of power

N: Noise power

The SINR is often expressed in decibels or dB.

3.3 Data Rate

In amount of data rate that is moved from one place to another in each time in Mb/s.

$$\boldsymbol{DR = BW * M * C} \tag{3.2}$$

$$\boldsymbol{M = 2^N}$$

Where

M: Modulation level

N: Number of bit per sample

C: coding rate

BW: available bandwidth

3.4 Throughput

The throughput as a ratio of the expected value of the payload information sent in a slot time to the expected duration of a slot time.

Is the average data rate of successful message delivery over communication in bit/S.

$$\boldsymbol{TH = \frac{DR}{T}} \tag{3.3}$$

Where

T: the time it takes for all inventories to go through the process

Throughput= Payload information sent in a slot Time/Length of a slot time. This means the throughput can be measured in bit/s.

In general terms, throughput is the rate of production or the rate at which something can be processed

When used in the context of communication network, such as Ethernet or packet radio, throughput or network throughput is the rate of successful message delivery over a communication channel the data these messages belong to may be delivered over a physical, logical link or it can pass through a certain network node throughput is usually measured in bit per second (bit/s) and sometimes in data per packets per second (p/s) or data packets per time slot.

The system throughput or aggregate throughput is the sum of the data rates that are delivered to all terminals in a network. Throughput is essentially synonymous to digital bandwidth consumption, it can be analyzed mathematically by applying the queuing theory, where the load in packets per time unit is denote as arrival rate (λ) and throughput in packets per time unit, is denoted as the departure rate (μ).

The throughput of a communication system may be affected by a various factor, including the limitations of underlying analog physical medium, available processing power of the system components and end-user behavior. When various protocol overheads are considered, useful rate of the transferred data can be significantly lower than the maximum achievable throughput, the useful part is usually referred to as good put.

3.5 Spectral Efficiency

Spectral efficiency refers to the information rate that can be transmitted over a given bandwidth in a specific communication system. It is a measure of how efficiently a limited frequency spectrum is utilized, measured in bit/s/Hz.

$$\boldsymbol{\eta = \frac{DR}{BW}} \qquad \textbf{(3.4)}$$

Where

$\eta =$ Spectral efficiency

3.6 Delay

Is the delay caused by the data rate of the link in seconds (s).

$$\textbf{Delay}=\frac{\boldsymbol{N}}{\boldsymbol{DR}} \tag{3.5}$$

3.7 Bandwidth Utilization

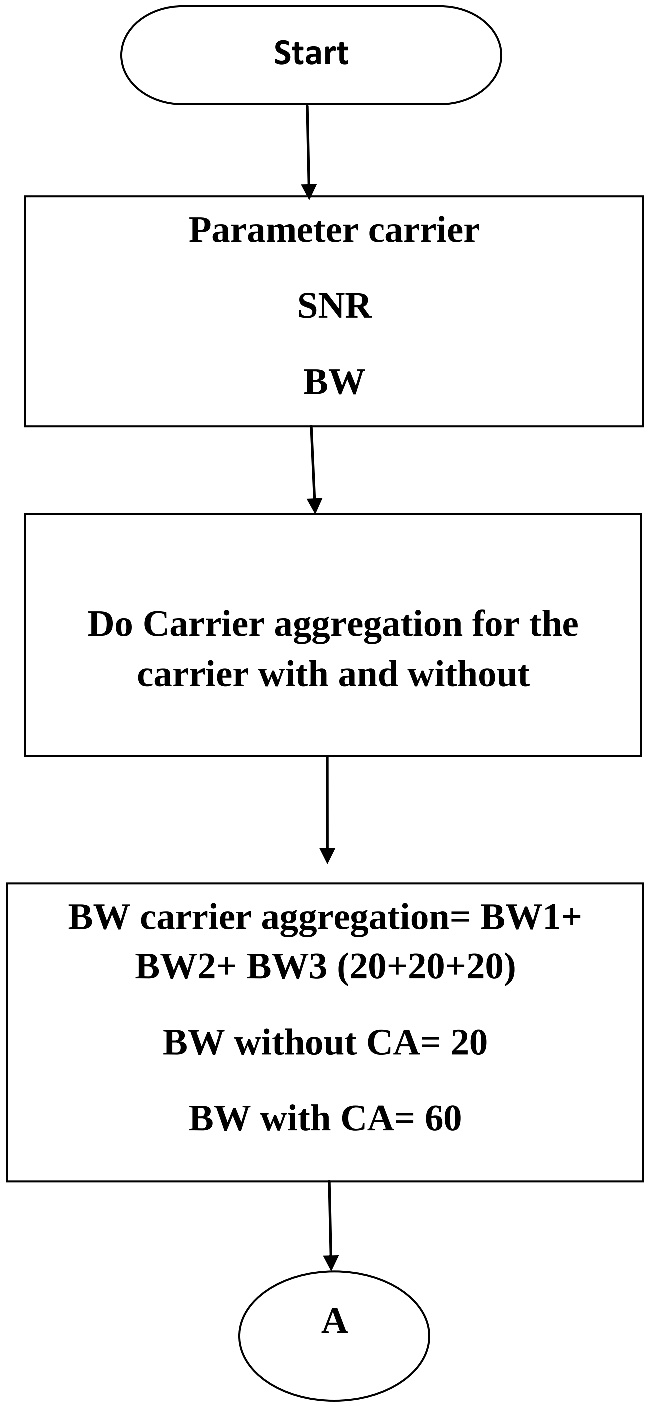
The bandwidth utilization is the percentage of bandwidth utilized of the total bandwidth available.

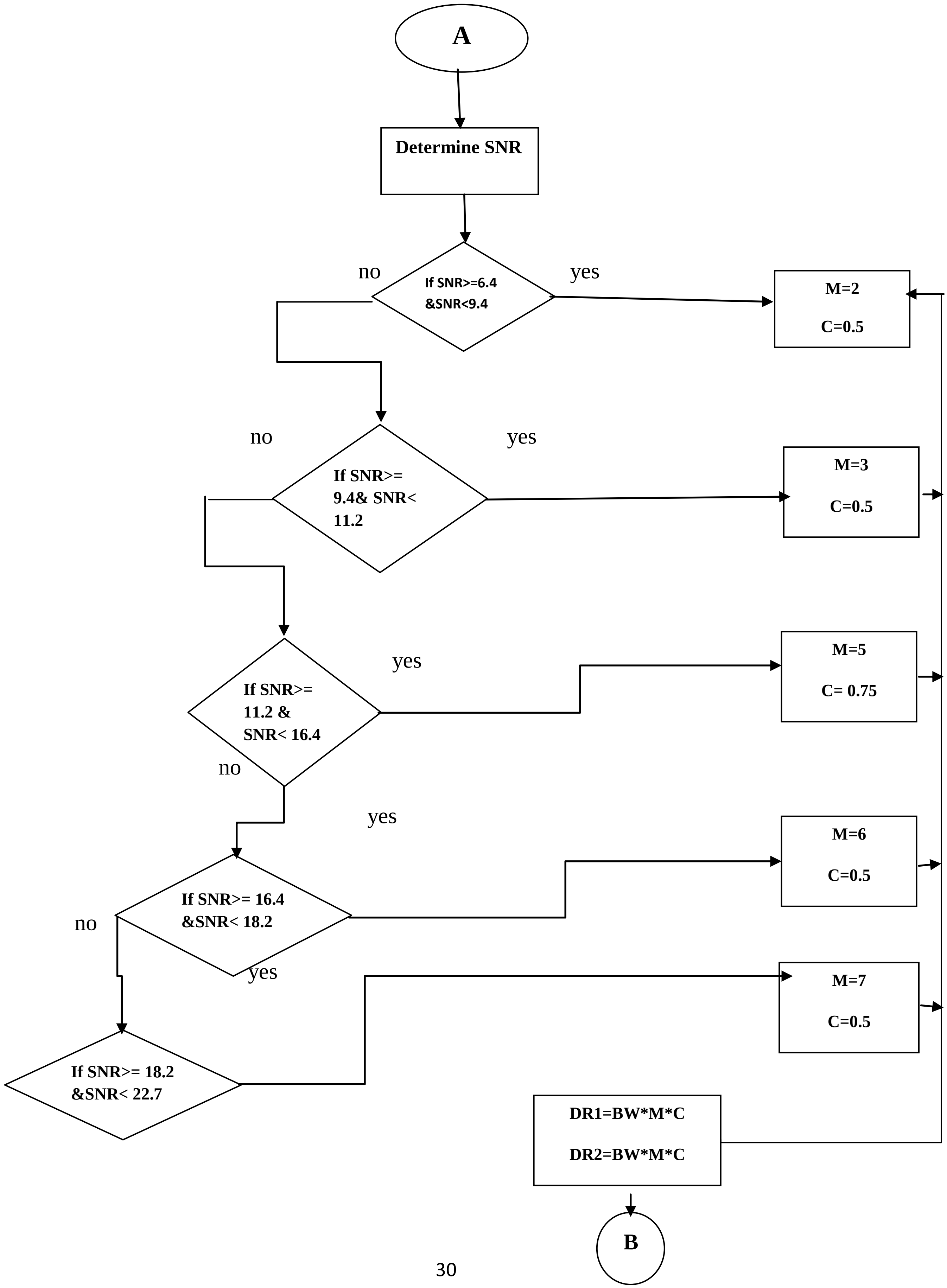
Bandwidth utilization = Bandwidth of User/Total Bandwidth

The maximum bandwidth utilization, expressed in bit/s/Hz, when using 64 QAM consisting of 64 signaling alternatives and the providing up to 6 bits of information per modulation symbol. However, the higher bandwidth utilization comes at the cost of reduced robustness to noise and interference.

3.8 Flow Chart

The figure 3.4shows the flow chart that we have three CA, BW, SINR. Each BW is 20 MHz in without carrier aggregation while with carrier we have 60 MHz




A
Determine SNR
no
yes
If SNR>=6.4
&SNR<9.4
M=2
C=0.5
no
yes
If SNR>=
9.4& SNR<
11.2
M=3
C=0.5
yes
If SNR>=
11.2 &
SNR< 16.4
no
M=5
C= 0.75
yes
M=6
C=0.5
If SNR>= 16.4
&SNR< 18.2
no
yes
M=7
C=0.5
If SNR>= 18.2
&SNR< 22.7
DR1=BW*M*C
DR2=BW*M*C
B

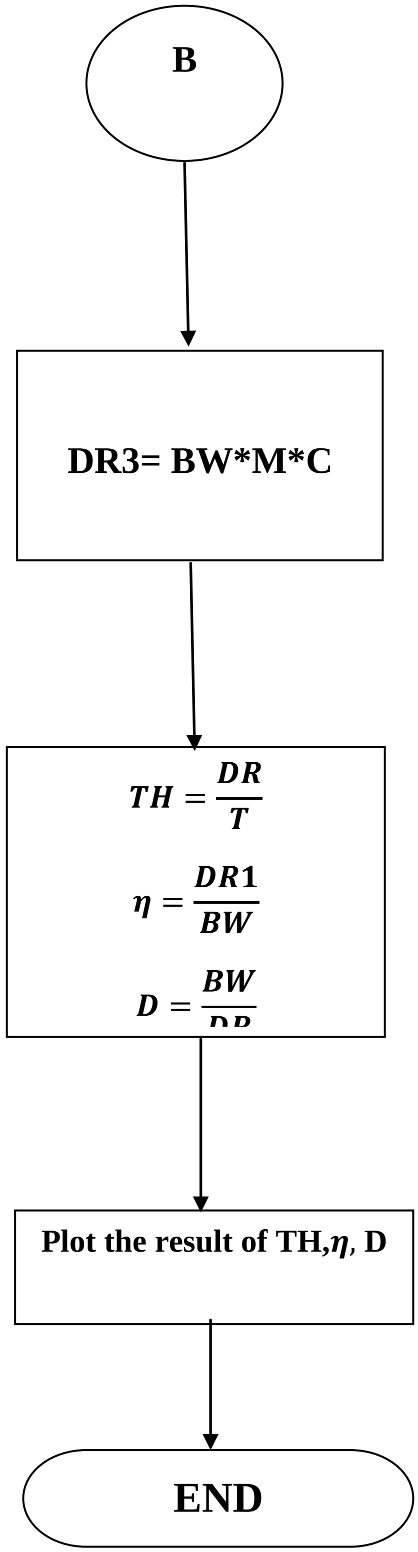


Figure 3.4 Show flow chart of carrier aggregation

Chapter Four

Simulation and Results

4.1 Simulation Description

This Simulation investigates five aspects of CA which are SNIR, data rate, throughput, spectral efficiency, delay and bandwidth.

Bandwidth is the difference between upper and lower frequencies in a continuous set of frequencies. It is typically measured in hertz and may sometimes refer to pass band bandwidth or sometimes to baseband bandwidth depending on context [19].

Pass band bandwidth is the difference between the upper and lower cut off frequencies for example, a band pass filter, a communication channel or a signal spectrum. In the case of a low pass filter or baseband signal, the bandwidth is equal to its upper cutoff frequency.

4.2 Simulation Parameter

In this part we will discuss the design procedure of the LTE-A simulator with the simulation Parameters (shown in table 4.1) in the details parameter.

The simulation are performed in CA by regular hexagonal Cellular layout with BW, one FC, one HB and G and data simulation setup follows the assumption of CA.

.

Table 4.1 Simulation Parameters

Parameters	Value
Time	0.2s
Bandwidth non-CA (BW)	20 MHz
Bandwidth CA (BW)	60 MHz
Frequency Carrier	500 KHz
Height Base Station (HB)	30 m
Height Mobile	2 m
Power (P)	2 dB
Power Gain (G)	2 dB
Data	2 bits
Interference	2 dB

4.2.1 Bandwidth

Figure 4.6 shows the bandwidth we have three BW CA in non-CA we have 20 MHz while CA we have 60 MHz

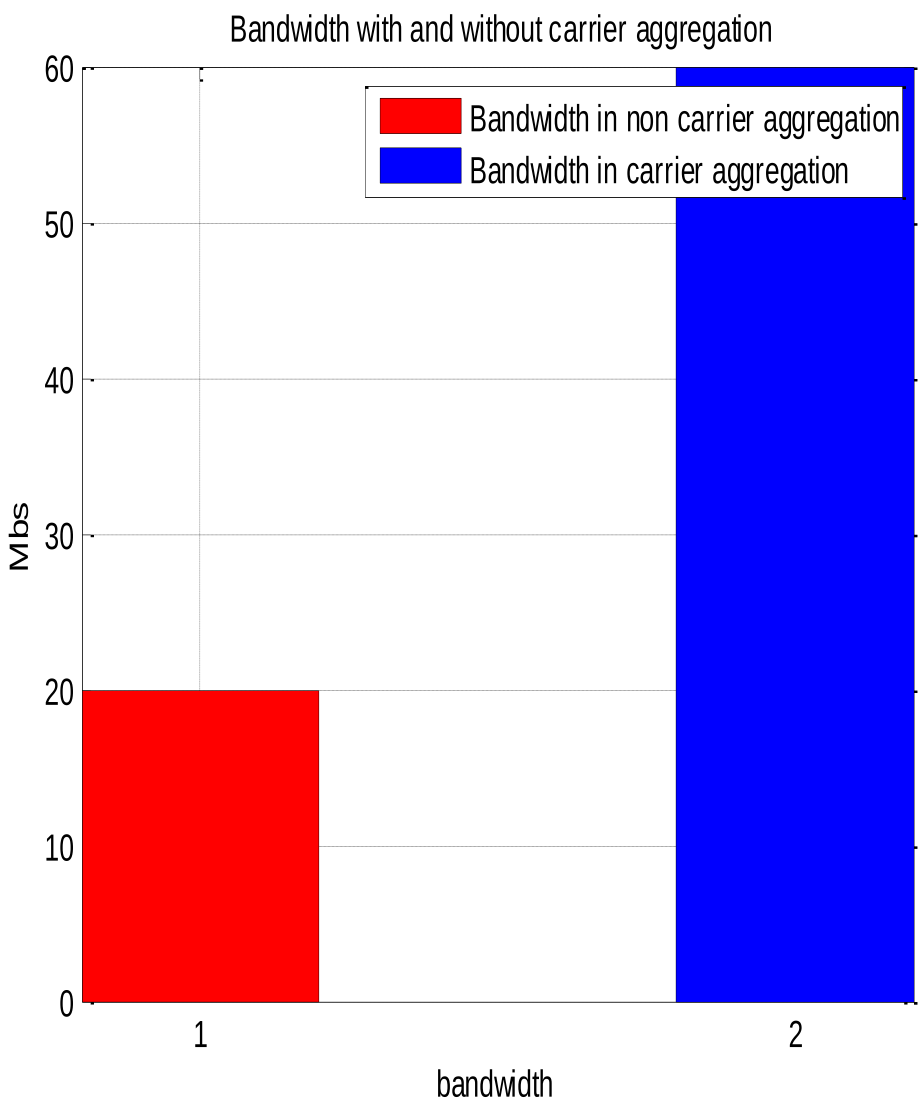


Figure 4.1 Shows Bandwidth vs time

4.2.2Signal-to-Interference-Plus-Noise Ratio (SINR)

Figure 4.2 shows the simulation result of SINR with and without CA. After we applied the code, the result will show the same line in both carrier and same result.

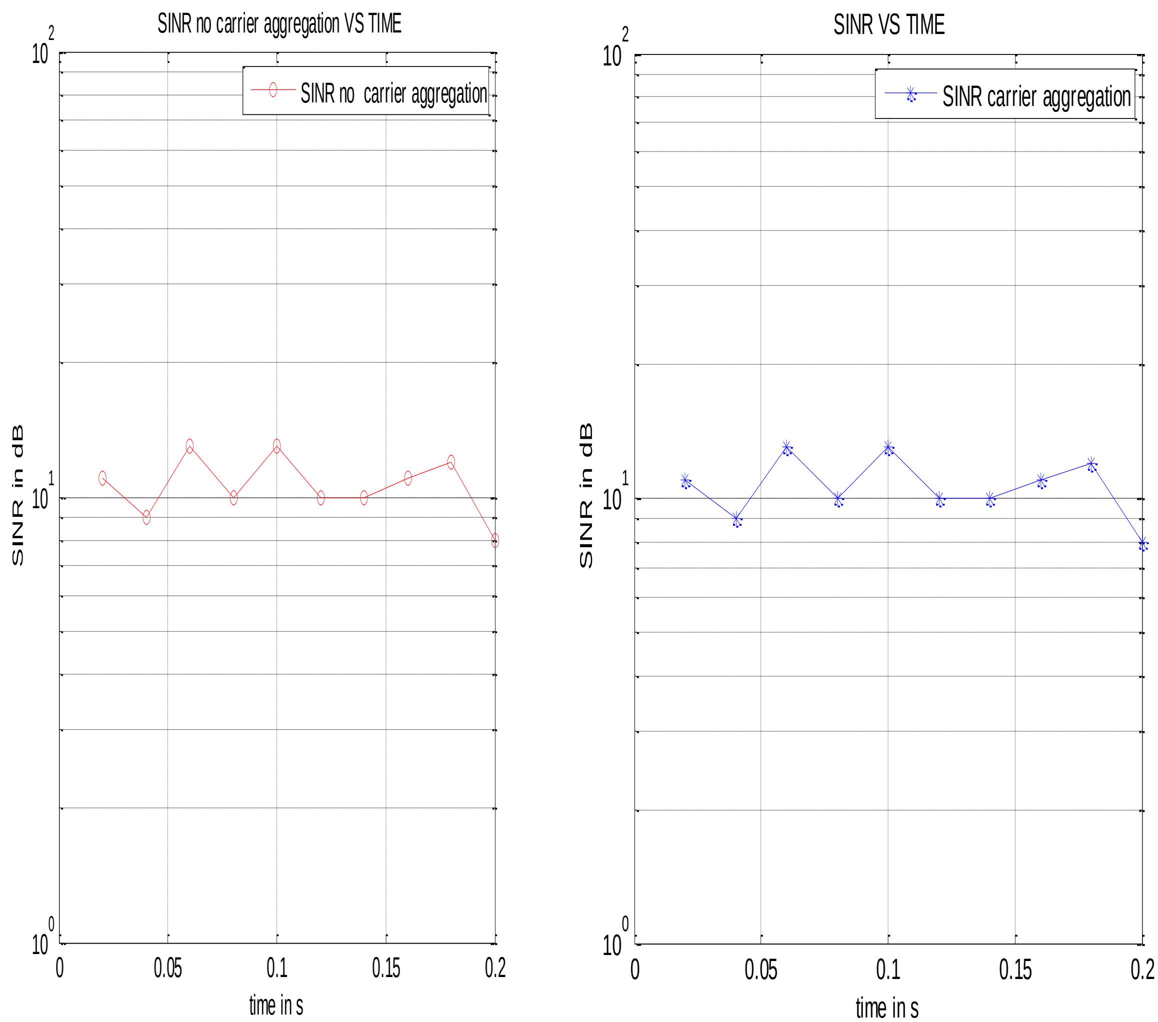


Figure 4.2 Shows SINR vs Time

4.2.3 Data Rate

Figure 4.3 shows the result of data rate with and without CA. After we applied the code the data rate increased from non-CA to CA for bandwidth range (178%) if we depend in 20 MHz for each carrier, due to high bandwidth in CA.

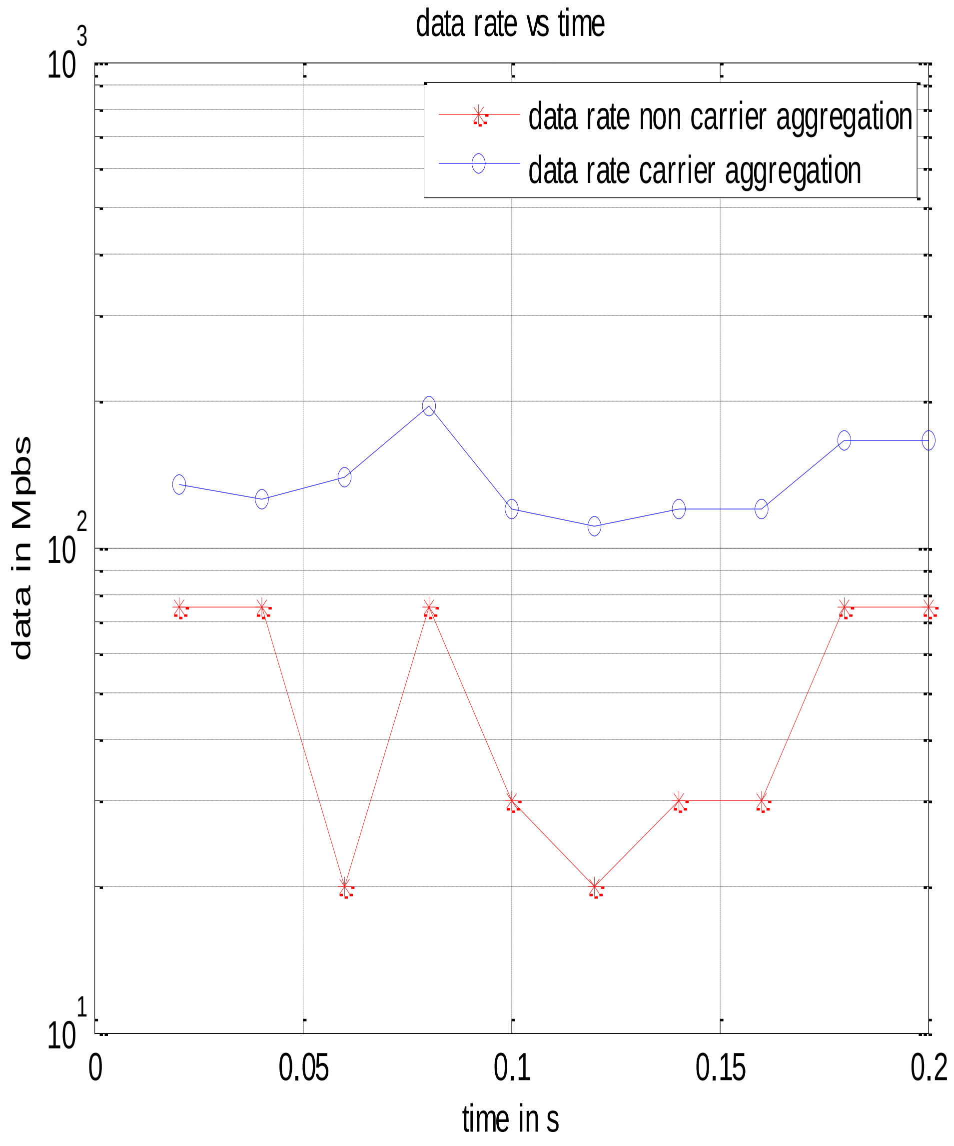


Figure 4.3 Shows Data Rate vs Time

4.2.4 Throughput

Figure 4.4 shows the result of throughput with and without CA. After we applied the code the throughput increased from non-CA to CA for bandwidth range (178%) if we depend in 20 MHz for each carrier, due to high data rate in CA.

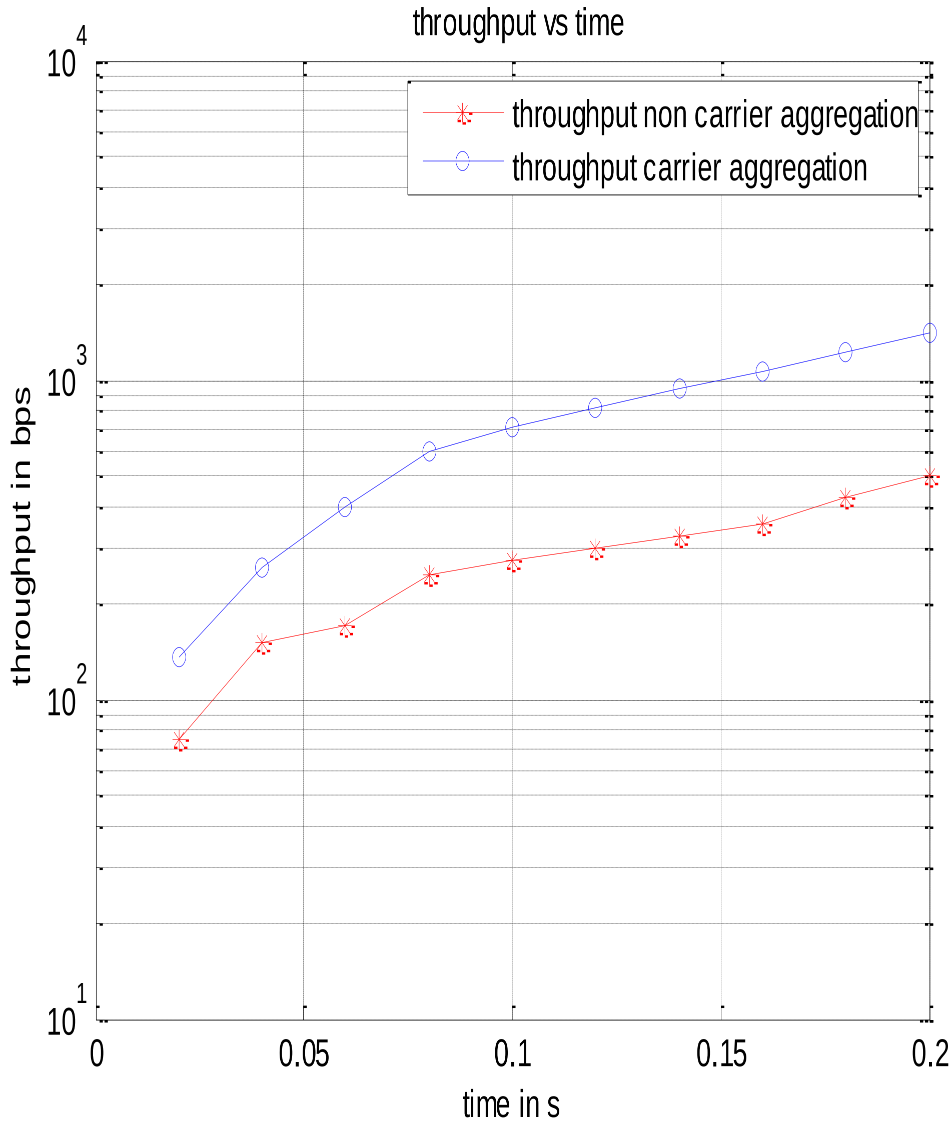


Figure 4.4 Shows Throughput vs Time

4.2.5 Spectral Efficiency

Figure 4.5 shows the result of spectral efficiency with and without CA. After we applied the code the spectral efficiency increased from non-CA to CA for bandwidth range (178%) if we depend in 20 MHz for each carrier, due to high data rate in CA.

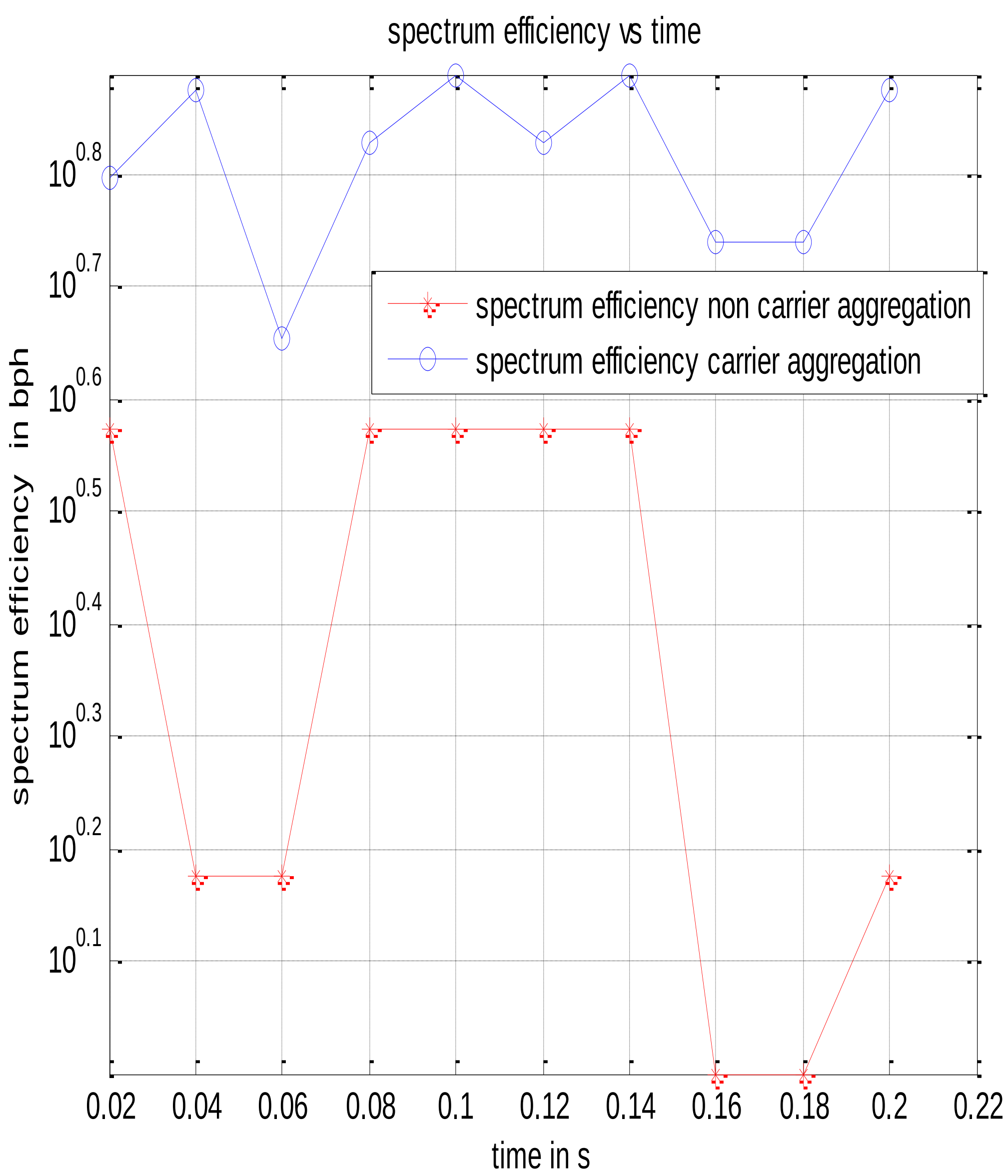


Figure 4.5 Shows spectrum Efficiency vs Time

4.2.6 Delay

Figure 4.6 shows the result of delay with and without CA. After we applied the code the delay decreased from non-CA to CA for bandwidth range (178%) if we depend in 20 MHz for each carrier, due to high data rate in CA.

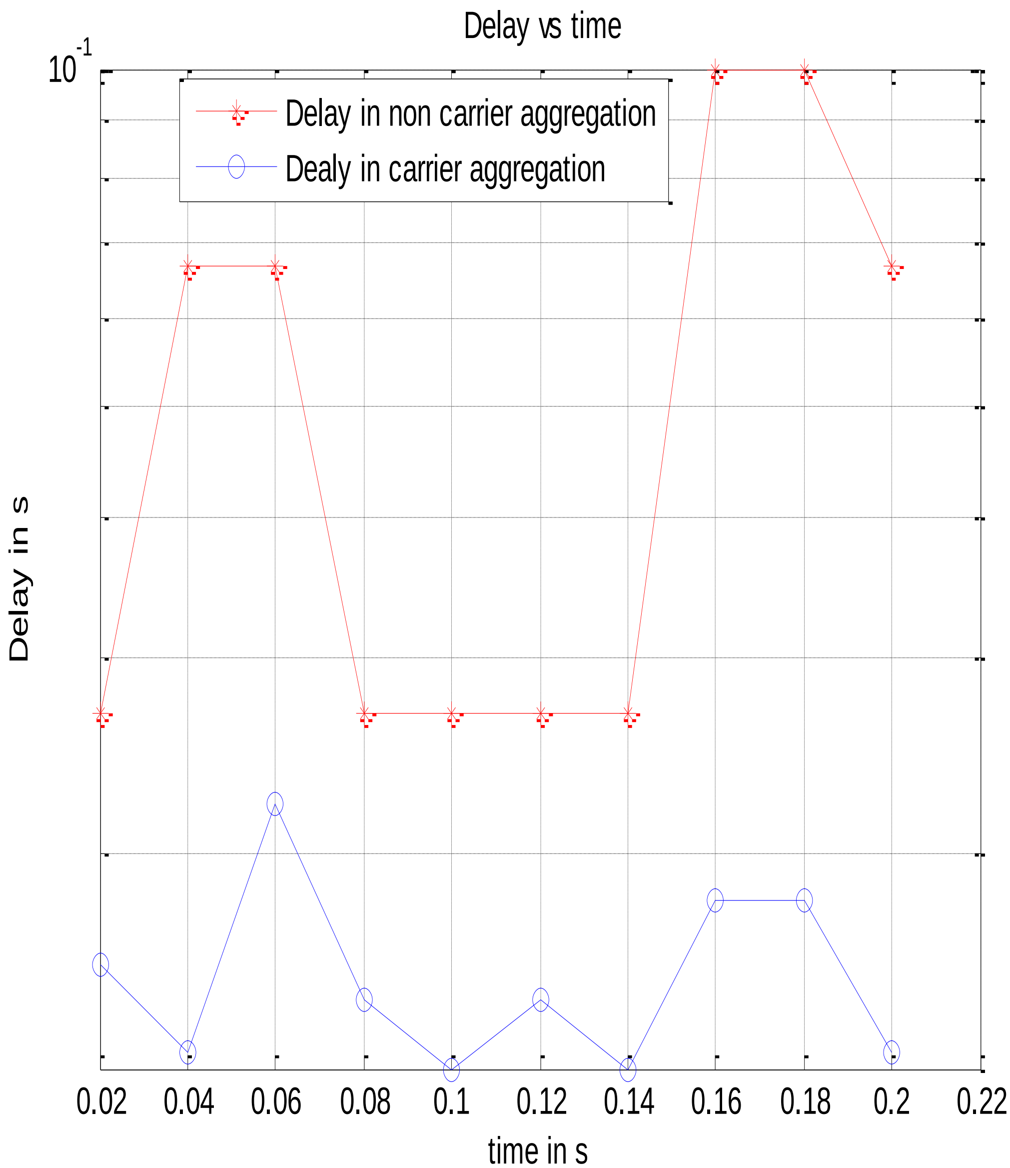


Figure 4.6 Shows Delay vs Time

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

This thesis presented a study on performance of LTE-Advanced feature referred as Carrier Aggregation. The literature part gives an overall description on Long Term Evolution, the LTE-A techniques and Other LTE-A technologies. The characteristics and functionalities of Carrier Aggregation are the main part of the literature review. The CA performance was evaluated with measurements and the results are presented in this thesis.

The simulation compared into two different scenarios which have parameters. The first is without CA scenario indicates when non CA. In this case we are using 20MHz of bandwidth. The other scenario is with CA it transmits/receives three carrier aggregations. This CA can be improved in the system performance; they are SINR, Data Rate, Throughput, Spectral efficiency and Delay. The SINR CA is the same to without CA. The data rate increase up to 178%, the throughput increases after CA been applied, the amount of increasing up to 178%, the spectral efficiency has been improved to 178% and delay decreased due to 178%.

5.2 Recommendations

In the future need to do more study about Networks that support three carriers that are already emerging. Testing 3CC system would be the clear next item to study in CA. More carriers create more scenarios for cell management and load balancing, and there should be more possibilities for network optimization.

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Appendix

```
clearall,clc, close all
Bw1=20;
Bw2=20;
Bw3=20; % bandwidth system MHz
%BW_carrier_agregation=Bw1+BW2+BW3;
T=0.2; %sec
Fc=500; %kHZ
hB=30; %meter
hM=2;%meter
Pt=30; %power tx(dB)
G=2; %power gain(db)
data=2; %the data 2k bps
Dr=zeros(1,10);
DR1=zeros(1,10);
DR2=zeros(1,10);
DR3=zeros(1,10);
M1=zeros(1,10);
M2=zeros(1,10);
M3=zeros(1,10);
C1=zeros(1,10);
C2=zeros(1,10);
C3=zeros(1,10);
I=2;
Result=zeros(10,12);
pr1=randi([10 15],1,10);
SNR1=(pr1+G)-((randi([1 2],1,10)+I));
pr2=randi([10 15],1,10);
SNR2=(pr2+G)-((randi([1 2],1,10)+I));
```

```
pr3=randi([10 15],1,10);
SNR3=(pr3+G)-((randi([1 2],1,10)+I));
Result(:,2)=SNR1
Result(:,3)=SNR2
Result(:,4)=SNR3
for n= 1:10
Result(n,1)= n * 0.02;

if   ( SNR1(n) >=6.4 & SNR1(n) < 9.4  )
M1(n)=2;
C1(n)=0.5;
elseif ( SNR1(n) >=9.4 & SNR1(n) < 11.2  )
M1(n)=3;
C1(n)=0.5;
elseif ( SNR1(n) >=11.2 & SNR1(n) < 16.4  )
M1(n)=5;
C1(n)=0.75;
elseif ( SNR1(n) >= 16.4 & SNR1(n) < 18.2  )
M1(n)=6;
C1(n)=0.5;
elseif ( SNR1(n) >=18.2 & SNR1(n) < 22.7  )
M1(n)=7;
C1(n)=0.5;
end;
DR1(n)=Bw1*M1(n)*C1(n);
DR1(n)=DR1(n)/1000000;
Result(n,5)=DR1(n);
if   ( SNR2(n) >=6.4 & SNR2(n) <  9.4)
M2(n)=2;
C2(n)=0.5;
elseif ( SNR2(n) >=9.4 & SNR2(n) <11.2  )
M2(n)=3;
```

```
C2(n)=0.5;
elseif ( SNR2(n) >=11.2 & SNR2(n) <16.4  )
M2(n)=4;
C2(n)=0.75;
elseif ( SNR2(n) >=16.4 & SNR2(n) <18.2  )
M2(n)=5;
C2(n)=0.5;
elseif ( SNR2(n) >=18.2 & SNR2(n) <22.7  )
M2(n)=6;
C2(n)=0.5;
end;
DR2(n)=Bw2*M2(n)*C2(n);
DR2(n)=DR2(n)/1000000;
if   ( SNR3(n) >=6.4 & SNR3(n)<9.4  )
M3(n)=2;
C3(n)=0.5;
elseif ( SNR3(n) >=9.4 & SNR3(n) < 11.2  )
M3(n)=3;
C3(n)=0.5;
elseif ( SNR3(n) >=11.2 & SNR3(n)<16.4  )
M3(n)=4;
C3(n)=0.75;
elseif ( SNR3(n) >=16.4 & SNR3(n)<18.2  )
M3(n)=5;
C3(n)=0.5;
elseif ( SNR3(n) >=18.2 & SNR3(n)<22.7  )
M3(n)=6;
C3(n)=0.5;
end;
DR3(n)=Bw3*M3(n)*C3(n)
DR3(n)=DR3(n)/1000000;
```

```
%DR
Result(n,5);
Result(n,6)=DR1(n)+DR2(n)+DR3(n)
%TH
Result(1,7)=DR1(1)/T
Result(1,8)=[DR1(1)+DR2(1)+DR3(1)]/T
if n >= 2
Result(n,7)=Result(n-1,7)+DR1(n)
Result(n,8)=Result(n-1,8)+DR1(n)+DR2(n)+DR3(n)
end
%SE
Result(n,9)=DR1(n)/Bw1
% Result(n,10)=(DR1(n)+DR2(n)+DR3(n))/(Bw1+Bw2+Bw3)
V1(n)=DR1(n)/Bw1
V2(n)=DR2(n)/Bw2
V3(n)=DR3(n)/Bw3
Result(n,10)=V1(n)+V2(n)+V3(n)
%DELAY
Result(n,11)= data/(DR1(n))
Result(n,12)=data/((DR1(n)+DR2(n)+DR3(n)))
end;
Result(:,9)
Result
M1
C1
Bw1
DR1
M2
C2
Bw2
DR2
```

```
M3
C3
Bw3
DR3
%****************************
%SINR 1 2 3
figure
%subplot(3,1,1);
semilogy(Result(:,1),Result(:,2),'bo-')
%grid
xlabel('time in s')
ylabel('SNR1 in dB')
title('SNR no carrier aggregation VS TIME')
legend('SNR no  carrier aggregation')
%subplot(3,1,2);
%semilogy(Result(:,1),Result(:,3),'bo-')
grid
%xlabel('time in s')
%ylabel('SNR 2 in dB')
%title('SNR carrier 2 VS TIME')
%legend('SNR2 carrier 2')
%subplot(3,1,3);
%semilogy(Result(:,1),Result(:,4),'k+-')
%grid
%xlabel('time in s')
%ylabel('SNR 3 in dB')
%title('SNR carrier 3 VS TIME')
%legend('SNR3 carrier 3')
%*************SNR carriers agrigation
figure
semilogy(Result(:,1),(Result(:,2)),'r*-')
```

```
%hold on
%semilogy(Result(:,1),Result(:,2),'r*-')
%hold on
grid
xlabel('time in s')
ylabel('SNR in dB')
title('SNR VS TIME')
legend('SNR carrier aggregation')
%****************data rate
figure
semilogy(Result(:,1),Result(:,5)*1000000,'r*-')
hold on
semilogy(Result(:,1),Result(:,6)*1000000,'bo-')
hold on
grid
xlabel('time in s')
ylabel('data in Mpbs')
title('data rate vs time')
legend('data rate non carrier aggregation','data rate carrier aggregation')
%*******************throughput
figure
semilogy(Result(:,1),Result(:,7)*1000000,'r*-')
hold on
semilogy(Result(:,1),Result(:,8)*1000000,'bo-')
hold on
grid
xlabel('time in s')
ylabel('throughput in bps')
title(' throughput vs time')
legend('throughput non carrier aggregation','throughput carrier aggregation')
%********************spectrum efficiency
```

```
figure
semilogy(Result(:,1),Result(:,9)*1000000,'r*-')
hold on
semilogy(Result(:,1),Result(:,10)*1000000,'bo-')
grid
xlabel('time in s')
ylabel('spectrum efficiency  in bph')
title(' spectrum efficiency vs time')
legend('spectrum efficiency non carrier aggregation','spectrum efficiency carrier aggregation')
%*****************Dealy
figure
semilogy(Result(:,1),Result(:,11)/1000000,'r*-')
hold on
semilogy(Result(:,1),Result(:,12)/1000000,'bo-')
grid
xlabel('time in s')
ylabel('Delay in s ')
title(' Delay vs time')
legend('Delay in non carrier aggregation','Dealy in carrier aggregation')
%*****************Bandwith
figure
bar([Bw1 0],0.4,'r')
hold on
bar([0 Bw1+Bw2+Bw3],0.4,'b')
grid
xlabel('bandwidth')
ylabel('Mbs')
title('Bandwidth with and without carrier aggregation')
legend('Bandwidth in non carrieraggregation','Bandwidth in carrier aggregation')
```