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Bachelor of Science Thesis

A Novel Genetic Algorithmic Approach to Coordinate Base Station Transmissions in LTE Cellular Networks

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Abstract

This thesis addresses the inter-cell interference problem experienced in Long Term Evolution (LTE) networks. In the case of no coordination between base stations and while frequency reuse 1 scheme is utilized, several transmissions may be occur in the downlink at the same time, leading to high interference levels, especially for adjacent cells. Therefore, a possible solution for this problem is being presented. Firstly, a throughput optimization problem is formulated in terms of coordinated base station scheduling and secondly, it is shown that accommodating base stations' transmissions into subframes in different order, results in different system throughput. By means of the MATLAB software, a genetic algorithm optimal search is applied to the optimization problem and a near-optimal solution is obtained quickly in terms of base station scheduling map. Afterwards, the performance of this approach is compared with other legacy solutions. Finally, the significant superiority is shown in terms of effectiveness at the expense of little control overhead in the LTE Evolved Packet Core (EPC). This work has been submitted for participation in the context of the Future Network and Mobile Summit 2013 conference, which is going to be held in Lisbon, Portugal.

Keywords: LTE, Genetic Algorithms, Base station scheduling, ABSF.

Abstract (Greek)

Η παρούσα πτυχιακή εργασία ασχολείται με το πρόβλημα των παρεμβολών που εμφανίζεται στα κυψελοειδή δίκτυα τεχνολογίας Long Term Evolution (LTE). Στην περίπτωση που οι σταθμοί βάσης (Base Stations - BS) δε συνεργάζονται άμεσα και χρησιμοποιείται η τεχνική επαναχρησιμοποίησης μόνο μίας (1) συχνότητας, υπάρχουν αρκετές πιθανότητες, να δημιουργηθούν κατερχόμενες μεταδόσεις (downlink) την ίδια στιγμή, με αποτέλεσμα να οδηγήσει σε πολύ υψηλά επίπεδα παρεμβολών, ειδικά σε παρακείμενους σταθμούς βάσης. Κατ'επέκταση, θα υπάρξει σημαντική μείωση της απόδοσης του δικτύου. Η λύση που προτείνεται στην εργασία αυτή έχει ως εξής: Πρώτον, διατυπώνεται ένα πρόβλημα βελτιστοποίησης της ρυθμοαπόδοσης όσον αφορά τον χρονοπρογραμματισμό των σταθών βάσης. Δεύτερον, παρατηρούνται διαφορετικές ρυθμοαποδόσεις (thoughput), όταν προγραμματίσουμε τις μεταδόσεις των σταθμών βάσης με διαφορετική σειρά. Αυτό επιτυγχάνεται, τοποθετώντας τις μεταδόσεις αυτές σε subframes με συγκεκριμένο τρόπο. Με τη βοήθεια του λογισμικού MATLAB και της εργαλειοθήκης των Γενετικών Αλγορίθμων (GA), επιτυγχάνεται λύση, η οποία είναι σχεδόν βέλτιστη και παρέχεται σε μορφή ενός πίνακα. Ο πίνακας δείχνει τη σειρά μετάδοσης των σταθμών βάσης στο δίκτυο. Τέλος, η παραπάνω λύση συγκρίνεται με άλλες ήδη γνωστές - συμβατικές λύσεις και στη συνέχεια παρουσιάζονται τα αποτελέσματα, δείχνοντας έτσι τη σημαντική υπεροχή της πρώτης, επιβαρύνοντας ελάχιστα το Evolved Packet Core (EPC), στο οποίο υλοποιείται η προτεινόμενη προσέγγιση επίλυσης του προβλήματος των παρεμβολών. Η εργασία υποβλήθηκε προς εξέταση και συμμετοχή στο συνέδιο Future Network and Mobile Summit 2013, που θα διεξαχθεί στη Λισαβόνα της Πορτογαλίας.

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Moschos Stylianos

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List of Acronyms

3GPP	Third Generation Partnership Project
HARQ	Hybrid Automatic Repeat reQuest
CDF	Cumulative Distribution Function
CDM	Code Division Multiplexing
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CQI	Channel Quality Information
EDGE	Enhanced Data rates for GSM Evolution
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
GPRS	General Packet Radio Service
HARQ	Hybrid ARQ
HSDPA	High-Speed Downlink Packet Access
HSUPA	High-Speed Uplink Packet Access
HSPA	High-Speed Packet Access
ICI	Inter-Cell Interference
IP	Internet Protocol
ISI	Inter Symbol Interference
LTE	Long-Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAR	Peak-to-Average Ratio
PDF	Probability Density Function
PHY	PHYsical layer
QoS	Quality-of-Service
RAN	Radio Access Network
RLC	Radio Link Control
RRM	Radio Resource Management

RU	Resource Unit
SINR	Signal-to-Interference-and-Noise Ratio
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access

Chapter 1

Introduction

Wireless communications is, by any measure, the fastest growing segment of the communications industry. More specifically, the number of mobile users is growing swiftly and applications require day by day higher data rates, so that the current 4th generation (4G) of broadband wireless technologies, such as 3GPP Long Term Evolution Advanced (LTE-A) [1] and IEEE 802.16m [2], has to be empowered with new solutions to satisfy this increasing demand. Considering the high cost for cellular resources, both in terms of frequencies and also in capital expenditures for the antenna sites, one of the most important design goals is achieving high spectral efficiency. In this context, it has been shown that frequency reuse 1 can provide substantial improvements in terms of efficient utilization of the insufficient and exprensive wireless resources. This implies that neighboring Base Stations (BS) should be allowed to transmit on all available time-frequency resourse blocks simultaneously, thus, causing strong interference to each others' users. This contrasts with interference mitigation and / or cancellation techniques that have been used for many years in the past, which basically exploited orthogonality of frequency and / or spatial resources [3]. More recently, advanced solutions have been designed that manage to actively reduce or cancel interference when orthogonality cannot be guaranteed [4,5]. Moreover, using frequency reuse 1 scheme is often the only viable solution for commercial operators, since the number of frequency bandwidths available for commercial systems is very limited, so that few operators world-wide have at their disposal more than 1 or 2 frequencies for 3G / 4G systems.

Motivated by such considerations, the focus of this thesis is on cooperative interference mitigations schemes in cellular networks adopting frequency reuse 1. Aiming at scalable and flexible solutions that can be built on top of existing infrustructures can facilitate their deployment and diffusion. The Genetic Algorithmic (GA) solution, that is presented, requires base station cooperation, which in turn requires control messages to be exchanged over the LTE Evolved Packet Core (EPC). The messages have to be generated and exchanged periodically, thus having an impact similar to many “Hello” messages deployed for other protocols. Nonetheless, the aim of this thesis is the attainment of a significantly boosting network prerformance in terms of achievable throughput. In order to reach this target, a mechanism is defined to schedule base station activities in each subframe, thus mitigating interference.

1.1 Thesis Outline

The document is organized in 6 chapters. Chapter 2 provides a short historical review of the wireless telecommunicion systems and ends up with a brief overview of the LTE system, given also the most important technologies that have been already used to achieve the LTE-Advanced goals. Chapter 3 analyzes the interference problem and presents the reasons that cause it. Next, in chapter 4, some solutions that have been proposed so far are presented in detail. Chapter 5 presents a new approach that uses genetic algorithms by means of MATLAB software and finally chapter 6 provides the conclusions of this work and some future directions.

Chapter 2

Background

This chapter starts with a historical review of telecommunications, from the 1st generarion networks to the current 4th Generation. Next, there is an overview of the LTE system, its architecture and the advanced technologies it uses in order to achieve the specifications set by IMT-Advanced [6]. Most of the material related to the first part, i.e. historical review, is taken from [7]. The parts related to LTE Releases and specifications were taken from the 3GPP website. References [1][8-9] helped a lot to acquire deeper knowledge on how the technologies of the LTE sytems actually operate.

2.1 Historical Review

First ever approaches of wireless telecommunication networks in early 80's were analog (1G) and have been replaced by digital approaches. The digital wireless telecommunication networks (2G) started with a Circuit-Switched (CS) approach called Global System for Mobile Communication, known in its abbreviated form as GSM. The CS approach was well known form the fixed telephony system and allowed the compatibility of both systems. As the Internet and the Mobile Services emerged and the performance of Embedded Systems increased, new services were available. The idea of bringing data transmission to mobile devices led to the first packet-switching extension of GSM, which is called GPRS (General Packet Radio Service) and further EDGE (Enhanced Data Rate for GSM Evolution). The continuous growth of subscribers led to several GSM extensions and finally to UMTS (Universal Mobile Telecommunication System), which became very popular as the first 3G (3rd Generation) technology. It was standardized by 3GPP (3rd Generation Partnership Project). UMTS required new base stations and new frequencies, which made the deployment more difficult and cost-intensive. On the other hand, UMTS supports much higher data rates and enables advanced mobile services. Further evolutions of UMTS are HSDPA (High-Speed Downlink Packet Access), HSUPA (High-Speed Uplink Packet Access) and HSPA+, which support data rates close to fixed ADSL links.

There are also competing technologies to GSM / UMTS. The main competitor is IS-95 (also known as cdmaOne) (2G) and CDMA2000 (Code Division Multiple Access) (3G). They are also widely spread, especially in Asia and North America. GSM / UMTS and IS-95 / CDMA2000 are not compatible with each other.

The Internet has shown that packet-switching telephony (e.g. VoIP, SIP) is a reliable alternative to native circuit-switched telephony. This leads to the conclusion that the complex circuit-switched core network is no longer needed. Therefore 4G mobile networks do not support any circuit-switched domain. In addition the continuous growth of mobile subscribers and data transfer shows that more advanced and efficient telecommunication networks with the latest and/or new technologies are required. The evolution of mobile handsets from simple phones to general purpose computers (Smartphones) is a key characteristic for the new generation networks. These mobile devices allow further mobile services that go beyond telephony and messaging. Especially new service scenarios such as IPTV, Mobile Payment and Real-Time gaming require high bandwidth, high availability and of course very low delays. Furthermore, 4G networks can be used to bring high speed access to more rural areas, which so far are not covered by the fixed high speed networks. Figure 1 shows the historical evolution of the technologies over more than twenty years, subject to the increasing mobility feature and the increasing data rates.

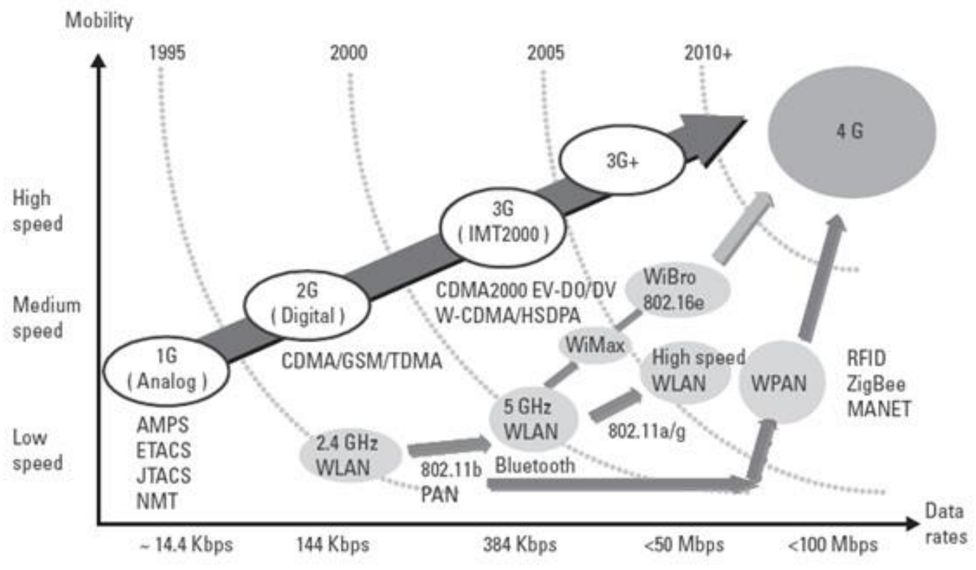

Figure 1: Evolution of the telecommunication networks [25].

The ITU-R (International Telecommunication Union – Radiocommunication Sector) has specified the IMT–Advanced [6] (International Mobile Telecommunications Advanced) requirements for 4G standards. Nevertheless the term “4G” is widely used for advanced telecommunication networks that are based on OFDMA (Orthogonal Frequency Division Multiple Access), use different forms of MIMO (Multiple Input – Multiple Output) technology, e.g. Single User (SU)-MIMO, Multiple User(MU) – MIMO and have an IP-only architecture. The above mentioned technologies will be explained later on in the current chapter.

2.2 LTE

Motivated by the growth of the users and the increasing demand, in 2004 3GPP started the work on the Long Term Evolution in UMTS (known as LTE). The development of LTE was driven by certain aspects. Firstly, the wireline data networks improved and higher data rates were possible. This led to new applications and services which are often refered to as “Web 2.0”. The current technological approaches of 2004, i.e. UMTS / HSDPA / HSPA (+), were capable to deliver this first generation of Web 2.0 services. But it was obvious that this kind of services would evolve and the demands of higher bandwidth and lower delays would grow dramatically. Secondly, in order to cover the mentioned tremendous growth of mobile subscribers (Figure 2), new technologies were required. In addition competing standards, for instance WiMAX (IEEE 802.16), were and still are under development and the competition for 3GPP gets more challenging. Furthermore, the prices reduction for data delivery made it essential for the telecommunication companies (as key partner of 3GPP) to have a competing and efficient telecommunication archtitecture.

Fixed packet-switched networks have shown their capability to fulfill these requirements. Therefore an all-IP approach is consequential. With the LTE technology the mobile network operators are not required to maintain an additional complex circuit-switched domain. Some technologies, such as SIP (Session Initiation Protocol) or IMS (IP Multimedia Subsystem) show that traditional services, e.g. telephony and messaging, can be established in all-IP networks reliably.

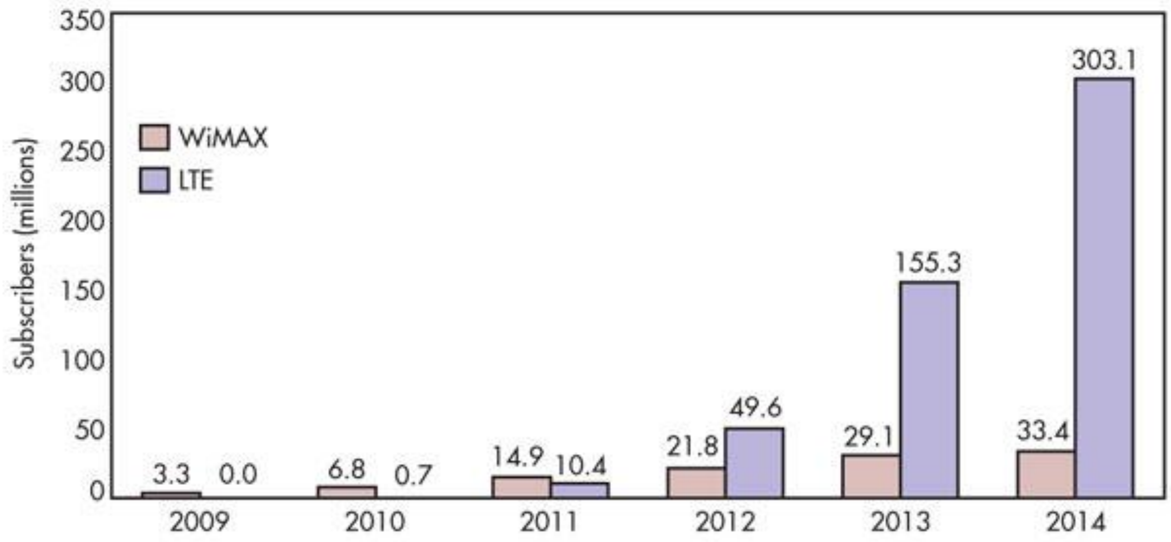

Figure 2:The continuous growth of the subscribers using LTE and WiMAX over the recent years [26].

3GPP has completed the specification for LTE as part of Release 8 in 2009 and first deployment occurred in the begin of 2010 in Oslo and Stockholm. By the end of that year, two more LTE systems were developed in U.S and Japan. Although LTE Release 8 and 9 have been marketed as 4G technology, they do not satisfy the technical requirements the 3GPP consortium has adopted for the new generation, which requirements were set by ITU-R organization in its IMT-Advanced specification. More specifically, these releases do not have peek data rates up to 1 Gb/s. Thus, a new LTE release was submitted in 2009 as a formal candidate 4G system. Finally it was approved by IMT-Advanced and was finalized on March 2011. After almost one year, the technology received its first implementation in Russia.

LTE- Advanced has also paid attention to the fairness among the users and further improves the cell capacity and coverage. Concluding with LTE basic description, new proposals are submitted continuously in order to achieve even better performance. Some research categories are listed below:

- Flexible spectrum usage
- Hybrid OFDMA and SC-FDMA
- Multiple carrier spectrum Access

- Support for relay nodes
- Coordinated Multipoint (CoMP) transmission and reception
- Interference Managemenet and Suppression

The last two categories will be explained analytically in the next chapters, as they are closely related to the subject of this thesis.

2.2.1 Architecture

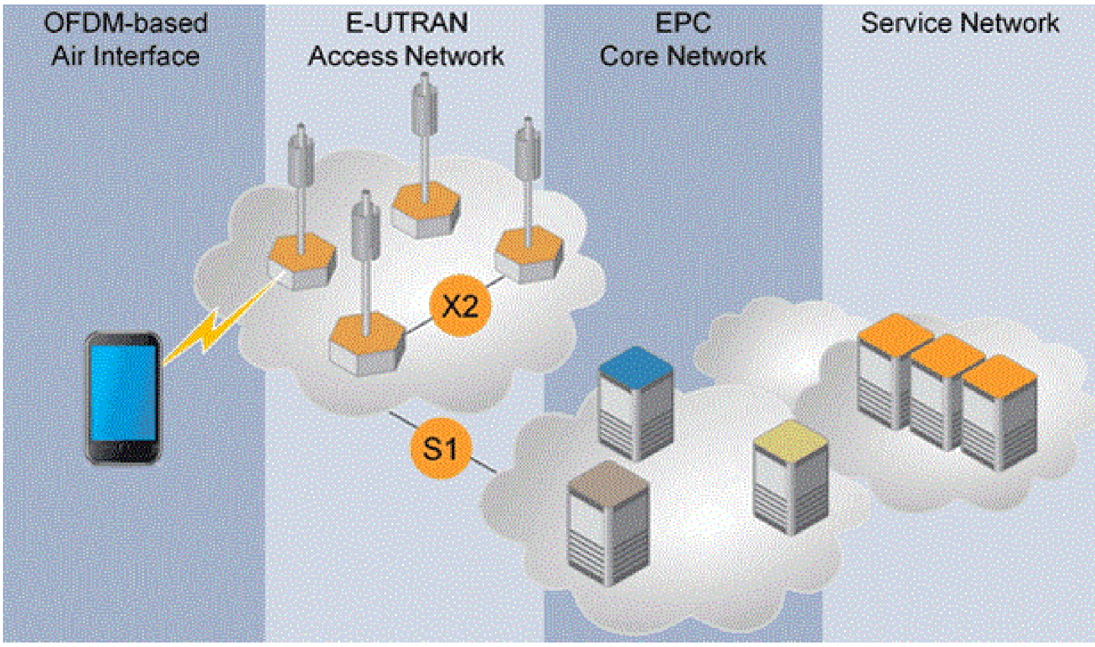

Figure 3: LTE Architecture [27].

A flat architecture is substantial to realize the main targets of LTE development. Hence, this flat architecture requires fewer nodes, which lead to lower delays and a higher reliability. Therefore, 3GPP LTE Release 8 introduced three different types of nodes. As prior telecommunication networks, LTE divides these nodes into two different planes.

The SAE GW (System Architecture Evolution Gateway) operates in the User Plane (UP), whereas the MME (Mobility Management Entity) is used in the Control Plane (CP). The eNodeB provides functionality in both planes. Basically, the LTE architecture consists of four different domains, as it is presented in Figure 3 .

1) User Equipment (UE) Domain: UE is the device that the end user utilizes for communicating. Typically it is a handheld device, e.g. a smartphone, a datacard or a USB stick which is used along with a personal computer or a tablet. UE also contains the Universal Subscriber Identity Module (USIM) that is a separate module from the rest of the UE, which is often called Terminal Equipment (TE). USIM is an application placed into a removable smart card called the Universal Integrated Cirtcuit Cart (UICC). USIM is used to identify and authenticate the user and to derive security keys for protecting the radio interface transmission.

   Functionally the UE is a platform for communication applications, which signal the network to set up, maintain and remove the communication links the end user needs. This includes mobility management functions, such as handovers and reporting the terminals location. Concluding in the UE domain, the most important is that the UE provides the user interface to the end user.

2) E-UTRAN Domain: E-UTRAN (Evolved Universal Terrestrial Radio Access Network) is the access network of LTE. The only node it contains is the eNodeB (E-UTRAN NodeB), which is an enhanced base station. These base stations are distributed throughout the network's coverage area, each residing near the actual radio antennas.

   The eNodeB is a key entity with multiple roles. Firstly, it is the connection bridge between the EPC (Evolved Packet Core) and the UE. In addition, it passes on the user plane data towards the core network entity (SAE GW), by ciphering / deciphering the IP data and compression / decompression of IP headers. Furthermore, the eNodeB provides functionality to the control plane. It is responsible for the Radio Resource Management (RRM), which controls the usage of the radio interface in terms of resource allocation and traffic scheduling according to QoS. At last, the eNodeB analyzes UE-carried signals and makes measurements by itself for Mobility Management (MM) aspects. Based on these measurements it makes decision to handover UEs between cells. Additionally, handover signaling is also exchanged with the MME and other eNodeBs to provide routing information. Measurements are made also in order to avoid / mitigate interference levels experienced by the UEs and caused by the transmission of resource blocks in the same frequency or in the same time slot from adjacent cells. The latter function of the eNodeB is being explained and analyzed in depth in the next chapters, being the main focus of this thesis.

3) EPC domain: The EPC provides the core network functions for LTE, which is only IP packet based. The EPC contains the nodes MME and SAE GW.
   a) Mobility Management Entity (MME): The MME is the main control entity in the 3GPP LTE network. Furthermore, is basically responsible for three functions, which are Authentication and Security, Mobility Management and Subscription Profile and Service Connectivity Management.

      Authentication and Security: The UE is authenticated by the MME to assure that it is who it claims to be. In this procedure the permanent identity of the UE is detected. Further an authentication vector is asked from the Home Suscription Server (HSS) of the EPC. The User Equipment is only authenticated, if the authentication vector is correctly repeated by the UE. This procedure is done with the first registrationto the network and periodically to keep the authentication up to date. In addition, the MME allocates a unique temporary identity to avoid the permanent sending if the IMSI (International Mobile Subscriber Identity) over the air interface which protects the privacy of the users.

      Mobility Management: The MME keeps track of the UE position either at eNodeB level in active mode or at the Tracking Area (TA) level. The TA is a group of eNodeBs where the location of a UE is known in idle mode. Furthermore the MME is responsible to notify the HSS the current location of the UE. Based on the UE mode the MME is able to control the allocation and release of network resources. Finally, it is also involved in handover of UE in active mode.

      Subscription Profile and Service Connectivity Management: The subscription profile of the UE has to be retrieved by the MME. This profile contains information about the Packet Data Network access and whether certain services should be allocated. Additionally, the MME will set up the default bearer. Further servce setups from dedicated bearers are also realized by the MME.

b) System Architecture Evolution Gateway (SAE GW): Another very important entity in the LTE network is the SAE GW, which operates in the user plane. The key function is the transfer of the actual user data through the network. This includes data packets for VoIP, messaging or other Internet services. The SAE GW represents a combination of two gateways. The Serving Gateway (S-GW) and the Packet Data Network Gateway (P-GW). However, the interface and the operations between the two gateways have been specified. Therefore, a separate deployment is possible.

   Serving Gateway (S-GW): Basically the S-GW is responsible for the tunnel management and switching and is directly connected to the eNodeB. It controls only its own resources and allocates them upon request of the MME or the P-GW. The S-GW plays a major role in the active handover when the UE is in connected mode. The MME commands S-GW a tunnel switch from one eNodeB to another. For idle mode the S-GW terminates the Downlink data path and triggers the paging when DL data arrives.

   Packet Data Network Gateway (P-GW): The P-GW is the connectivity point for the UE to external data packet networks. It provides highest level mobility support when a UE switches the S-GW. The Packet Data Network Gateway is also responsible for performing policy enforcement, gating and packet filtering. In addition, it collects and reports the charging information. Furthermore, a UE can connect to multiple P-GWs.

4) Services Domain: The Services domain may include various sub-systems, which in turn may contain several logical nodes. The following is categorization of the types of services that is available and a short description of what kind of infrastructure would be needed to provide them:

- IMS based operator services: The IP Multimedia Sub-system (IMS) is a service machinery that the operator may use to provide services using the Session Initiation Protocol (SIP).
- Non-IMS based operator services: The architecture for non-IMS based operator services is not defined in the standards. The operator may simply place a server into its network and the UEs connect to that via some agreed protocol that is supported by an application in the UE (i.e. a video streaming service).
- Other services not provided by the mobile network operator, e.g services provided through the Internet.

2.2.2 IP Quality of Service (QoS) support

An important aspect for any packet network is a mechanism that guarantees differentiation of packet flows based on its QoS requirements. Applications such as video streaming, HTTP or video telephony have special QoS needs and should receive differentiated service over the network. With EPS, QoS flows (so called EPS bearers) are established between the user and the PDN-GW. Each EPS bearer is associated with the QoS profile, composed of a radio bearer and a mobility tunnel, and the network can prioritize packets accordingly.
The QoS procedure for packets arriving for the Internet is shown in Figure 4. When receiving an IP packet, the PDN-GW performs packet classification based on parameters, such as rules received, and sends it through the proper mobility tunnel. Based on the mobility tunnel, the eNodeB can map packets to the appropriate QoS bearer.

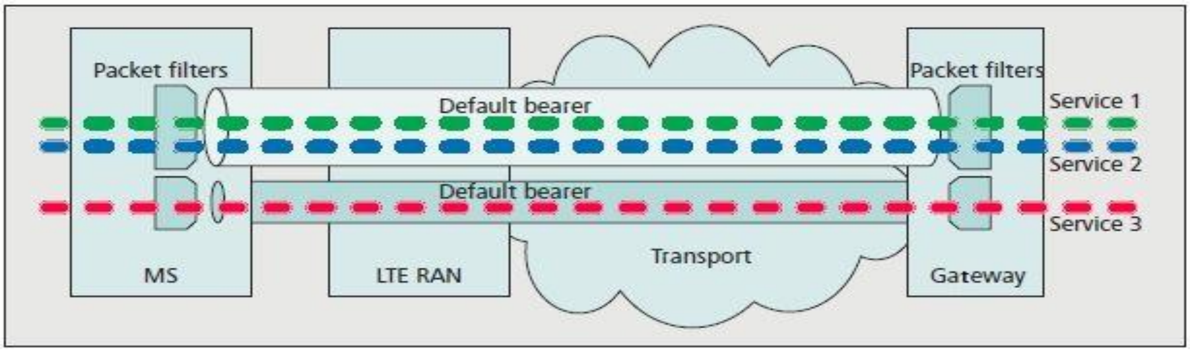

Figure 4: P-GW performs packet classification and assigns them to the proper mobility tunnel. Thus, QoS is achieved in LTE sytems [28].

2.2.3 Interfaces and Protocols

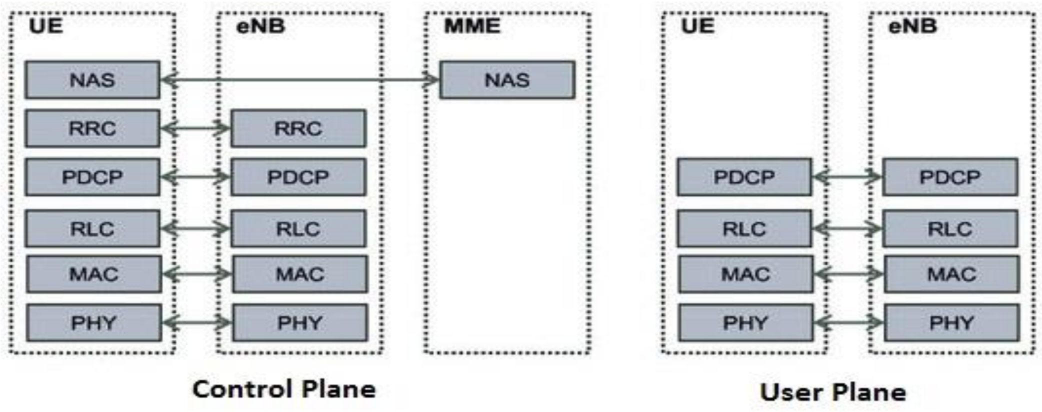

Figure 5: LTE Simplified Protocol Stack [29].

Figure 5 shows the Control Plane and the Plane protocols related to the UE's connection to a PDN. The topmost layer in the CP is the Non-Access Stratum (NAS), which consists of two separate protocols that are carried on direct signaling transport between the UE and the MME. The content of the NAS layer protocols is not visible to the eNodeB, and the eNodeB is not involved in these transactions by any other means, besides transporting the messages, and providing some additional transport layer indications along with the messages in some cases. The NAS layer protocols are:

1. EPS Mobility Management (EMM): This protocol is responsible for handling the UE mobility. It includes functions for attaching to and detaching from the network, and performing location updating in between. Note that the handovers in connected mode are handled by the lower layer protocols, but the EMM does include functions for reactivating the UE from the idle mode. The UE initiated case is called Service Request, while Paging represents the network initiated case. The authentication and protection of the UE identity, as well as the control of NAS layer security functions, encryption and integrity protection are also part of the EMM layer.

2. EPS Session Management (ESM): This protocol may be used to handle the bearer management between the UE and MME, and it is used in addition for E-UTRAN bearer management procedures.

The radio interface protocols are:

- Radio Resource Control (RRC): This protocol is in control of the radio resource usage. It manages UE's signalling and data connections, and includes functions for handover.
- Packet Data Convergence Protocol (PDCP): The main functions of PDCP are IP header compression (UP), encryption and integrity protection (CP only).
- Radio Link Control (RLC): The RLC protocol is responsible for segmenting and concatenation of the PDCP-PDUs for radio interface transmission. It also performs error correction with Automatic Repeat reQuest (ARQ) method.
- Medium Access Control (MAC): The MAC layer is responsible for scheduling the data according to priorities and multiplexing data to Layer 1 transport blocks. The MAC layer also provides error correction with Hybrid ARQ (HARQ).
- Physical Layer (PHY): This is the Layer 1 if LTE-Uu radio interface.

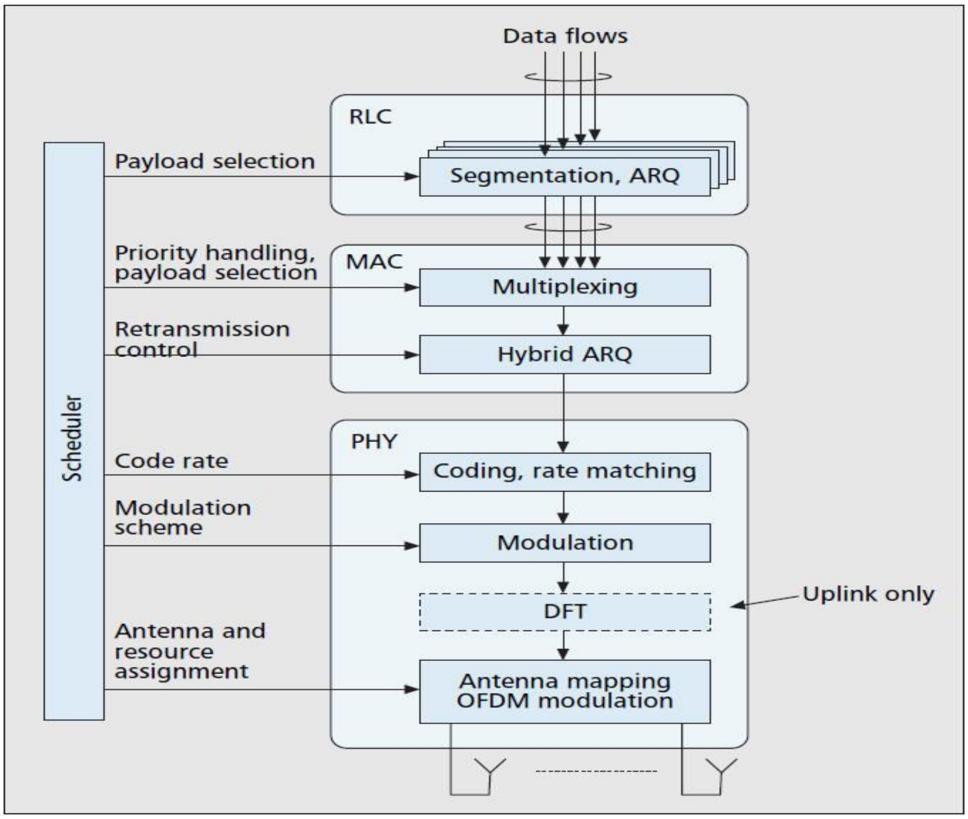

Figure 6: LTE protocol stack and its functionalities [39].

2.2.4 Characteristics of LTE

LTE uses OFDM (Orthogonal Frequency Division Multiplexing) and SC-FDMA (Single Carrier - FDMA) in the physical layer which allows the deployment in different frequency ranges. OFDM allows the allocation of different sized spectra with a large number of narrow-band subcarriers. This is a very flexible approach and provides the opportunity to make further extensions. Since the digitalization of TV-signals, more frequency bands can be used for telecommunication networks. Also the future shut-down of previous telecommunication networks, such as GSM and CDMA200, will release distinct bands which can also be used for LTE. 3GPP has defined the operation of LTE in frequency bands.Therefore LTE supports FDD (Frequency Division Duplex) and TDD (Time Division Duplex). FDD applies different carrier frequencies to the transmitter and the receiver, whereas in TDD both use one carrier frequency, but in different time slots. Table 1 shows the frequency bands defined by the 3GPP in the last Release of LTE.

Table 1: Current Frequency allocations for LTE
[3GPP TS 36.101 V11.1.0]

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
	F_{UL_low} – F_{UL_high}	F_{DL_low} – F_{DL_high}	
1	**1920 MHz– 1980 MHz**	**2110 MHz– 2170 MHz**	**FDD**
2	**1850 MHz– 1910 MHz**	**1930 MHz– 1990 MHz**	**FDD**
3	**1710 MHz– 1785 MHz**	**1805 MHz– 1880 MHz**	**FDD**
4	**1710 MHz – 1755 MHz**	**2110 MHz– 2155 MHz**	**FDD**
5	**824 MHz – 849 MHz**	**869 MHz– 894MHz**	**FDD**
6[1]	**830 MHz – 840 MHz**	**875 MHz– 885 MHz**	**FDD**
7	**2500 MHz – 2570 MHz**	**2620 MHz– 2690 MHz**	**FDD**
8	**880 MHz–915 MHz**	**925 MHz–960 MHz**	**FDD**
9	**1749.9 MHz – 1784.9 MHz**	**1844.9 MHz– 1879.9 MHz**	**FDD**
10	**1710 MHz – 1770 MHz**	**2110 MHz– 2170 MHz**	**FDD**
11	**1427.9 MHz– 1447.9 MHz**	**1475.9 MHz– 1495.9 MHz**	**FDD**
12	**699 MHz – 716 MHz**	**729 MHz – 746 MHz**	**FDD**
13	**777 MHz – 787 MHz**	**746 MHz – 756 MHz**	**FDD**
14	**788 MHz – 798 MHz**	**758 MHz – 768 MHz**	**FDD**
15	**Reserved**	**Reserved**	**FDD**
16	**Reserved**	**Reserved**	**FDD**

17	**704 MHz– 716 MHz**	**734 MHz – 746 MHz**	**FDD**
18	**815 MHz – 830 MHz**	**860 MHz – 875 MHz**	**FDD**
19	**830 MHz – 845 MHz**	**875 MHz – 890 MHz**	**FDD**
20	**832 MHz – 862 MHz**	**791 MHz – 821 MHz**	**FDD**
21	**1447.9 MHz – 1462.9 MHz**	**1495.9 MHz – 1510.9 MHz**	**FDD**
22	**3410 MHz – 3490 MHz**	**3510 MHz – 3590 MHz**	**FDD**
23	**2000 MHz – 2020 MHz**	**2180 MHz – 2200 MHz**	**FDD**
24	**1626.5 MHz – 1660.5 MHz**	**1525 MHz – 1559 MHz**	**FDD**
25	**1850 MHz – 1915 MHz**	**1930 MHz – 1995 MHz**	**FDD**
26	**814 MHz – 849 MHz**	**859 MHz – 894 MHz**	**FDD**
27	**807 MHz – 824 MHz**	**852 MHz – 869 MHz**	**FDD**
28	**703 MHz – 748 MHz**	**758 MHz – 803 MHz**	**FDD**
…			
33	**1900 MHz – 1920 MHz**	**1900 MHz – 1920 MHz**	**TDD**
34	**2010 MHz – 2025 MHz**	**2010 MHz– 2025 MHz**	**TDD**
35	**1850 MHz– 1910 MHz**	**1850 MHz– 1910 MHz**	**TDD**
36	**1930 MHz– 1990 MHz**	**1930 MHz– 1990 MHz**	**TDD**
37	**1910 MHz– 1930 MHz**	**1910 MHz– 1930 MHz**	**TDD**
38	**2570 MHz– 2620 MHz**	**2570 MHz– 2620 MHz**	**TDD**
39	**1880 MHz– 1920 MHz**	**1880 MHz– 1920 MHz**	**TDD**
40	**2300 MHz– 2400 MHz**	**2300 MHz– 2400 MHz**	**TDD**
41	**2496 MHz 2690 MHz**	**2496 MHz 2690 MHz**	**TDD**
42	**3400 MHz – 3600 MHz**	**3400 MHz – 3600 MHz**	**TDD**
43	**3600 MHz – 3800 MHz**	**3600 MHz – 3800 MHz**	**TDD**
44	**703 MHz – 803 MHz**	**703 MHz – 803 MHz**	**TDD**
Note 1 : Band 6 is not applicable			

As stated before, one of the main goals of the 4G telecommunication networks is the increase of the data transmission speed. The 3GPP has also defined different terminal categories. Tables 2 and 3 show the different terminal categories in LTE Advanced, as well as specific characteristics such as the approximate down- and uplink peak rates, the modulation and the use of multiple antennas (MIMO). Initially for releases 8 and 9, only the first five categories had been defined. However, in order to accommodate the LTE- Advanced capabilities have been added the three new categories. All terminal categories have to support all RF (Radio Frequency) options form 1.4MHz to 20 MHz.

Table 2: LTE Advanced UE Receivers and Categories for the Downlink [ETSI TS 136 306 V10.2.0].

UE Category	Max.number of DL-SCH transport block bits received within a TTI	Max. number of bits of a DL-SCH transport block received within a TTI	Total number of soft channel bits	Max.Num of supported layers for spatial multiplexing in DL
1	10296	10296	250368	1
2	51024	51024	1237248	2
3	102048	75376	1237248	2
4	150752	75376	1827072	2
5	299552	149776	3667200	4
6	301504	149776 (4 layers) 75376 (2 layers)	3654144	2 or 4
7	301504	149776 (4 layers) 75376 (2 layers)	3654144	2 or 4
8	2998560	299856	35982720	8

Table 3: LTE Advanced UE Receivers and Categories for the Uplink [ETSI TS 136 306 V10.2.0].

UE category	Max. Number of UL-SCH transport block bits transmitted within a TTI	Max. Number of bits of an UL-SCH transport block transmitted within a TTI	Support for 64QAM
1	5160	5160	No
2	25456	25456	No
3	51024	51024	No
4	51024	51024	No
5	75376	75376	Yes
6	51024	51024	No
7	102048	51024	No
8	1447960	149776	Yes

In addition to high data rates, low delays are also desirable for 4G telecommunication networks. Certain requirements have been adopted for LTE in the control and the user plane. There are two measurements in both of them which measure the time that the terminal needs to change from a non- active state to an active, where the terminal is able to send or receive data. Depending on the non-active state this should not exceed 50ms and 100ms. In the user- plane the latency is measured by sending a small IP packet from the terminal to the RAN (Radio Access Network) edge. This time should not exceed 5ms.

In networks, such as GSM / UMTS, a circuit- switched domain assured the QoS in telephony services.Therefore high delays in the packet- switched domain are not a big issue for these services. To assure an equivalent QoS for LTE (which is IP-packet based) low delays in the network are substantial. Telephony quality is not only measured by the delay time of data packets, but also by measuring the opinion of the actual user correlated with the certain dalay times (Quality of Experience - QoE). A recent study [10] reveals that callers identify delays in the conversation when the round trip delay exceeds 250 ms.

LTE Release 8 offers 326 Mbps with 4×4 MIMO and 172 Mbps with 2×2 MIMO in 20 MHz spectrum. LTE supports both Frequency Division Duplexing and Time Division Multiplexing. Its major advantage is the provision of high throughput with low latency (~5 ms). Moreover, it supports mobility in an improved way, in which the UEs can move at up to 350 km/h or 500 km/h, depending on the frequency band.

Downlink Access is OFDMA and Uplink Access is Single Carrier FDMA (SC-FDMA). The latter has been chosen due to its lower power consumption compared with OFDMA. LTE supports cell sizes with radius that range from some tens of meters (picocells, femtocells) up to 100 km cells with acceptable performance. It can also support at least 200 active data clients in every 5 MHz cell. An important feature its backward compatibility with older telecommunication systems, and thus can be a part of a Heterogeneous Network (HetNet).

According to 3GPP, LTE-Advanced (Rel. 10 and beyond) focus on higher capacity, thus surpassing even the IMT-Advanced specifications. Some of the targets are listed below:

- Increased peak data rate (DL 3 Gbps, UL 1.5 Gbps).
- Higher spectral efficiency (from a maximum of 16bps/Hz in Release 8 to 30 bps/Hz in Release 10).

- Increased number of simultaneously active subscribers.
- Improved performance at cell edges (e.g. for DL 2x2 MIMO at least 2.40 bps/Hz/cell).

2.3 Key Functionalities and Technologies

This section presents some of the most important techniques and functionalities that helped LTE to achieve and surpass the specifications set by IMT-Advanced.

2.3.1 OFDMA

LTE radio transmission in the downlink is based on OFDM, a modulation scheme that is used in a variety of wireless communication standards (e.g HSDPA, UMTS etc.). OFDMA, a variant of OFDM which allows several users to simultaneously share the OFDM subcarriers, is employed in LTE in order to take advantage of multiuser diversity and to provide greater flexibility in allocating (scheduling) radio resources. Specifically, the OFDM subcarriers are spaced 15 KHz apart and each individual subcarrier is modulated using QPSK, 16-QAM, or 64- QAM following turbo coding. Adaptive Modulation and Coding (AMC) is used to allow the optimal Modulation and Coding Scheme (MCS) to be chosen, based on current channel conditions.

A major difference between packet scheduling in LTE and that in earlier radio access technologies, such as HSDPA, is that LTE schedules resources for users in both Time Domain (TD) and Frequency Domain (FD), whereas HSDPA only involved TD. This additional has been shown to provide substantial throughput and coverage gains. In order to make good scheduling decisions, a scheduler requires knowledge of channel conditions. Ideally at each scheduling time, the scheduler should know the channel gain for each sub- carrier and each user. However due to limited signalling channel resources, subcarriers are grouped into RBs, each consisting of 12 adjacent subcarriers. Each RB has a time slot duration of 0.5 ms, which corresponds to 6 or OFDM symbols depending on whether an exended or normal cyclic prefix is used. The smallest resource unit that a scheduler can allocate to a user is an SB, which consists of two consecutive RBs, spanning a subframe time duration or TTI of 1 ms and a bandwidth of 180 kHz.

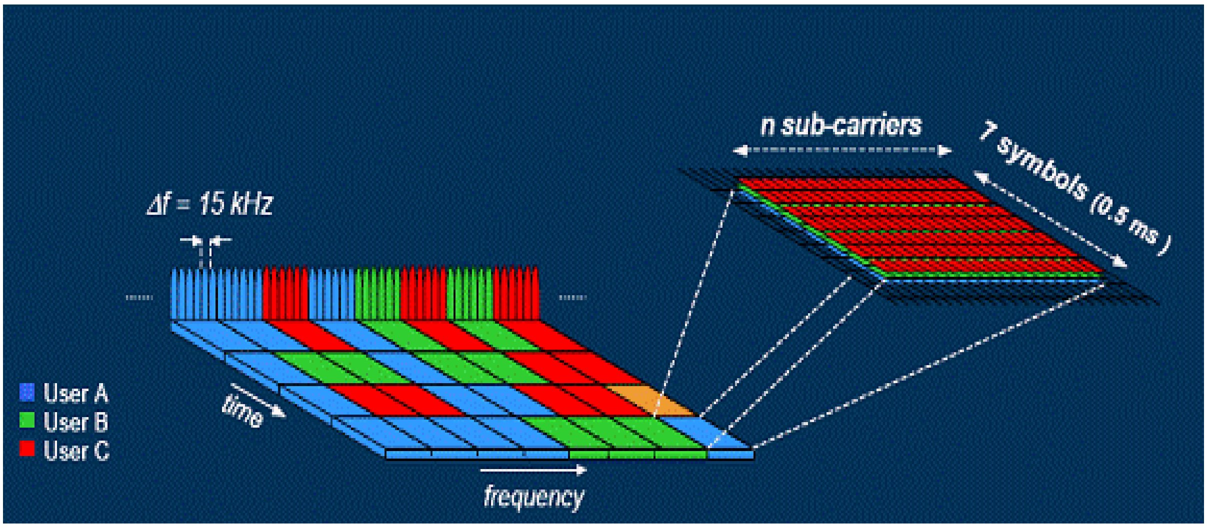

Figure 7: OFDMA depiction [30].

Conluding with OFDMA some more advantages in bullet points are:

- Flexibility of deployment across various frequency bands with little needed modification to the air interface.
- Averaging interferences from neighboring cells, by using different basic carrier permutations between users in different cells.
- Interferences within the cell are averaged by using allocation with cyclic permutations.
- Enables Single Frequency Network coverage, where coverage problem exists and gives excellent coverage.
- Offers frequency diversity by spreading the carriers all over the used spectrum.

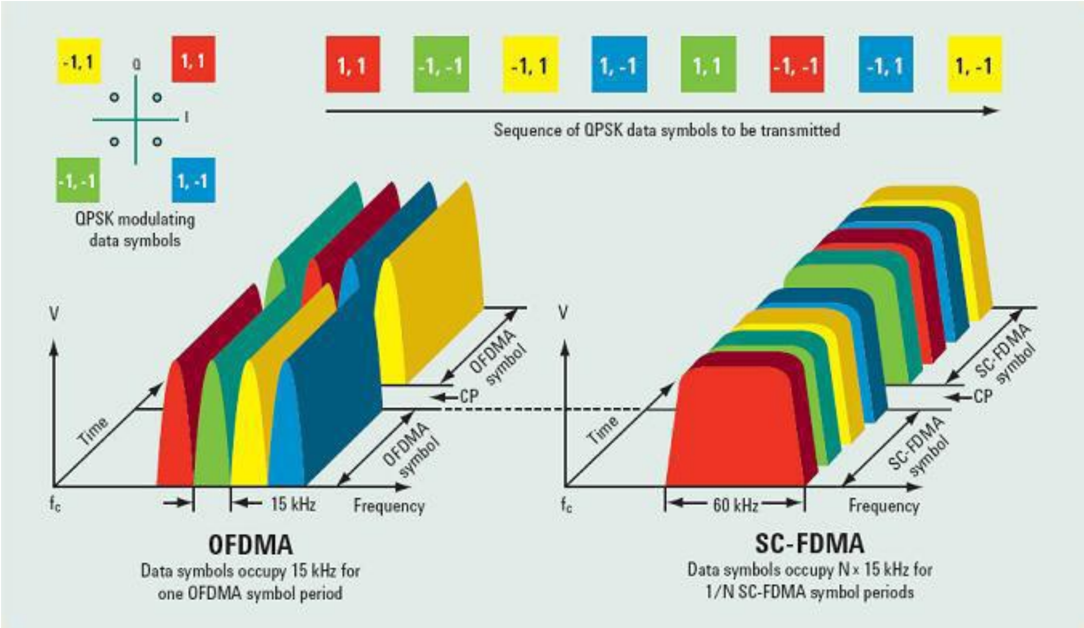

Figure 8: OFDMA is used in the downlink transmissions, while SC-FDMA is used in the uplink transmissions [30].

2.3.2 MIMO

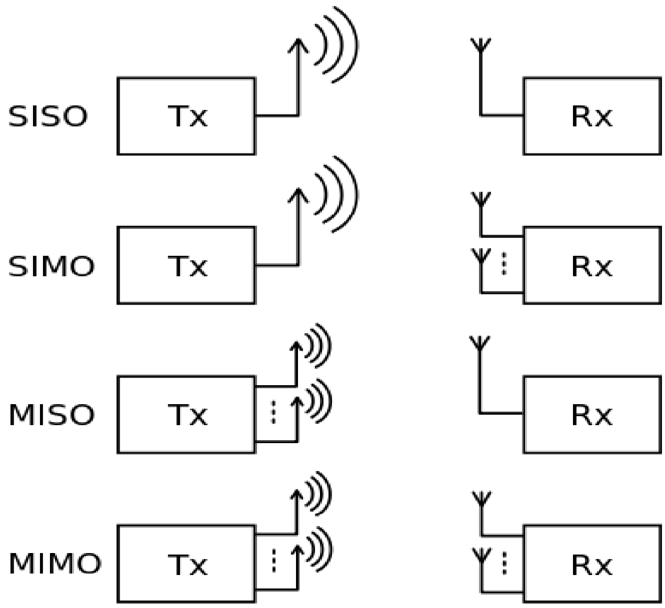

Figure 9: Understanding of SISO, SIMO, MISO and MIMO [31].

MIMO (Multiple Input Multiple Output) is an antenna technology for wireless communications in which multiple antennas are used at both the source (transmitter) and the destination (receiver). The antennas at each end of the communications circuit are combined to minimize errors and optimize data speed. MIMO is one of several forms of smart antenna technology. Other forms are MISO (Multiple Input Single Output) and SIMO (Single Input Multiple Output).

In conventional wireless communications, a single antenna is used at the source, and another single antenna is used at the destination. In some cases, this gives rise to problems with multipath effects. When an electromagnetic field is met with obstructions such as hills, canyons, buildings, and utility wires, the wavefronts are scattered and, thus, they take many paths to reach the destination. The late arrival of scattered portions of the signal causes problems such as fading, cut-out (cliff effect), and intermittent reception (picket fencing). In digital communications systems it can cause a reduction of the data speed and an increase on the number of transmission errors. The use of two or more antennas, along with the transmission of multiple signals (one for each antenna) at the source and the destination, eliminates the trouble caused by multipath wave propagation, and can even take advantage of this effect.

MIMO technology has aroused interest because of its possible applications in digital television (, Wireless Local Area Networks (WLANs), Metropolitan Area Networks (MANs), and mobile communications.

2.3.3 Carrier Aggregation

In order to achieve the targets set by IMT-Advanced, another technique that has been proposed is Carrier Aggregation (CA). Due to its efficient functionality has been introduced in 3GPP LTE Release 10.

Carrier Aggregation (or Channel Aggregation) is aggregating multiple carriers of same or varying bandwidths aiming the increase of the overall transmission bandwidth. Carrier Aggregation is one of the most distinct features of 4G LTE-Advanced, as it is possible to attain very high data rates by extending the transmission bandwidth up to 100MHz by aggregating up to five LTE carriers. These carriers may be in continuous elements of the spectrum or may be even in non continuous (intra- band, inter- band). Carrier Aggregation facilitates efficient use of fragmented spectrum and can be used for both FDD and TDD.

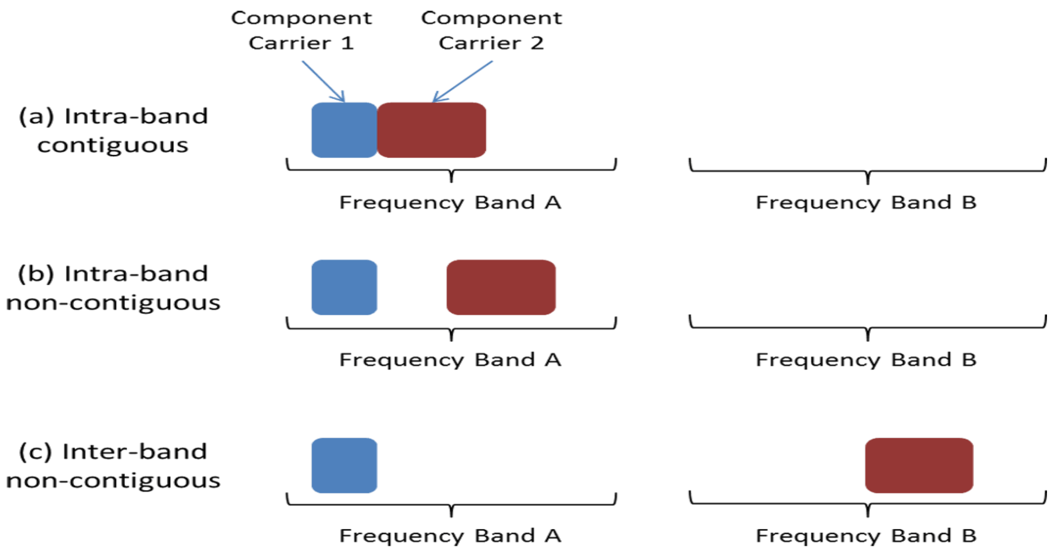

Figure 10: Different ways of Carrier Aggregating [32].

There are many ways in which LTE carriers can be aggregated:

2.3.3.1 Intra-band

This form of Carrier Aggregation uses component carriers within the same operating band (as defined by LTE specifications). There are two main variants for this type of Carrier Aggregation:

- Contiguous, where the carriers are adjacent to each other.
- Non-contiguous, where the component carriers belong to the same operating frequency band, but have a gap or gaps, in between.

2.3.3.2 Inter- band non- contiguous

This form of Carrier Aggregation uses different operating bands. It is of particular use because of the fragmentation of bands, some of which are only 10 MHz wide. For the UE it requires the use of multiple transceivers within the single item, with the usual impact on cost, performance and power. Additional complexities are caused by the requirements to reduce inter-modulation and cross-modulation from the two transceivers.

Moreover, the Carrier Aggregation can be Symmetric or Assymetric, which depends on the equality of number of component carriers existing for the uplink and downlink.

2.3.4 ARQ - HARQ

In addition of achieving the desired high data rates, there is also a need for reliability in transmissions and/or receptions of the packets, from both the sides of UEs and eNodeBs. Thus, there are some mechanisms, which are applied on the devices in order to detect and correct the errors. These mechanisms are the ARQ and Hybrid ARQ. Both of them have been already used successfully and tested in previous mobile telecommunication systems, such as HSPA and UMTS.

HARQ is implemented to correct the erroneous packets in PHY layer. Of course, there is a possibility that some of these packets can pass the control of HARQ mechanism, without being corrected, and go further to upper layers. For this case ARQ is implemented in the next, upper layer, which is RLC, and finally are corrected by either fixing the errors or by discarding the erroneous packet. The next table describes the process.

Table 3: ARQ - HARQ details

ARQ	HARQ
Works at RLC layer	Works at PHY layer but is controlled by MAC layer
If received data has an error, it is discarded and a new retransmission is requested	If received data has an error, it is stored to a buffer and asks for re- transmitting. After reception, combines the just arrived data with that in the buffer and detects – corrects the error
Stop And Wait in order to get an ACK/NACK. Afterwards they proceed to the next steps	

2.3.5 Relay Nodes

The relay nodes functionality in the LTE-A networks yields to more efficient heterogeneous network planning. More concisely, low power Base Stations are introduced in larger cells and provide enhanced coverage and capacity at cell edges. Moreover, it can be used to connect remote areas without fibre connection.

The Relay Node is connected to the Donor eNB (DeNB) via a radio interface, which is a modification of the E-UTRAN air interface. Hence, in the Donor cell the radio resources are shared between UEs served directly by the DeNB and the Relay Nodes.

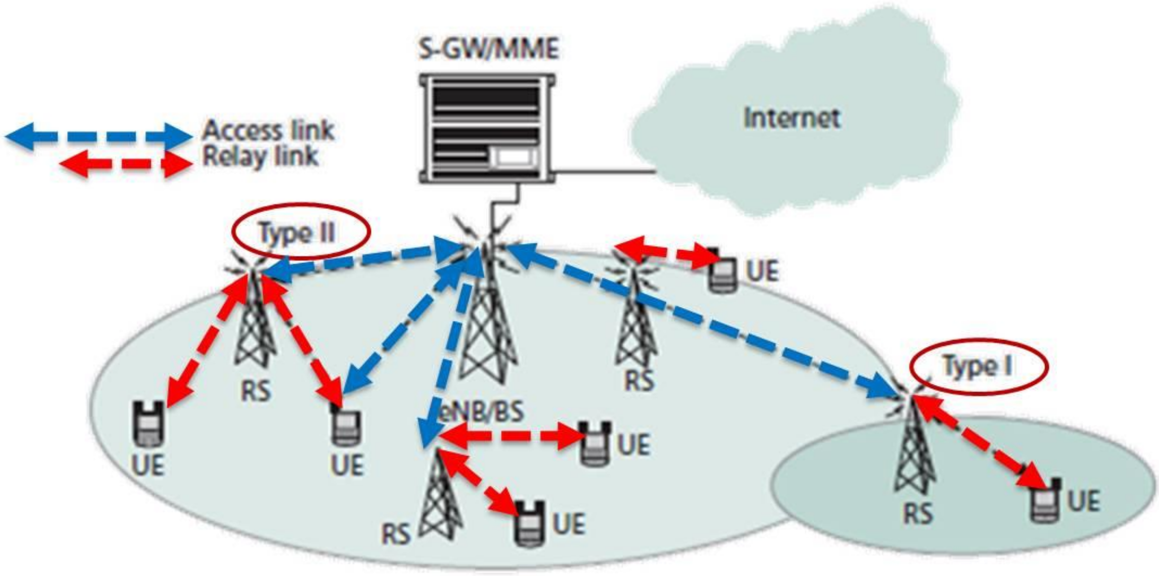

Figure 11: Relay nodes under a greater Donor eNB (DeNB) [33].

Chapter 3

Problem Description

As mentioned previously, dense reuse of available frequency spectrum and heterogeneous deployment is planned for LTE systems in order to achieve high data wireless transmissions and ubiquity in user experience. Thus, Inter-Cell Interference (ICI) mitigation becomes more challenging than before.

3.1 Intra-cell interference

It worths mentioning that the Intra-cell interference problem has been already solved due to the use of OFDM. More specifically, the subcarriers of OFDM are orthogonal between each other and this results to the solution of the problematic frequency selective fading. Thereby, the Inter Symbol Interference (ISI) is eliminated.

3.2 Inter-cell interference

LTE is designed for frequency reuse 1, in order to maximize spectrum efficiency, which means that all the neighbour cells are using same frequency channels and therefore there is no cell-planning to deal with the interference issues.

Thus, InterCell Interference (ICI) is a major problem in LTE- based systems. As particularly the cell users experience a higher degree of interference compared to the cell centre users, improving the cell-edge performance is an important aspect of LTE systems design.

In this case User Equipment moves away from the serving eNodeB and therefore the degradation in its Signal-to-Interference-and-Noise Ratio (SINR) can be attributed to two factors. On the one hand, the received desired signal decreases. On the other hand, ICI increases as the UE moves closer to a neighbouring eNodeB.

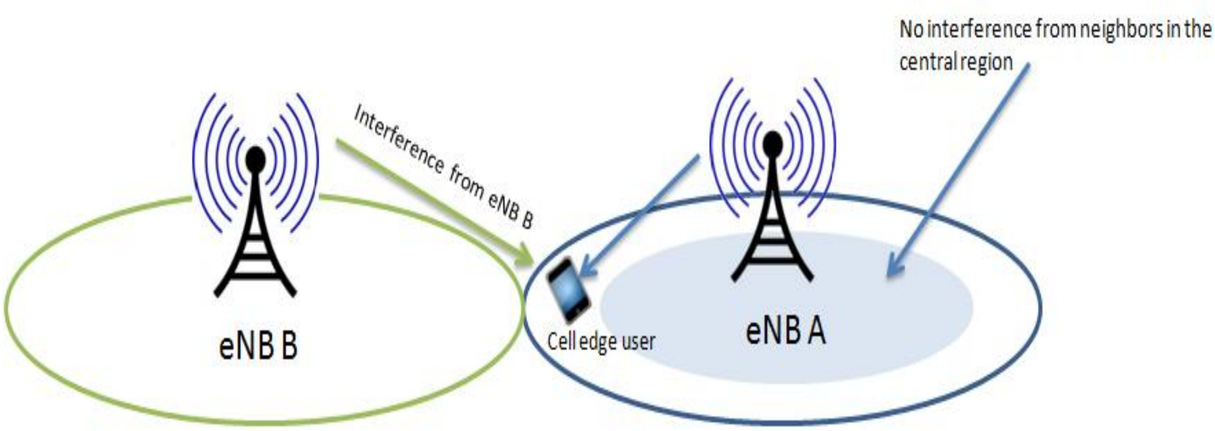

Figure 12: Cell edge user experiences high level of Interference [34].

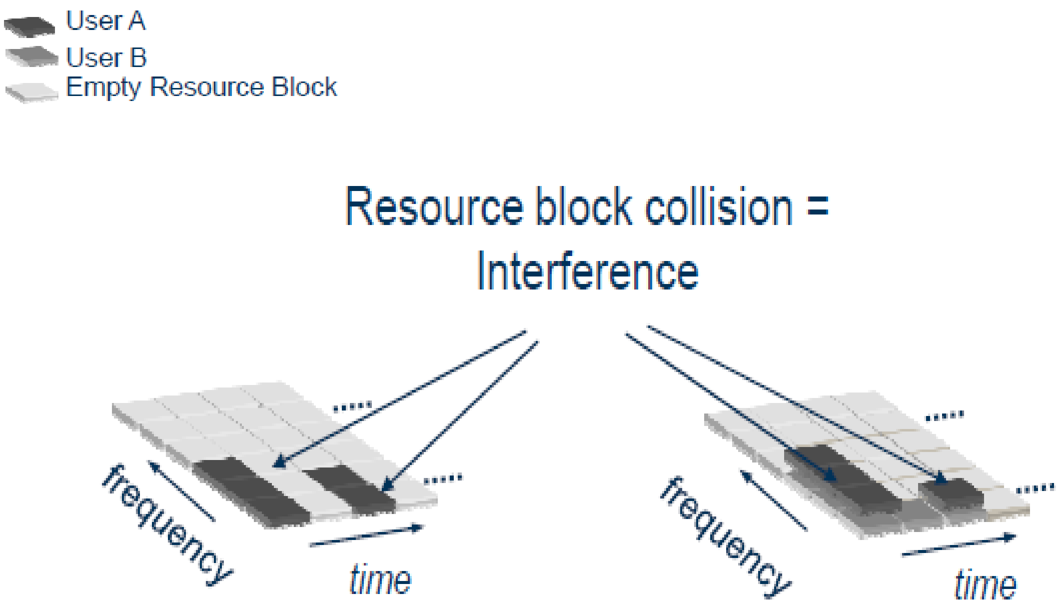

Figure 13: Same Resource Blocks are allocated for the same UEs, from different cell. This relults to Resource Block collision [34].

The interference issue becomes more severe for a heterogeneous LTE network (Figure 14), where the low-power nodes such as small-cell, pico- / femto- cells are deployed within the coverage area of a macro-cell network to improve the coverage and spectrum efficiency. While such heterogeneous deployment could effectively eliminate the coverage holes and incease the system capacity, it also results in a more significant ICI.

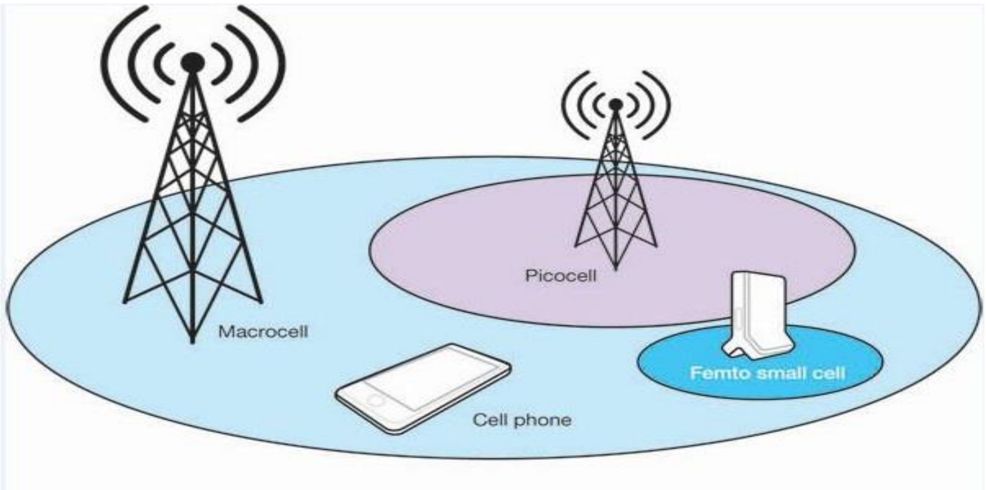

Figure 14: HetNet that contains a Pico- and a Femto-cell [35].

Many efforts are made the last years in order to manage the Intercell interference in LTE systems. An approach for mitigating by coordinating the base station transmissions with Genetic Algorithms is presented in the fifth chapter. Before, in the next chapter, a quick overview of different and most important ways, that have been unveiled so far, is being presented.

Chapter 4

Literature Study

A wide variety of interference management techniques have been proposed in the literature. These techniques can be categorized as follows:

- Interference cancellation
- Interference randomization
- Interference mitigation

The Interference cancellation approach is based on spatial filtering and it requires the employment of multiple antennas User Equipment.

Interference randomization policy spreads the users' transmission over a distributed set of subcarriers in order to randomize the interference scenario and achieve frequency diversity gain.

Interference mitigation techniques vary and can be devided into further categories, such as intereference whitening (e.g interference scrambling [11]), beamforming [12], Coordinated Multipoint Transmission and Reception (CoMP) [5], Intercell Interference Coordination (ICIC) [4] by employing power management techniques. Moreover, it is worth mentioning that each category of the above can be divided further, so as different ways manage to mitigate/avoid/cancel/randomize the interference levels experienced by the users.

Next, some of the techniques that have been researched a lot in the recent years will be explained further , as they have been proven very efficient to eventually achieve the greatest desired results.

4.1 Fractional Frequency Reuse

Fractional Frequency Reuse (FFR) could effectively suppress the Inter-Cell Interference. There are different types of FFR [13-14]. Note that in all discussions, cell center users refer to users that are physically close to a BS such that it suffers limited ICI. On the other hand, cell-edge users are defined as users that are close to the cell boundary and receive strong ICI from the transmissions in other cells.

4.1.1 Static FFR

Static FFR can be roughly grouped into two categories, i.e, the hard and the soft FFR strategies. The hard FFR strategy divides the entire frequency spectrum into a few non-overlapping frequency sub-bands. Cell-center and cell-edge users from the same cell operate over different frequency sub-bands. Cell-edge users of neighboring BSs also operate over non-overlapping frequency sub-bands to avoid strong ICI. A drawback of the hard FFR scheme is that the spectrum might be under-utilized. A soft FFR scheme aims to utilize the spectrum more efficiently by allowing the cell-center user to use the frequency band allocated to cell-edge users for transmission, but at reduced power levels. This solution could lead to high spectrum usage in some situations. An example is providedin Figure 15.

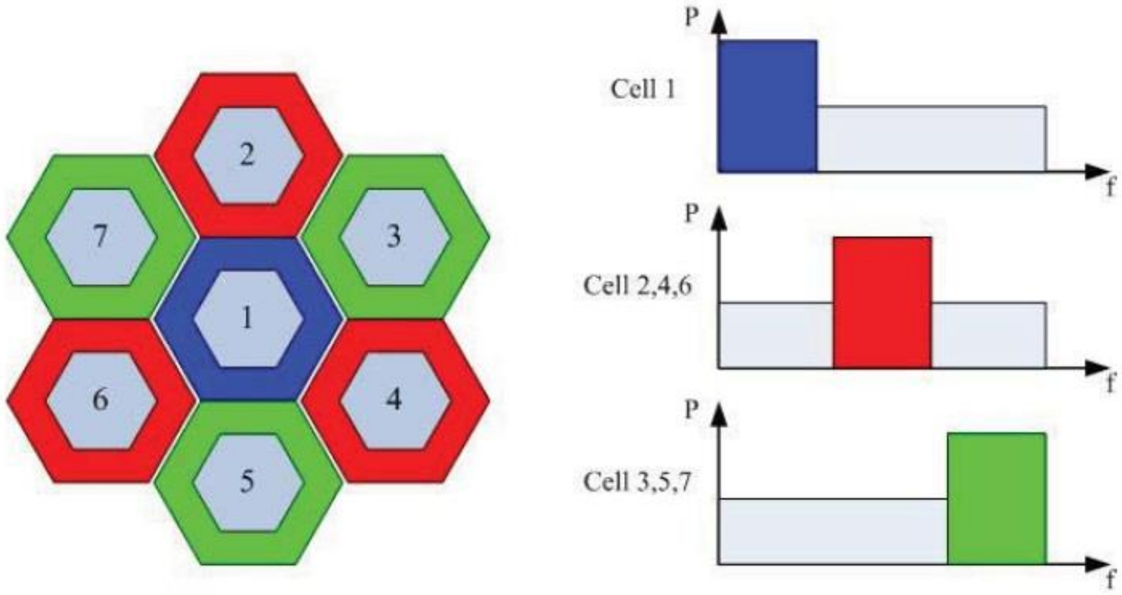

Figure 15: Soft Freuncy Reuse (SFR) [35].

4.1.2 Dynamic FFR

The static FFR solution assumes stable traffic load during the operation of a wireless network. In practice, the traffic load and the channel conditions of users could vary significantly over time. The goal of the dynamic FFR solution is to take into account the load of each cell, as well as the channel and traffic conditions of users so as to maximize the system capacity. There have been significant research efforts ongoing for dynamic FFR, ranging from the game-theoretically approach to the graph based dynamic FFR scheme [15-17]. The latter approach will be intercalled below as an example that represents the dynamic FFR schemes. Concluding, this type of solution has shown dramatic performance improvements. They can also be combined with the different scheduling algorithms to achieve higher capacity gain. It should be noticed, however, that such dynamic scheme may require larger amount of information exchange between neighboring BSs via X2 interface and also incurs more control overhead.

4.1.2.1 Graph based approach

The problem of interference mitigation can be formulated as an interference graph in which UEs correspond to the respective edges. To minimize interference, connected UEs should no be allocated the same set of resources. Such a problem is directly related to the graph coloring problem in which each color corresponds to a disjoint set of frequency resources. The goal is for each node in a graph to be assigned a color in such a way that no connected nodes are assigned the same color, In [18], a centralized graph coloring approach is proposed, where a “generalized” frequency reuse pattern is assigned to UEs at the cell by a centralized coordinator, In order to generate the interference graph, UEs are required to measure the interference and path losses, and report back to their respective eNBs. Subsequently, every eNB sends the necessary information to the central coordinator, which then generates the interference graph and performs the necessary optimization. Note that the definition of the graph is model- and problem specific.

4.2 Beamforming

With multiple antennas at the eNodeB, transmitter can focus the transmitter power in the destination direction in some degree and thus reduce the interference to users served in the neighboring sectors by the digital processing at the transmitter. Traditionally, this is named smart antenna. The effect of beamforming [12] on interference is shown in figure 16.

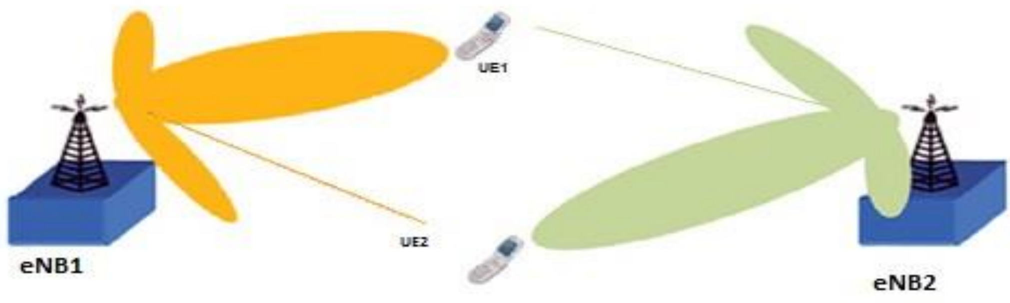

Figure 16: Beamforming [36].

4.3 Coordinated Multi-Point (CoMP) techniques

CoMP represents a framework of transmission / reception methods through utilizing multiple antennas that are geographically distributed such that the ICI can be reduced. To fulfill the coordinated transmissions, all nodes participating in the transmission need to exchange real-time information through the X2 interface. CoMP can be broadly grouped into two categories, ie, Coordinating Beaming (CB) and Joint Processing (JP). In a CB system, a mobile station receives data from one BS only and the other neighboring BSs employ the beamforming / precoding strategies to cancel the interference. On the contrary, in the JP approach, an mobile station could receive data streams from multiple BSs. Both simulation and experimental studies have shown that the CoMP strategies could substantially enhance the cell-edge user performance at the expense of extra information exchange among the neighboring BSs. Furthermore, the realization becomes increasingly difficult when the number of BSs participating the joint transmission, increases.

A recent proposal, which belong to the CoMP category, leverages base station scheduling rather than user scheduling in order to minimize the intercell interference and eventually increase the spectral efficiency. Its name is BASICS (BAse Station Inter-Cell Scheduling) [19] and its way to achieve the desired results is mapping base station activies over subframes after formulating the base station scheduling problem as a multi-dimensional vector bin-packing problem. All the measurements are made in cooperation of all BSs and final commands are given to BSs through the X2 interfaces by the EPC, where is implemented the algorithm.

The above is an example to show in a better way, how CoMP techniques actually operate. Such an example is also shown in the Figure 17.

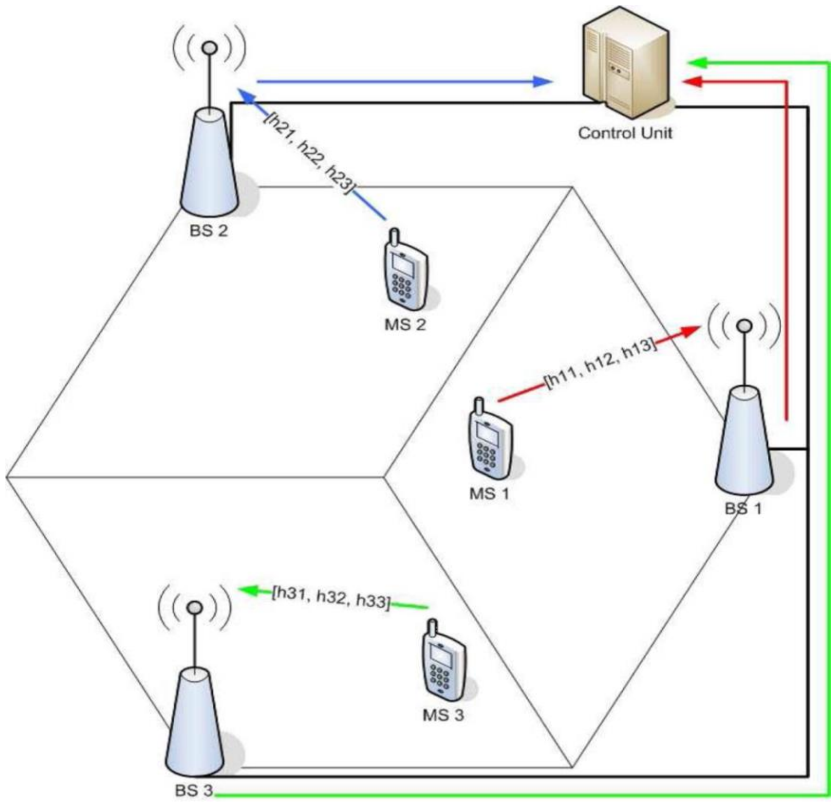

Figure 17: Centralized CoMP technique [37].

The next chapter presents a new CoMP approach that uses Genetic Algorithms and strikes near-optimal throughput results.

Chapter 5

Genetic Algorithms and Implementation

5.1 Introducing the Genetic Algorithms

In the field of artificial intelligence, a Genetic Algorithm (GA) is a stochastic global search method that mimics the process of natural biological evolution [20]. GAs operate on a population of potential configurations for an optimization problem by applying the principle of survival of the fittest with the aim to reach a solution, which is near optimal. In order to achieve this result, new sets of solutions are successively created by the selecting individuals, i.e., solutions, according to their level of fitness in the problem domain and by the mating of such individuals. Mating solutions (parent individuals) generate new solutions (offspring individuals). Parent and offspring are then subject to natural selection, i.e, only a subset of individuals, the ones who are better suited to their environment, are kept for the next mating round.

Using a GA, individuals are encoded as strings, consisting in chromosomes. Several representations can be used for the string elements, such as ternary, integer, real-valued and so on. In this work is used the binary alphabet {0,1}, as in most of similar cases [21] [22]. Each chromosome is formed by a variable number of phenotypes.

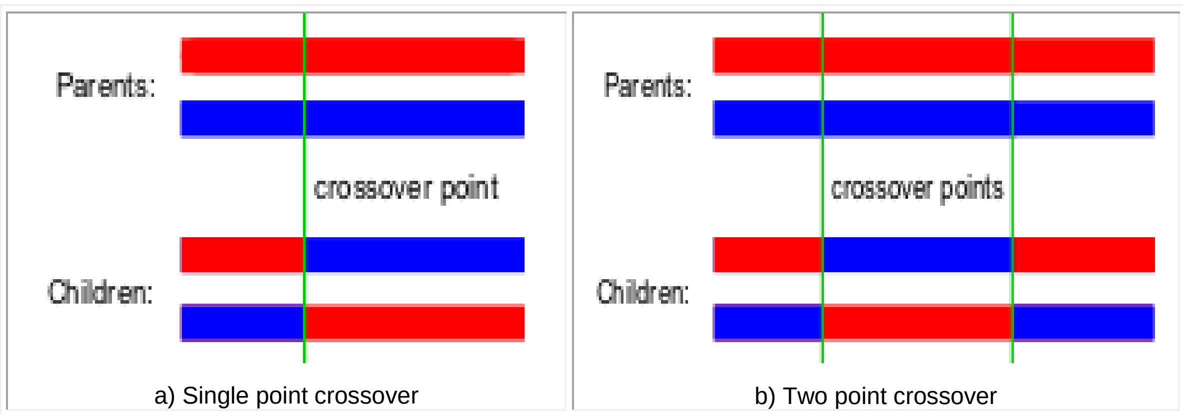

Figure 18: Crossover operator examples [38].

A phenotype corresponds to one or more string elements and one or more phenotypes encode a configuration component in the search space of the optimization problem. These problems form a solution and are searched by the GA protocol. Generally, they are called decision variables. The fitness of a solution is computed based on an objective function that characterizes an individual's performance in the problem domain. In the natural world, the fitness of an individual would represent the adaptation to changes in its current environment. Thus, the objective function establishes the basis for selecting pairs of individuals that will mate and generate offspring. Once the offspring individuals have been generated, they are assigned a fitness value, based on which they are sorted and selected, in preparation for the next reproduction cycle.

Offspring individuals are generated by manipulating the chromosomes. The simplest recombination operator is the ***crossover***. In that case, each pair of parent's chromosomes is split into one or more parts and randomly swapped (Figure 18). I.e., one or more segmentation points to randomly chosen for each chromosome pair and segments are kept or exchanged to form a new chromosome pair (corresponding to two sibling generated with the pairing). A second genetic operator is the mutation. It can be applied to each new chromosome and consists in changing one or more phenotypes according to some probabilistic rule. In the binary string representation, mutation will change bits from 0 to 1 or vice versa.

After recombination and mutation, the individual strings are decoded in terms of decision variable. The objective function is evaluated to draw a fitness value and thereafter select the fittest individuals. Some parent individuals (the fittest ones) can be retained for the next round, so the total population is kept constant. In this way, the average performance of individuals in a population is expected to increase, as strong individuals are preserved in the natural evolution and bred with one another while the less fit individuals die out. GA terminates when a certain number of generations is reached, getting better and better results, i.e. getting higher results from the objective function.

5.2 Problem statement

In this section is evaluated the performance of the wireless cellular system in terms of throughput. The system is a typical LTE network with *N* cells, where the users are being served by one base station per each cell. Base stations are only allowed to transmit into a certain number of subframes (each subframe lasts 1 ms) according to a coordinated base station scheduling decision. In all other subframes cannot be sent data, as dictated by ABSF paradigm [23]. Users, namely User Equipments (UEs) (according the LTE specifications) experience a useful signal form the serving base station and $N-1$ interference signals from the rest base stations in the network. The SINR of the user u,can be expressed as follows:

$$SINR_u = \frac{S_b^u}{N_0 + \sum_{j \neq b} I_j^u} \qquad (1)$$

where N_0 is the background noise, S_b^u is the useful signal received by the user u from the serving base station b, I_j^u is the interference experienced by the user u from any other base station $j \neq b$ in the system. To guarantee fairness, is assumed that the base station scheduling decision consists in a periodical scheduling map, which allocates all base station once per period. Since allocation is performed per subframe, the longest scheduling map can include as many subframes as the number of base stations, i.e. N. The target here is to minimize the system's total throughput Z in each cycle, as formulated in the following optimization problem.

$$\begin{cases} maximize\ Z = \sum_{i=1}^{N} \left\{ \sum_{b=1}^{N} \left[\frac{1}{|U_b|} \sum_{u \in U_b} f\left(\frac{S_b^u}{N_0 + \sum_{j \neq b \cdot} I_j^u x_{ij}} \right) \right] x_{ib} \right\} \\ subject\ to \qquad \sum_{i}^{N} x_{ij} = 1,\ j \in \{1, \dots, N\}, \\ \qquad x_{ij} \in \{0,1\},\ i \in \{1, \dots, N\},\ j \in \{1, \dots, N\}, \end{cases} \qquad (2)$$

where U_b is the set of the users of base station b , i indicates the subframe and $f(.)$ is the function used to obtain the user throughput from its SINR value. The decision variable x_{ij} assigns base stations to subframes:

$$x_{ij} = \begin{cases} 1, & \text{if base station } j \text{ is scheduled into subframe } i \\ 0, & \text{otherwise.} \end{cases}$$

Note that the first sum in the expression for the throughput Z in equation (2) contains at most N non-zero terms and empty subframes can be suppressed, thus yielding scheduling map periods shorter than N. According to the Shannon formula the throughput function $f(.)$ can be expressed as follows:

$$f\left(\frac{S_b^u}{N_0 + \sum_{j \neq b \cdot} I_j^u \ x_{ij}}\right) = \log\left(1 + \frac{S_b^u}{N_0 + \sum_{j \neq b \cdot} I_j^u \ x_{ij}}\right) \qquad (3)$$

Next, is being defined the scheduling map as the matrix X, with size $N \times N$, whose rows correspond to subframes while columns correspond to base stations. Each element x_{ij} of this matrix is the binary dicision variable which indicates whether the base station j will be accommodated into subframe i in the scheduling period. With the first constraint in the optimization problem equation (2) is being assumed that certain base station j can be allocated once. The scheduling process aims to solve this optimization problem, i.e. to find the scheduling map X ,which achieves the highest throughput in the network.

5.3 Using a genetic algorithm to search the scheduling map

The optimization problem equation (2) is clearly NP-hard. Therefore, a way to search the best scheduling map X , which is being proposed here, is by using a genetic algorithm specifically designed for this problem. In this case, there is one binary decision variable per base station per subframe, expressing in this way whether the base station is scheduled in that subframe. Consequently, the collection of all decision variables corresponds to the scheduling map. Each individual of the genetic algorithm search space is a scheduling map, represented as a binary matrix with subframes indexes in the rows and base stations in the columns. Therefore, only one element of each column is an ace(1), i.e. the one corresponding to the subframe in which the base station is scheduled. The scheduling information contained in the scheduling map matrix X, can be compressed by replacing each column with the binary index of the subframe in which the base station reported on the column is cheduled (i.e., a column can be replaced with the row index of the only 1 appearing in that column). The latter representation is suitable to be used as a binary chromosome as shown in Figure 19. Being *N* the number of base stations, there are at most *N* subframes in a scheduling map, and therefore, $n = \lceil \log_2 N \rceil$ bits are needed to encode a subframe index. Hence, using a fixed-length binary representation, the chromosome will be composed by $n \cdot N$ bits.

Individual

BS1	BS2	BS3	BS4	BS5	BS6	BS7	BS8
001	010	110	101	000	110	111	010

Scheduling Map (X)

sf/BS	BS1	BS2	BS3	BS4	BS5	BS6	BS7	BS8
000	0	0	0	0	**1**	0	0	0
001	**1**	0	0	0	0	0	0	0
010	0	**1**	0	0	0	0	0	**1**
011	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
101	0	0	**1**	0	0	0	0	0
110	0	0	**1**	0	0	**1**	0	0
111	0	0	0	0	0	0	**1**	0

Figure 19: Example of base station scheduling map, with 8 base stations, 3 bits per subframe index, and a total chromosome length of 24 bits mapped onto a candidate scheduling map.

After having defined the structure of individuals for the GA search,is being described the particular GA algorithm, implemented and evaluated with MATLAB simulations. First step is to start with a randomly generated set of *W* individuals, which are going to be mated together. During the pairing, it is considered as recombination operators a single-point crossover with probability *p* and a single-bit mutation process with probability *μ.* I.e.Firstly, the chromosomes are split into two segments, with the splitting point being randomly selected according to a uniform distribution across the uniform length, and segment are kept like in the parent's chromosome with probability $1-p$ or swapped with probability *p.* Secondly, a single bit of each sibling generated by the crossover, is selected randomly (with a uniform distribution), and inverted with probability μ. The offsprings generated, consisting of *W* individuals, are evaluated aiming at the selection of only the mapping solutions which yield the higher throughput *Z*, as formulated in Problem (2). *Z* is then associated to a fitness value in the range 0 to 2, where 2 is assigned to the best performing scheduling map (i.e. to the fittest individual). Finally, natural selection is applied. A fraction ρ of the offspring and a fraction $1-\rho$ of the parents survive, and thus the population size remains stable at every new generation. More specifically, the fittest $\rho \cdot W$ children and the fittest $(1-\rho) \cdot W$ parents will form the set of individuals, which are going to mate in the next pairing cycle. The entire process carries on for *M* iterations, producing a final polulation of *W* solutions, out of which only the fittest is chosen and decoded as the actual scheduling map X to be used in the system.

5.4 Scheduling map distribution

In a real system, the scheduling map has to be distributed to all base stations by using a small binary map, similar to the string representation used in the GA search. Since the GA runs for a set of base stations, it is bound to think that the base station scheduling is performed by a controller entity located in the LTE EPC. Therefore, the overall base station scheduling not only requires the GA algorithm, but also a signaling protocol which collects interference levels experienced by the users and distributes the scheduling map computed by the GA algorithm.

Computing the scheduling map is a periodic task which should follow the dynamics of interference levels existing in the network. Thus, in a mobile environment, it is reasonable to assume that a new scheduling map should be recomputed every few tens of frames, so that signaling messages should have a periodicity of about a few hundreds of milliseconds, which is comparable with the periodicity of other well known signaling protocols for wireless networks, such as the beacon interval of IEEE 802.11-based WLAN systems (sent every 100 ms) or the wireless "hello" messages (typically sent once per second).

5.5 Performance evaluation

In this section the performance achieved by means of the GA search is evaluated and is compared against other existing approaches and to the optimal map (which is the optimal scheduling solution found by means of an excaustive search). In order to evaluate the above approach of finding a near optimal throughput in a LTE network, a custom genetic algorithm has been designed and implemented using MATLAB genetic algorithm toolbox [20]. Specifically, after generating randomly the first population of individuals, follows the procedure of recombining the possible solutions by applying single-point crossover and mutation. Then, is assessed the fitness according to the implemented objective function. In each round of the algorithm, the objective function takes each individual in the current population, builds the corresponding scheduling map and the frame by allocating properly base stations into subframes, and computes the downlink network throughput by means of equation (3). Afterwards, a fitness function is applied to these throughput values and the fittest solutions are selected. The cycle is repeated *M* times. Four different scenarios are evaluated here increasing the number of base stations in the system from 4 to 12 BS. A complete overview of the parameters used in the simulations is shown in Table 4.

Table 4: Genetic algorithm parameters used in the simulations

Genetic Algorithm Parameters	
Parameter	Value
M	2000
ρ	0.9
W	{ 40,60 }
n	{ 2, 3, 4 }
N	{ 4, 6, 8, 12}
p	0.7
μ	0.7

A Genetic Algorithm is a global search method which has been proved to solve problems efficiently leading to the optimal solution after a huge number of generations. In the current thesis, the aim is to evaluate how far is the proposed solution from the optimal case, when the number of generations is limited to a reasonable number *M.* In fact, such a number of generations have to be computed and evaluated in a few hundreds milliseconds, thus permitting to collect interference information, compute the scheduling map *X*, and distribute it to the base stations every few of tens of frames. Here, it is used *M = 2000,* since with this value a normal core-single personal computer can run the GA algorithm and find a sub-optimal scheduling map for a network with 12 base stations and approximately 50 users per base stationin less than a second. To compare GA performance with the optimal scheduling map performance, all possible scheduling maps are evaluated in terms of throughput. Since the number of possible base station scheduling combinations growths with the number of base station involved in the system, according to the Number of Bell [24], the number of base station is kept relatively low in these experiments (up to 12). Furthermore, it has been used for comparison (i) a legacy scheduling scheme which allocates all base stations in the same sub-frame and (ii) a scheme in which only one base station is scheduled per subframe. These two schemes represent the extreme cases for a base stations scheduling approach. Simulation results are depicted in Figure 20 and 21, in which it is clearly visible how the GA-based solution outperforms the other two legacy solutions, especially as the number of base stations grows (Figure 20). Furthermore, the GA-based approach achieves nearly optimal throughput, although the number *M* of generations simulated in this algorithm is 2000. With a higher number of generations, results achieved by the GA-based approach would be better, even though further improvements would require a much higher number of generations, as shown in Figure 21 for the case $N = 12$. However, computational time would frow proportionally to *M.* Interestringly, $M = 2000$ guarantees near-optimal throughput performance for the considered network sizes and can be computed in sub-second time scales with current inexpensive hardware resources. Eventually, the conclusions are twofold. Firstly, the proposed optimization problem leads to a base station scheduling mechanism, which can potentially boost cellular capacity, especially in dense networks. Secondly the GA-based scheme it has been proposed and validated in this work achieves a sub-optimal results and could be used for actual deployments in LTE networks.

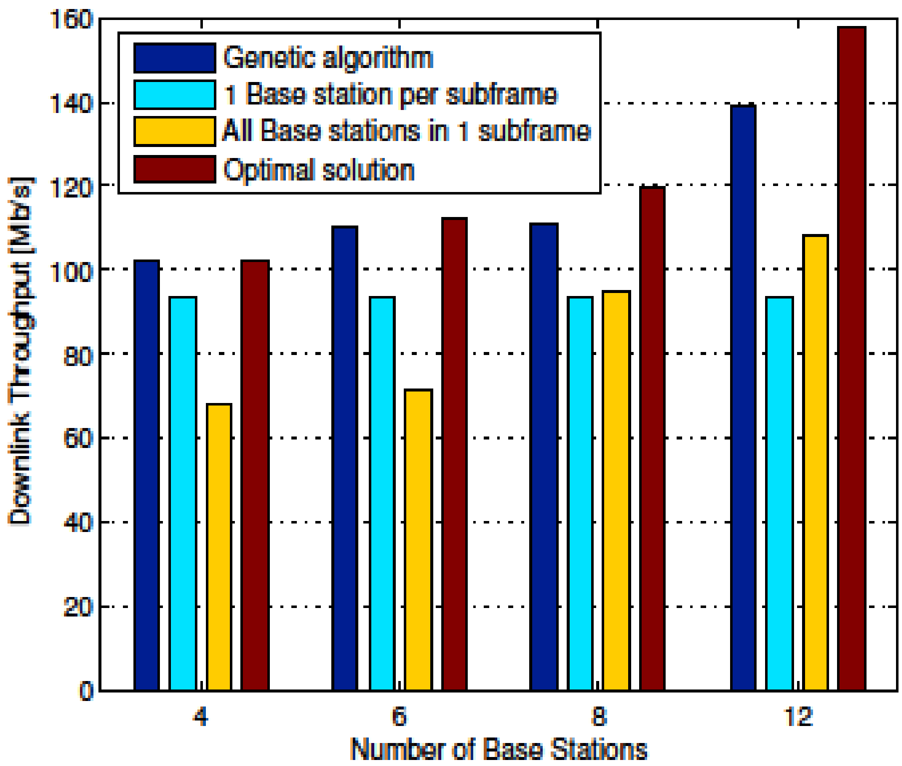

Figure 20: GA vs. optimum and other legacy cases.

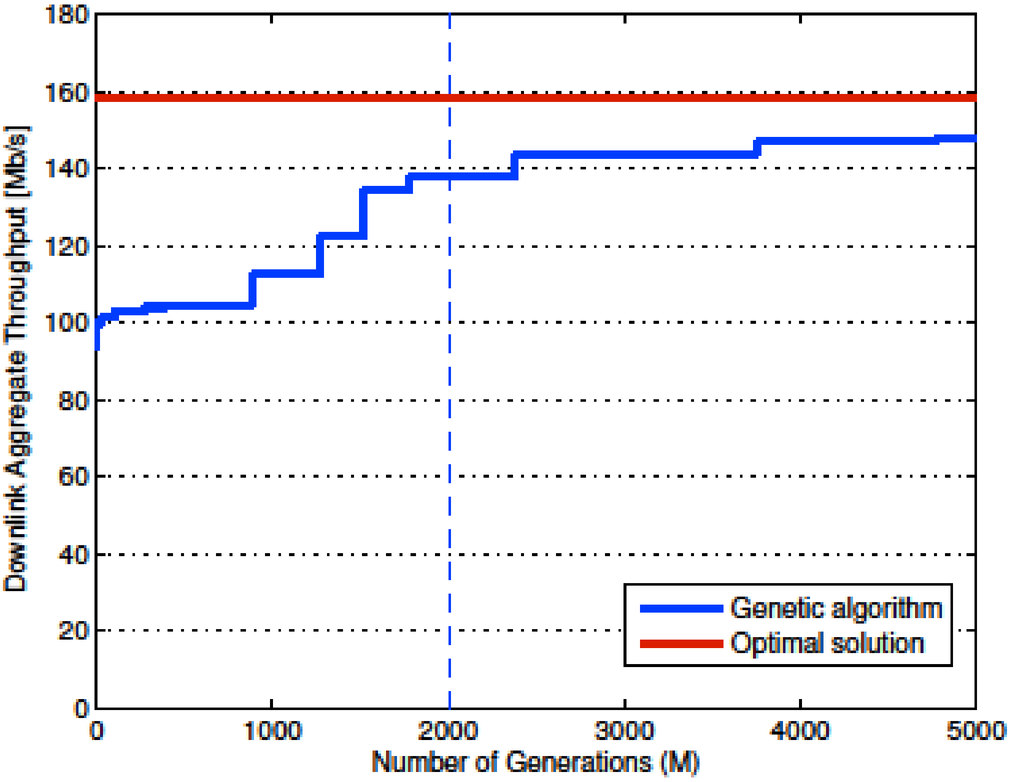

Figure 21: Impact of *M* used in GA with *N* = 12 base stations.

Chapter 6

Conclusions and Future work

6.1 Conclusion

Motivated by the excessive emergence of the 4G networks, this thesis focuses on Long Term Evolution and its improvements. At the beginning an overview of LTE is provided. LTE intends to achieve high peak data rates, to improve the system capacity and coverage. It also aims to the improvements of the fairness among the users and the reduction of the delays throughout the entire system. To manage all these aspects many new technologies have been added and tested successfully. Nonetheless, the ongoing research aims to even higher goals, surpassing in this way the above mentioned requirements. The use of OFDMA, the advanced MIMO technologies, the Carrier Aggregation , the Heterogeneous Networks) with Pico-cells, Femto-cells and Relay nodes are some eye catching concepts fot the researchers.

One of the obstacles, which results in significant difficulties is the so called Inter-Cell Interference. Since the number of frequency bandwidths for commercial systems is very limited, using frequency reuse 1 scheme, is the only viable solution for operators. This means that in a LTE network, even the adjacent base stations should transmit simultaneously to all resource blocks, which causes high interference levels to the users and more generally the performance of the network degrades.

To manage this important problem, many solutions have been proposed in the recent years. These solutions are divided in three categories and are listed below:

- Inter-Cell Interference Cancellation
- Inter-Cell Interference Randomization
- Inter-Cell Interference Mitigation

Due to the really wide range of the existing techniques, this thesis refers to some of them for the sake of the example. Researchers intend to address the problem impoving already known techniques, such as Beamforming, Power Management, MIMO, etc. and using advanced scheduling algorithms either for the users or for the base stations.

In this work, a base station scheduling approach (CoMP technique) has been presented, which belongs to the inter-cell interference mitigation category and exploits the recently proposed ABSF mechanism. It has also been shown that base station scheduling is promising, since it allows to use frecuency reuse 1 scheme while boosting network capacity. Base station scheduling is an NP-hard problem. Nonetheless, a genetic algorithm-based search of the optimal base station scheduling map, allows to achieve near-optimal results in throughput with limited computational complexity. In the end the efficiency of this approach it is shown by comparing it against other legacy – extreme cases.

6.2 Future Work

Research on Inter-Cell Interference of LTE networks can be carried on, as it is mostly an unsolved problem and therefore a very interesting field. The first step is making the scenario more realistic, by adding all the functionalities of LTE systems. An option for that is either the use of a network simulator, such as OPNET, Network Simulator 3 (NS3), which have built-in LTE implementations or the use of LTE implementations in MATLAB, that have been made recently by some universities and companies. In this way, there will be taken into account important issues, such as fairness among the users, mobility of the UEs and many more.

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* The last time the URLs have been accessed is on 1st of July 2013.

Appendix A

```
LIND = 15;                    % Length of individual vars.
NVAR = 2;                     % No. of decision variables
NIND = 40;                    % No. of individuals
GGAP = 0.9;                   % Generation gap
XOV = 0.7;                    % Crossover rate
MUTR = 0.0175;                % Mutation rate
MAXGEN = 30;                  % No. of generations
                          % Binary representation scheme

Chrom = crtbp(Nind, Lind*NVAR);           % Create binary population
ObjV = objfun(bs2rv(Chrom, FieldD));       % Evaluate objective fn
Gen = 0;                                   % Counter

while Gen < MAXGEN
   % Assign fitness values to entire population
   FitnV = ranking(ObjV);

   Plotgraphics          % Visualisation
   % Select individuals for breeding
   SelCh = select('sus' , Chrom , FitnV, GGAP);

   SelCh = recombin('xovsp' ,  SelCh, XOV);

   % Apply mutation
   SelCh = mut(SelCh, MUTR);

   % Evaluate offspring, call objective function
```

```
    ObjVSel = objfun(bs2rv(SelCh, FieldD));


    [Chrom ObjV]=reins(Chrom, SelCh, 1, 1, ObjV, ObjVSel);
    % Increment counter
    Gen = Gen+1;
End
% Convert Chrom to real-values
Phen = bs2rv(Chrom, FieldD);
```

Figure 22: MATLAB Code for a simple GA

A short description of the figure's code is given below on which is based the MATLAB implementation of this thesis.

The first lines set the paramaters that the GA uses. These are the number oand the length of the chromosomes, the crossover and the mutation rates, the number of generations and the binary representation scheme. Next, an initial distributed random binary population is created using the GA function **crtbp.** The objective function, objfun, is then evaluated to produce the vector of objective values, **ObjV**.

After the initialization, it proceeds with the generational loop. Firstly, is determined the fitness vector **FitnV**. Plotgraphics displays the performance if the current best controller allowing the user to assess the state of the search. Afterwards, the individuals from the population are selected using the stochastic universal sampling algorithm, **sus,** with a generation gap, ***GGAP*** = 0.9, as has been set in the first lines. The 36 (***GGAP x NIND***) selected individuals are then recompined using single- point crossover, **xovsp**, applied with probability of *XOV = 0.7.* Binary mutation, ***mut,*** is then applied ti the offspring with probability ***MUTR*** = 0.0175, and the objective function values for the new individuals, ***ObjSel***, is calculated. Finally, the new individuals are re-inserted in the population, using Toolbox function ***reins*** and the generation counter, ***gen***, is incremented.

The GA terminates after ***MAXGEN*** iterations and eventually provides the results.