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Enhancing the Capacity of Macro Cell Network by Wi-Fi Traffic Offloading

By Thamary Abdullah Al-Ruhaili

A thesis submitted for the requirements of the degree of Master of Science

[Computer Science]

Supervised By

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FACULTY OF COMPUTING AND INFORMATION TECHNOLOGY

KING ABDUAZIZ UNIVERSITY

JEDDAH-SAUDI ARABIA

RAMADAN 1438 H – JUNE 2017 G

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FACULTY OF COMPUTING AND INFORMATION TECHNOLOGY

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DEDICATION

It Was a Long Journey... But yet Worth to take...

To whom my Heart is filled with Endless Love…

To Whom Saying “thank you” can’t express enough my Feelings,

Gratitude and Appreciation for their Faith all the way long…

To the Soul of My Father Abdullah

To My Loving Mother Saadyah

All I am now is because of your efforts while raising me

To My beloved Sister Athary

And My Dear Brothers Thamer, Amer Nawaf and Nayef

To My Solid Rock Salwa Al-Ghamdi

To My Strong Believer Maryam Bahamdeen

And My Endless supporters Ahlam Al-Jaafari, Kholod Al-Enazi,

My Lovely Maryam Hajjar

To everyone who loved me and believed in Me

With the Deepest love and With Enormous Gratitude

I Dedicate My Master Thesis ... My Sweet Dream

To All of You …

Thamary Abdullah Al-Ruhaili

June 1st 2017

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Abstract

Nowadays, the popularity of smart phones creates huge capacity requirements for networks during mass events where thousands of people coexist in specific area. At such events, large numbers of people use their smartphones to share pictures and download information. Thus, planning for these dense network conditions must consider Macro-cell offloading. In this context, reducing the cell size has always been the best way to increase the network capacity of LTE. Wi-Fi Access Points are used to enable offloading data-traffic from the Macro-cell network to increase the capacity. In this thesis, to achieve efficient user offloading from macro to Wi-Fi As, we propose an optimized offloading algorithm based on throughput or perceived rate threshold in the down link power control with taking into account balancing the load between the two tires. This will enable better network capacity where mobile users can satisfy their minimum Quality of Service (QoS) requirements, and increasing overall performance of dense cellular networks. In addition, the proposed offloading mechanism in terms of total throughput and outage probability is studied. Results showed that the potential increase of the number of supported users per Macro-cell in joint macro and Wi-Fi APs deployments highly depends on the type of used channels in APs along with the number of APs deployed in the area.

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LIST OF SYMBOLS AND TERMINOLOGY

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third-Generation Partnership Project
4G	Fourth Generation
AMPS	Advanced Mobile Phone System
BS	Base Station
Bps	Bits per second
CDMA	Code Division Multiple Access
CDMA-TDD	CDMA Time Division Duplex
DL	Down Link
ENodeB	Enhanced NodeB
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication

Het-Net	Heterogeneous Network
HSCSD	High Speed Circuit Switched Data
HSS	Home Subscriber Service
ICIC	Inter-cell Interference Coordination
IMT-Advanced	International Mobile Telecommunication-Advanced
IP	Internet Protocol
ITU	International Telecommunication Union
LTE	Long Term Evolution
MAC	Medium Access Control
Mbps	Megabits per second
MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
NAS	Non-Access Stratum
OFDMA	Orthogonal Frequency-Division Multiple Access
PCC	Policy and Charging Control
PCRF	Policy and Charging Rules Function
PDCP	Data Convergence Protocol
PDF	probability distribution function
PDN	the Packet Data Network
P-GW	Packet Data Network Gateway

PHY	Physical layer
QoS	Quality of service
R8	Release 8
RB	Resource Block
RE	Resource Element
RLC	Radio Link Control
RRC	Radio Resource Control
SC-FDMA	Single Carrier Frequency Division Multiple Access
SFR	Soft Frequency Reuse
S-GW	Serving Gateways
SINR	Signal to Interference and Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMB	Ultra-Mobile Broadband
UMTS	Universal Mobile Telecommunications System
U-Plane	User Plane
UTRAN	Universal Terrestrial Radio Access Network

Chapter 1

Introduction

1.1 Introduction

Mobile communication and wireless networks are the hottest developing areas with the evidence of significant growth of emerging techniques for mobile and wireless communication. To satisfy the increasing demand for data rate and higher throughput, wireless communication networks need either additional spectrum or other techniques to exploit further the existing available frequency bands. For this the International Telecommunication Union (ITU) established IMT-advanced in October 2007, International Mobile Telecommunication-Advanced is a system that is capable of providing services in a wide range for telecommunications. As a response to that innovation the Third Generation Partner Ship Project (3GPP) introduced in 2008 the advanced Long Term Evaluation (LTE), which later on 2010 was ratified as an IMT- Advanced technology. LTE attracts a lot of attention due to its reduced installation cost, optimized packet transmission, reduced implementation complexity and improved flexibility . Wireless operators using the LTE Networks can handle more mobile traffic by also incorporating additional spectrum [2].

LTE macro cell network deployments appear to be a good solution to accommodate the fast growth of data traffic , but with the proliferation of using advanced mobile phones with enhanced features (such as internet connectivity and multimedia capabilities) this solution is prone to be short lived. This dilemma pushes the operators to look for another solution to enhance and increase the capacity of users in dense and high traffic areas [3]. This led to the introduction of concepts such as Heterogeneous Network (Het-Net) to go even beyond the 4G capabilities and gain more capacity with low deployment costs from the operator's perspective. By adding the Het-Net elements into an existing cellular network the abovementioned targets for enhancing the capacity and the user experience can be achieved [4]. This is a significant issue especially with the mass events as operators prefer to find low cost solutions that can provide a good user experience for a short and specific period like fireworks festival, huge sports events in stadiums and hajj pilgrimage that accrue once a year.

A Het-Net can be defined as a multi-tier network consisting of large Macro-cells and smaller cells including Microcells, Pico-cells and Femto -cells. Another possible scenario for a Het -Net is using small cells equipped with Wi-Fi access points for mobile offloading [5]. Wi-Fi offloading is considered to be one of the most economical and efficient ways to be used by operators in order to enhance the capacity and coverage and can be used as a possible interesting solution for the mass events capacity issues [4].

This Thesis will investigate a way for a Macro-cell user to switch to a Wi-Fi access point to offload the data traffic from a Macro-cell in a cellular network with the objective of increasing the capacity for the overall system. Investigate a suitable cell association that assign's users to the best tier and the most suitable base station/access point in order to balance the load among the different Het Net tiers. This can be done by taking into account suitable approaches for managing the network selection method, in order to gain the expected capacity enhancements.

1.2 Evolution of Mobile Wireless Access Network

The International Mobile Telecommunications (IMT-2000) lunched by the International Telecommunication Union (ITU). IMT-2000 goal was to provide high QoS for multimedia communication responding to increased demand sending data. Responding to ITU-IMT-2000 initiative, two partnership organizations were established: The Third Generation Partnership Project (3GPP), and The Third Generation Partnership Project2 (3GPP2). Mobile communication Development have been viewed as a successive sequence of generations developed by 3GPP and 3GPP2, 2G,3G and even beyond 3G mobile systems. The first generation of mobile communication was supporting analog, while the second generation supported digital communication. The third generation was targeting to provide voice service along with multimedia transmission. In this section I will demonstrate mobile generations as a path leading to LTE systems [6].

1.2.1 The First Generation (1G)

Various systems of First- generation cellular Networks (1G) was introduced in the late 1970s and early 1980s. 1G mainly was an analog based and limited to Voice services. The first 1G system was introduced in USA, Advanced Mobile Phone System (AMPS). Another 1G variation, the Nordic Mobile Telephone System (NMT) and the Total Access Communication System (TACS). These systems were developed individually in different countries, although they all can offer a reasonable voice quality limited to the country boundaries, but it still suffers from limited spectral efficiency. Most of those countries replaced 1G to 2G to overcome the drawbacks of such systems [6, 7]

1.2.2 The Second Generation (2G)

The Second –generation (2G), is a digitally based system, which promises a better voice service and higher capacity. The main widely known 2G systems are: Global System for Mobile Communication (GSM), Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA) and Personal Digital Cellular (PDC) .GSM and CDMA both later on forming separate 3G partnership projects (3GPP,3GPP2) respectively, based on CDMA technology they have developed IMT-2000-compliant standards. GSM is a Circuit-Switched Data (CSD), which offers a throughput up to 14.4kb/s. It is designed to provide voice services and limited data communication, such as Short Message Services (SMS) containing less than 160 characters. These limitations led to the standardization of the High Speed Circuit Switched Data (HSCSD) and General Packet Radio Service (GPRS). HSCSD enables GSM with higher data rates (up to 57.6 kb/s) by aggregation of several time slots per TDMA frame with HSCSD, while GPRS ensures designing the GSM around a number of guideline principles such as frequency bands, radio modulation, and frame structure to support non-real-time packet data efficiently. GSM allows up to eight users to share a single 200 kHz radio channel by allocating a unique time slot to each user. Using GPRS as a GSM radio technology began the move to 2.5G by adding the packet switching technique, where voice or data sent to destination in broken packets and this was a significant growth towards 3G. GSM transmission method is TDMA and slow frequency hopping for the voice communication, and enhances the data rate for Global Evolution (EDGE) by adapting high levels of modulation schemes with the existing 200 kHz bandwidth to rise up the data rate up to 384 kHz [6-9].

The CDMA spread-spectrum-based code-division multiple access uses phase shift-keyed and was introduced in July 1993. It's also known with Cdma-One differentiating it from 3G CDMA systems. CDMA uses 1.25 MHz channel that can be shared by many users up to 64 users, it uses either 850 MHz or the 1900 MHz bands. Like GSM the throughput was limited to 14.4 KB/s, but then afterwards seven supplementary codes are assigned as an addition to the fundamental code, so data rates can reach 64 KB/s. TDMA system was originally designed to fit with AMPS as a single subcarrier, which is assigned to 30kHz channel. TDMA can allow the users to share a single channel by dividing the 30 kHz channel into three channels and allocate different time slots to each user. A community of TDMA is moving to the development towards GSM. PDC is a Japanese TDMA based standard, which was exclusively used in Japan. It uses 800 and 1500 MHz bands, and was slowly phased out in favor of 3G technologies like Wideband W-CDMA and CDMA2000 as 3G systems [6-9].

1.2.3 The Third Generation (3G)

The need for higher throughput and more capacity, 3G is evident to be needed globally as a network design standard which can provide services independent from the platform. The ITU defined two main proposed systems for 3G: first Universal Terrestrial Mobile System (UMTS), which is composed of two different systems, Wideband CDMA (W-CDMA) and also known with Frequency Division Duplex (FDD) or CDMA Time Division Duplex (CDMA-TDD). The second 3G system is cdma2000, which it is an evolution of Cdma-One in 2G. UMTS is a technical specification that can work with FDD and TDD standard done by 3GPP, and FDD is considered to be the main technology for UMTS, which is originally inherited from CDMA and also uses pseudo-random codes. Cdma2000 is a technical specification which has been introduced by 3GPP2 can provide peek speeds up to 2.4 Mbps with an average user throughput 400 and 700 Kbps, while the average uplink data rate can reach 60 to 80 Kbps [6-9].

1.2.4 The Fourth Generation (4G)

The most important objective for the next generation of wireless communication is the high data rate for multimedia services. Now a day's 3G systems operates on the 2GHz frequency band but this generation still have limitations which they are looked up to be solved with the 4G offering an ideal basis and band width to provide more efficient services as the network is all-IP based [9, 10]. The 3GGP group as step towards 4G broadband wireless, they started the investigation of Long-Term Evolution (LTE) as a standard in 2004. LTE is promising a high spectral efficiency and it’s compatible with the earlier 3GPP releases. From the other hand 3GPP2 upgraded cdma2000 cellular system to Ultra-Mobile Broadband (UMB), which offers many new features and techniques to fulfill the high data traffic expectations. Data rates can reach up to 275 Mbit/s in the downlink (base station to mobile) and 75 Mbit/s in the Uplink case(mobile to base station)[1].

1.3 Global Mobile Data Traffic

A number of wireless access technologies (both 3GPP and non-3GPP) beyond LTE can also be connected to the Evolved Packet Core (EPC), for example, Wi-Fi. It is predicted that mobile data traffic will increase drastically over the years to come and thereby create high capacity demands. A multitude of new services and improved device capabilities mean that mobile broadband traffic and consumer data-rate demands are growing at an unprecedented rate. In particular, mobile broadband traffic has seen exponential increases, and new report from Ericsson which is a representative base for calculating world total mobile data traffic in 2G, 3G and 4G networks says mobile data traffic will grow 10-fold between 2011 and 2016. Ericsson's findings show that Mobile broadband subscriptions globally grew 60 percent in one year and are expected to grow from 900 million by the end of 2011 to almost 5 billion in 2016, and by 2016 it is also forecasted that users living on less than 1 percent of the Earth's total land are set to generate around 60 percent of mobile data traffic [11].

The data traffic increase is contributing to revenue growth for mobile operators when more and more consumers use data traffic generating devices such as advanced Smartphones and PCs. Particularly using LTE smart phones, as in the latest Ericsson forecast data consumption per subscriber will increased total traffic ten-fold for all devices by the end of 2021 [11]. As it is depicted in Figure 1 predicted by Cisco , a sevenfold increase over 2016.A growth of 49 Exabyte per month by 2021 for mobile data traffic, and this estimates a data growth at a CAGR of 47 percent from 2016 to 2021.This report also shows that total Smartphones traffic will triple in 2011 and global penetration is now at 82%, and the total number of mobile subscriptions is at around 5.8 billion [12]. In 2018, global Internet traffic reached 17,144 EB, and Figure 1 provides a view of the historical benchmarks for total Internet traffic.

- ✓ Annual growth rate 47% (2016-2021)
- ✓ Expected to reach 24.3 Exabyte per month by 2021.
- ✓ 7-fold increase over 2016.

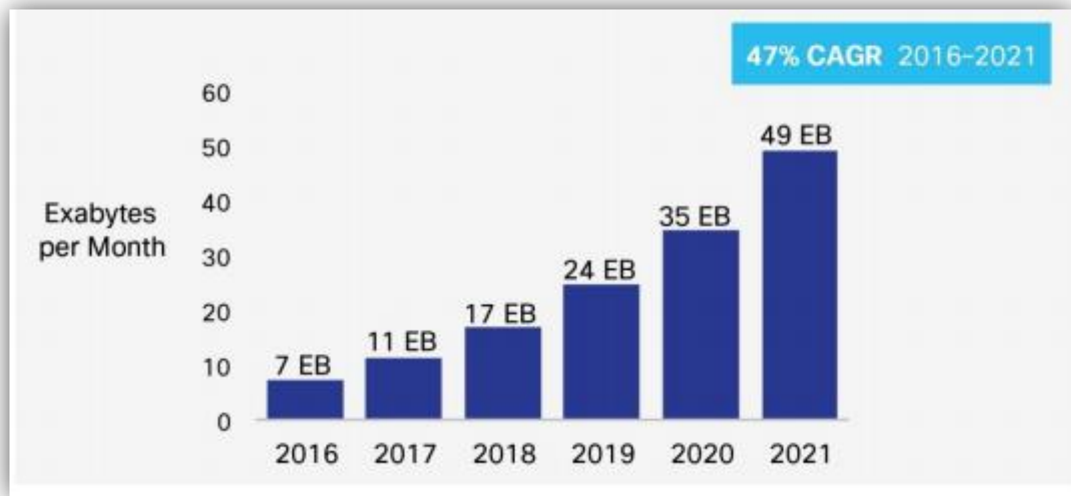

Figure 1: Global Mobile Data Traffic Growth Projection (source: Cisco VNI 2017)

1.4 Cellular Mobile Network Capacity

Capacity can be noted with using the cellular network system with a high spectral efficiency. The fundamental measure of spectral efficiency is the bits per second (bps) obtained relative to Hertz (Hz) of spectrum used (bps/Hz).

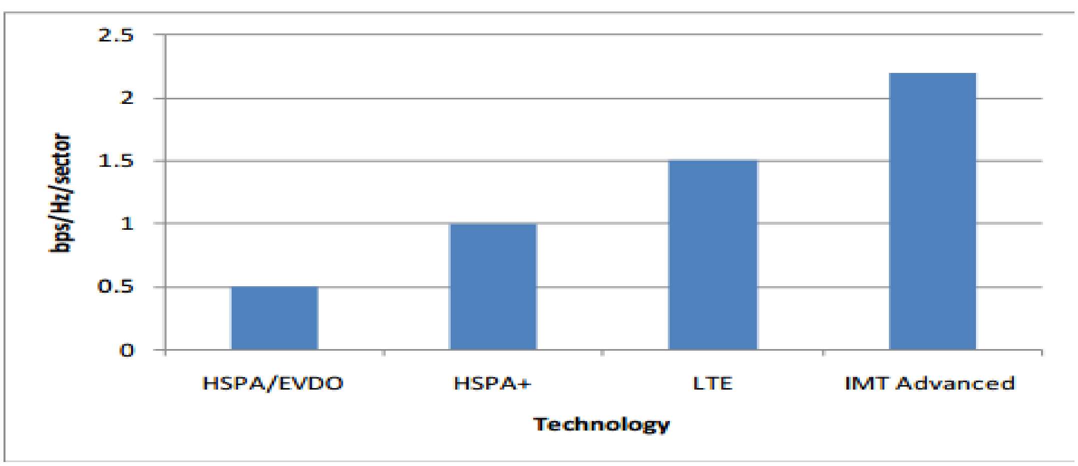

Figure 2: Data Spectral efficiency evolution, based on [13]

Figure 2 summarizes the cited spectral efficiency values. Downlink spectral efficiency in wireless systems is greater than uplink spectral efficiency, often at about double of the uplink value. This is partially because base station transmits at greater power than the mobile devices. In addition, mobile devices, transmit on their separate radio, thus coordinating the shared channel is important. Unlike the downlink case, where there is just the base station transmits on the radio channel. Network capacity can be enhanced through using more than one transmitter, as the downlink uses MIMO technology to provide higher throughput. Although using MIMO can enhance the capacity, still it is not enough to address the prosper capacity demand for mobile services [13].

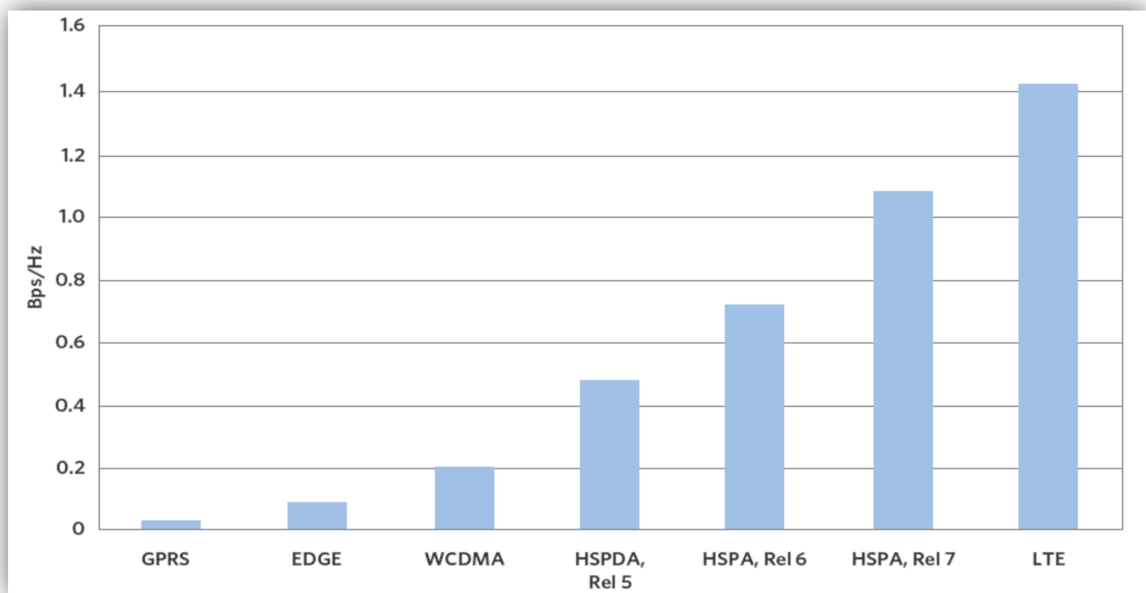

Figure 3 : Historical Increases in Spectral Efficiency , based on [14]

Figure3 shows the historical increase in cellular network generations spectral efficiency with 18% growth since 2007 with High Speed Packet Access (HSPA) Rel 6 until 2013 with LTE, cell site increase 7% per year and 8% growth in the available bandwidth spectrum per year. This will lead us to an annual growth rate with 36% per year, as 108% * 107%*118%= 136%.

Comparing the growth of data traffic with 61% with network capacity growth with 36% , there is a huge gap , which need to be narrowed down through operators and cellular vendors [14].

1.5 Research Issues & Motivations

Mobile networks are facing the growing flood of Internet data, as evident by Cisco, the traffic from smart phones will grow from 92 percent to 99 percent by 2021. Solutions needed to be found by vendors and mobile operators to reduce network congestion with a low cost to preserve customers [12]. This issue is emphasized with mass events, which accrue once a year such as hajj, festivals and football's games at stadiums, as shown in Figure 4. Operators need to find low cost solution with a good quality of service provided to participants. Half of smartphones and over 90% of 3G enabled laptops and notebook PCs are already Wi-Fi enabled. Hundreds of millions ubiquitous Wi-Fi access points provide large enough complementary capacity space for mobile networks. The motive of this thesis is to study this spectacular growth of the mobile data and discuss how the Wi-Fi technology can help the operator to turn this overwhelming growth to be an opportunity instead of a threat.

Figure 4: Different examples for Mass Events

1.6 Problem Statement and Research Scope

Different solutions have been proposed to increase the capacity of cellular network, as this field has gained the attention of international research in order to find and study the benefits of the introduced paradigms and approaches. The traditional expensive ways is by adding new macro base stations, cell splitting or frequency reuse [3, 10]. To satisfy the increasing demand for data rate and higher throughput, wireless communication networks need either additional spectrum or other techniques to exploit further the existing available frequency bands. LTE networks attracts a lot of attention due to its reduced installation costs, optimized packet transmission, reduced implementation complexity and improved flexibility[1]. Although LTE proved to be a good solution for mobile data traffic growth, with a fixed LTE bandwidth and increased number of mobile users a high blocking ratio will accrued, especially in crowded areas. The Blocking ratio in LTE network as the number of users increases. Figure 5 shows a 90% blocking ratio In LTE Network with 1000 users in the Macro-cell under a specific simulation parameters, as red represent blocked users versus connected users with green.

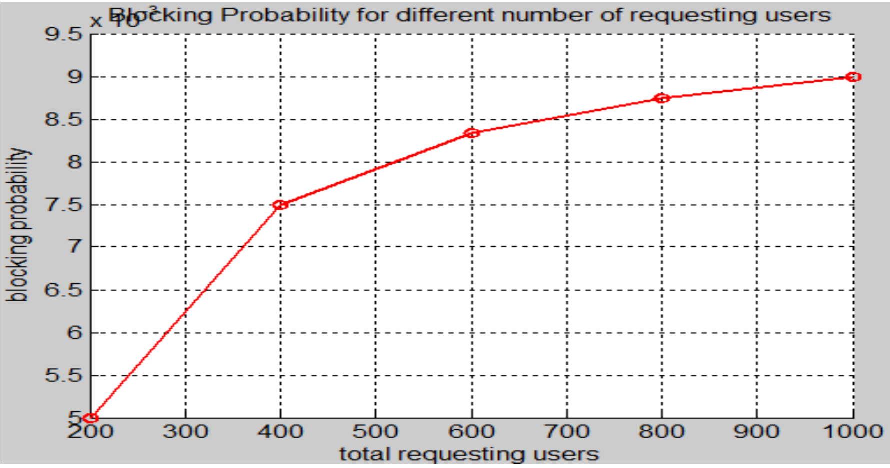

Figure 5: A 90% blocking ratio In LTE Network with 1000 users in the Macro-cell

One promising solution to cope with the huge capacity requirements generated by increasing number of mobiles, is using Het-Nets to go even beyond the 4G capabilities and gain more capacity with low deployment cost [3].In mass events operators prefer to deploy low cost, energy efficient solutions with a good QoS in a specific time period like fireworks festivals, huge sports events in stadiums and religious events such as the Hajj pilgrimage. In [15] the Saudi Telecom Company (STC) partnered ship with Nokia Siemens Networks (NSN) as STC moved on using NSN in their sits at Mecca, Medina and other pilgrim areas during the Hajj. Solutions and services provided by NSN have proven a better quality of service in highly demand areas with huge data traffic over the past years.

A Het-Net can be defined as a multi-tier network consisting of large Macro-cells and any kind of small cells such as Micro-cells, Pico-cells and Femto-cells, using the same air interface (3G, 4G). Another possible scenario for a Het -Net is using small cells equipped with Wi-Fi access points for mobile offloading [5, 16], as shown in Figure 6.

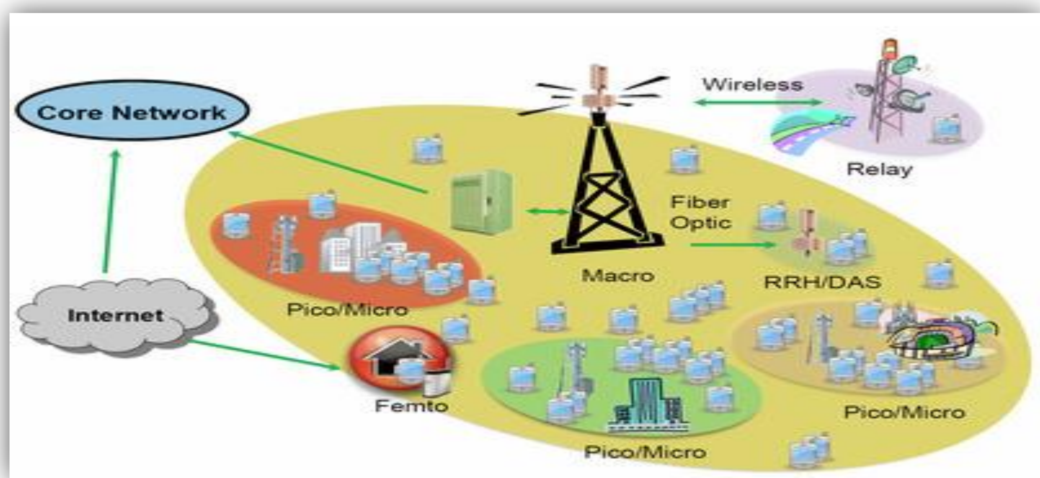

Figure 6 : Het-Net Topology, based on [16]

Table 1: Different coverage areas and characteristics for Het-Net Elements

Cell Type	Coverage Type	Cell Radius	Transmit Power
Macrocell	Outdoor	> 300 m	46 dBm
Microcell	Outdoor	100-300 m	40 dBm
Picocell	Outdoor – Indoor	< 300 m	23-30 dBm
Wi-Fi AP	Outdoor – Indoor	< 30 m	20 dBm
Femto cell	Indoor	< 50 m	< 23 dBm

Heterogeneous elements involve Micro cells, Pico cells, Femto cells and Wi-Fi AP as shown in Table 1. Each element is distinguished by its coverage; transmit power, backhaul, propagation characteristics and physical size [3].

In Het-Nets using another network technology to deliver data traffic originally supposed to be delivered with LTE BS is known as data offloading. Offloading terminology is defined as A Complementary Network Technology to deliver data which is originally targeting the cellular network [17].Wi-Fi offloading is considered to be one of the most economical and efficient ways to be used by operators in order to enhance the capacity and coverage and can be used as a possible interesting solution for the mass events capacity issues [4]. This type of offloading is the focus of this research as Wi-Fi have several advantages such as: it's built in most smart devices, vast on unlicensed band, high data rate, advanced QoS and security.

This research will investigate a way for an LTE Macro-cell user to switch to a Wi-Fi access point to offload the data traffic from a Macro-cell in a cellular network with the objective of increasing the capacity for the overall system, as shown in Figure 7. There will be a need to investigate a suitable cell association that will assign users to the best tier and the most suitable base station/access point in order to balance the load among the different Het Net tiers to gain the expected capacity enhancements [10].

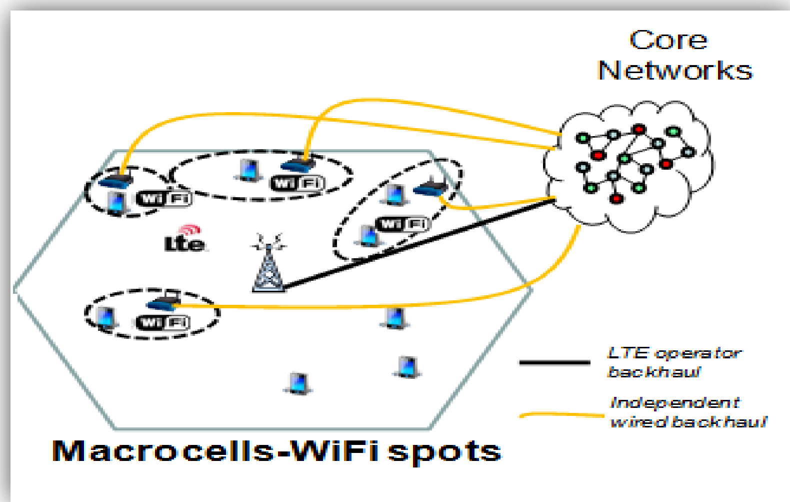

Figure 7: Proposed Wi-Fi Offloading configuration

This type of offloading configuration has mainly two challenges:

- Load Balancing Mechanism, a suitable Cell Association.
- Interference Management Methods (Co-Channel interference**)**

1.7 Objectives

- Enhance load balancing between the Het Net tiers for optimum user-cell association
- Enhance the Network capacity in terms of connected users and throughput.
- Propose optimized Offloading Algorithm effectively Enhancing Capacity & QoS

1.8 Methodology

- Overview of the state-of-art in LTE field & a Wi-Fi band/channelization, and small cell formation methods in Het Nets.
- Study the coverage and capacity dimensions for the two Het Net tiers, Wi-Fi access points along with the LTE macro cell.
- Investigate the behavior of a dense LTE macro cell Along with Wi-Fi deployment in order to help developing the analytical model.
- Study different Offloading Algorithms & Mechanisms.
- Identify the resource management optimization problem along with constrains and critical parameters and factors that will affect the optimization function.
- Determine algorithms for optimum user-cell association to a macro cell base station or a Wi-Fi access point.
- Design a simulation environment for testing offloading mechanisms of LTE macro cell to Wi-Fi access points with the objective of balancing the macro cell load and enhance overall network Capacity.
- Validate the proposed offloading mechanism between LTE macro cell and Wi-Fi via analysis and simulation.
- Compare different offloading algorithms from the literature along with an LTE standard case to verify the capacity enhancement with the proposed Optimized offloading algorithm.

1.9 Thesis Structure

The thesis is organized as follows: In chapter 2, a detailed background of LTE specifications along with Wi-Fi specifications is introduced. Followed by, types of integrations between LTE and Wi-Fi network. In chapter 3 the related works in wireless networks concerned with Het-Net Offloading generally and Wi-Fi offloading algorithms specifically were demonstrated. In chapter 4, the proposed optimized offloading algorithm and resource allocation methodologies are described. Chapter 5 the first part system validation for the proposed offloading algorithm and the second part discusses the findings and results. Finally, chapter 6 summarizes the thesis along with conclusions and future work.

1.10 Publications

- A survey on Het-Nets: Challenges and Solutions for Enhanced Capacity and Energy Efficiency, Submitted to IEEE ACCESS Journal, March 2017.

- Performance Evaluation for Wi-Fi Offloading Schemes in LTE Network Published in the International Journal of Computing & Information Sciences (IJCIS) Vol.12, September 2016, PP.121-131.

- Optimized Wi-Fi Offloading Scheme for High User Density in LTE Networks In-progress to be submitted.

Chapter 2

Background

2.1 Introduction

The first part of this section covers the background of the LTE standard and gives an overview of its most important components. The second part covers the background of IEEE 802.11 Wi-Fi standard, structure and access modes. The third section will cover the categories of offloading integration between LTE networks and Wi-Fi. The last section covers Link budget, channel modeling effects either with LTE or Wi-Fi network.

2.2 LTE Basics

2.2.1 LTE Overview

LTE or the Evolved Universal Terrestrial Access Network (E-UTRAN) is considered as the latest generation of 3GPP standards. LTE is designed to support only the Packet switched services, and it can support IP- network with 150 Mbps data rate. LTE brings up a x50 performance enhancement, as it aims to provide a seamless Internet protocol connectivity(IP) between the User Equipment (UE), and the Packet Data Network (PDN) [18]. LTE arise over earlier 3GPP releases, due to its compatibility and interworking with existing 2G and 3G cellular infrastructure. Thus the handoff between those standers and LTE can be seamless. LTE supports High spectral efficiency, with this high data rate new applications can be streamed such as Voice over IP, video conferences and other types of multimedia. LTE release 9 standardization based on 3GPP is as following [19]:

- High spectral efficiency with low latency.
- Simplified Architecture.
- High data rates: Up to 300 Mbps in downlink and 75 Mbps in uplink when using 4x4 MIMO and 20 MHz bandwidth.
- Uses OFDMA air interface in downlink and SC-FDMA in uplink.
- Support advanced antenna like multiple antenna scheme (MIMO) to significantly increase spectrum efficiency

Based on IHS report [20], the number of LTE subscribers has dramatically increased, and the expected growth is up to 1 billion users by 2016. Another recent research by ABI [21], expected that the LTE subscribers would even reach to 1.4 billion globally by the end of 2015. In [11] shows that LTE subscriptions have reached the first billion during 2015 and by the end of 2021 will reach a 4.3 billion subscriptions. Figure 2, shows the number of global LTE subscribers expectations based on GSMA Intelligence [22].

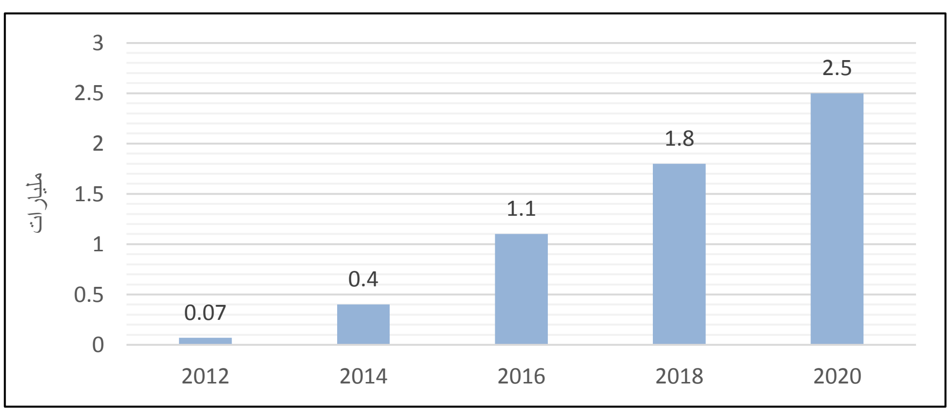

Figure 8: Number of Global LTE Subscriber Forecast, based on [22]

2.2.2 LTE Architecture

3GPP group specifies new packet core for LTE architecture, called Evolved Packet System (EPS). It has two main components: the access network and the core network as shown in Figure 9. The access network is the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) while the core network is the Evolved Packet Core (EPC). The core network is all IP-centric and is fully packet switched which provides QoS support and it's designed to support non-3GPP access for mobile IP. Both Radio Access Network (E-UTRAN) and EPC could achieve many functionalities including: Network Access Control Functions, Packet Routing and Transfer Functions, Mobility Management Functions. Security Functions, Radio Resource Management Functions, and Network Management Functions [6, 23].

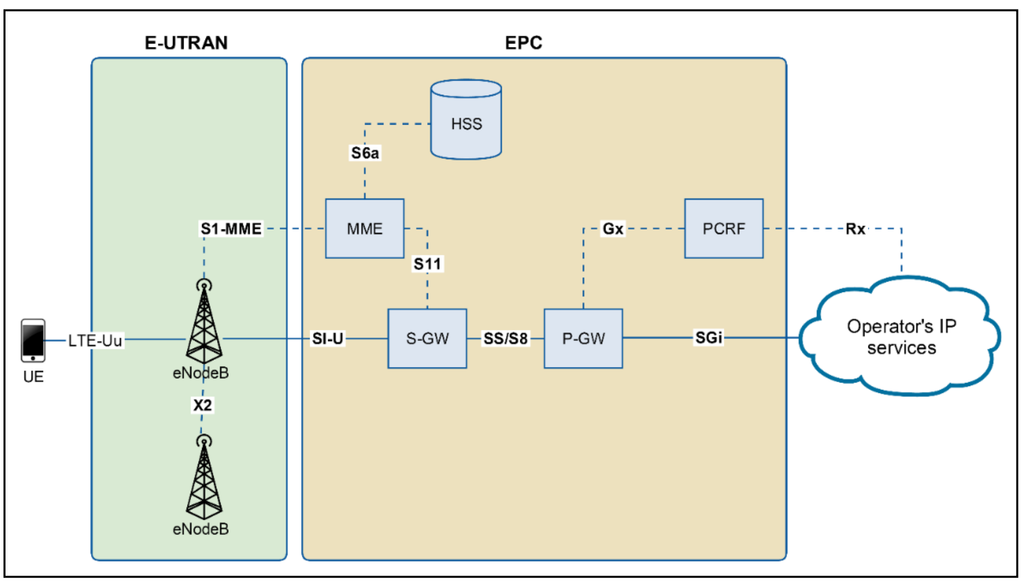

Figure 9: LTE reference Architecture Model, based on [23]

2.2.2.1 LTE ACCESS NETWORK (E-UTRAN)

E-UTRAN is the air interface for LTE, as it meant to be a replacement of UMTS technologies specified in 3GPP earlier releases. E-UTRAN is an entirely new interface system, which provides lower latency and high data rates. It uses OFDMA radio access in the downlink, and for uplink SC_FDMA radio access is used. The basic architecture components of E-UTRAN are: eNodeBs (eNBs) at the RAN, Mobility Management Entities (MMEs) and Serving Gateways (S-GW) at the core as shown in Figure 10. The eNodeBs are connected to each other through X2 interface while they are connected to entities at the core (MMEs and S-GWs) using the S1 interface. This simplified architecture is for reducing latency of all radio interface operations [23-26].

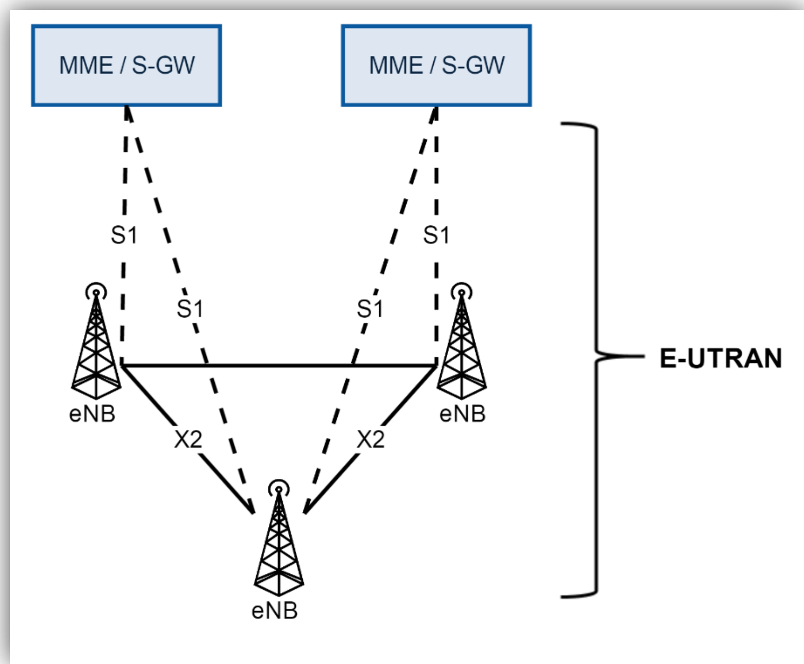

Figure 10: E-UTRAN Architecture, based on [23]

2.2.2.2 LTE Core Network (CN)

The main component of the System Architecture Evolution (SAE) is the Core Network (CN), which is also known as EPC. The EPC is composed of five network elements: the Serving Gateway (S-GW), the Packet Data Network Gateway (P-GW), the Mobility Management Entity (MME), the Policy and Charging Rules Function(PCRF), and the Home Subscriber System (HSS)[6, 24]. The S-GW is responsible of forwarding user packets, and acting like mobility anchor for the user while inter-eNodeB handovers between LTE and another 3GPP technologies such as 2G, 3G. In LTE, MME component is the Key control node, as it’s responsible for choosing the S-GW for a UE in the handover process. P-GW provide connectivity to UE for external data networks, it acts like a mobility anchor between 3GPP and non-3GPP technologies. The QoS and policy control decision making is done through PCRF. HSS stores all permanent subscribers’ data and integrate the Authentication Center (AuC)[6, 26, 27].

2.2.3 LTE Multiplexing and Frequency Bands

Flexible bandwidths used in LTE are: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz. LTE supports both types of multiplexing Frequency Division Duplex (FDD) and Time Division Duplex (TDD). LTE FDD has a paired spectrum, and separate frequency bands are used for Uplink (UL) and Downlink (DL) respectively. An Example for FDD multiplexing: FDD20 MHz comprise tow pair of 20MHz bandwidth, 20 MHz for DL and 20 MHz for UL, hence UL and DL transmissions are separated in the frequency domain. TDD spectrum is known with Un-Paired spectrum , and its shred for both Ul and DL [28] .

Using the same example with TDD20 MHz, imply a shared bandwidth of 20MHz used for both UL and DL at different time slots .The multiplexing technique can directly affect the throughput , such as LTE FDD has a symmetric bandwidth for both UL & DL with the same throughput. In LTE TDD an asymmetric bandwidth assigned for both UL & DL, sharing the same throughput. Choosing the multiplexing type depend on the defined band, such as 700 MHz Band used in US is FDD, while 2300 MHz band used in India is TDD [28, 29]. Figure 11 shows the difference between FDD and TDD multiplexing.

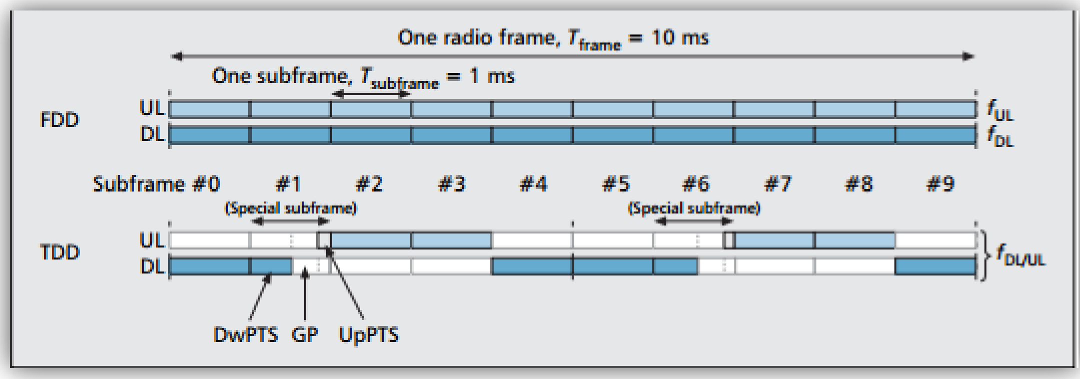

Figure 11: Difference between FDD and TDD multiplexing, based on[29]

2.2.4 LTE Frame Structure

The LTE Frame structure has two types of frame structure, and there is a difference between the Time Division Duplex (TTD) and the Frequency Division Duplex (FDD) in the requirements and separating transmitted data.

2.2.4.1 LTE FDD mode systems

LTE FDD frame has a total length of 10 ms, with a 10 sub frames each consists of two slots with duration of 0.5 ms as shown in Figure 12. One slot consists of either 7 or 6 OFDM Modulation symbols depending on the Cyclic Prefix length (CP). The modulation scheme affect the number of bits held in a one symbol, as in 64 QAM modulation scheme each symbol holds 6 bits [6].

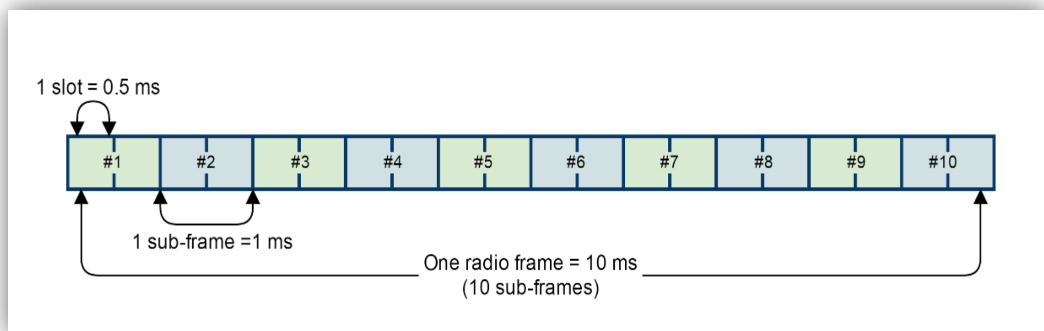

Figure 12: LTE FDD Frame Structure ,based on[23]

The normal CP length is about 4.69 microseconds, Then 7 OFDM symbol is placed in the 0.5 slot, as each symbol will occupy 71.29 microseconds. In the case of, using the Extended CP length, this is equal to 16.67 microseconds. Only 6 OFDM symbol is placed in the 0.5 slot, as each symbol will occupy 83.27microsecond.

2.2.4.2 LTE TDD modes systems

LTE TDD frame has a total 10 ms length, which consist of two half frames, each one with 5 ms long. Each half frame is split into another 5 sub frames with 1 ms long per each, as shown in Figure 13. The only difference between TDD and FDD is the existence of special sub-frames that switch between UL and DL transmissions, FDD frames are assumed in this thesis [30] .

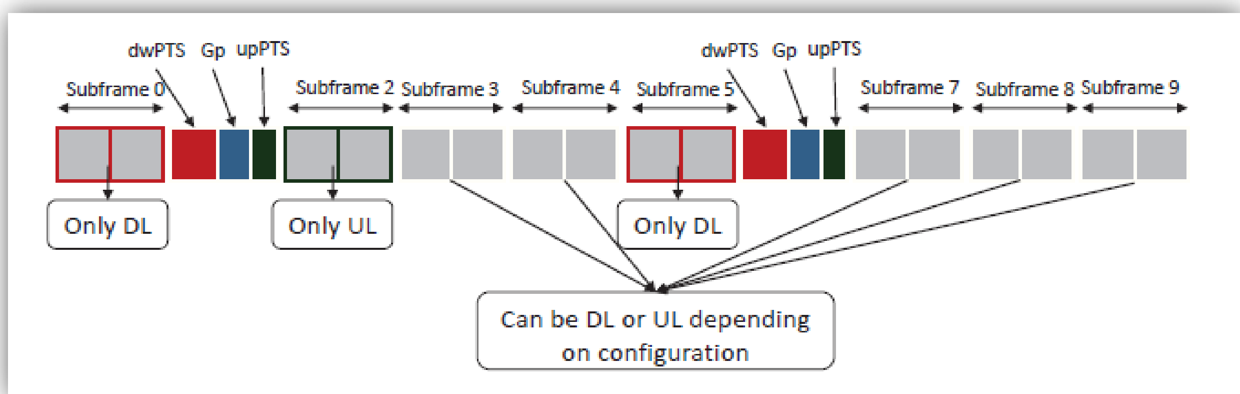

Figure 13: LTE TDD Frame Structure, based on [30]

2.2.5 Resource Block Structure

The Resource Element (RE) is the smallest time-frequency resource that can be allocated to a user either UL or DL transmission. Each RE corresponds to one subcarrier comprised with seven or sex OFDM symbols depending on CP type. In the case of normal CP every subcarrier holds seven OFDM symbols, and in the extended CP case sex OFDM symbols are used as shown in Figure14. Transmission in LTE is allocated in blocks of REs. A scheduler at the eNB allocates resources in Resource Blocks (RBs). A RB is 180 kHz in a single time slot, i.e., 0.5 ms. One RB consist of 12 subcarrier, which hold seven or sex OFDM symbols depending on the cyclic prefix employed. In Figure a normal cyclic prefix is presented, and the OFDMA subcarriers spacing is 15 kHz. The number of RBs varies between 6 and 100 Depending on the implemented channel bandwidth. Different Total number of RBs 6, 15, 25, 50, 75 and 100 are used for 1.4, 3, 5, 10, 15 and 20 MHz channel bandwidths respectively [6].

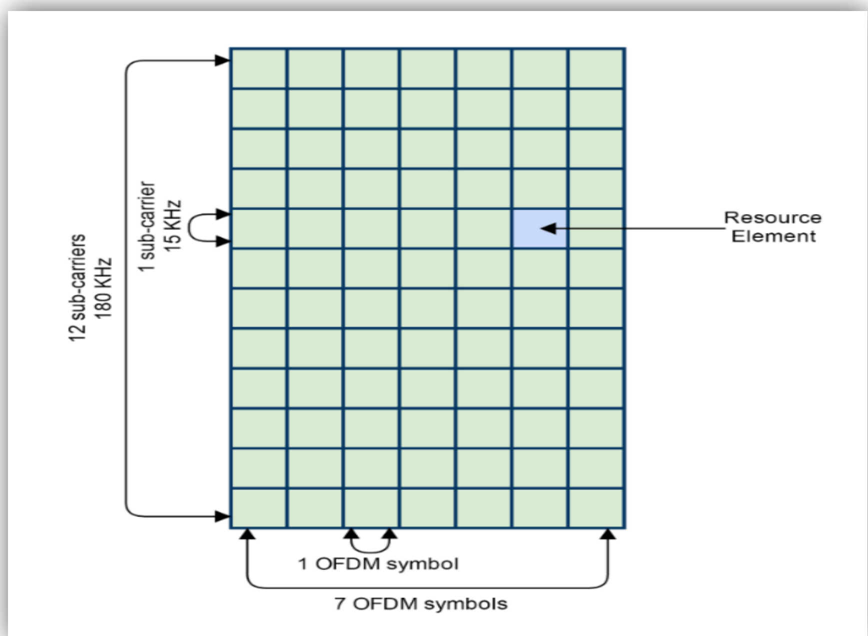

Figure 14 : LTE Resource Block, based on [23]

2.2.6 LTE Access Mode

2.2.6.1 OFDM Access Mode for Down Link (OFDMA)

OFDM is the suitable technology for high data rate and multimedia services therefore; it has adopted in 3GPP LTE system. The key advantage of OFDM over single carrier modulation schemes is the ability to subdivide the bandwidth into multiple sub-carriers, which are orthogonal while carrying data to improve bandwidth efficiency. The sub-carrier spacing is fixed with 15 KHz, with seven OFDM symbols in each based on the CP type. The big motivation of using OFDM in LTE is due to its significant features: low-complexity of base-band receiver, compatibility with advanced antenna technologies and link adaption and frequency domain scheduling. LTE uses OFDM for DL transmission, which is typically from eNodeB to the UE terminal. The transmission is done by transmitting data over many narrow band careers of 180 KHz each instead of spreading one signal over the complete 5MHz carrier bandwidth. OFDM modulation is used to transmit a reliable and cost-effective broadband signals. Due to the narrowband subcarriers used, OFDM is not vulnerable to wireless channel effects such as delay spread and frequency selective fading [31].

2.2.6.2 SC-FDMA Access Mode for Uplink

LTE in the UL uses another form of OFDM called Single Carrier Frequency Division Multiple Access (SC-FDMA). Mobile battery life is one of the most important considerations; need to pay attention to from vendor’s side. Battery could drain fast affected using inefficient power amplifier in the mobile for transmitting a specific signal format and modulation. Signals that have a high peak to average ratio and require linear amplification do not lend themselves to the use of efficient RF power amplifiers. To deal with this drawback, which usually comes with OFDM, SC-FDMA solves this problem by grouping together the resource blocks in such a way that it reduces the need for linearity. The power consumption in the mobile amplifier is reduced quite well. SC-FDMA is a hybrid format that combines OFDM flexibility in sub-carrier allocation with multipath interference resilience [31].

2.2.7 LTE Maximum Throughput

The estimated theoretical maximum throughput that can be attained by LTE depends on a number of factors.

1. Bandwidth:

   The number of total RBs used in LTE varies as mentioned earlier in section 2.2.3 based on the bandwidth used. In the case of using 20 MHz for LTE with 10% of the band reserved for guard band, this implies having a total of 18 MHz effective bandwidth.

   The maximum LTE bandwidth is 20 MHz with 10% of the band reserved for guard. A single RB is 180 KHz, dividing 18 MHz over 180 KHz result with having a 100 RBs as a total number of RB of 100 RBs in 18MHz.

2. Antenna Configuration:

   The capacity of a radio link is enhanced using the Multiple Input Multiple Output (MIMO) antenna configuration, due to multipath propagation. The UE category can dramatically affect the throughput multiply by 2,4 and 8, based on the MIMO technology type, either 2×2, 4×4, or 8×8 MIMO. Some categories do not support

MIMO, which in this case the antenna is considered as SISO (Single Input Single Output).

3. Modulation Scheme:

 The selection of the modulation scheme affects the throughput and it depends on two aspects: channel quality and UE category. The modulation schemes supported by LTE are QPSK, 16 QAM, and 64 QAM. Each modulation can hold different number of bits per one symbol. QPSK modulation can carry 2 bits per symbol, 16QAM modulation can carry 4 bits per symbol, and 64QAM modulation can carry 6 bits per symbol. Signaling and control overhead is estimated to be between 20% and 25% for 20 MHz band. Different bands have different overhead percentages.

4. Cyclic prefix:

 The total number of REs in a RB is affected by the type of CP employed as mentioned earlier in section 2.2.5. Normal cyclic prefix results with having seven OFDM symbols per slot, while in extended cyclic prefix results with having six OFDM symbols per slot.

With the assumption of using a 20 MHz band, 4×4 MIMO, 64 QAM, 25% overhead and a normal cyclic prefix, the maximum LTE throughput can be calculated as follows in the DL case.

1) Calculating the total no. of REs in a sub-frame:

   100 RBs × 12 sub carriers × 7 symbols × 2 slots = 16,800 REs/sub-frame.

2) Calculate bit rate, according to 64 QAM:

   16,800 × 6 = 100,800 bits/ms = 100.8 Mbps.

3) Multiplying throughput with 4×4 MIMO:

   100.8 Mbps × 4 = 403.2 Mbps.

4) Taking control signaling overhead off:

$403.2 – (403.2 \times 0.25) = 302$ Mbps.

Therefore, 302 Mbps is the maximum LTE capacity provided with the above assumptions. 4×4 MIMO is more often used in the downlink. For the uplink it is only available for UEs category 8 while category 7 has a 2×2 MIMO, and all other lower categories are SISO. Therefore, the maximum LTE capacity in the uplink with no MIMO assumed is 75 Mbps [32].

2.2.8 Voice over LTE

Voice over LTE (VoLTE), might considered one of the most significant applications for 4G-LTE networks. There are many different aspects affect the VoLTE call capacity: voice coder, radio frequency conditions and the eNodeB scheduler algorithm. The number of resource block RBs allocated to one VoLTE call can dramatically affect capacity. Assuming to work with 20MHz LTE band, Adaptive Multi-Rate Wideband (AMR-WB) 12.65 coder and Robust Header Compression (RoHC). The coder AMR-WB 12.65 is able to generate coded speech with 253bits every 20ms. To reduce the speech codec rate between the sender and the receiver, Explicit Congestion Notification (ECN) is needed to enhance the performance. Mac layer will also add their overhead resulting with roughly 300 bits to be transported over air interface, this would imply throughput requirement for transmitting voice over LTE is 15 Kbps [33].

2.3Wi-Fi Basics

2.3.1 Wi-Fi Overview

Wireless Local Area Networks (WLAN) provide users in a limited geographical place a high bandwidth access. WLAN is based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards. Detailed specification in IEEE standard includes Physical Layer (PHY) and Medium Access Control Layer (MAC). The PHY in WLAN is different from the wired media, with its limited connection range and it’s shared by all stations. MAC protocol is complicated from other side due to hidden terminal problem. WLAN uses unlicensed spectrum either 2.4 or 5 GHz frequency band. WLAN supports seamless connectivity, flexibility, mobility, reliability and high speed access to the internet. It is usually known with hotspot in public places, enterprises and homes [34, 35].

The initial version of Wi-Fi 802.11a, 802.11b, 802.11g used Direct-Sequence Spread Spectrum (DSSS) modulation scheme to reduce overall signal interference, and Frequency-Hopping Spread Spectrum (FHSS), which it’s used as a multiple access method . In contrast, the improved version of 802.11 (a, g, n) uses OFDM modulation scheme while only version802.11b uses DSSS. Wi-Fi is widely deployed because it doesn't require licensed spectrum, provides high bandwidth with low cost, and its already built in a large number of devices. Peak data rates are 11 Mbps for 802.11b, 54 Mbps for 802.11a/g, and a maximum data rate from 54 Mbit/s to 600 Mbps for 802.11n. There are two types of access modes in Wi-Fi, either its open access like free massive Wi-Fi AP used in public places such as Malls. The second access mode is closed access, as in restricted Wi-Fi AP, which can be used in both indoor and outdoor environment [34, 35].

2.3.2 Wi-Fi IEEE 802.11 Architecture

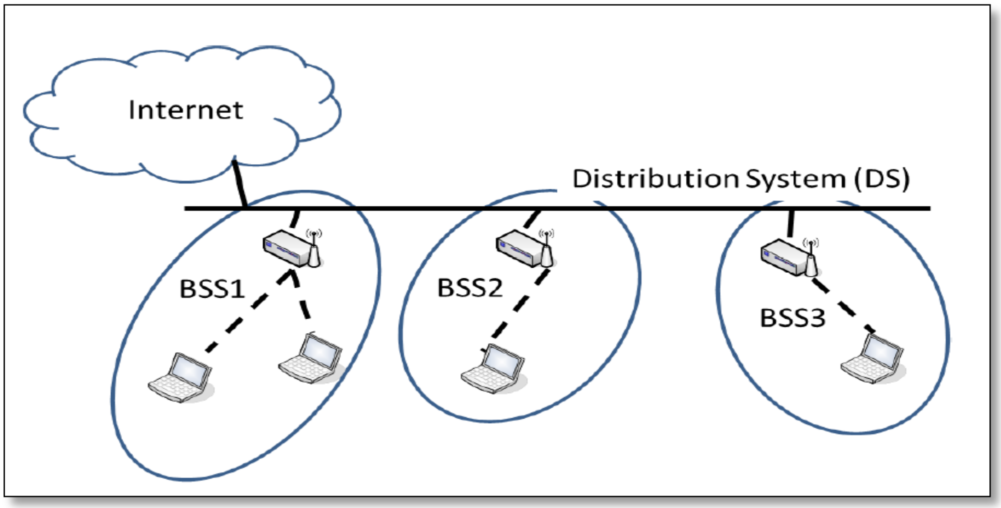

Figure 15: Wi-Fi Architecture, based on [36]

The WLAN network consist of a number of Access Points (APs) and Users clients Equipment (UE). Figure 15 shows the typical reference architecture for WLAN 802.11 based. The WLAN is divided into zones called Basic Service Set (BSS), controlled by AP along with its associated UE. The boundary of each BSS is limited to the AP coverage range, as all UE within these boundaries can gain connection.

The interconnection between different BSS is handled by an Ethernet-based backbone network, usually known as Distributed System (DS).The DS is responsible for determining which UE can communicate with an organization's wired LANs or external networks. BSS could also be connected to Wireless network, the interconnected zone between different BSS is called Extended Service Set (ESS) [34, 36].

2.3.3 Wi-Fi IEEE 802.11 PHY Structure and standers

Wi-Fi IEEE 802.11 use either 2.4 or 5 GHz frequency band depending on the type of standard deployed .There are 14 channels designated in the 2.4 GHz range spaced 5 MHz apart, with the exception of a 12 MHz spacing before channel 14.For 802.11g/n it is not possible to guarantee Orthogonal Frequency-Division Multiplexing (OFDM) operation, this will affect the number of possible non-overlapping channels depending on radio operation. There are 3 channels considered as a non-overlapping channels, channel 1,6 and 11 as shown in Figure 16 below [37].

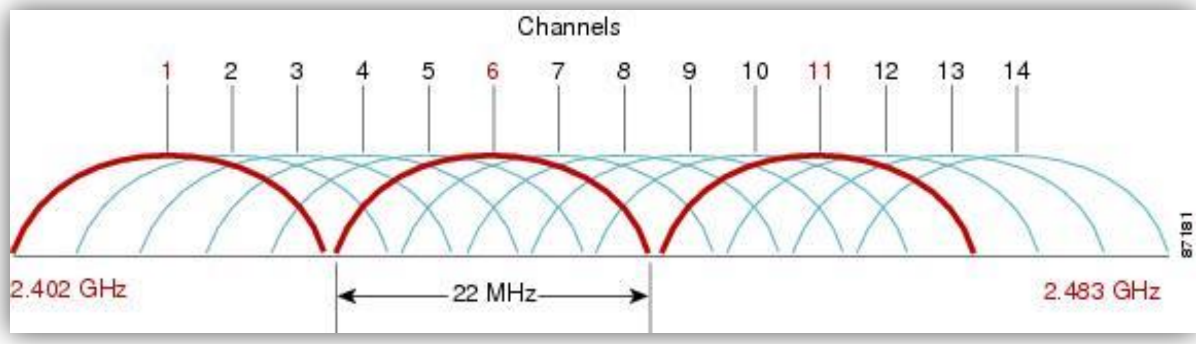

Figure 16: The 2.4GHz channels in IEEE 802.11, based on [37]

Wi-Fi IEEE 802.11 family comprised of different standers, with different bands as shown in Table 2. IEEE 802.11a provides significant high bitrates at high frequencies and shorter transmission distance for a given power level. The advantage of using this standard is low interference from neighboring APs, and the disadvantage it suffers more from multi path propagation. IEEE 802.11b operates in the unlicensed frequency band 2.4-2.485GHz competing for frequency spectrum with 2.4 GHz phones and microwave ovens. IEEE 802.11n is a new standard added to the WLAN family, with a better throughput and uses the MIMO technology to improve system performance. It can operate on both 2.4GHz and5GHz spectrum [34, 37].

Table 2: Wi-Fi IEEE 802.11 Standards family

Standard	**Frequency band**	**Bandwidth**	**Modulation**	**Maximum data rate**
802.11	2.4 GHz	20MHz	DSSS,FHSS	2 Mb/s
802.11b	2.4 GHz	20MHz	DSSS	11 Mb/s
802.11a	5 GHz	20MHz	OFDM	54 Mb/s
802.11g	2.4 GHz	20MHz	DSSS,OFDM	54 Mb/s
802.11n	2.4 GHz , 5 GHz	20MHz , 40MHz	OFDM	600 Mb/s
802.11ac	5 GHz	20,40,80,160MHz	OFDM	6.93 Gb/s
802.11ad	60 GHz	2.16 GHz	SC, OFDM	6.76 Gb/s

2.3.4 Wi-Fi IEEE 802.11 Contention Based Multiple Access Schemes

Wi-Fi MAC protocol uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method, as mobile stations contend to use a common channel. When the station wants to send data, it must listen to the channel and send only when the channel is sensed to be free for a certain time. First, if the channel is sensed as free and available, the station waits for the duration of an Inter-Frame Space (IFS). After the IFS period has passed the source that perceives the channel as free sends a ‘Request to Send’ (RTS). The destination replies with a ’Clear to Send’ (CTS). The source station sends the data to the destination .Other stations remain silent during the source-destination packet exchange as shown in Figure 17 [38].

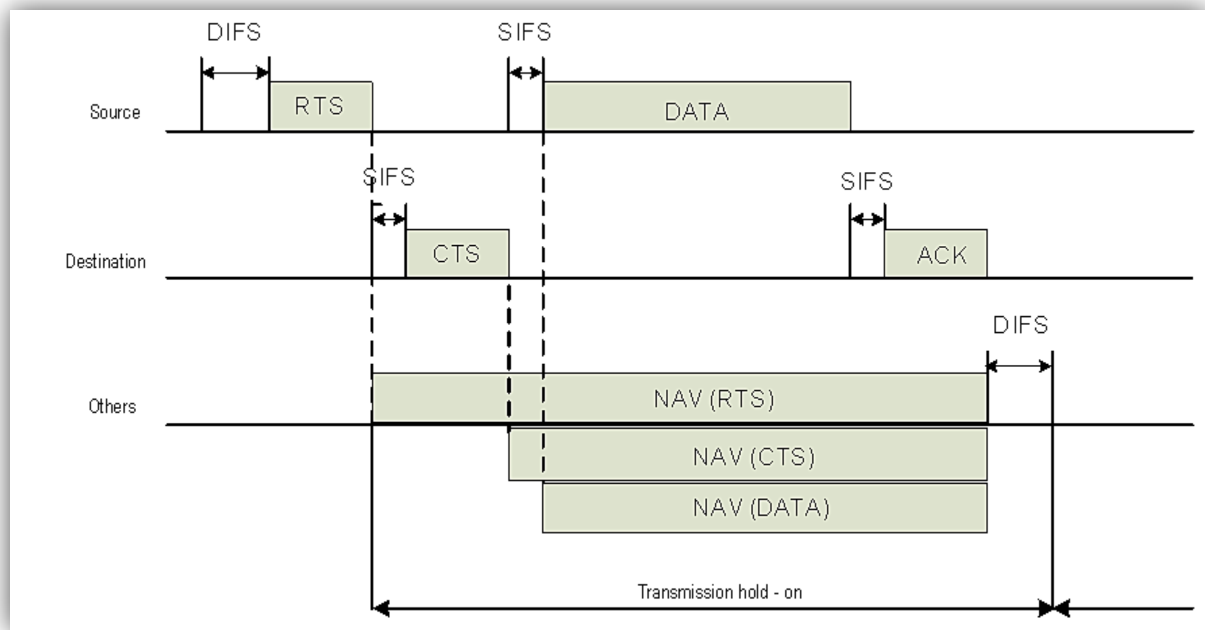

Figure 17: Wi-Fi MAC protocol uses a carrier sense multiple access with collision avoidance (CSMA/CA), based on [38]

2.3.5 Wi-Fi IEEE 802.11 Maximum Throughput

IEEE 802.11n support high throughput, with the ability to transmit multiple streams simultaneously between sender and receiver. This ability is referred to using several antennas, which called MIMO. Different aspects can affect the calculation of the PHY data rate, or Wi-Fi maximum throughput. Throughput in IEEE 802.11 can depend on a number of factors:

1. Bandwidth:

   The selected bandwidth basically depends on the type of IEEE 802.11 is used, as each standard has a specific bandwidth operating on. This has been declared in Table 2 section 2.3.3, which shows having 20, 40, 80, or 160 MHz available bandwidth. In the case of using IEEE 802.11n 20 MHz and 40 MHz are valid to use. Wi-Fi is designed to be fair to UE as if there are other devices operating on 20 MHz, it will mandate UE to reduce their channel width to 20 MHz immediately. IEEE 802.11n standard supports MAC-layer frame aggregation, to achieve higher throughput as 84% of MAC header is removed.

2. Antenna Configuration:

   The capacity of a radio link is enhanced using the Multiple Input Multiple Output (MIMO) antenna configuration, due to multipath propagation. IEEE 802.11n transmits multiple streams simultaneously; this ability is referred to MIMO. The UE category can dramatically affect the throughput multiply by 2,4 and 8, based on the MIMO technology type, either 2×2, 4×4, or 8×8 MIMO.

3. Modulation Scheme:

   The modulation schemes supported by IEEE802.11 are 16QAM, 64QAM and 256QAM. Each modulation can hold different number of bits per one symbol, as in 16QAM modulation can carry 4 bits per symbol. Bit rate is affected by the modulation scheme, as 26, 65, and 87 Mbps for 16 QAM, 64 QAM, and 256 QAM, respectively.

4. Guard Interval:

   The guard interval either it's normal with 4μs or short guard interval with 3.6 μs symbol length. When the interference condition allows, using short guard interval can increase the efficiency by reducing guard intervals between symbols.

With the assumption of using a 20 MHz band, 4×4 MIMO, 64 QAM, 84% overhead and a short guard interval, the maximum IEEE 802.11n throughput can be calculated as follows in the DL case as follows [36]:

1.0385 (factor of 20 MHz) × 65 Mbps × 4 antennas × 1.11 (factor of short guard interval) = 600 Mbps, by reducing MAC overhead, the total throughput is approximately equal to 100 Mbps.

2.3.6 Voice over Wireless LAN (VoWLAN)

Voice over Internet Protocol is considered the most important technology in the communication world. VoIP technology uses a Compression/Decompression (CODEC) to convert audio signals from analog to a digital bit stream and vice versa. VoIP over Wireless LAN (WLAN) is challenging for several reasons, such as the loose wireless network nature, providing a good level of QoS and providing an acceptable security level for calls. There are many compression schemes existed, and **G.729** CODEC is one of the most used CODECs with VoIP devices now a days. **G.729** CODEC optimize the used bandwidth per connection, with the use of a compressed algorithm to deliver a stream with a throughput requirement equal to 8 Kbps for transmitting a VoIP over WLAN [37, 39, 40].

2.4 LTE and Wi-Fi Offloading integration Levels

Offloading uses a complementary network to relieve congested LTE macro cell. There are three main levels of integrating Wi-Fi network with cellular networks: un-managed data offloading managed data offloading and integrated offloading as presented in Table 3.

Table 3: Characteristics of Wi-Fi integration levels

Offloading type	**Advantage**	**Disadvantage**	**Adoption approach**	**Coupling architecture**
Un-managed data offloading [41, 42]	1) Whenever there is Wi-Fi coverage moves data to it. 2) Bypass the core network. 3) QoS for voice services delivered by core network	1) Operators lose control on subscribers. 2) Operators losses, revenue.	No need for network equipment	----
Managed data offloading [41, 42]	1) Operators have control on subscribers	1) Operators losses, revenue	Through placing intelligent session aware gateways	----
Integrated data offloading [41-43]	1) Operators have control on subscribers 2) Operators don't lose revenue	1) Need to form a coupling bridge between Wi-Fi and cellular system	Forming a bridge between networks to allow data flow	1) Loose Coupling 2) Tight Coupling

2.4.1 Un-managed Data Offloading (Bypass)

The first approach is un-managed data offloading or bypass offloading, considered the easiest type of offloading, where data are directed to Wi-Fi whenever the coverage is found with no need for equipment installation as in Figure 18. The voice services in this type of offloading will remain on the mobile core network. This immediate offloading solution suffers from different issues such as: 1) the operators will lose visibility, control on their own subscribers 2) The operators will not be able to send subscribed content, which leads to lost revenue [41, 42].

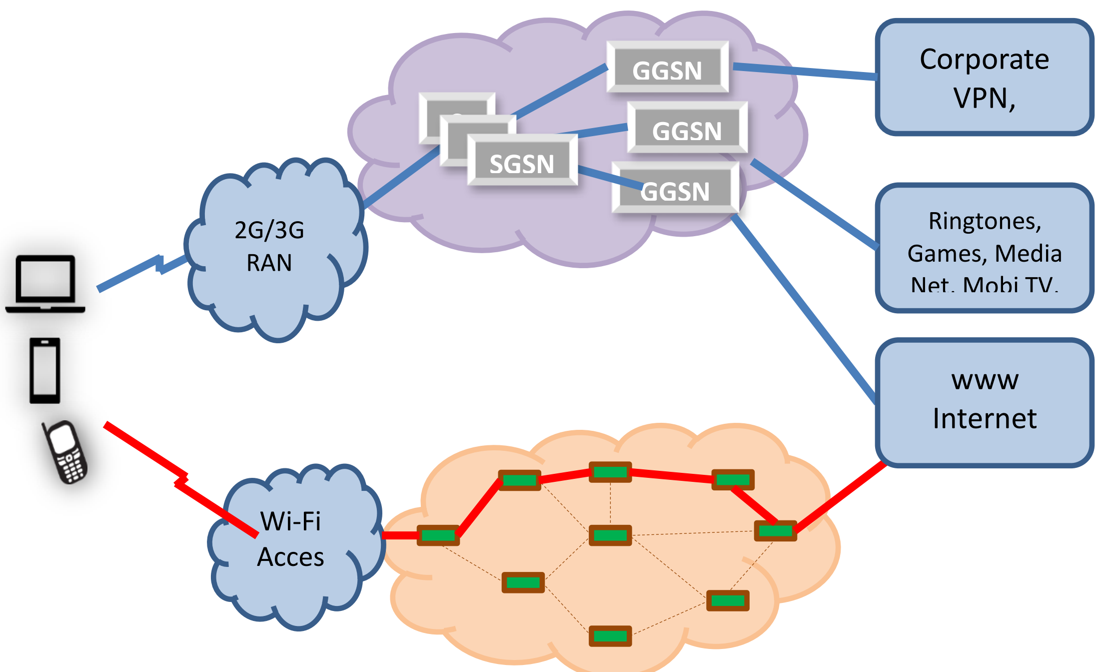

Figure 18: Network Bypass Unmanaged Data Offloading

2.4.2 Managed Data Offloading

The Second approach is managed data offloading shown in Figure 19, is used by the operators who don't want to lose control of their subscribers, however they are not allowed to send subscribed content. This offloading strategy might be interested in vendors whom not happy with the previous Bypass offloading, as the tow networks are controlled disjointed. Some operators insist on giving their subscribers a certain level of security while connecting to Wi-Fi or it might be important for vendors to be aware of subscribers browsing behaviors. Managed data offloading, give operators a limited control on their subscribers without the need to fully integrate the two networks. Managed offloading stops operators from providing any subscribed content by operator, although it can solve network congestion issue very well [41, 42].

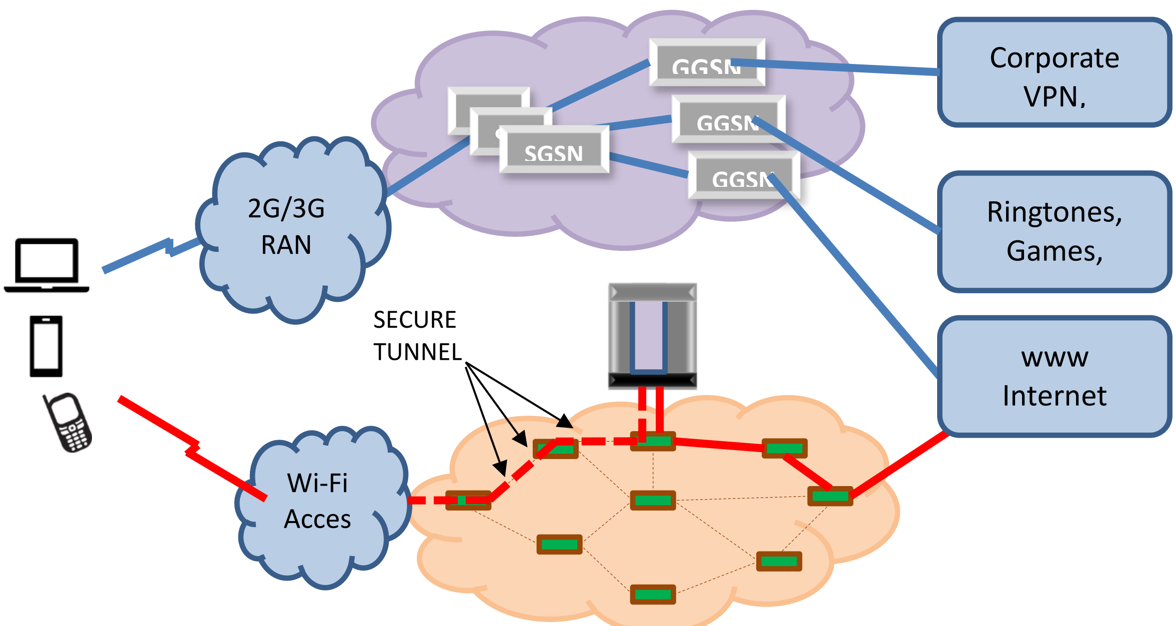

Figure 19: Managed Network Bypass Offloading

2.4.3 Integrated Data Offloading

The Third offloading approach is integrated data offloading, which empower the operators with a full control over their subscribers along with the ability to send subscribed content. The drawback of the latter offloading in order to establish the data flow is forming a bridge between cellular networks and Wi-Fi network. Integrated offloading will raise the coupling architecture for

Wi-Fi with cellular systems, which they can be divided into two coupling architectures: loose coupling and tight coupling [41, 42, 44].

In loose coupling architecture, no need for a major cooperation between Wi-Fi network and the cellular network and both can be independent from each other. The service in this architecture can be provided by using an external IP network and roaming between the two networks as in Figure 20. The user in loose coupling architecture gets benefits from both networks operators', with a little enhancement required. In tight coupling architecture there have to be a cooperation between the two networks through a common core and there will be a central administration for the majority of network functions such as: billing, resource management and vertical handover. In tight coupling each network is required to modify its services, protocols, and interfaces for interworking together as both owned by the same operator. This is provided through I-WLAN standard from 3GPP, which allows transferring data through Wi-Fi between user's devices and cellular systems [41-43, 45].

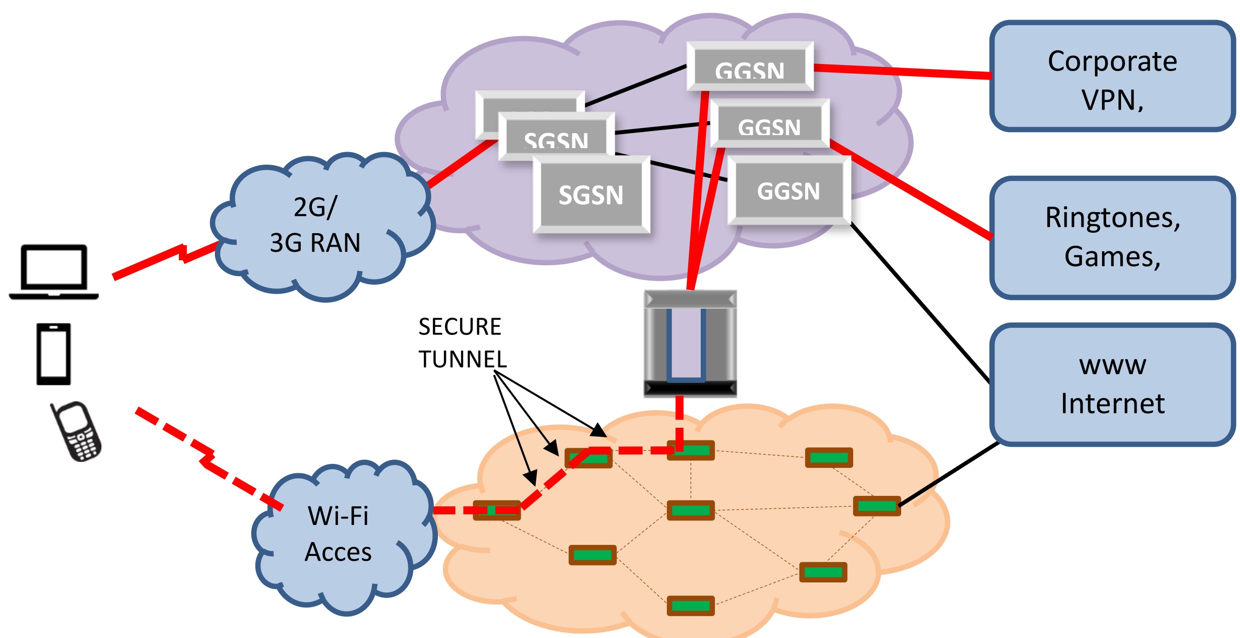

Figure 20: Integrated Network offloads

2.5 Environment Effect and Link Budget

The signal when it propagates from a transmitter to a receiver suffers from different environmental effects, which will govern the signal quality. This is known with channel modeling, as it's a mathematical representation for a radio channel. A channel can be modeled by calculating the physical processes that affect and alter the transmitted signals. Figure 21 illustrates the channel modeling concept, with transmitter (Tx) and receiver (Rx)[46].

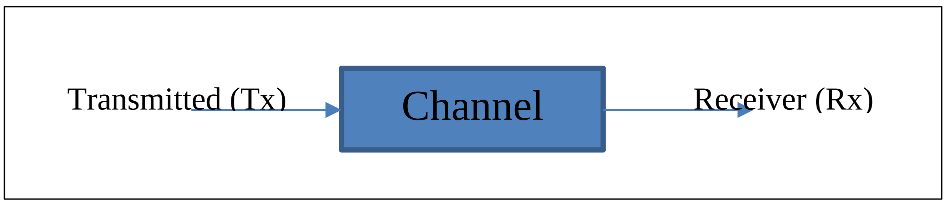

Figure 21: Channel Model Diagram

In order to estimate link Budget all the effects on the radio channel must be taken into account, which they are three main factors:

1- Propagation channel effects (Path loss, Slow fading "Shadowing", Fast fading)
2- Interference
3- Noise power

2.5.1 Link Budget

Link budget is a way of quantifying the link performance, with power estimation under overall loses. The link budget is used to define and calculate the Signal to Interference and Noise Ratio (SINR). For downlink traffic, SINR is used to estimate the channel quality or link budget for each user, either from eNodeB or Wi-Fi AP. SINR is calculated as follows in equation 1:

$$SINR_{i,DL} = \frac{\frac{P_{tx,j}}{L_{ji}}}{I+N} \qquad (1)$$

where $P_{tx,j}$ is the eNodeB transmission power or WLAN AP, while L is the total path loss between the user and eNodeB or WLAN AP, I is the total value of interference, and N represents the thermal noise [46].

2.5.2 Path Loss

Three main factors affect the radio channel: path loss, shadowing and fast fading [23]. Path loss measures the power reduction of a transmitted signal when it propagates through space from sender to receiver. This power attenuation or reduction could be a reflection, refraction or free-space loss outcome. The path loss is calculated as shown in equation 2, assuming P_{Tx} is the power of the transmitted signal and P_{Rx} is the power of the received power.

$$P_L = \frac{P_{Tx}}{P_{Rx}} \qquad (2)$$

Path loss can be calculated in dB as in equation 3:

$$L = 10\ log\frac{P_{Tx}}{P_{Rx}} \qquad (3)$$

There are different mathematical models for calculating the path loss in a wireless network. It depends on the radio link conditions, there for several path loss models were developed to give an accurate estimation. The most well-known path loss models include: Hata model, Okumura model, free space model and log-distance path loss model, which is assumed in this study. In the log-distance path loss model the P_{Rx} Is decreased in a logarithmic scale with distance. This is valid for both radio environments, indoor and outdoor. The log-distance path loss model estimates the path loss of a signal over a distance, whether a user is connected to either eNodeB or Wi-Fi AP as shown in equation 4.

$$L = r^e \tag{4}$$

Where r is the distance between a user to either eNodeB or Wi-Fi AP, and it is calculated by the Euclidian distance. The path loss exponent e, specifies the increasing rate for path with distance. The path loss exponent value depends on the type of environment as in Table 4 illustrated [47].

Table 4 : Path Loss Exponent Values, Based on [47]

Environment	Path loss exponent
Free space	2
Urban area cellular communication	2.7 to 3.5
Shadowed or obstructed cellular radio	3 to 5
Indoor OS	2.6 to 2.8
Indoor NLOS	4 to 6

2.5.3 Slow Fading (Shadowing)

Slow fading or shadowing is the power reduction caused by obstacles or huge objects in the propagation path such as buildings. These obstacles has different sizes and locations, hence it curtail to have statistical models to represent the shadowing effects. The most shadowing model widely used is the log-normal model, which can be used in both outdoor and indoor propagation environments [48].

With the assumption that the ratio of the power transmitted and the power received is Ps in linear scale, and S for the shadowing in logarithmic scale, as in equation 5:

$$S = 10\, log\, P_S \qquad (5)$$

Adding the shadowing effect to log-distance path loss model, path loss can be calculated as in equation 6:

$$\mathrm{L} = \mathrm{r}^{\mathrm{e}} * 10^{\frac{\mathrm{shadowing}}{10}} \quad (6)$$

Fast fading, which happen due to multi-path propagation. This factor has a minor affect to the signal compared to path loss and slow-fading. Therefore, it’s neglected in this Thesis for simplicity reasons.

2.5.4 Interference

Interference is a phenomenon, when two signals are interaction or affecting each other. This could happen due to using the same frequency or generating from the same source. Interference in general can be calculated according to equation 7 as follows:

$$\mathrm{I} = \sum \frac{\mathrm{P_{tx}}}{\mathrm{L}} \quad (7)$$

Where I, represent the total interference for one node or UE to all other UEs using the same frequency or RB. $\mathrm{P_{tx}}$ Represents the transmission power for any node using the same frequency or RB at the same time and L represents the path loss from UE to all interfering UEs.

2.5.5 Noise

Noise power in a receiver usually is a thermal noise generated from the amplifier, it is the unwanted energy from natural and man-made sources. Noise calculated as follows:

$$N = K \times T \times B \qquad (8)$$

From the latter equation:

1- N is the noise in linear scale
2- K is Boltzmann's constant, which is equal to 1.381 × 10-23
3- T is the reference receiver temperature in Kelvin, equals to 290
4- B is the noise bandwidth in hertz.

The noise value in LTE differs from Wi-Fi depending on the bandwidth allocated to the user in each according to equation (8), hence each network has different noise value.

Chapter 3

Literature Review

3.1 Introduction

The uptake of mobile data services driven by tablets, laptops and smart phones as in [17], the data traffic growth will be tenfold until 2016. Although LTE macro-cells can provide high speed data, they can't fulfill the increased subscribers' demands in high density places. Heterogeneous networks (Het-Net) seem to be a promising low cost solution for operators' point of view. Het-Net incorporates the coexistence of low power nodes along with a macro base station to improve coverage in high demand areas. The Het-Net variations are categorized into a single RAT multi-tier network and a multi RAT multi-tier network. The possible single RAT scenarios are: Micro-cell, Pico-cell, Femto-cell or fixed relays. For the multi RAT scenario, the possibility network components are: Wi-Fi offload, mobile hot spots and virtual carrier.

The contribution of this chapter is introducing a novel classification of energy efficient Het-Nets categories along with the possible small cells scenarios and offloading approaches in each category. It is worth pointing out that, the existing surveys usually cover one type of Het-Nets. The main purpose is to present a detailed view and exhaustive information for all new possible enhancement schemes for capacity and energy consumption problems, as the data growth increased. Most of the research paper covers the Single Rat category either with Pico cells or Femto cell, as addressed in [8, 12,15-17,30-33]. In fact, in these papers, the authors have basically discussed limited issues regarding one type of small cells with specific challenges or solutions. Unlike these works, this survey aims to give an overview for both categories with a detailed description of the possible challenges and solutions in each, and that is the novelty aspect about this literature review “survey”, which allows it to be a good reference for any reader interested in the basics of different types of Het-Net.

Het-Nets are an obvious part of 5G, including all types of small cell deployment. Consequently, dealing with Het-Nets can be considered as addressing the basics of 5G technologies. This chapter viewed the most important issues regarding densification which can be seen as a road map for wireless evolution into 5G [49] . The most significant hypothesis affecting for offloading settings such as: interference, mobility management, power control, and resource allocation is presented as well. The focus of this study is a multi-tier network topology consisting of macro cells and smaller cells with Wi-Fi access points to offload the data traffic, and one of the challenges is to avoid interference to gain the expected capacity enhancement.

3.2 Het-Net Offloading

3.2.1 Capacity Enhancement Schemes

The future cellular network is facing a huge challenge with the data traffic explosion, as the number of users is increasing exponentially [1, 3, 50]. Moreover, dealing with massive events and areas with high user densities in an efficient way is still a significant issue [51]. Indeed, the operators need to identify low cost solutions to solve the network capacity issues. Therefore, this field has gained a remarkable momentum within the research committee in order to find and study the benefits of the introduced paradigms and approaches. The new trend in solving the cellular network capacity is by using Het-Nets and small cells instead of the traditional expensive ways, such as adding new macro base stations as shown in Figure 22 [2, 3, 5, 52, 53].

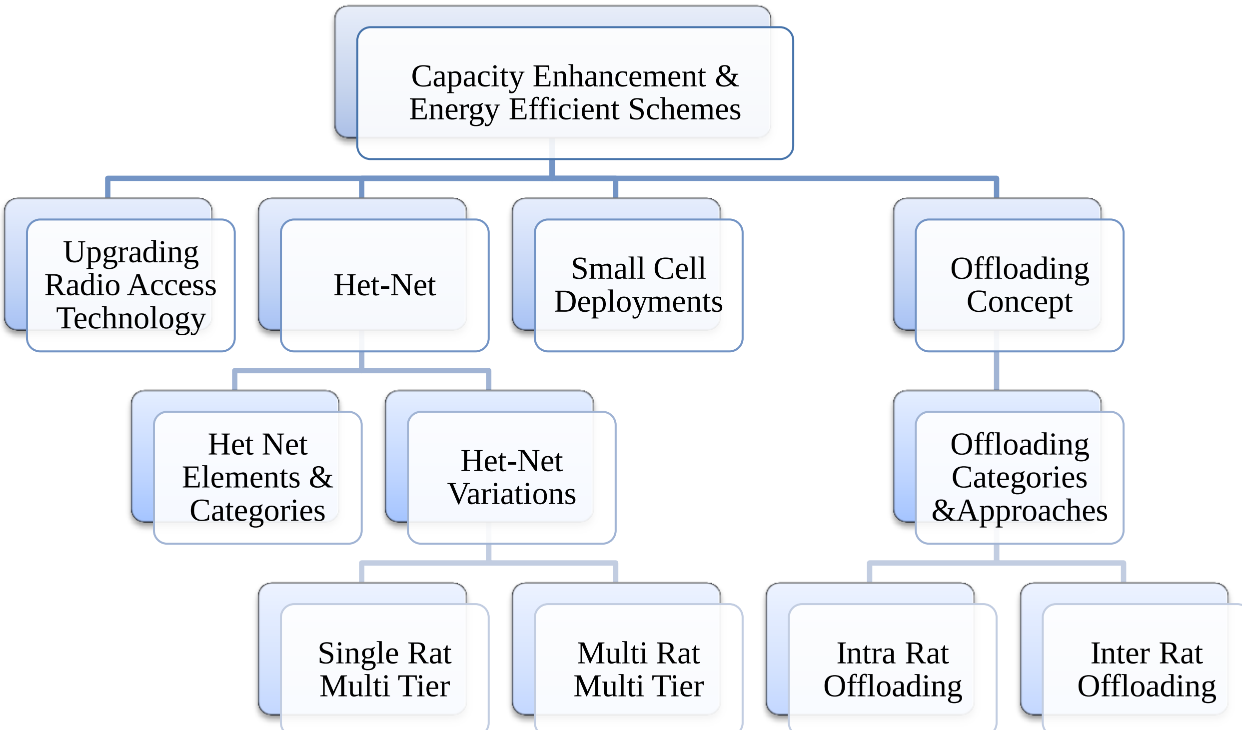

Figure 22: Capacity Enhancement & Energy Efficient Schemes

3.2.1.1 Upgrading Radio Access Technologies

Network macro-cells have been reliable in providing a good balance between wireless coverage and capacity. According to mobile data services, growth driven by tablets, laptops and smart phones has accelerated to the point where the macro-cells are no longer able to meet the subscribers' demands in high density places. To achieve high data rate and throughput, operators need to use wider bands. HSPA and LTE macro-cell network deployments appear to be a good solution to accommodate the fast growth of data traffic as both can increase the cellular network bandwidth [3, 50]. LTE-Advanced was introduced with the ability to reduce the OPEX and CAPEX, while the data rate and the quality of user experience is increased as LTE can optimally utilize the available spectrum resources [1].

3.2.1.2 Het-Net

The next step in performance enhancement of wireless systems would be in the network topology by using a Heterogeneous Network as it can provide a uniform broadband experience to the users everywhere and at the same time the operators will be interested in deploying it for its low cost. Het- Net can be used by deploying low power nodes overlaid in a macro-network. This can be done in a way that macro nodes will be responsible to provide broad coverage while low power nodes are placed in locations with high data demand [52]. Het- Net can consist of different cell sizes as shown in Figure 23.

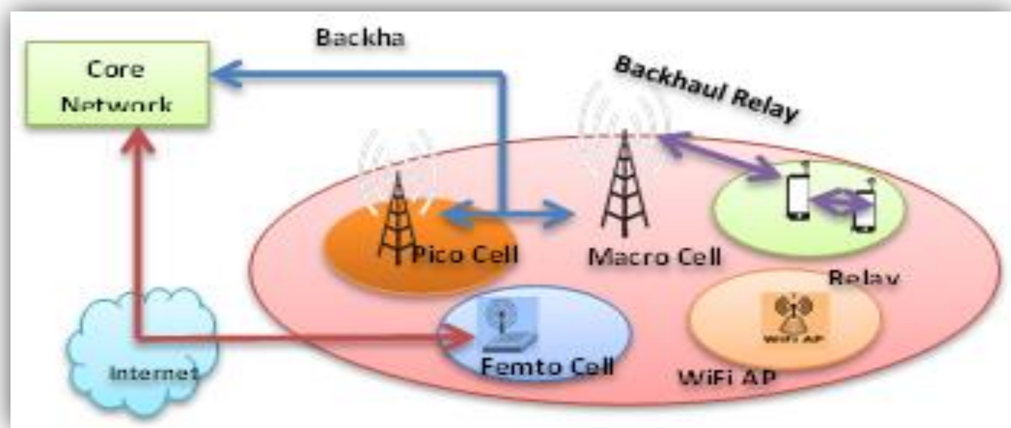

Figure23: Typical Het-Net Architecture

A. Het-Net Elements and Categories

Heterogeneous elements involve coverage areas of various sizes such as Micro-cells, Pico-cells and Femto-cells. Each element is distinguished by its coverage; transmit power, backhaul, propagation characteristics and physical size, as shown in Table 5. This new trend comes with challenges such as the network management and co-existence difficulties [3]. To overcome these challenges, some advanced techniques have been proposed to leverage the Het-Net benefits more efficiently, such as range extension and adaptive inter-cell interference coordination [53]. In [54] the authors provided a brief overview on Het-Nets by presenting the possible deployment scenarios to have a better understanding of a multitier and multiple radio access technology (RAT). According to [11], Het-Nets can be categorized based on spectrum usage to either single carrier or distinct carrier usage; for single carrier the authors have shown that cross-tier interference can be reduced with interference management schemes in order to gain significant coverage and capacity improvements.

Table 5: Different Het-Net elements specification

Het-Net Element Type	**Transmit Power**	**Cell Radius**
Macrocell	46 dBm	> 300 m
Microcell	40 dBm	100 – 300 m
Picocell	23-30 dBm	< 300 m
Femtocell	< 23dBm	< 50 m
Relay	30 dBm	300 m

B. Het-Net Variations

- *Single RAT (Radio Access Technology) Multi-Tier Network Component*

In Single RAT Multi-Tier Network, all devices in different tiers are assumed to belong to the same network and to operate with the same radio technology while sharing the same spectrum. To form a multi-tier network with different footprints, there are different possible deployment equipment/options: macro-cell/micro-cell, Pico-cell, Femto-cell base stations, fixed operator relays and mobile client relays. The advantage of a Single RAT is that its operations are less complex compared with a Multi-RAT network, such that authentication and accounting systems are not needed in this type of network. However, this type of network, usually suffers from the cross-tier interference due to spectrum limitations for each operator, so managing the interference in this Single RAT is quite a challenge when the network capacity is increased [54, 55]

- *Multi RAT (Radio Access Technology) Multi-Tier Network Component*

In Multi-Rat Multi-Tier Network, the operators have the ability to exploit different radio networks as a way to add low cost capacity and QoS and improve the coverage. In the Multi-RAT Het-Net, multiple RATs could be Worldwide Interoperability for Microwave Access (WiMAX), Wireless Local Area Network (WLAN), and Wideband Code Division Multiple Access (WCDMA). These can be jointly operated with LTE macro-cells in the same coverage area in a complementary manner. The possible Multi-RAT scenarios would be Wi-Fi offload, virtual carrier and mobile hotspots. The latter is known as a personal area network. An outdoor network WCDMA/LTE with WLAN indoor hot spot is an example of Multi-RAT Het-Net. One of the advantages of using such types of networks is that there is no cross-tier interference as it utilizes a different frequency spectrum, but the integration process is a major challenge due to different architecture and technology [54, 55].

3.2.1.3 Small Cell Deployments in Het-Net Scenarios

The deployment of Small Cell Base Stations (SCBS) within an existing macro cellular system is attracting the research field as it is seen as the key solution for boosting the capacity, and optimizing coverage and traffic offloading. SCBSs are envisioned to be multimodal to have the ability to transmit on both licensed bands and unlicensed bands [5]. Small Cell solutions have attracted a lot of attention from 3GPP to solve mass events and congested networks since the release of LTE 10 as shown in [56]. Different types of small cells can be identified in a macro-cell, namely, i) Micro-cell for outdoor applications; enterprise usage and indoor application, ii) Pico-cells for indoor residential application, iii) Femto-cells for indoor applications and iv) Wi-Fi AP for both Indoor and outdoor environments, v) originate clusters inside LTE cell with promoting a user to be a cluster head, to act as a relay station[57] .Different small cell coverage's shown in Table 6.

With the new techniques such as coordinated multipoint transmutation/reception (CoMP), and enhanced inter-cell interference coordination (eICIC), LTE Release 12 is focusing more on the small cell enhancement. In fact, authors in [56] have discussed the relevant deployment scenarios along with the technology requirements for enhancing the LTE small cells. In [2, 58] their approach to increase the capacity was through the use of a mix of macro-cells and small cells (Pico-cell) as in managing the LTE spectrum. According to [59-61], LTE operators have two options to increase the capacity either by using an advanced LTE Het-Net with the same channel or using the unlicensed spectrum via 802.11 Wi-Fi access points.

Table 6: Different coverage of small cells coexistence with Macro cell

Cell Type	**Coverage Type**
Macrocell	Outdoor
Microcell	Outdoor
Picocell	Outdoor – Indoor
Wi-Fi AP	Outdoor – Indoor
Femtocell	Indoor

3.2.1.4 Offloading Concept in Het-Nets Categories and Approaches

The exponential growth of data traffic in the cellular network caused an immediate need to offload the traffic to relieve the macro-cells, so data offloading is considered to be a huge industry segment in the near future. The concept of data offloading refers to the use of a complementary network technology to deliver data which are originally targeting the cellular network [62]. Although LTE macro-cell network deployments seem to be a good solution to deal with high traffic, the researchers have predicted in their studies that this solution is likely to be short-lived. Operators should consider low cost and flexibility in order to compete with traditional communications [63]. In this section some of the low cost technologies will be illustrated by dividing the types of offloading into two basic categories and describing different offloading approaches.

A. *Intra-Rat Offloading*

In [5] the authors have categorized the offloading into intra-RAT and multi-RAT offloading. In intra-RAT, the traffic is offloaded from a macro-cell to a smaller cell (Pico- or Femto- cell). The majority of research works has focused on intra-RAT offloading. Indeed, in [2, 3, 64], authors propose an offloading scenario from a macro-cell to a Pico-cell, while in [4, 58] the offloading scenario was between macro-cell and Femto-cell. In [65-67], an example of Femto-cell intra-RAT offloading was proposed. Accordingly, Femto is connected to the service provider network via broadband such as (DSL) Digital Subscriber Line. Using Femto-cells will allow the providers to improve the coverage and capacity by extending the service coverage especially in limited access areas. The Femto concept is applicable to all standard GSM, WCDMA, WiMAX, and LTE. It can provide an easy and effective offloading method for traffic carried originally by a macro-cell. This improves the users' experience on both macro-cell and the Femto-cell subscribers due to better radio conditions as claimed in [68, 69].

There are several reasons that make Femto-cell offloading effective. First, It provides a seamless experience to the users as long as Femto-cells are owned, deployed and managed by the enterprises or users. Second, it’s much easier to deploy Femto BS rather than deploying a traditional macro-cell, which needs to take several conditions into account like site planning, radio infrastructure and backhaul. Finally, Femto-cell is a promising offloading solution as it is naturally designed for indoor coverage, where most of the traffic is generated. Indeed, authors in [68, 69] claimed that 55% of data usage occur in the home, which is more than the office usage which reaches only 26%.

B. Inter- Rat Offloading

The second category is called inter-RAT offloading or integration, which in some papers is referred to as Multi-mode SCBS using Wi-Fi RATs. The inter-RAT offloading is still considered to be in its infancy, but it attracts a lot of attention due to its low cost deployments. Most studies are heading towards exploring possible benefits and enhancements that can be done through exploiting the Wi-Fi RAT [5, 70, 71]. Wi-Fi access point offloading is a type of inter-RAT offloading. Wi-Fi (Wireless Fidelity) is a wireless solution based on IEEE 802.11 standards. Wi-Fi is a broadband access used in indoor environments, which provides high data rates with limited mobility and coverage compared to classic mobile communication technologies like Universal Mobile Telecommunications System (UMTS), High-Speed Packet Access (HSPA), and Long Term Evolution (LTE). Wi-Fi networks are mostly used as a model to shift toward ubiquity and outdoor/ citywide Wi-Fi networks.

When it comes to data offloading, Wi-Fi appears to be the natural and simple solution, because Wi-Fi is already built in smart phone interfaces. In overloaded macro-cells suffering from service degradation due to the increasing number of users, they can be switched to Wi-Fi, as has been done in [70, 72, 73]. This solution is attractive to the operators as it shifts the data from costly band into free unlicensed bands 2.4 GHz and 5 GHz. The offloading to Wi-Fi process depends on the level of integration between Wi-Fi and cellular networks. Different studies show that the expanding networks using Wi-Fi compared to a rollout network are extremely less expensive [68, 69].

3.3 Het-Net Challenges

Using the Het-Net technology is a huge shift from the centralized traditional macro-cell approach to a more autonomous and intelligent approach. Although there are many advantages of shifting the network towards the offloading scenarios either with the Single RAT or Multi-RAT, many technical challenges have been raised due to complex network topology with different elements. In this section we will address some of these challenges by classifying them into two basic categories based on the type of network component, either Single RAT (Radio Access Technology) Multi-Tier Network Component or Multi-RAT (Radio Access Technology) Multi-Tier Network Component as shown in Figure 24.

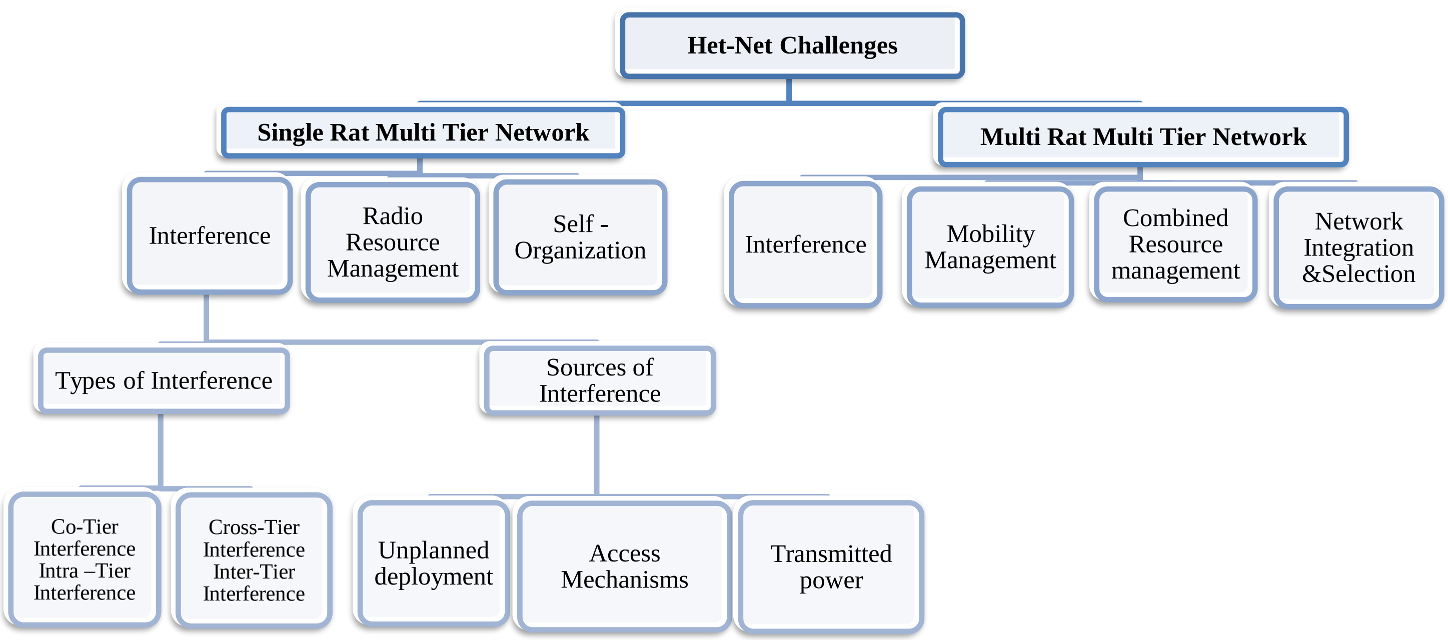

Figure 24: Het-Net Challenges

3.3.1 Single RAT Multi-Tier Network Challenges

3.3.1.1 Interference

Interference is considered to be the biggest challenge in the Het-Net especially for the Single RAT type as it uses the same band for multiple tiers, unlike the single tier [62]. Note that, the overall throughput and quality of service can be boosted, and the offloading can be utilized to the maximum limits, when the interference is mitigated. In this part we will categorize the interference into two different types, and describe some possible causes of interference.

A. Types of Interference

In general, in any cellular mobile communication system, two types of interference can be recognized: the Co-Tier Interference, also known as intra-cell interference, and the Cross-Tier Interference, also known as inter-cell interference. Figure 25 shows the different types of interference that may occur in Het-Net scenario.

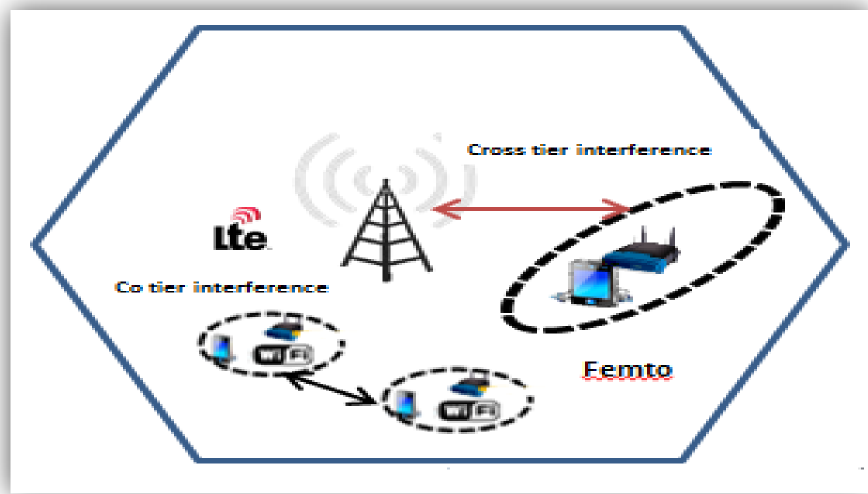

Figure 25: Co-Tier Interference in the same Network Tier (Wi-Fi APs) & Cross-Tier Interference in different Network tiers (LTE-Femto)

Co-Tier Interference (Intra-Tier Interference): In this case, the users belong to the same network tier, i.e. they are in adjacent macro-cells or Pico-cells and use the same frequency channel/resource block [57, 74, 75]. Many studies have tackled this type of interference, as in [74] the authors suggested a scheme to manage intra-tier interference cells in the frequency domain between adjacent macros by using the Soft Frequency Reuse (SFR) for allocating frequency bands. The whole frequency band is used in the center of the macro, while the edges use sub-bands with a reuse factor of 3. In [66, 71, 76] the authors suggested a different solution to deal with congested macro-cells by using Wi-Fi access point coverage. This scenario may suffer from co-tier interference between adjacent Wi-Fi access points. For this reason, they have proposed a beneficial coordinated approach between Wi-Fi access points by exchanging context information to assist the management, coordination and select the best configuration that minimizes interference.

Cross-Tier Interference (Inter-Tier Interference): In this case users' belong to different network tiers that reuse the same frequency channels/resource blocks [67, 74, 75]. Usually cross-tier interference happens between LTE macro-cells with Pico- or Femto-cells as they might be using the same channels. In [65, 74] the authors suggested managing the cross-tier interference between macro-cells and Pico-cells by applying Almost Blank Sub-frame (ABS) techniques in the time domain. The idea behind this is to let the Pico-cell avoid the interference by transmitting the signal in the ABS of the macro-cell. In [76], another solution was proposed to deal with inter-tier interference by discussing a different Het-Net scenario, where Femto-cells coexist with LTE macro-cells. The authors suggested dealing with such dynamic deployment of Femto access points with rich context information for both Resource Allocation (RA) and Interference

Management (IM). Moreover, they suggested organizing and defining the rich context information for the future RA and IM, as this helps in decreasing delay by accessing the required information.

B. Sources of Interference

Unplanned Deployment: Single RAT multi-tier deploying low power nodes' such as Femto-cells and Pico-cells can be an addition to wireless network coverage. However, the random and ad-hoc deployment of such kind of cells may cause problems. Indeed, users can randomly plug-and-play either Pico or Femto in any place, which will cause a performance degradation in the whole network system due to high levels of interference produced from this random deployment as claimed in [62, 74]. In [77], authors show that small cells can limit the frequency resources in loosely correlated deployment in Hyper-Dense network. In fact, in Hyper-Dense scenarios an autonomous process in small cells is needed to deal with unplanned deployment, as it can cause significant interference problems for macro and small cell users.

Different Types of Access Mechanisms: There are different types of Access modes for the dynamic low power nodes deployed within a macro-cell. For example Femto-cells have three types of access which are: open access, closed access and hybrid access as mentioned in [78]. In the open access everyone can join the Femto-cell, while in closed access, the Femto BS accepts only registered users. In hybrid access, users from outside the Femto-cell can join with a specific restriction configured by the owner. In a hyper-dense area having Closed Subscriber Group (CSG) Femto-cells serious interference may be generated between macro-cell and Femto-cell users, which must be controlled to enhance the overall network performance [62, 77].

Transmitted Power: The transmission power used in the macro tier is higher and quite different from the transmission power for the Pico or Femto tiers that involve low power nodes. This imbalance in the transmitted power may cause other challenges as interference and handover boundaries as mentioned in [53]. The work in [52] discussed how placing a mix of (high-power) macro with (low power) Pico, Femto or relay nodes will cause large disparities in transmit power. This power inequality will affect the advantage of using low power nodes relative to high power nodes. Indeed, users connected to high power nodes will cause high interference to low power ones operating on the same frequency channel. Moreover, in [54] authors mentioned that different power transmission for a Femto base station may affect the coverage area, but it can also affect neighboring users due to the tremendous generated interference.

3.3.1.2 Radio Resource Management

The environment in a heterogeneous network is quite different from the homogenous network. Consequently, conventional methods for resource allocation or managing interference are not applicable. For example, due to the different coverage areas for macro- and Pico-cell, there is a mismatch boundary handover between uplink and downlink. So the selection of user associations to the appropriate base station is more difficult [53].

Some studies have highlighted this problem from different angles such as in [53] where the authors have shown that, due to imbalance in coverage and transmission power for Pico- and macro-cells, the resource allocation wouldn't be fair as most users will be connected to the macro and not getting use of Pico base stations. This dilemma highlights the need for a proper resource allocation to balance the load between the two tiers. In [74] authors show that due to the interference between the macro- and Pico-cell the quality of service will be degraded, so non-conventional resource allocation is needed to solve this dilemma. In [52] authors mentioned that using different types of low power nodes' with different access capabilities will create a challenging scenario to allocate users efficiently.

3.3.1.3 Self-Organization

Low power base station deployment usually is not under the operator's supervision, as users can deploy them manually in any location they prefer. Due to this uncoordinated deployment it is important for the low power nodes to possess self-organizing features that will result in a stable operation of the whole system of small cells. In [62] authors classified the self-organizing process into three processes:

a. Self-Configuration: This process happens before going to the operational state. The new cell deployment is automatically configured by downloading a suitable software with the appropriate configuration parameters.
b. Self-Healing: This process is related to an automatic failure recovery that is executed whenever a problem is detected.
c. Self-optimization: In this process, the cells decrease interference and improve network coverage by constantly monitoring the network status.

As the number of parameters considered in the above mentioned procedures increases, the task of deploying self-organizing nodes becomes more complicated. Furthermore, the varying arrival times of users to such systems with different data traffic demands make the self-organizing deployment quite challenging.

3.3.2 Multi RAT Multi-Tier Network Challenges

In Multi-RAT Multi-Tier network systems, there are two different frequency bands that are used by each tier as a solution to add more capacity to the network. Each tier can provide different services to users with different limitations or benefits, such as bandwidth, coverage and cost. For example, different capabilities can be provided using the unlicensed spectrum via IEEE 802.11Wi-Fi access points or by offloading the data over TVWS band. Moreover, Multi-Tier Het-Nets introduced challenges such as interference issues, mobility issues, the combined resource allocation and network selection [55]. Some of these challenges will be addressed in the next section.

3.3.2.1 Interference

The interference problem is considered one of the most important challenges in the multi-tier network, which might degrade the network performance if it's not managed properly. This type of network is composed of two different tiers with different types of frequencies, so cross-tier interference doesn't appear in multi-RAT as in single RAT network. According to [69, 77], the interference is raised in the landscape between the neighboring small cells, such as neighboring Wi-Fi access points. Note that, interference is produced in a multi-tier network for similar reasons as in a single RAT network as mentioned earlier in this paper. Most importantly, unplanned deployment is a key cause for co-channel interference between small cells. Indeed, in the hyper-dense network a large number of small cells can be deployed without any planning from the operator's side, as the users or enterprises can deploy them manually. In this way, the deployment will not take into account the traffic demand on a specific area, and there will be no consideration for the adjacent cell interference. This will limit the benefits from using the available resources as they are not correlated with the user demand [77]. In [79], they categorized the deployment into indoor/outdoor commercial areas, which is mostly done by the operators. Another type of deployment is performed in the residential areas, as it's done by the subscribers themselves, without planning.

Concerning the use of Wi-Fi access points to form small cells within a multi-RAT network, similarly, the better we plan the deployment of Wi-Fi access point, the more we avoid interference and hence better performances are achieved from the co-existence between Wi-Fi small cells along with the macro-cell. In fact, in [69] the authors deploy AP according to a threshold called T, which is a reference value used to consider the APs with an equal or greater rank to decide about adding a new AP to serve the unconnected users. It is worth noting that, Wi-Fi has different access types, one of which is open access as any user can connect to it [65]. However, some Wi-Fi APs are owned by users or enterprises, and this type is usually a closed AP that requires authentication. For instance, the AP installed in homes, which is known as CSG is an example of closed AP as explained in[62, 75].

3.3.2.2 Mobility Management

The deployment of a large number of small cells each using different frequency bands from the one used by the macro- cells will add more complexity to the mobility management, as each tier has different frequency characteristics, different transmit power, different handover boundaries for both down link and uplink and different coverage areas as asserted in [53]. In [69], the authors consider a homogenous network where they use two different thresholds in deciding the mobility state for a user, either low, medium or high mobility state. Note that, this is not the case for heterogeneous networks as there is a need for an extensive monitoring and evaluation for Key

Performance Indicator (KPI) related to handover parameters or to the establishment of the offloading mechanism between the two different tiers in a seamless way. Mobility management in Het-Nets are having an asymmetry coverage in uplink and downlink as discussed in [29]. The coverage of a macro-cell in the downlink is much larger than a small cell, due to the difference in transmission power of macro BS and AP in a small cell. However, this is not the case in the uplink as the user is the one who transmits. Consequently, if the received signal strength is basic for the handover mechanism, then uplink and downlink handover need to be investigated.

3.3.2.3 Combined Resource Management

Multi-RAT networks have a complex architecture. This complexity comes from using different access protocols. So using the traditional and conventional resource allocation is not convenient in this type of network as mentioned in [55]. Many of the new studies concentrate on enhancing the throughput, user experience, and the load balancing of the network, but few studies have tackled improving the whole Energy Efficiency (EE) for a Multi-RAT network through resource management strategies. In [76] authors have discussed the use of Wi-Fi AP along with LTE as an example of a Multi-RAT. They showed that thanks to the random deployment nature of AP, which can be performed by users at home, coordination between these AP would be beneficial to support the resource management.

3.3.2.4 Network Integration and Selection

In the Multi RAT using different Access technologies with different capabilities, leads to an integration challenge. That's why, the 4G generation main objective is on how to integrate various access technologies into a common network. The resulting network aims at giving users Always

Best Connection (ABC), by providing them, based on their specific requirements with the ability to choose the best available access network. This type of network is known as Open Wireless Architecture (OWA). The operation allowing users to choose the best network connection is called Network Selection or Vertical Handover Decision (VHD). One of the most advanced network selection is the Adaptive Vertical Handover, since it enhances the overall network performance. However yet it's still challenging to enhance and optimize the EE through the available VHO [55].

3.4 Het-Net Solutions

This section will address candidate solutions to the aforementioned challenges, by classifying them into two basic categories based on the type of network components; either Single RAT Multi-Tier Network Component or Multi RAT Multi-Tier Network Component as shown in Figure 26.

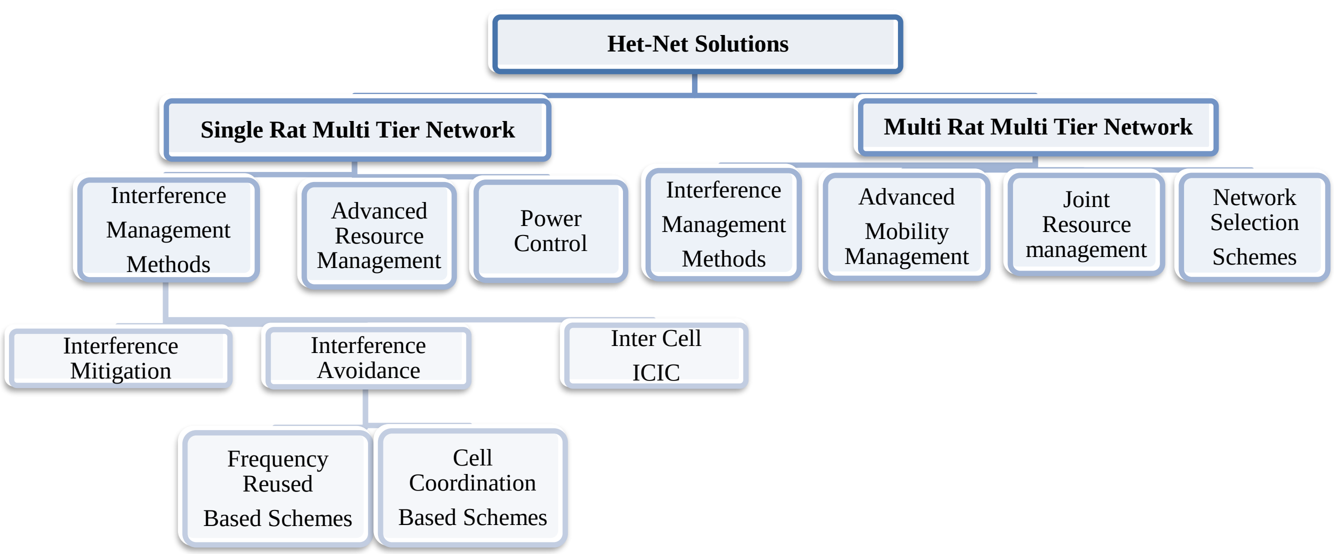

Figure 26: Het-Net Solutions

3.4.1 Single RAT Multi-Tier Network Solutions

3.4.1.1 Interference Management Methods

In the traditional mobile communication systems Macro BS can usually provide ubiquitous coverage, as in 3GPP LTE systems. A single RAT network is formed by deploying SC of Pico-cells or Femto-cells, which suffers from network performance degradation due to interference as explained in [55]. In LTE systems, it is challenging to deal with inter-cell interference (Cross-Tier) especially with edge cell users. Unlike the intra-cell interference (Co-Channel) where LTE downlink uses the Orthogonal Frequency Division Multiple Access (OFDMA) to avoid interference. However, Inter-cell interference is avoided due to the orthogonal allocation of OFDM-subcarriers. Recently, a key technology was introduced to enhance LTE systems using Inter-Cell Interference Coordination (ICIC). ICIC techniques can be divided into two categories, interference mitigation and interference avoidance as explained in [75]. Figure 27 shows Inter-Cell Interference Techniques.

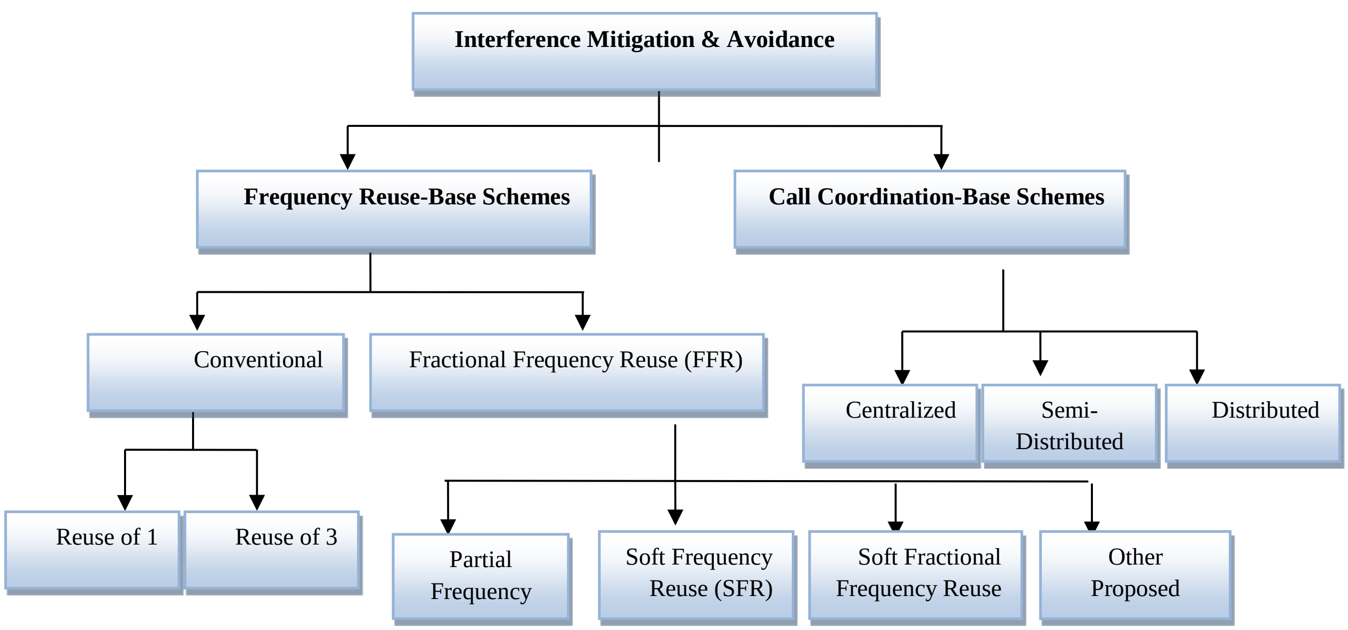

Figure 27: Inter-Cell Interference Techniques

A. Interference Mitigation Techniques

This type of technique is used to reduce the impact of ICI after the reception of the signal or during the transmission time. A user near to the (Macro BS) eNodeB will receive high signal strength, which decreases as the user moves towards cell edge while the interference from adjacent cells will increase. Therefore the overall signal to interference plus noise ratio will decrease, and reducing the ICI especially for the edge cell users which will improve their throughput. In [55, 75] the authors propose three inter-cell interference mitigation methods: Interference Randomization, Interference Cancelation and Adaptive Beam Forming. Interference Randomization (frequency hopping) allows interference repression at the user side, by randomizing the interfering signals. The interference cancelation works by detecting the interference part of the received signal and effectively removing it to only keep the desired received signal [49]. With beam forming, the antenna itself changes its radiation pattern dynamically according to the measured interference levels.

B. Interference Avoidance Techniques

The main goal of interference avoidance techniques is to control the resource allocation process, by allocating different resources to users such as: frequency slots, time slots or power. The main objective is to keep the ICI within acceptable limits, and to enhance the edge cell users' throughput by increasing the signal to noise ratio. These techniques can be divided into two main categories: Frequency Reuse-based Schemes, and Cell coordination-Based Schemes [75].

Frequency Reuse-Based Schemes: This scheme is basically used to control ICI in a mobile communication system, and it can be divided into two categories: the conventional frequency reuse, and the fractional frequency reuse. Conventional frequency reuse is considered to be the simplest way to allocate frequencies, by changing the reuse factor from 1 up to 3. In the case of using an FRF of 1, all available frequencies will be reused in every sector with no restrictions on the power levels or on the resource usage. This would be the worst case scenario as it produces a high level of ICI especially for cell edge users. On the other hand using an FRF of 3 may minimize interference by using only 1/3 of resources in each sector, so this will come at the price of large waste of capacity due to restrictions on resources.

The second category to deal with ICI is called Fractional Frequency Reuse (FFR). The basic idea behind it is to divide all available frequency resources into two groups. In the first group (Major), frequencies are used to serve the cell edge users, while in the second group (Minor), frequencies are used to serve the call center users [66, 67]. FFR can reduce interference for cell-edge users. This can be done by forming different FFR schemes with FRF between 1 and 3 with different combinations in power and frequencies. The FFR may be subdivided into two main classes: Partial Frequency Reuse (PRF), and Soft Frequency Reuse (SFR) as presented in [55, 75]. Figure 28 shows the difference between Conventional Frequency Reuse and Fractional Frequency Reuse.

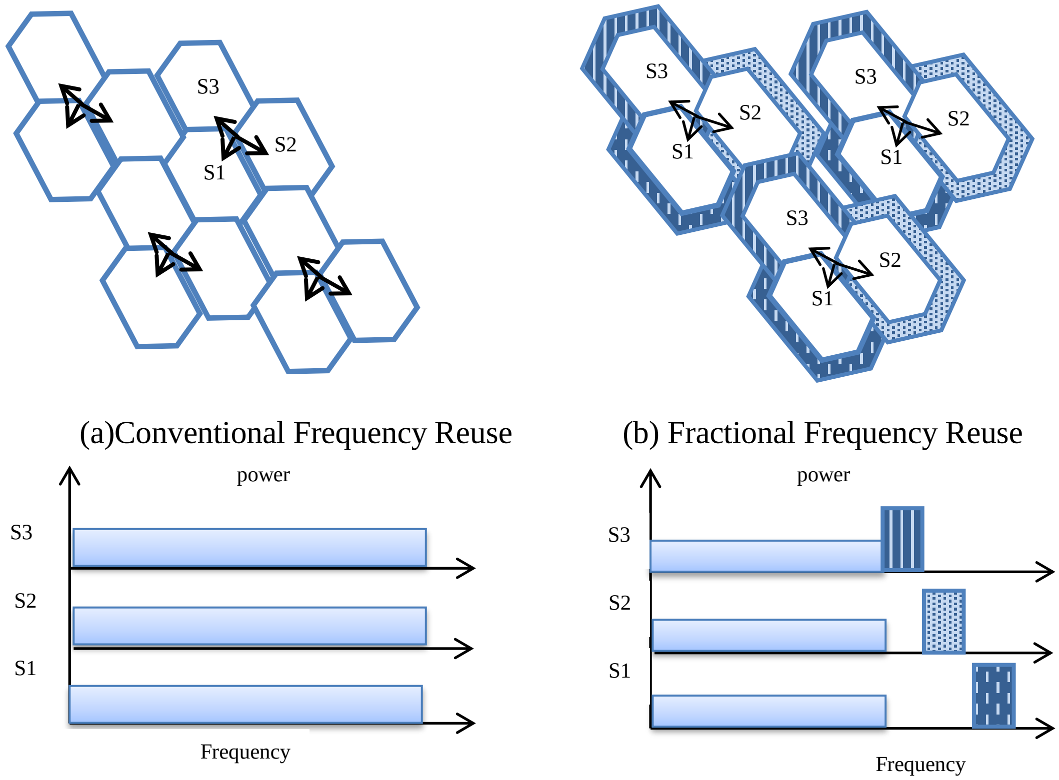

Figure 28 : (a)Conventional Frequency Reuse vs. (b) Fractional Frequency Reuse

Cell Coordination-Based Scheme: Frequency Reuse-based Schemes are good to use with homogenous networks in terms of having an equal load for all the cells. FRF schemes would not be suitable for heterogeneous networks with different loads, as the load is adopted through only changing power over carriers. This raises the need for a dynamic frequency allocation to suit the continuous changes in the heterogeneous load. For this reason Cell Coordination Schemes have been introduced to cope with the dynamic loads of the cellular network. Accordingly, Interference is managed through real time coordination in all cells, to avoid using the same subcarrier by two adjacent cell edge users. In order to utilize the resources among all the cells without a-priori resource partitioning, adaptive algorithms have been efficiently developed for this purpose as explained in [75] .

Although cell coordination schemes seem to be a good solution to manage dynamic loads, considerable complexity is added with respect to overhead and delay. That is because the coordination between two base stations requires the establishment of signaling and proper interfaces. The coordination types between cells for interference avoidance can be subdivided into Centralized, Semi-Distributed and Distributed. In the Centralized category, there is a central entity such as the radio network controller (RNC). RNC is responsible for coordination between macro base stations based on information reported to it from each station. In Semi-Distributed coordination schemes the coordination process happens at two levels: eNodeB level and RNC level. In [75] authors reviewed a work on OFDMA systems with Radio Resource Control (RRC), and how to perform a global optimization. This could be done through the RNC controller as it must have information of all users, traffic status and channel state all the time from all cells. Lastly, In the Distributed scheme, there is no need for a center entity as in the semi-distributed, and the resource allocation is done at the eNodeB level. As we move from centralized to distribute schemes, we may overcome the disadvantage of the delay and signaling overhead between the RNC and the eNodeB at the expense of higher complexity requirements in each base station.

C. Inter-cell Interference Coordination with ICIC

One of the key interference management methods that can be used with Het-Net is Interference Coordination and Interference Cancelation (ICIC) technique. 3GPP group has introduced ICIC with LTE release 8, as a solution for interference from cell edge users. ICIC uses the frequency and power domain to mitigate neighboring cell interference at the edges, and the information of eNBs is exchanged through X2 interface. 3GPP group elaborates ICIC and introduces eICIC with the release 10, which can deal more efficiently with the interference issues in the Het - Net. Accordingly, the intra-cell interference is mitigated through the triple control of frequency, power and time domains. ABS was also introduced in release 10. In [9], authors suggested that information about ABS should be exchanged between BS through X2 interface. eICIC has three categories to manage interference: frequency domain techniques, power domain techniques and time domain techniques as explained in [75]. Time domain partitioning is more investigated in LTE Advanced as a way to enable more connected users to small cells. In [77] further enhancement of ICIC is discussed by adding a non-zero power ABS to eliminate any inefficient bandwidth segmentation or cancelation from the user side. Another technique is discussed in order to balance the load and improves cell edge performance, which is Multi Flow. This technique is a flow-level technique, which improves cell edge performance and balances load. Multi Flow allows users to receive multiple data in the downlink from multiple small cells. It senses macro cells spectrum usage to optimize the spectrum overall usage.

3.4.1.2 Advanced Resource Management and Power Control Scheme

The conventional resource allocation would not be applicable to the single RAT network. In [74] the authors present a way to mitigate the co-tier interference and reduce the cross-cell interference as well. The resource allocation in their proposed work is done through using SFR to manage the interference in the frequency domain, and ABS in the time domain to do the same. In [53] authors proposed using the slow-adaptive resource coordination, in allocating resources over time scales that are much larger than the scheduling intervals. This can help in finding a good combination of transmission power for base stations and users along with the frequency or time resources that can maximize network utilization. The authors suggested using resource partitioning. Actually, adaptive resource partitioning was first introduced with LTE Rel-10, along with an X2 interface in resource coordination for scheduling data traffic. Authors have clarified that using resource partitioning in managing co-channel have to be paired with interference cancelation at user side to gain the full potential of this kind of allocation [52].

Power control techniques are one of the most widely discussed schemes in 3GPP group mostly to deal with interference. It was introduced in eICIC. The main idea behind it, is to reduce the transmit power of the interference that is affecting the victim user. Different ways have been proposed to deal with power control scheme. In [80], the authors discussed adjusting power settings in fixed eNodeB, which can be performed either with Closed-Loop Power Setting (CLPS) mode or with Open Loop Power Setting (OLPS). The difference between CLPS and OLPS is in how the eNodeB adjusts its transmission power, as CLPS depends on the coordination between Macro-eNB, while OLPS mode depends on the predefined parameters or on the result measurement. From another point of view, in [55] authors discussed Energy Efficiency (EE), which is not efficient in FASs deployment in dense areas, as the FAPs operates the whole time even if there are no users to serve. Hence, to deal with continuous changing with the traffic demand using the sleep mode will be more efficient to cope with low traffic demand to save more energy.

Cell range expansion (CRE) is a technique to expand the range of Pico-cells virtually, by adding a bias value (Biasing) to the Pico received power [49, 64]. As there is a difference in the transmit power for macro and Pico base stations this will lead to different coverage areas in the downlink. It may cause unbalanced user association as most users will connect to macro due to its high power signal rather than Pico stations. So from a network capacity view, it’s better to balance the load by expanding the coverage for the Pico-cell instead of increasing Pico base station power, to improve the overall throughput as explained [52]. In [3, 53, 75] authors have suggested balancing the load between macro- and Pico-cells by using the range expansion in order to allow more users to connect to low power stations such as Pico- or Femto-cells.

3.4.2 Multi RAT Multi-Tier Network Solutions

3.4.2.1 Interference Management Methods

As mentioned in section 3.2.1.2, a multi-RAT multi-tier network can provide an additional spectrum to serve blocked users from eNodeB. A Wi-Fi network is one element that can be used as a second layer in the network to boost the capacity. However the more Wi-Fi APs are deployed, the more the throughput degradation is increased due to interference between adjacent Wi-Fi APs. Several solutions will be proposed in this section to deal with such situations. Self-Interference Cancelation (SELIC) approach is introduced in [77] as a way to enable a device to employ an Active Interference Cancellation (AIC) with the coexistence of heterogeneous radios at the same mobile. This has been introduced to avoid the problem of multi-radio cross-interference resource allocation in time, frequency or power domain.

In [76] the frequency band dedicated to Wi-Fi is split into overlapping channels and interference in one channel is avoided through using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Although it's a promising solution to use the 2.4 GHz band to increase the capacity, in a high user density area the addition of more Wi-Fi Aps might degrade the overall network throughput, because of the frequent collisions that might happen and the interference between adjacent overlapping channels. To overcome this, Wi-Fi network operator can use only the non-interfering channels, which they are 1, 6 and 13. This solution could be limited as Wi-Fi APs can be home deployed, and hence the total avoidance of overlapping channel interference is not possible. In [81] the authors introduced a network architecture composed of small cells using the same Wi-Fi systems unlicensed spectrum without affecting their performance. They proposed two different schemes to deal with interference; in the co- channel interference between small cells and Wi-Fi system, they suggested using (ABS) scheme with no priority. They have proposed as well an interference-avoidance scheme to facilitate the coexistence of small cells with Wi-Fi system sharing the same unlicensed spectrum, by estimating the density of near Wi-Fi AP.

3.4.2.2 Advanced Mobility Management

In Het-Nets due to the small cell formation as a second layer in the network, the user may have to perform frequent handovers as it transcends the cell boundaries more often. This will cause degradation in the Het-Net handover performance compared to pure Macro cell. In [77] several mobility management solutions are introduced, such as user grouping based on their mobility patterns. In this approach mobile users are allocated to the macro BS while stationary users are allocated to small cells. Another mobility management technique considers virtual cell formation to help users to reduce the handover events. Mobile users see the clustered cells as a single cell; hence the mobility event is triggered only if a virtual cell boundary is crossed. Another method is using the neighbor list management to enhance the mobility. This technique assumed that neighboring small cells can share information lists to manage the handover among clusters of small cells in a macro-cell.

3.4.2.3 Resource Management and Network Selection Schemes

During the initial development for each RAT various types of wireless access technologies were developed to cope with the related challenges. Consequently, different access technologies have been developed to serve users with different requirements and services. This will indicate that each RAT can offer the user a service bounded with its own limitations and benefits, such as coverage and bandwidth. The integration part will be a challenge to deal with the available resources, due to the complex architecture of Multi-RAT as it consists of different types of access protocols. In [55], authors suggested a way to manage the resources by using a joint resource management (JRRM) or common RRM and a Joint Call Admission Control (JCAC) for the Multi-RAT environment. The adaptive resource management can affect the performance of the whole network, as many CRRMs and JCACs can optimize the Multi-RAT operations. Most of the latest studies focus on enhancing the network throughput, load balancing and user experience.

Various schemes for network selection have been presented in different papers. The work in [72] aims at combining the licensed spectrum (cellular network) and the unlicensed spectrum (Wi-Fi) whenever the network capacity is low. This work illustrates the balance in shifting the traffic, as the premium traffic goes to the cellular network, and the bulk traffic is shifted to Wi-Fi network. The work in [70] is a quantitative study in a real dense urban area about how much can an indoor Wi-Fi offload a 3G macro cellular network, which is important as the quantitative gain amount from using the Wi-Fi is still unknown. The Wi-Fi offloading has been studied as a function of access point density. They showed that the average user throughput is boosted up to 300% by using 10 access points/Km2. Moreover, they prove that the gain increases with the access point density. Furthermore, the authors proposed three Wi-Fi deployment algorithms: uniform random, outage-centric, and traffic-centric. At the end, they made a comparison between the Wi-Fi offloading solution and HSPA Femto-cell offloading solution. Performance evaluation results showed that a higher average user throughput and network outage reduction can be achieved through Wi-Fi than HSPA Femto-cells by exploring 20 MHz unlicensed ISM band.

In [73], The authors have developed a generic framework called Mobile Femto cells utilizing Wi-Fi (MFW), that can exploit both Wi-Fi and Femto-cell networks at the same time. The proposed framework allows operators in a public transportation system to offload the traffic generated by the users onto a mobile Femto Base Station (mob FBS), which utilizes the Wi-Fi as a backhaul to route the traffic to the cellular network instead of the congested macro-cell. A numerical experiment has been conducted on MFW with practical applications such as YouTube and Skype, and the efficiency was demonstrated in terms of data traffic offloading. As a conclusion, when the mob FBS is saturated MFW can offload up to 50% of macro-BS data traffic. A performance investigation was held in [61] for downlink in a realistic indoor for both Wi-Fi and Femto cells, as a solution to offload an LTE macro network with the 50x growth assumption for data traffic. In Wi-Fi deployment, we can meet the target network Key Performance Indicator (KPI) of 90% network coverage and a minimum data rate of 1 Mbps, with an access point density of 230AP/Km2. Note that, more AP density is required to meet the KPI in the out-band LTE Femto-cell deployment scenario. On the other hand, the least favorable scenario is in-band Femto cell, where the Femto-cells share one carrier with the macro-layer. The authors have shown that for the same access point density out-band Femto cells and Wi-Fi APs can offload a similar number of users, while in-band Femto cell can be improved by interference mitigation.

3.5 Offloading Scenario Settings

To enhance the overall network capacity with the Het-Net architecture, challenges and solutions is demonstrated earlier in section 3.3 and 3.4. Het-Nets are an obvious part of 5G including all types of small cell deployment to move even further than 4G to 5G. Capacity will be increased, energy consumption and cost will be decreased [82]. The new cellular communication will need to be supported with more diverse set of devices, and it is worth mentioned the expected rise of machine to machine or D2D communication. Offloading is considered as one of the key technologies to cope with future densification. It was clearly stated in this chapter the new taxonomy and classification for both types of Het-net and offloading approaches. Several technologies are illustrated such as a Cell Range expansion with Pico cells, and advanced interference cancellation IC. The coexistence of low power and high power nodes introduce challenges related to interference mitigation and avoidance, mobility management, uncoordinated small cell deployment, different access types and joint resource allocation. All of these issues have been classified with the proper solutions per each. The novelty aspect about this literature is being a good reference for any reader interested in the basics of different types of Het-Net and offloading. The possible offloading scenario settings are listed in Table7, while Table 8 demonstrates all the research approaches increasing capacity. Different hypothesis and issues affect the offloading have been classified in this research as shown in Table 9.

Table 7: Offloading Scenario Settings

Offloading Scenario Settings	Ref.No
Single RAT Multi -Tier Network	[1],[2],[3],[4],[8],[9],[10],[11],[12],[13],[14],[15] [17],[18],[20],[21],[23],[24],[25],[26],[27]],[29],[30][31],[37]
Multi RAT Multi -Tier Network	[2],[3],[4],[6],[7],[8],[11],[12],[15],[17],[18] [20],[22],[26],[27],[30],[28],[34],[36]

Table 8: Offloading Approaches to Increase Capacity

Offloading Approaches to Increase Capacity	Ref.No
LTE Macro-Femto Cell	[4],[6],[8],[9],[10],[11],[12],[15],[16][17],[19], [22][27],[24],[30],[32],[33],[34],[35],[36]
LTE Macro-Pico Cell	[2],[3],[6],[8],[9],[10],[11],[19],[22],[25],[31], [34], [36],[37]
LTE Macro –Phantom Cell	[13]
LTE Macro –Wi-Fi AP	[2],[4],[6],[8],[11],[12],[15],[16],[17],[22] [27],[29],[30],[28],[31],[33]
LTE Macro –Wi-Fi Direct (D2D)	[7],[16],[20]
3G Macro –Pico Cell	[21]
3G Macro – Wi-Fi AP Or Wi-Fi Direct (D2D)	[17],[22]
Different Relaying Scenario	[1],[11],[14],[20]

Table 9: Hypothesis to be taken into Account in Offloading

<table>
<tr><th colspan="2">Hypothesis</th><th>Ref .No</th></tr>
<tr><td colspan="2">Co-channel interference</td><td>[1],[6],[8],[9],[11],[12],[13],[14],[15],[16],[17],[18],[20],[22],[27],[30],[31],[32],[33],[34],[35],[36]</td></tr>
<tr><td colspan="2">Cross-Tier Interference</td><td>[1],[2],[3],[6],[8],[9],[10],[11],[12],[13],[18],[19] [22],[24],[27],,[30],[31],[32],[33],[34],[35][36]],[37]</td></tr>
<tr><td rowspan="2">Deployment Scenario</td><td>Planned Deployment</td><td>[21],[23],24],[28]</td></tr>
<tr><td>Un Planned Deployment</td><td>[2],[10],[12],[15],[19],[22],[26],[27],[30],
[31],[32],[34],[33]</td></tr>
<tr><td rowspan="3">Access Type for
Het-Net element</td><td>Open Access (OSG)</td><td>[1],[2],[3],[4],[6],[7],[8],[9],[13],[15],[16],[19],[20]
[22],[23],[31],[33],[34]</td></tr>
<tr><td>Close Access (CSG)</td><td>[8],[9],[11],[17],[19],[22],[34]</td></tr>
<tr><td>Hybrid Access</td><td>[9],[24]</td></tr>
<tr><td colspan="2">EICIC</td><td>[2],[3],[9],[10],[12],[13],[17],[18],[20],[27],[29][31]</td></tr>
<tr><td colspan="2">Radio Resource Management</td><td>[1],[2],[3],[6],[7],[8],[9],[10],[11],[12],[13],[15],[16]
[17],[18],[19],[20],[23],[25],[26],[27],,[30],[31],[33]</td></tr>
<tr><td colspan="2">Mobility Management</td><td>[1],[2],[3],[4],[6],[7],[9],[10],[11],[12],[13],[16],[17]
[18],[20],[22],[24],[25],[27],[29],[30],[31]</td></tr>
<tr><td colspan="2">Power Control</td><td>[3],[9],[10],[11],[12],[21],[23],[24],[27],[29],[32]</td></tr>
</table>

3.6 Effective Capacity Offloading Algorithms

Offloading approach is used to overcome the congestions in a cellular network, by offloading data traffic to a complementary access network. The offloading decision can be taken based on different criteria's in order to balance the load between different tiers as shown in Table 10.

Table 10: Cell Association Criteria for Load Balancing in Offloading

No	Trigger Criteria	Equation
1	**RSSI Received** **Signal Strength Indicator**	$P_{rx} = P_{tx}/\ L$
2	**SNR** **(Signal to noise ratio)**	$SNR = \dfrac{P_{tx,i}}{L_{ij} \times N}$, i = 1,2, ……, n and j = 1,2, ……, m
3	**SINR** **(Signal to interference plus noise ratio)**	$SINR_{i,DL} = \dfrac{\frac{P_{tx,j}}{L_{ji}}}{\sum_{\substack{k=1 \\ k\neq i}}^{n} \frac{P_{tx,k}}{L_{ki}} + N}$
4	**Distance**	Euclidean Distance $= \sqrt{}(x_{user(i)} - x_{cell}) + \left(y_{user(i)} - y_{cell}\right)$
5	**Path-Loss**	$Li = \ {d_{ij}}^{PLE} \ * \ 10^{\frac{shadowing}{10}}$
6	**Throughput** **User-Preserved Rate**	$Thr = Min \{MAX\ Thr, BW log_2\ (1 + SINR)\}$

Network access selection or offloading decisions, are made based on different parameters with different objectives as well, such as boosting the capacity or user QoS [41, 43, 83]. Table 11 shows the most effective Wi-Fi offloading Algorithms. Different algorithms have been tackled this in research; the first one is Wi-Fi if coverage, which considers the SNR value to trigger the offloading decision to Wi-Fi [17]. This algorithm can end with overloaded Wi-Fi APs with a poor user throughput at high traffic loads. A similar offloading algorithm, usually adopted by mobile operators is presented in [84], which is a Wi-Fi First algorithm (WF). It depends on connecting the users first to Wi-Fi, whenever there is Wi-Fi coverage, and only joins LTE if there is no availability of Wi-Fi. The authors studied WF performance under non-uniform and a uniform Wi-Fi backhaul capacity distribution, and the result shows that WF is worse in terms of fairness and average throughput per user.

Another offloading algorithm using WLAN is mentioned in [17], which is Fixed SNR Threshold. In this algorithm the network offloading is based on choosing the best SNRmin for WLAN APs, which is close to Wi-Fi if coverage concept only at low traffic loads. The SNRmin in Fixed SNR Threshold is a function of the WLAN load. In every WLAN AP the SNRmin increases individually whenever the load increases as well; otherwise the user will connect to LTE instead of WLAN. Fixed SNR algorithm is considered better than Wi-Fi if coverage in terms of balancing the load between a Wi-Fi AP tier and an LTE tier.

In [85] the authors studied another traffic steering policy for network selection, which is called Best-Server algorithm. This algorithm behaves similar to Wi-Fi if coverage and WF algorithms, as the user connects first to Wi-Fi. This happens if SINR perceived by the user is greater than a certain threshold; otherwise he will connect to an LTE network. The difference between Best-Server algorithm and the previous algorithms mentioned is that it depends on SINR while in WF and Wi-Fi if coverage they depend on SNR by assuming using non-overlapping channels. All three algorithms do not guarantee a quality of service to connected users to Wi-Fi; they only guarantee the connection. Another offloading scheme presented in [84] is Physical Data Rate Based algorithm (PDR), which is purely based on the PDR provided by different available RATs. This algorithm compares the PDR for Wi-Fi and LTE, and chooses the highest value a user can get. A similar algorithm presented in [85], called the SMART algorithm, triggers the offloading based on the minimum data rate perceived by the user as long his experienced SINR exceeds the threshold.

A performance investigation presented in [61] to down link in a realistic indoor Wi-Fi and Femto-cells, as a solution to offload LTE macro networks with the 50x growth assumption for data traffic. The Wi-Fi deployment can meet the target network (KPI) Key Performance Indicator 90%, with a minimum data rate of 1 Mbps at 230AP/Km2 access point density. More AP density of 1200 AP/Km2 is required to meet the KPI in the out band LTE Femto-cell deployment scenario. On the other hand, the least favourable scenario is in-band Femto-cell, where the Femto-cell shares one carrier with the macro layer. The authors have shown that for the same access point density out-band Femto-cells and Wi-Fi APs can offload a similar number of users, while in-band Femto-cells can be improved by interference mitigation.

In [73], the authors have developed a generic framework called (MFW), which stands for mobile Femto cells utilizing Wi-Fi, that can exploit both Wi-Fi and Femto-cell networks at the same time. The proposed framework allows operators in a public transportation system to offload the traffic generated by the users onto Femto base stations (mob FBS), and the mob FBS utilizes the Wi-Fi as a backhaul to route the traffic to the cellular network instead of the loaded macro-cell. A numerical experiment has been conducted on MFW with practical applications such as YouTube and Skype, and the efficiency was demonstrated in terms of data traffic offloading. As a conclusion, when the mob-FBS is saturated, MFW can offload up to 50% of Macro-BS data traffic. Table 11shows the most effective Wi-Fi offloading algorithms.

Table 11: Effective Capacity Wi-Fi offloading Algorithms

No	Offloading Algorithm	Trigger Criteria	Wi-Fi Coverage	Wi-Fi Model	Wi-Fi AP Deployment
1	**Wi-Fi if coverage**	Best AP SNR	Outdoor	IEEE 802.11 a , b	Planned Deployment
2	**Traffic Steering**	SINR + Min DR	Indoor	IEEE 802.11 g	Traffic Centric
3	**Wi-Fi First**	Connect to Wi-Fi First	Outdoor	IEEE 802.11 g	Planned Deployment
4	**PHY Data Rate Based**	Higher PDR	Outdoor	IEEE 802.11 g	Planned Deployment
5	**Fixed SINR threshold**	Best AP SNR + Load	Outdoor	IEEE 802.11 a, b	Planned Deployment
6	**MFW**	RSSI	Outdoor	IEEE 802.11 r, e	Planned Deployment
7	**Best Server**	Best SNR LTE-Wi-Fi	Indoor	IEEE 802.11ac	Traffic Centric

Chapter 4

Proposed Model

4.1 Introduction

This chapter introduces the adopted system model for Wi-Fi data offloading in this thesis for single LTE cell with non-overlapping scenario for Wi-Fi APs; detailing the system model, components, assumptions for the purpose of increasing the capacity of LTE networks. Section 4.2 will discuss the site planning, while the detailed system model and the target offloading structure are presented in section 4.3. Capacity enhancement scheme with Wi-Fi offloading is introduced in section 4.4. Section 4.5 explains down link power allocation. Sections 4.6 and 4.7 discusses Wi-Fi APs deployment and single LTE cell implementation. Finally, section 4.8 demonstrates network access selection, along with traffic offloading schemes.

4.2 Site Planning

The site being under study is the Mina district of Mecca in western province in Saudi Arabia. It is located five kilometers away from the holy city of Mecca. Mina is also known as the Tent City, and it covers an area of approximately 5.5 Km^2, which is covered with several eNodeBs. Based on hajj statistics for last year 2016, the total number of pilgrims was approximately around 1800,000 [86]. The bandwidth for Macro LTE is assumed to be 20 MHz, with18 MHz effective bandwidth as explained earlier in section 2.2.7. RB bandwidth is equal to 180 KHz, which consist of 2 time slots in time domain with one ms in the frequency domain. One RB consist of 12 sub-carriers, while LTE frame structure consists of 10 sub-frames with a total of 10 ms in time domain. The Total number of available RBs per Transmission Time Interval (TTI) or 'sub-frame' is equal to 100. Based on that, the theoretical maximum number of serving users per frame is equal to 1000 users, with the assumption of giving one user one RB in a sub- frame. In this work I assume each user occupies one RB for some fraction of the time, which is equal to one ms in the frequency domain. This work is FDD based with one sub-frame in the time domain as if it's a snapshot case scenario.

Further assumptions imply a 10 % activity, hence a single Macro LTE cell can accommodate a total of 10,000 users as shown below:

- Number of active_UE = 10 % of total_UE
- *Number of total_UE = active_UE / 0.1   (9)*
- Number of total_UE per cell (active + inactive):

total_UE = 1000 / 0.1 = 10,000 people/cell   (10)

- To cover a 1,800,000 pilgrims, the number of cells required

  no_of_ macro cells= 1,800,000/10,000 (11)

  no_of_ macro cells = 180 macrocells.

- Area per macro cell can be estimated as

  Area/macrocell =*Mina_Area/no_of_ macro cells.*

  Area/macrocell =*5, 500,000 /180 = 30,555* m^2. (12)

- Macro cell range *r* then can be estimated based on circle area equation as,

$$r = \sqrt{\frac{Area}{\pi}} = \sqrt{\frac{30555}{\pi}} \approx 100\ m \qquad (13)$$

Macro cell range for LTEeNodeB is assumed to be 100 m, based on the above calculations. The number of RBs M is assumed to be 100 for a one sub frame in the frequency domain.

4.3 System Model and Target Offloading Structure

The integrated data offloading approach empowers operators to have a full control on their subscribers either they connect to LTE or Wi-Fi network to send their subscribed content. The coupling architecture for Wi-Fi with cellular systems either its loose coupling or tight coupling.

In this thesis work I assume having a loose coupling architecture, as loose coupling doesn’t require a major corporation as have been mentioned in 2.4.3. In this thesis, we assume a 3GPP network operator controlled scenario, and the overall assumption is having a network operator in charge of both the LTE and Wi-Fi networks. This helps the network operator to have control over Wi-Fi traffic and to ensure a better customer experience across the available networks. For example, UE's IP address allocation, access to general IP services, as well as network features like security, charging, Quality of Service (QoS) and policy control can be made independent of the access technology. Therefore migration between LTE and Wi-Fi is easily possible as shown in Figure 29.

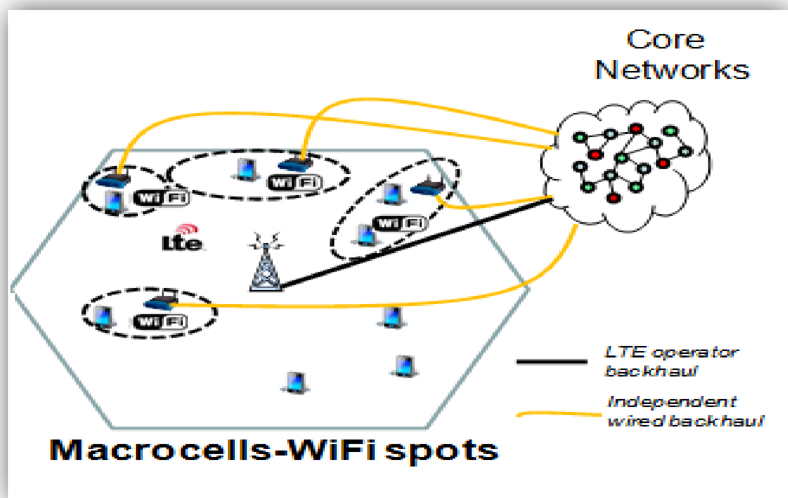

Figure 29: The Target Offloading Structure

The system is composed of a single macro cell covered with one LTE eNodeB in the center. Inside the macro LTE cell, several numbers of Wi-Fi APs are located within the boundaries, operating on IEEE 802.11n standard. All Wi-Fi APs are assumed to work on the open access mode. The locations of the Wi-Fi APs are fixed in a specific location, predefined manually by operator. Users are randomly distributed in the macro LTE cell and overplayed by Wi-Fi APs region's as well. The proposed architecture is mainly to be tested in congested areas such as"

Mina City of Tent ", with the objective of improving capacity for the whole system in terms of connected users and network throughput. The expected capacity enhancement is done by offloading the users to Wi-Fi APs in order to relive LTE network. Users can connect to either LTE or Wi-Fi based on specific parameters to meet their traffic demand and serve them with a better QoS, as both are controlled by the same operator.

4.4 Capacity Enhancement Scheme with Wi-Fi Offloading

Capacity comes with different terms in the network, either to denote the maximum number of users per service per cell, or to point out the maximum throughput per cell. Throughput and number of connected users are conducted in this Thesis as a proof of capacity enhancement. There are different aspects can affect the capacity calculation in any wireless system, and they can be divided into four main sections: system capabilities, environment effects, system measurements and system target, as shown in Figure 30. In the system capabilities air interface transmission parameters are specified such as modulation and coding schemes or multiple antenna schemes along with the theoretical maximum throughput for each network either LTE or Wi-Fi. Environment effects will consider the path loss model used in the system, shadowing, interference and Noise. System measurements imply the actual values of the system being measured before gaining a connection. The most important two are: measured SNR and measured throughput. System target specifies the required level of SNR or throughput based on the service type to gain connection to the best access network.

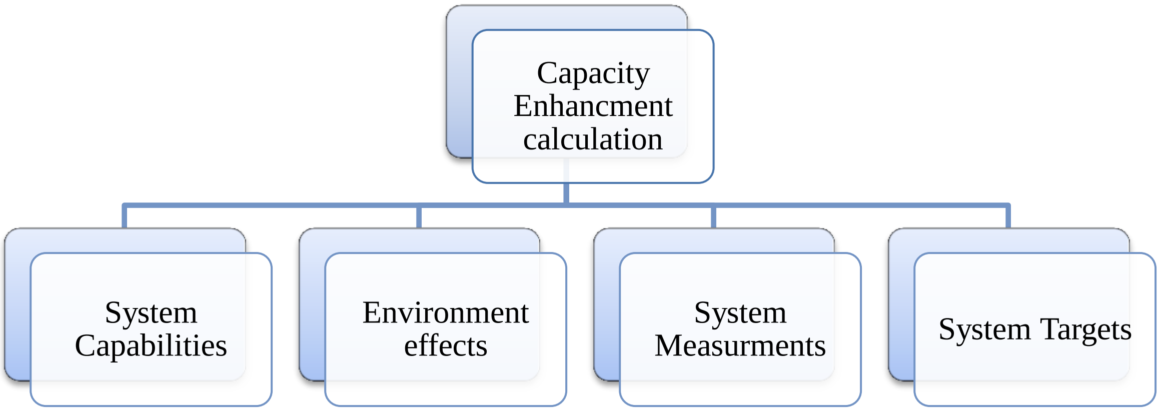

Figure 30: Main Factors for Capacity Enhancement Calculation

4.4.1 System Capabilities

Throughput can be varied due to several factors: bandwidth, cyclic prefix, modulation scheme, antenna configuration, and Mac overhead for both LTE and Wi-Fi.

4.4.1.1 Maximum Throughput for LTE

As discussed in section 2.1.1.7, the maximum throughput of LTE under a given assumption is 300 Mbps in the downlink. Assuming to have LTE bandwidth of 20MHz with 10% reserved guard band, thus the effective bandwidth is 18MHz. Knowing that RB bandwidth is equal to 180 KHz, the total number of available RBs, can be estimated as in equation 14:

$$RBs=LTE\_TotalBW/RB\_BW \qquad (14)$$

Based on equation 14 the total RBs in a sub-frame with 1 ms duration is equal to 100 RBs, then the maximum throughput for each user will be 300 Kbps in the downlink as shown in equation 15.

$$\text{LTE\_Tmaxuser} = \text{LTEDL\_Tmaxframe/RBs} \quad (15)$$

$$\text{LTE\_Tmaxuser} = 300\ \text{Kbps}$$

4.4.1.2 Maximum Throughput for Wi-Fi

In the Wi-Fi case considering IEEE 802.11n with the assumption of using a 20 MHz band, 4×4 MIMO, 64 QAM, 84% overhead and a short guard interval, the maximum IEEE 802.11n throughput can be calculated as follows in the DL case as follows in equation 16:

$$\underbrace{1.0385}_{\text{(Factor of 20 MHz)}} \times 65\ \text{Mbps} \times 4\ \text{antennas} \times \underbrace{1.11}_{\text{(Factor of short guard interval)}} = 600\ \text{Mbps} \quad (16)$$

By reducing MAC overhead, the total throughput is approximately equal to 100 Mbps, as this have been clarified in earlier section 2.3.5 [6, 36].

4.4.2 Environment effect

4.4.2.1 Path loss

We consider the main two factors that affect radio channel, path loss, and shadowing. The path loss is the power reduction of the transmitted signal when it propagates through space. Path loss value between a users connected either to eNodeB or Wi-Fi AP is calculated from a log-distance path loss model with equation 4 as mentioned earlier in section 2.5.2.

Shadowing, which is the power reduction caused by large objects such as buildings and trees is assumed in this work. By combining path loss and shadowing, the path loss is calculated based on equation 6 in section 2.5.3. Shadowing for LTE is assumed to take a value of 3 dB, while in Wi-Fi is neglected with the assumption of indoor environment.

4.4.2.2 Interference

Interference is assumed to be neglected in this Thesis, as the proposed area is composed of one single LTE macro cell with no boundary effect from surrounding LTE cells. Another assumption is assumed for connecting UE to LTE, each UE is allocated one Resource Block (RB) in the frequency domain, as its FDD based system. This way there is no interference between allocated users as they are using different RBs in one sub-frame. For the Wi-Fi APs interference between APs is neglected as well, due to conducting a non-overlapping scenario, by using the non- overlapping channels 1, 6 and 11.

4.4.2.3 Noise

Noise power in a receiver usually is a thermal noise generated by the amplifier, and it is unwanted energy. Noise can be calculated with equation 8, mentioned in section 2.5.5. According to this equation, the noise value in LTE differs from Wi-Fi depending on the bandwidth allocated to the user in each. In this thesis, we assume to perform an FDD simulation base, thus LTE allocates each user 1 RB with 180KHz bandwidth for a 1 ms sub-frame in the time domain. In Wi-Fi the connected users allocate the whole bandwidth for a specific time as it uses the CSMA/CA approach for all users contending to use the same channel.

Based on previous information noise can be calculated as follows based on equation 8, as equation 17 is for LTE noise, while equation 18 is for WLAN noise calculation:

$$\text{LTE\_ Noise} = 1.381 \times 10^{-23} \times 290 \times 180 \text{ KHz} = -121 \text{ dBm} \quad (17)$$

$$\text{Wi-Fi Noise} = 1.381 \times 10^{-23} \times 290 \times 20 \text{ MHz} = -130.9 \text{ dBm} \quad (18)$$

4.4.3 System Measurements & Link Budget Calculations

4.4.3.1 Measured SNR

Link budget estimation SINR can be calculated with equation 1, mentioned in section 2.5.1 for down link traffic. With the assumption for interference I is equal to zero for LTE macro cell and Wi-Fi APs, hence in this work, by substitution from equation 1 with I=0, link budget can be calculated as in equation 19:

$$SNR = \frac{P_{tx,i}}{L_{ij} \times N}, \ \mathrm{i} = 1,2,\ldots\ldots,\mathrm{n} \text{ and } \mathrm{j} = 1,2,\ldots\ldots,\mathrm{m} \qquad (19)$$

Based on previous information the measured SNR in LTE and Wi-Fi can be calculated as follows in equation 20 and 21 respectively:

$$SNR\_LTE = \frac{P_{tx\_LTE}}{L_{LTE\_UE} \times N_{LTE}} \qquad (20)$$

$$SNR\_WiFi = \frac{P_{tx\_WiFi}}{L_{WiFi\_UE} \times N_{WiFi}} \qquad (21)$$

4.4.3.2 Measured Throughput

Throughput could be used to determine the network selection decision for a UE, as there is an actual measured throughput and required throughput. The required throughput usually depends on the type of service selected by the UE to achieve the minimum required SINR to have an acceptable service.

Throughput in general can be calculated based on Shannon Capacity equation number 22 as follows:

$$C = B \times \log_2(1 + SNR) \qquad (22)$$

Equation 23 is used to calculate throughput as:

$$T_i = \min(T_{max}\ , B \times \log_2(1 + SNR_i)) \qquad (23)$$

Where,

- B is the bandwidth.
- T_{max} Is determined by air interface capabilities.

Based on previous information the measured throughput in LTE and Wi-Fi can be calculated as follows in equation 24 and 25 respectively:

$$\text{LTE\_Thr} = \min\left(\text{LTE}_{\text{Tmaxuser}},\ \text{RB}_{\text{BW}} * \text{Log}_2\ (1 + \text{SNR\_LTE}\right) \qquad (24)$$

$$\text{Wi\_Fi\_Thr} = \frac{1}{n}\min\left(\text{WiFi}_{\text{Tmaxuser}}, WiFi_{\text{BW}} * \text{Log}_2\ (1 + \text{SNR\_WiFi}\right) \qquad (25)$$

4.4.4 System Target & SINR Requirement's

4.4.4.1 SINR Requirement's calculation

Network selection for users can be determined through SINR Requirement's, which guarantees an acceptable service for UEs. It depends on the required throughput for a specific service, which is discussed in section 4.4.3.2. The required SINR can be computed as follows [87] :

$$SINR_{min} = \left(\frac{E_b}{N_0}\right)_{min} \frac{R_b}{W} \qquad (26)$$

Based on equation 26, Eb/N_0 is a ratio of Energy per Bit (E_b) to the Spectral Noise Density (No). R_b is the bit rate, and W is the bandwidth. The relation between Eb/N0 and the Bit Error Rate (BER) is presented in the chart presented in Figure 31.

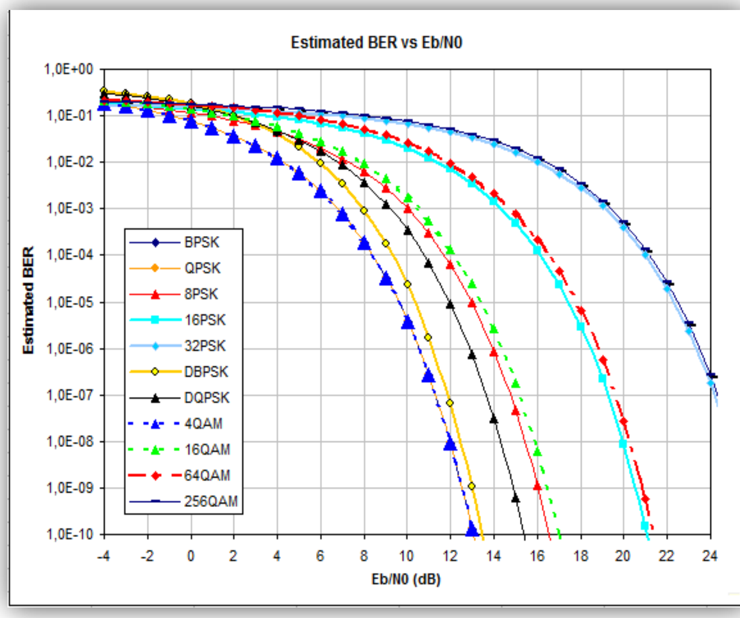

Figure 31: Estimated BER vs Eb/No, based on [87]

In the case of using the modulation scheme 64 QAM, the required E_b/N_0 for the minimum acceptable BER of, which is assumed to be 10^{-5} is 18dB as its shown in the chart.

SINR Requirement Calculation:

There is another way to calculate the SINR requirement from equation 22 'Shannon Capacity equation ', which is presented earlier in section 4.4.3.2. To calculate the required SNR to users connected either to LTE or Wi-Fi using the equation (27) as follows:

- Use Shannon's equation 22:
  - $T = B \times log_2(1 + SNR_i)$
  - $\frac{T}{B} = log_2(1 + SNR_i)$
  - $2^{T/B} = 1 + SNR$
  - $SNR = 2^{T/B} - 1$ (27)

4.4.4.2 SINR Requirement's for Web Browsing Service

Based on the information presented in section 4.4.4.1 Assuming a web browsing service with a required throughput of 240 Kbps either for LTE or Wi-Fi [88]. By substituting all these values in equation (27), the required SINR for a single connection will be computed for LTE and Wi-Fi as follows:

- $LTE\_SNR_{requirement,\,web} = 1.82$ dB (28)

- $Wi-Fi\ \_SNR_{requirement,web} =$ -20.78 dB (29)

4.4.4.3 SINR Requirement's for VoIP Service

Based on the information presented in section 4.4.4.1 assuming a VoIP service with a required throughput of at least 15 Kbps for LTE and 8Kbps in Wi-Fi using compressed G.729 CODEC [33, 37, 39, 40]. By substituting all these values in equation (27), the required SINR for a single connection will be computed for LTE and Wi-Fi in equations 30 and 31 respectively as follows:

- $LTE\_SNR_{requirement,\,VoIP} =$ -12.26 dB (30)

- $Wi-Fi\ \_SNR_{requirement,VoIP} =$ -35.58 dB (31)

4.5 Down Link Power Allocation

Power allocation in downlink case has a fixed transmission power for either LTE eNodeB or Wi-Fi APs to all users within boundaries. This power value will be denoted as $P_{tx,}$ and will be assumed to have the value of 21 dBm For LTE. Transmission power for Wi-Fi IEEE 802.11n is assumed to be 23dBm, which is known as normal value [89] . The normal power with a refrence desingne of 4*4 MIMO , could cover a range of 100 Feet.

$$Ptx,_{LTE} = 21 \text{ dBm} \qquad (32)$$

$$Ptx,_{WiFi} = -23 \text{ dBm} \qquad (33)$$

Therefore, a connection in downlink case is verified based on whether the required SINR and throughput values are met or not. The measured SINR will be computed using detailed equation 34 as follows:

$$SINR_{i,DL} = \frac{\frac{P_{tx,j}}{L_{ji}}}{\sum_{\substack{k=1 \\ k \neq i}}^{n} \frac{P_{tx,k}}{L_{ki}} + N} \qquad (34)$$

In the downlink, as we are interested in the received signal, the SINR for user *i*, is the SINR of the received signal. $P_{tx,j}$ is the transmission power of the sender node *j* and L_{ji} is the path loss between the sender *j* and node *i*, *n* is the total number of users using the same RB *i* in LTE case or same channel *i* in Wi-Fi as, $P_{tx,k}$, denotes the transition power of each of the *n* users, L_{ki} is the loss between *k* and *i*, and *N* is the noise. Due to neglecting the interference part in both networks either LTE or Wi-Fi. The throughput then can be calculated based on the Shannon capacity as follows in equation 35:

$$T_i = Min\{Max\_Throughput\_DL,\ W\ log_2(1 + SNR_{i,DL})\} \qquad (35)$$

4.6 Wi-Fi Access Points Deployment Scenario

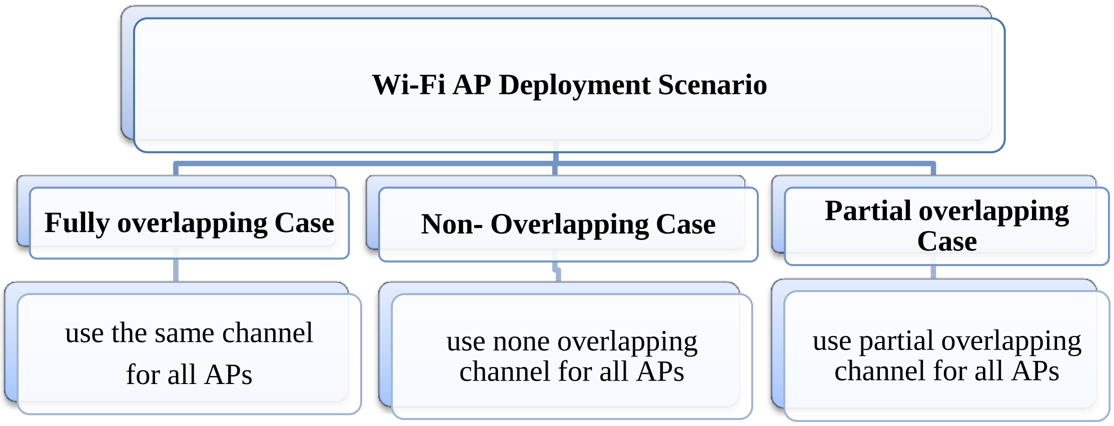

Figure 32: Wi-Fi Access Points Densification Scenario

There are different deployment scenarios in selecting the channels operating in each APs, as have mentioned in earlier sections that IEEE 802.11n Wi-Fi Aps support 14 different channels. Only 13 channels from the 14 channels can be assigned to multiple APs in the simulation scenario, forming mainly three possible schemes. The assignment procedure for the 13 Channels shown in Figure 32, two different APs. The channel assignment could be performed with various resource allocation algorithms, such as graph coloring or Dijkstra algorithm. Channel assignment in this thesis is not included in the focus of the study. For simplicity reasons, we assume that Wi-Fi assigns different non-overlapping channels to each AP, which they are channel 1, 6 and 11.

4.6.1 Fully Overlapping Channel Scenario

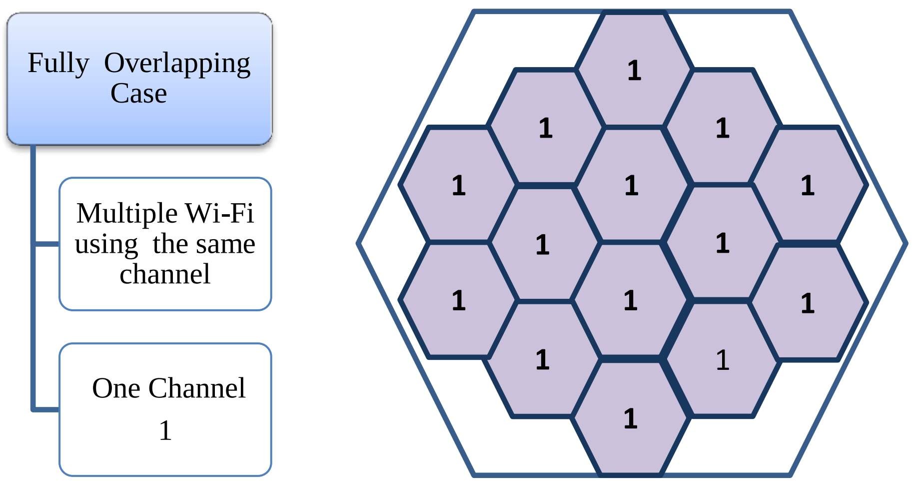

Figure 33: Fully Overlapping Case

The first scenario is fully overlapping case, as all APs tend to use the same channel for all APs deployed in the area. This type of deployment is considered to be the worst case scenario in AP deployment, due to the huge co-channel interference between adjacent APs. Figure 33 shows a deployment for 14 Wi-Fi APs inside a macro LTE cell. All the 14 APs painted with the same color to express that all APs are using the same channel. IEEE 802.11n standard operating on 2.4 GHz band, uses 13 channels, and based on fully overlapping concept, the assigned channel for all APs will be one channel of the available 13 channels, such as channel 1.

4.6.2 Partial Overlapping Channel Scenario

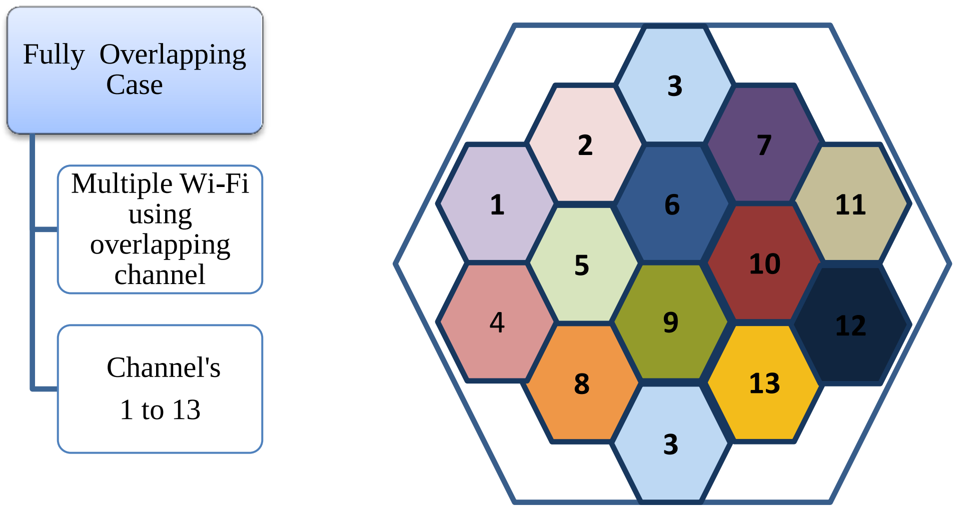

Figure 34: Partial Overlapping Case

The second scenario is partially overlapping case, as all APs tend to use partial overlapping channel from channel 1 till channel 13 in adjacent APs, so they also will face partial co-channel interference. Figure 34 shows a deployment for 14 Wi-Fi APs inside a macro LTE cell. All the 14 APs are painted with different colors to express that all APs are using different channels.

4.6.3 None Overlapping Channel Scenario

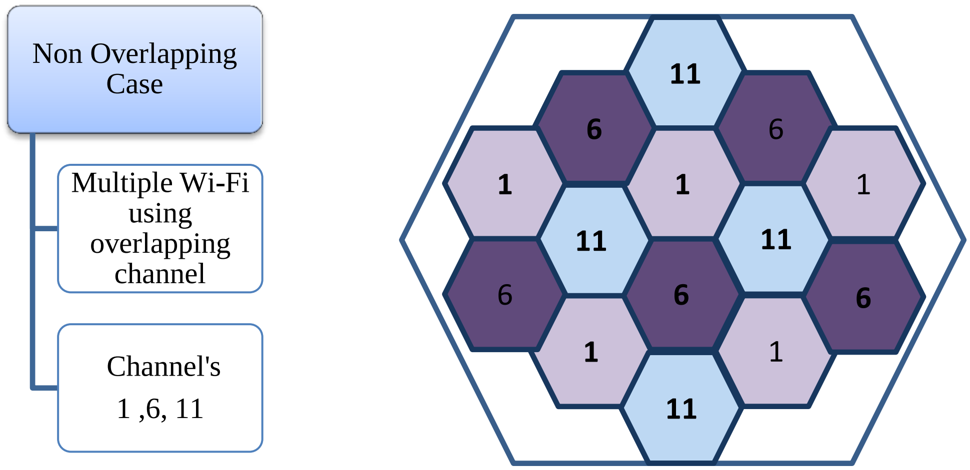

Figure 35: None Overlapping Case

The third case scenario considers to be the best in deploying the APs as they use a non-overlapping channels, which they are channel 1, 6 and 11. In this case APs will not suffer from the interference, especially if the deployment and the channel assignment is done in a planned manner. In this way every two APs using channel 1 for example will be distant from each other to eliminate the co-channel interference, due using the same channel. In Figure 35 there are three different colors for every 3 adjacent APs, to indicate a non-overlapping channel assignment.

4.7 Single Macro Cell implementation & DL Resource Allocation

4.7.1 Single Macro LTE Cell Implementation

In this section, a single LTE cell scenario is taken as a case. The eNodeB is deployed in the center of LTE Macro-cell. Inside the LTE single cell several Wi-Fi APs are deployed in a planned and fixed manner, each one is operating on a non-overlapping channel 1, 6 and 11 respectively. The eNodeB is assumed to store the information of all users trying to gain services in the variable U. The information for each user (u_i) in the case of downlink includes: user location, RB allocation if it's connected to LTE, Wi-Fi allocation if it's connected to Wi-Fi AP, transmission power, SNR, and throughput. The proposed services for users in this work are web browsing and VoIP, with different required throughput for each. This will affect dramatically the user network selection decision, either to LTE or Wi-Fi AP. This is performed in a way to guarantee QoS to connect subscribers.

LTE is assumed to be an FDD based system, TDD is neglected in this thesis for simplification. M variable represents the total number of available RBs, and each user connected to LTE is allocated with one RB. A single RB cannot be reused in the system between different users at the same time in the same LTE macro cell. The frequency reuse is 1 with the previous assumption. First, the study will conduct the LTE standard case scenario with no APs overlaid in the LTE macro cell. The down link resource allocation in the LTE standard case is presented later in section 4.7.2.

Wi-Fi APs are deployed in a planned manner, and users will first check Wi-Fi availability before seeking LTE connection. This implies that the Offloading concept for users to Wi-Fi APs gain the first priority in network selection. This is assumed for all the Wi-Fi offloading algorithms conducted in this work. The blocked users based on any Wi-Fi offloading algorithm will check LTE availability afterwards. If the total RBs (M) are not fully allocated, then users can connect to LTE, otherwise they will be blocked.

The configuration for users is randomly distributed in the LTE Macro-cell, and there are four tested scenarios in this thesis: 1) LTE standard case scenario, 2) LTE- Wi-Fi If Coverage algorithm, 3) LTE- Wi-Fi Fixed SNR threshold, 4) LTE- Optimized Wi-Fi offloading Algorithm. The selected algorithms from literature, as many research works, consider them the most well-known offloading algorithm. Another reason, the offloading decision is based on similar criteria's to Optimized Offloading under study.

The summary of notations used in the implementation of LTE or Wi-Fi offloading algorithms, with their description is presented in Table 12.

Table 12: Summery of notations

Parameter/function	**Description**
M	Total number of RBs
BS	Stores the x, y coordinates of LTE eNodeB
S	Total number of APs
AP= {ap_1,ap_2, ap_3,…, ap_S}	Set of all Wi-Fi AP allocated in LTE eNodeB, with the size of S
U= {u_1, u_2, u_3,…, $u_{\mathbb{N}}$}	Set of all requesting users of size $\mathbb{N}$. Each element of U has all user information, including user *ID*, *x* and *y* coordinates, *Tx_power*, allocated *RB*, allocated Wi-Fi AP, *SNR*, and *throughput.*
BU= {b_1, b_2, b_3,..., $b_{\|BU\|}$} ⊆ U	Set of un-allocated users of size |BU|
CU= {c_1, c_2, c_3,…, $c_{\|CU\|}$} ⊆ U	Set of allocated users of size |CU|
CU_LTE ⊆ CU	Set of all connected users to LTE eNodeB
CU_WiFi ⊆ CU	Set of all connected users to Wi-Fi AP
RB={rb_1,rb_2,rb_3,..,rb_M}	Set of RBs of size M, and each RB has an *ID.*
Distance (a, b)	A function that finds the distance between two nodes a, and b based on Euclidean equation.
Pathloss (a, b)	Compute the pathloss between two nodes a, and b based on equation 4.
SNR (a,b)	Compute the SNR between two nodes a, and b based on equation 20, 21 for LTE and Wi-Fi respectively.

4.7.2 Down Link Resource Allocation

In the downlink, power transmission for eNodeB and Wi-Fi AP are fixed powers, hence no power control is assumed. In the standard case with having only LTE BS in the cell users are connected with BS if their SNR requirements are met. Type of demanding service will affect the discussion of having a connection or being dropped. By assuming to have an FDD based system for LTE, the number of resource blocks is available to be used. If u_i SNR_measured is greater or equal to SNR_required, then u_i is allocated rb_i . Otherwise the user u_i is blocked from the connection, if SNR_required is not satisfied or if there is no more available RBs. Equations (32) and (33) are used to compute the SNR and throughput respectively. Parameter *CU* will contain users with satisfied throughput requirements after allocating the downlink resources, while *BU* contain blocked users.

Algorithm 1 Downlink Resource Allocation for LTE Standard Cell

Input: U, RB;
Output: CU, BU;
If $\mathbf{rb_i}$ **<= M // M is total Number of RBs**
    $\mathbf{U_i \leftarrow rb_i}$
    M ← M+1
    Distance ← Distance (u_i, BS)
    Pathloss ← Pathloss (u_i, BS)
    SNR ← Compute SNR_measured (u_i, BS)
        If SNR_measured u_i >= SNR_required
        CU ← CU + u_i
        Else
        BU ← BU + u_i
      End
    Else
    BU ← BU + u_i
End
Return CU , BU;

4.8 Network Access Selection & Traffic Offloading Schemes

4.8.1 Wi-Fi If Coverage Algorithm

In this algorithm the user u_i connect to the best Wi-Fi AP based on the best SNR value a user can receive from all APs. The best SNR should be greater than the requiredSNR_{min}, which is affected by the required throughput for the demand service. Wi-Fi if coverage algorithm implies that a user I connect to a Wi-Fi whenever there is a WLAN coverage. After checking the SNR for all available APs, if the link budget doesn't fulfill the user required SNR, then it will connect to LTE BS. This will happen only if there are available RBs, otherwise u_i is blocked.

This algorithm considers only SNR information to make the network selection decision; hence it's a traffic load independent access as in (36).

$$\text{access} = \begin{cases} \text{WLAN} & \text{if } (\text{SNR}_{\text{WiFi AP}} \geq \text{SNR}_{\text{min}} \\ \text{LTE} & \text{otherwise} \end{cases} \quad (36)$$

Algorithm 2 Wi-Fi if Coverage Algorithm

```
Input: U, AP, RB;
Output: CU, BU;
Set SNR_min
For i ← 1 to size |AP|        // size |AP| = S
    Distance ← Distance (u_i, ap_i)
    Pathloss ← Pathloss (u_i, ap_i)
    SNR ← Compute measured SNR_wifi (u_i, ap_i)
End
SNR_wifi ←Best measured SNR_wifi (u_i, ap_i)
If SNR_wifi <= SNR_min
    CU_wifi ← CU_wifi + u_i
Else if rb_i <= M  // M is total Number of RBs
    CU_LTE ← CU_LTE + u_i
Else
    BU ← BU + u_i
End
    CU ← CU_wifi + CU_LTE
Return CU , BU;
```

4.8.2 Fixed SNR threshold Algorithm

In the Fixed SNR threshold algorithm, WLAN gains the first priority in connection, as in Wi-Fi if coverage algorithm. User connects to the best Wi-Fi AP based on the measured SNR_wifi. If SNR_wifi is greater than or equal to the threshold SNRmin. Otherwise, the user is directed to a cellular network (i.e. LTE). The main parameter needed for network selection is the SNR information from WLAN. The threshold SNRmin is traffic load-dependent, which means when the load increases at each individual AP, the SNRmin is increased as well, as shown in the following expression in (37).

$$access = \begin{cases} WLAN & if \ (SNR_{WiFi\,AP} \geq SNR_{min} + Load \\ LTE & otherwise \end{cases} \qquad (37)$$

Algorithm 3 Fixed SNR Threshold Algorithm

```
Input: U, AP, RB;
Output: CU, BU;
Set SNR_min
Set Load_max  // for each AP this regulates the max number of users connected
For i ← 1 to size |AP|       // size |AP| = S
   Distance  ←  Distance (u_i, ap_i)
   Pathloss  ← Pathloss (u_i, ap_i)
   SNR   ← Compute  measured SNR_wifi (u_i, ap_i)
End
SNR_wifi ←Best  measured SNR_wifi (u_i, ap_i)
If Load(Best_ap_i) < Load_max &&  SNR_wifi <= SNR_min
    CU_wifi ← CU_wifi + u_i
 Else if  rb_i <= M  // M is total Number of RBs
    CU_LTE ← CU_LTE + u_i
 Else
     BU ← BU + u_i
End
    CU ← CU_wifi + CU_LTE
Return CU , BU;
```

4.8.3 Optimized Wi-Fi Offloading Algorithm

This optimized algorithm is a new offloading scheme proposed by the author, and it's a cost-function-based algorithm that guarantees QoS. The main three factors taken into account in the cost function optimization are: 1) network load, 2) path loss, and 3) throughput. The cost function's main optimizing objective is to maximize the throughput and minimize the network load and path loss. Those three factors have to be taken with an equal weight for both tiers, either LTE or WLAN. For each user needs a connection, two cost functions will be calculated, one for LTE and the second for Wi-Fi. After calculating the cost per each, the minimum value will be chosen; hence the user is connected with the minimum cost. This is considered as the first stage in the Optimized Offloading algorithm, by optimizing the three factors at the same time. The second phase of this algorithm is to guarantee QoS to the connected user either to LTE or Wi-Fi, by achieving the minimum cost along with the required throughput for a specific service. The proposed type of services is (web browsing and voice), each has a different required throughput as mentioned in sections 4.4.4.2 and 4.4.4.3 respectively. The offloading is triggered if SNR_{WiFi} or SNR_{LTE} is greater than or equal to $SNR_{min.}$ The SNR_{min} is calculated according to the required throughput to achieve a specific service, either web browsing based on equation28, 29 or voice services based on equation 30, 31 for LTE or WLAN respectively. If the user is not in the range of any WLAN AP then the user u_i is directed to the cellular network (LTE). The optimization is done through calculating a cost function as shown in equation (38):

$$C = Min(\alpha 1 * \frac{load}{load_{ref}} + \alpha 2 * \frac{pathloss}{pathloss_{ref}} + \alpha 3 * \frac{1/Thr}{1/Thr_{ref}}) \qquad (38)$$

Knowing that: $\alpha 1 + \alpha 2 + \alpha 3 = 1$

The most significant contribution of this thesis is proposing a new Optimized Offloading algorithm aims to minimize two criteria, the load for each Wi-Fi AP and LTE BS, and the path loss for each. This will happen while maximizing the third criteria, which is the throughput for users connected either to Wi-Fi or LTE.

The second significant enhancement of the proposed Optimized Offloading Algorithm is connected users will be served with a guarantee of QoS based on the service type assumed in this work. The load in equation 38 can be expressed by the total number of connected users, while path loss is calculated based on equation 4, and throughput is calculated based on equation 33. All the three factors have to be divided by a reference value for each, $load_{ref}$, $pathloss_{ref}$ and Thr_{ref} Respectively to make them all unit-less. This reference value of each factor differs in LTE and Wi-Fi, by taking into account the possible range of load, path-loss and throughput either in Wi-Fi or LTE.

The Third added enhancement is incorporating the contending users, when trying to connect to Wi-Fi AP in calculating the throughput. Throughput calculation has been mentioned earlier in section 4.4.3.2, as equation 25 is used to calculate the basic Wi-Fi throughput. The Optimized Offloading algorithm calculates Wi-Fi throughput based on equation 39, which incorporate the load of connected users to a specific Wi-Fi AP based on CSMA/CA contention domain.

$$\mathrm{Wi\_Fi\_Thr} = \min\left(\mathrm{WiFi}_{\mathrm{Tmaxuser}}, WiFi_{\frac{\mathrm{BW}}{\mathrm{n}}} * \mathrm{Log}_2 \ (1 + \mathrm{SNR\_WiFi}\right) \qquad (39)$$

As $WiFi_{\mathrm{BW}/\mathrm{n}}$ Represents the Wi-Fi bandwidth over n, which is the number of contending users in CSMA/CA contention domain for the AP.

Algorithm 4 Optimized Wi-Fi Offloading Algorithm

```
Input: U, AP, RB;
Output: CU, BU;
Set SNR_min   // Based on required service throughput(web browsing-Voice) QoS
Set Load_max // for each AP this regulates the max number of users connected
For j ← 1 to size |AP|       // size |AP| = S
    Distance  ←  Distance (u_i, ap_j)
If  Distance (u_i, ap_j) <= ap_j_range
     ap_i ← ap_j   // to check if  u_i is in the range of any ap_j otherwise connect toLTE
End
RB_counter← RB_counter-1
Cost_wifi ← Compute Cost Function (u_i, ap_i)
Cost_LTE ← Compute Cost Function (u_i, BS)
Min_Cost ← Min (Cost_wifi, Cost_LTE )
If  Min_Cost ← Cost_wifi
    Else If Load(Best_ap_i) < Load_max &&  SNR_wifi <= SNR_min
         CU_wifi ← CU_wifi + u_i
    Else
          BU ← BU + u_i
  End
 If  Min_Cost ← Cost_LTE
    Else SNR_LTE <= SNR_min
          CU_LTE ← CU_LTE + u_i
Else
          BU ← BU + u_i
End
      CU ← CU_wifi + CU_LTE
Return CU , BU;
```

4.9 Performance Metrics

In this thesis a performance evaluation is conducted for the two offloading algorithms from the literature; 1) Wi-Fi if coverage, 2) Fixed SNR threshold, compared with the proposed Optimized Wi-Fi Offloading algorithm. The LTE standard case is evaluated as well with the same performance metrics.

The performance is evaluated with three performance metrics in the down link case:

1) Number of connected users as in equation 40

$$\sum Connected\ users\ (CU)_{LTE+Wi-Fi} \quad (40)$$

This implies the number of successfully connected users, denoted as CU, either they are connected to LTE denoted as CU_LTE or connected to Wi-Fi denoted as CU_wifi.

2) Blocking ratio

This calculates the ratio of blocked users BU to all users U in the simulation scenario as in equation 41.

$$Blocking\ ratio = (blocked\ UEs\ (BU)/total\ UEs\ (U)) * 100 \quad (41)$$

3) Network throughput

$$Total\ Throughput = \sum Thr\ for\ all\ connected\ users\ (CU) \quad (42)$$

Network throughput expresses the total effective throughput of the network for all connected users as in equation 42. In the down link case throughput may vary due to the fixed power transmission, therefore average throughput is computed.

Chapter 5

Experimental Results

5.1 Introduction

In this chapter, an evaluation of the performance of the three offloading algorithms is presented along with the standard case of LTE eNodeB case. The second section will give the basic setup for the simulation study. The third section presents further assumptions to be taken into account. The comparative results between the three offloading algorithm schemes along with the basic LTE scenario presented in the fourth section with different type of service, with a proper discussion after the result is presented.

5.2 Simulation Setup

A total of 100 RBs are used in a single sub-frame, and the scheduling requirement will be fixed to 1 RB per user in the LTE case. For the Wi-Fi APs they were deployed in the hexagon area of LTE BS in fixed locations. The channel assignment for the APs is assumed to be a non – overlapping channel case, which they are 1, 6, and 11 respectively. The LTE eNodeB centered in the middle of the cell with coverage of 100 meters as have been clarified in site planning section

4.2, which gives a total area of 31,400 m^2. The Wi-Fi APs radius is around 20m per each, based on section 4.5. LTE is assumed to be an FDD system, with a pair of 20 MHz band. Different densifications of users are deployed and tested with each different simulation scenario for LTE and offloading algorithms. The maximum density user is assumed 1 m^2, which yields 31,400 total number of users in the whole area. Having a 10% of active users implies having a 3140 total users at a given time frame. The simulation will test a single sub-frame duration which consists of a maximum of approximated 1000 users accessing resources based on round-robin scheduling algorithm. All simulations are done using MATLAB, and all provided results are the averages for 100 iterations for each simulated scheme. Table 13 lists the main parameters of the simulation.

Table 13: Parameters Used in Simulation

Parameter	LTE	Wi-Fi	Parameter	LTE	Wi-Fi
Cell radius	100 m	20 m	**Position of BS & APs Position (x,y)**	(0,0)	x_wifi=[-50,50,-50,50,0,0,-50,50,0] y_wifi=[50,50,-50,-50,-50,50,0,0,0];
Base Frequency	2 GHz	2.4GHz	**Path loss exponent**	4	4
Effective Bandwidth	18 MHz	20MHz	**Noise**	-121 dBm	-130.9dBm
Required Throughput (R)	240Kbps web browsing 15 Kbps VoIP	240Kbps web browsing 8 Kbps VoIP	**Duplexing**	FDD	CSMA/CA
No. of Resource Blocks	100	1,6,11 Non-overlapping channels	**Modulating scheme**	64 QAM	64 QAM
Number of users	200,400,600, 800,1000	200,400,600, 800,1000	**BS, AP Ptx**	21 dBm	23dBm
Path loss exponent	4	4	**Max-Throughput**	300 Mbps	100 Mbps

5.3 Simulation Assumptions

Moreover, below are some assumptions and considerations:

- The locations of user nodes are randomly distributed in the cell area.
- The BS can gather information about users.
- Users have limited movement due to density, no mobility is assumed in this work.
- Simulation is done in 1 ms in time domain (single sub-frame) acquiring 1/10 of all active users.
- The total number of available RBs per TTI (sub-frame) is equal to 100 RBs.
- The Wi-Fi APs deployment is done manually in the system in predefined fixed locations.
- Wi-Fi Access points are assumed to be open access for all UEs.
- Wi-Fi IEEE 802.11n Maximum throughput with 20 MHz is equal to 600 Mbps, and after taking off the Mac overhead it reaches 100 Mbps.
- Wi-Fi IEEE 802.11n uses the MIMO with 4*4.
- Wi-Fi IEEE 802.11n is assumed to use normal transmission power with 23 dB to as it’s the legal power to most of the available channels.
- All users are contending to have access to the Wi-Fi AP channel through CSMA/CA contention based, as each user will gain the full capacity of the channel if he gain access to it for a period of time.
- LTE and Wi-Fi AP both are controlled by the same operator

5.4 Single Cell Scenario Results and Discussion

5.4.1 Optimized Wi-Fi Offloading Algorithm Validation

The research aims to evaluate the performance of incorporating Wi-Fi Access Points along with LTE network. The objective is to enhance the performance in terms of network capacity and reduce the number of outage users. For this reason the author contribution is proposing a new Optimized Wi-Fi offloading algorithm. The optimization is done through a cost function to take three criteria into account at the same time with equal weight. We validated the system through the three performance metrics mentioned in section 4.9. The new Optimized offloading algorithm has proven to function with all the three metrics. A simulation is done with different number of users from 200 to 1000 UEs considering a high density areas. Optimized Wi-Fi offloading algorithm as in Figure 36 has proved to significantly increase the number of CU with the growing number of users. In Figure 37 Optimized Wi-Fi Offloading was tested with the blocking ratio metric, and its increasing with a logarithmic scale. The growth of blocking percentage happens with nonlinear fashion with the growing number of users. However, this blocking ratio seems to be stable at the 800 users point. This might indicate Optimized Offloading could function better with the number of users as the blocking ratio will not increase much afterwards. Network throughput appears to enhance the overall network throughput with a considerable amount as in Figure 38. This validation proves that the new Optimized offloading algorithm is worth to be considered in enhancing the network capacity in terms of connected users or network throughput for high density areas.

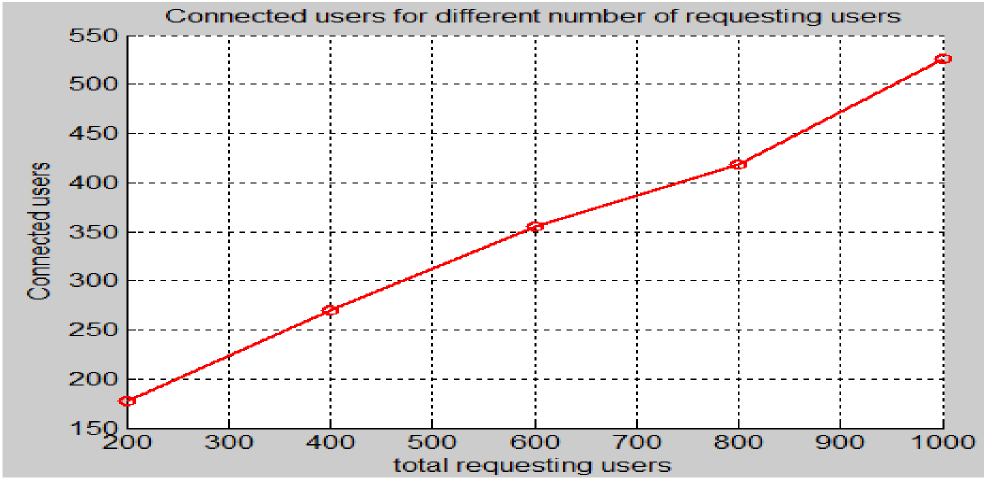

Figure 36: No. of Connected UEs vs. Total No. of UE

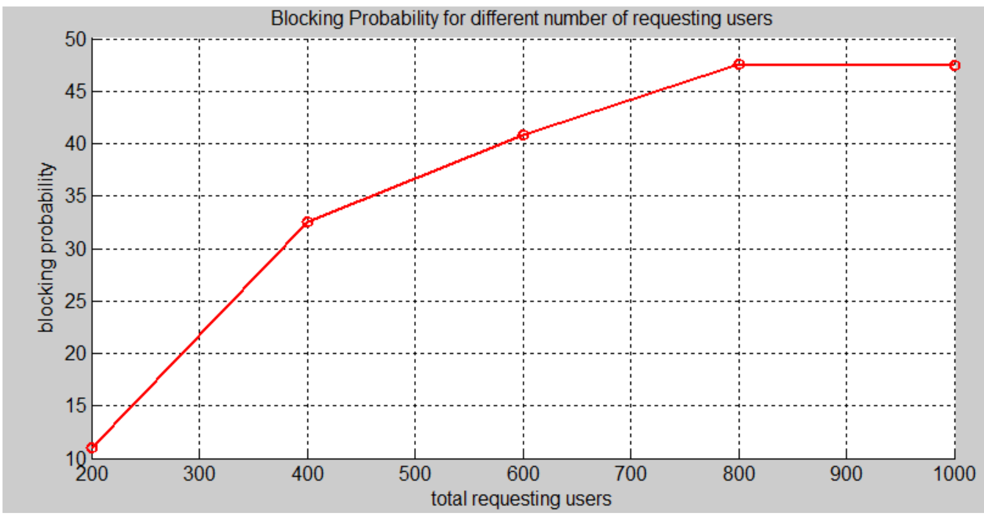

Figure 37: Blocking ratio vs. Total No. of UE

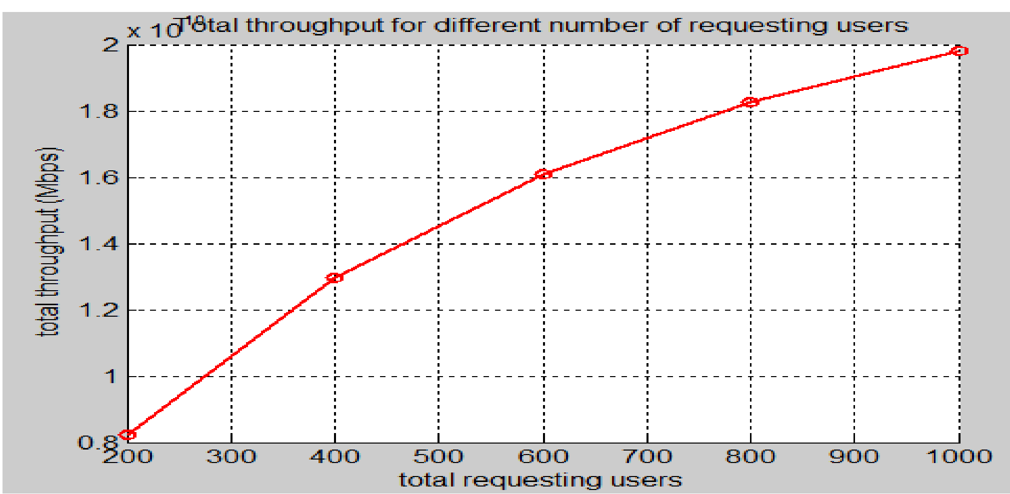

Figure 38: Total Network Throughput vs. Total No. of UE

5.4.2 Performance Evaluation for all Schemes with Web Browsing Service

The simulation is performed for different numbers of users generated randomly inside the LTE single cell in a uniform fashion. The number of users tested ranges from 200 to 1000 users with a step value equal to 200. The users are assumed to request for a web browsing service, with a 240KBps required throughput. Figure 39 shows the simulation for the standard LTE case with no offloading deployed. With the given assumptions in this research, a maximum number of users reaches 100 even with a total of 1000 users within LTE cell. This due to having only 100 RBs can be allocated to users in one sub-frame with 1 ms duration. The number of connected users is changed when the offloading is conducted through WLAN APs.

Figures 40 through 42 shows the simulation scenario when offloading is performed with deployed APs. The created connections for 1000 UEs with each offloading algorithm: Wi-Fi if Coverage, Fixed SNR Threshold, and Optimized Wi-Fi Offloading is demonstrated in the previous figures respectively. The connected users based on any offloading algorithm are represented by green nodes, either connected to the LTE BS or Wi-Fi APs. Nodes with the red color represent blocked users. It’s clearly shown that the number of blocked users is decreased with the offloading, especially with the Optimized Wi-Fi offloading based on performance metrics. The enhancement of the number of connected users with Fixed SNR threshold is less than Wi-Fi if Coverage and Optimized Wi-Fi Offloading.

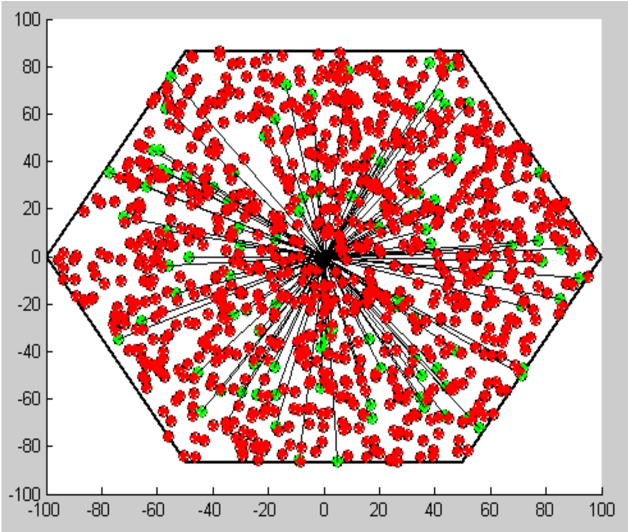

Figure 39: LTE standard Case with 1000UEs web browsing

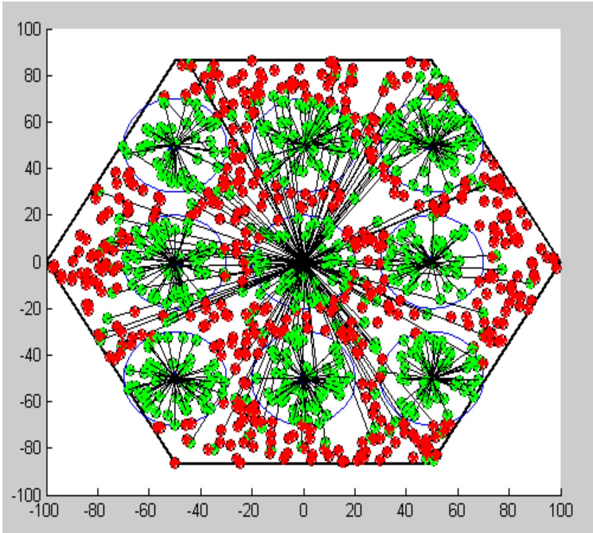

Figure 40: Wi-Fi if Coverage with 1000UEs web browsing

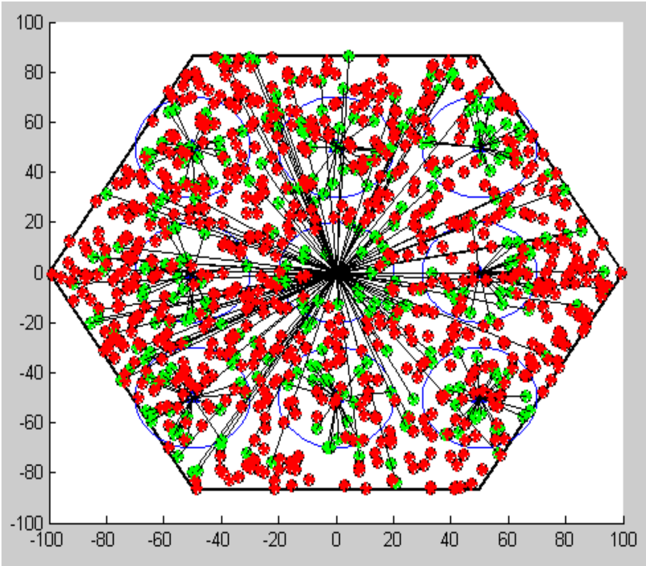

Figure 41: Fixed SNR Threshold with 1000 UEs web browsing

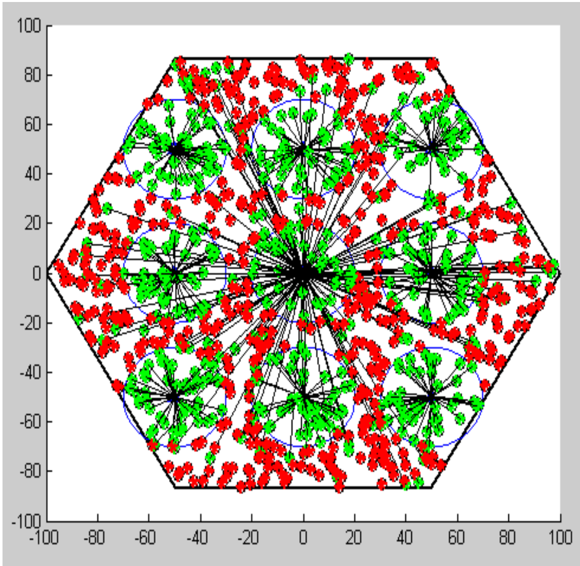

Figure 42: Optimized Offloading with 1000 UEs web browsing

After running the simulation for different numbers of users with 100 iterations, it is observed that offloading has a major effect in increasing the number of connected users compared with the standard LTE case. In Figure 43, the total number of connected users requesting a web browsing service is successfully enhanced with all three offloading algorithms compared to the LTE standard case. Fixed SNR Threshold performance in terms of the number of connected users CU is lower than Wi-Fi if Coverage and the proposed Optimized Wi-Fi Offloading algorithm, as they seem to have a similar performance.

Blocking probability is enhanced with the deployed Wi-Fi offloading scenarios compared to LTE standard case as shown in Figure 44. With 1000 users available in an LTE cell, depending only on LTE resource we may end with a blocking ratio of 90%. This is successfully enhanced through Wi-Fi offloading deployed with LTE, as the blocking ratio can drop to 46% with 1000 users available in the cell with the proposed Optimized Wi-Fi Offloading. Fixed SNR Threshold seems to have the worst performance in blocking users with 72%; however Wi-Fi if coverage performs better with a 49% blocking ratio with the web browsing service.

In terms of total network throughput, LTE standard can serve users with the available RBs; hence with the previous assumptions the total throughput is fixed even when the number of users is increased as shown in Figure 45. Optimized Wi-Fi Offloading seams outperform Wi-Fi if Coverage in increasing network throughput with the growing number of users. Fixed SNR has the worst performance in enhancing the network throughput as the load threshold and SNR threshold for each AP is increased with every user connected to the AP. This results in having a fixed number of connected users for each AP, and the blocking ratio will be increased for that.

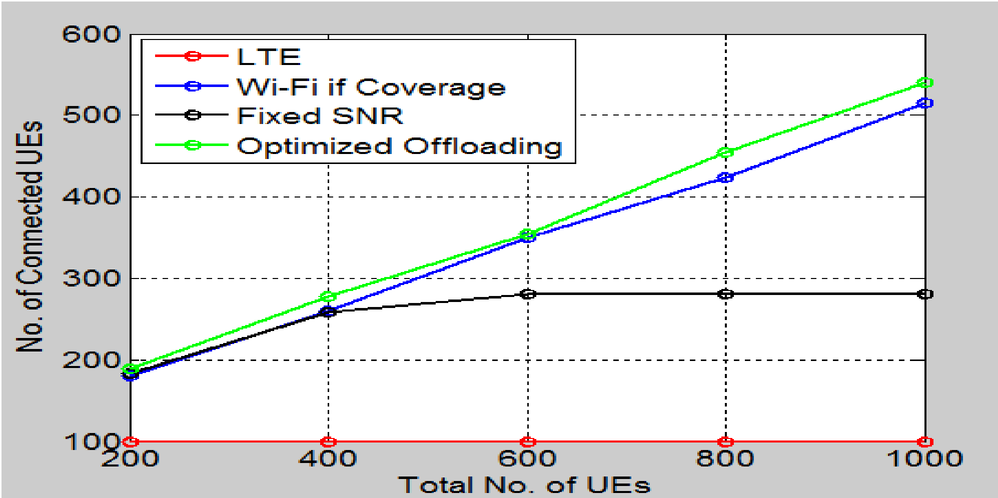

Figure 43: No. of Connected UEs vs. Total No. of UE

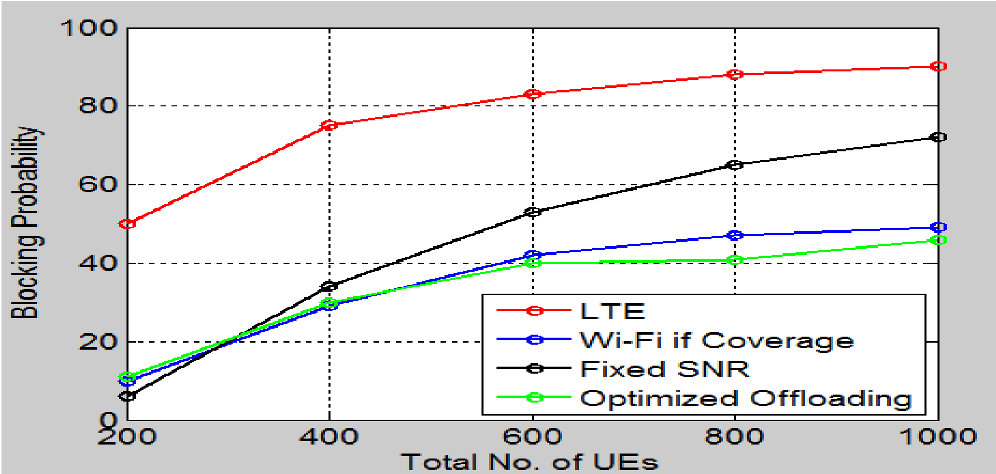

Figure 44: Blocking Probability vs. Total No. of UE

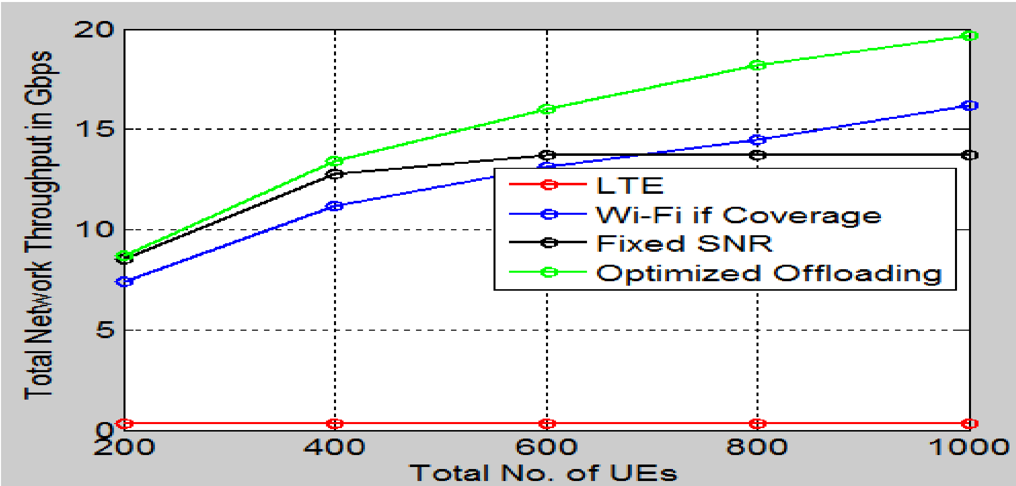

Figure 45: Total Network Throughput in Gbps vs. Total No. of UE

5.4.3 Performance Evaluation for all Schemes with VoIP Service

The simulation is performed for another type of service to be tested for different numbers of users generated uniformly in a random fashion inside the LTE cell. This time we are assuming 1000 users max and 200 users' minimum requesting a VoIP service. VoIP service has a different required throughput for being used over an LTE network or WLAN, for UEs to be served with a QoS. First, we tested the standard LTE case with no offloading deployed as shown in Figure 46. With the same assumption being conducted for LTE the maximum number of users being served cannot exceed 100 UEs in a sub frame. This due to having a total of 100 RBs in a single TTI (Single sub-frame) with 1 ms duration. As in the case of UEs requesting a web browsing service, it's clearly shown through simulation and performance metrics the dramatic improvements with WLAN APs being overlaid with LTE.

The performance of three offloading algorithms have been tested with UEs requesting a VoIP service: Wi-Fi if Coverage, Fixed SNR Threshold, and Optimized Wi-Fi Offloading is demonstrated in the previous Figures 47 through 49 respectively. Connected users are represented with green nodes, either being connected to LTE or Wi-Fi. Red needs are UEs being blocked from gaining a connection to any network. Each figure shows the performance comparisons of three offloading algorithms and LTE based on three performance metrics. First, the number of connected users, second, blocking ratio, third, network throughput. Capacity enhancement is tested in terms of number of successfully CU and total network throughput.

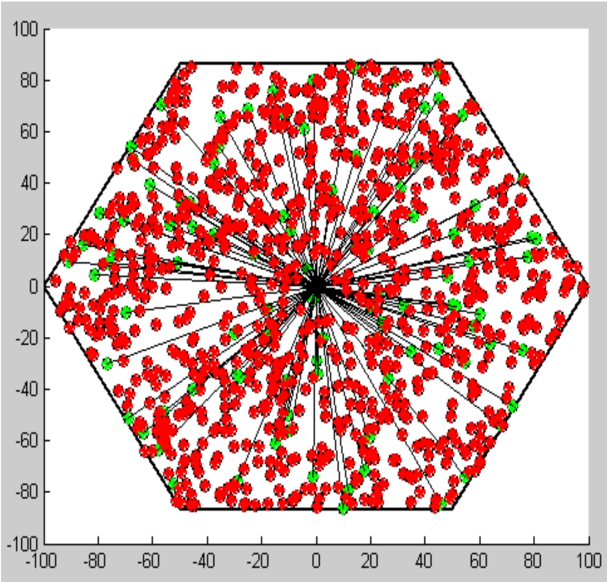

Figure 46: LTE standard Case with 1000UEs using VoIP

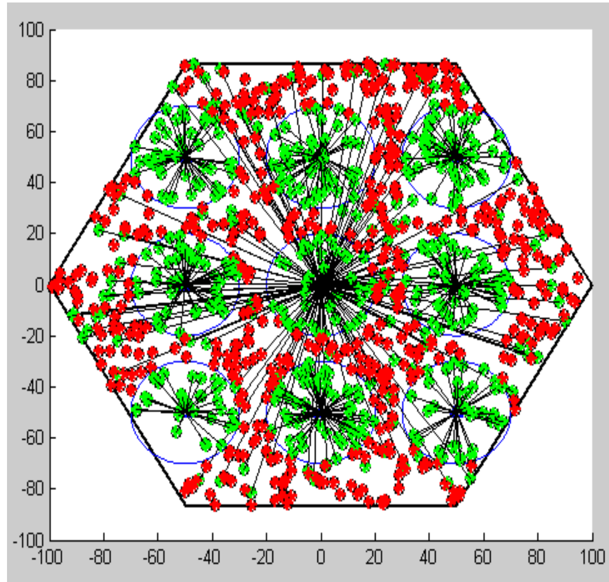

Figure 47: Wi-Fi if Coverage with 1000UEs using VoIP

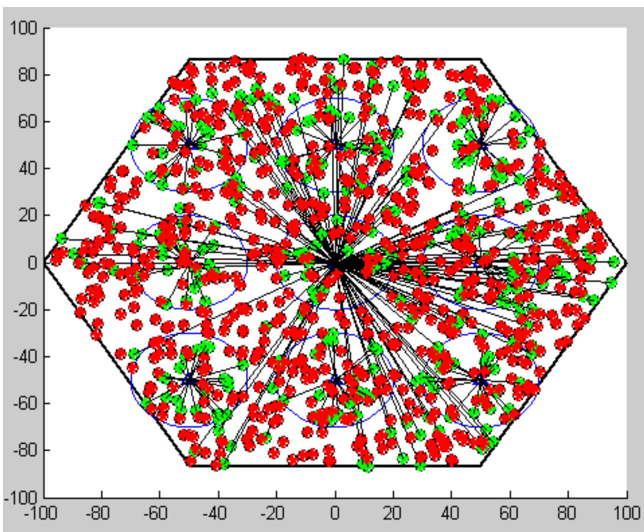

Figure 48: Fixed SNR Threshold with 1000 UEs using VoIP

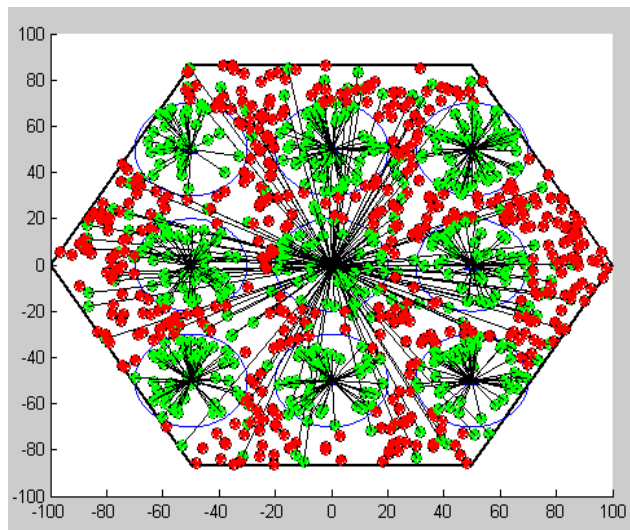

Figure 49: Optimized Offloading with 1000 UEs using VoIP

The author built a simulator for tow well known offloading algorithms from the literature as well as simulating an LTE macro cell to be compared with the proposed Optimized Wi-Fi offloading algorithm. The simulators run the experiments for 100 iterations to have the averages for more accurate results. The second simulation run conducted a different type of service with different requirements. UEs requesting a Voice service can be served with Wi-Fi if offloading incorporated with LTE in serving others. This might dramatically increase the number of connected users. Figure 50 shows that, total number of connected users requesting a VoIP service are successfully enhanced with all three offloading algorithms compared to the LTE standard case. It's clearly shown that LTE can serve a fixed number of users no matter how much is the growth in the number of requesting users. This is due to previous assumptions which implies having only 100 RBs can serve 100 UEs in a 1ms per TTI. The optimized Wi-Fi offloading algorithm seems to outperform both offloading algorithms from literature in terms of connecting users. Optimized offloading not only outperforms in enhancing the number of CU, it also guarantees the QoS for all CU to be served with their minimum requirement. Fixed SNR Threshold tend to be the worst in term of connecting more users.

Figure 51 shows that LTE standard case has the highest blocking ratio with high user densities, as it reaches a 90% blocking ratio with 1000 active users being in the cell. The reason behind this, LTE can serve only 100 users (CU_LTE) in one sub frame based on assumptions. The fixed SNR threshold has the second highest blocking ratio compared to the tow other offloading algorithm with almost 75 % blocking ratio with 1000 UEs in the cell. This is because the SNR threshold for each APs being deployed is incremented each time a user gain a successful connection to it. This will result in having a high threshold for APs, hence blocking users will increase as they don’t satisfy this requirement.

In Figure 52 shows the total network throughput for all connected users CU with Gbps. LTE seems to have a fixed throughput in the standard case with 0.33 Gbps for the whole network based on the successful number of CU_LTE. The throughput in LTE is bounded with its limits due to a fixed number of RBs allocated successfully to UEs requesting a voice service with a 15Kb throughput. Total network throughput is dramatically enhanced with incorporating Wi-Fi offloading along with LTE eNodeB, these appear with all three offloading algorithms compared with standard LTE case.

A fixed SNR threshold algorithm with the growing number of users it enhances the network throughput for a certain level, then throughput is fixed even with the increasing number of users. This is due to limits for this algorithm in serving a specific amount of users per AP, as been clarified in section 4.8.2. Wi-Fi if coverage and Optimized Offloading algorithm seem to have a major effect on enhancing the throughput capacity, but yet Optimized outperforms Wi-Fi if coverage and Fixed SNR threshold as well. The proposed algorithm achieves this with guarantees of QoS for both successful connected users CU_LTE and CU_wifi.

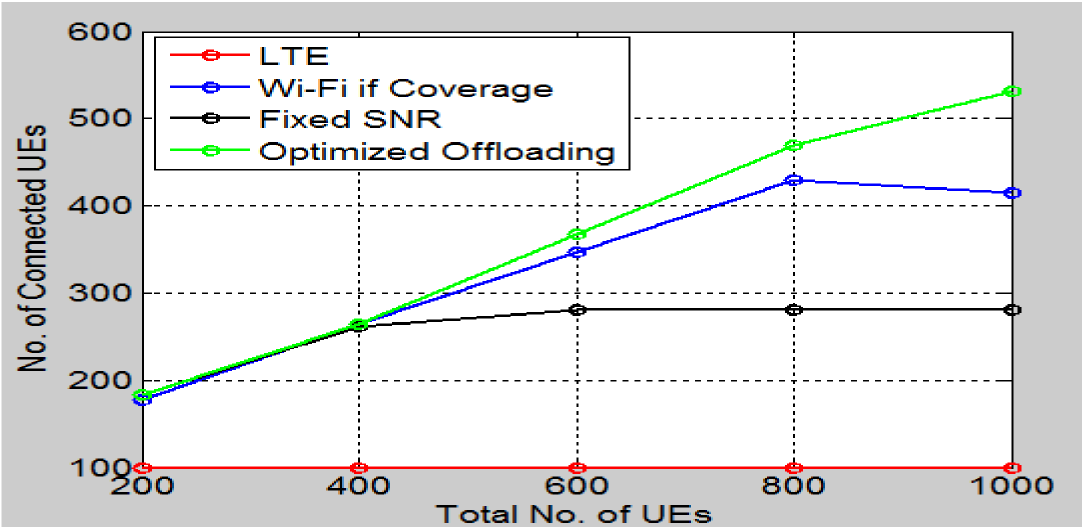

Figure 50: No. of Connected UEs vs. Total No. of UE for VoIP Service

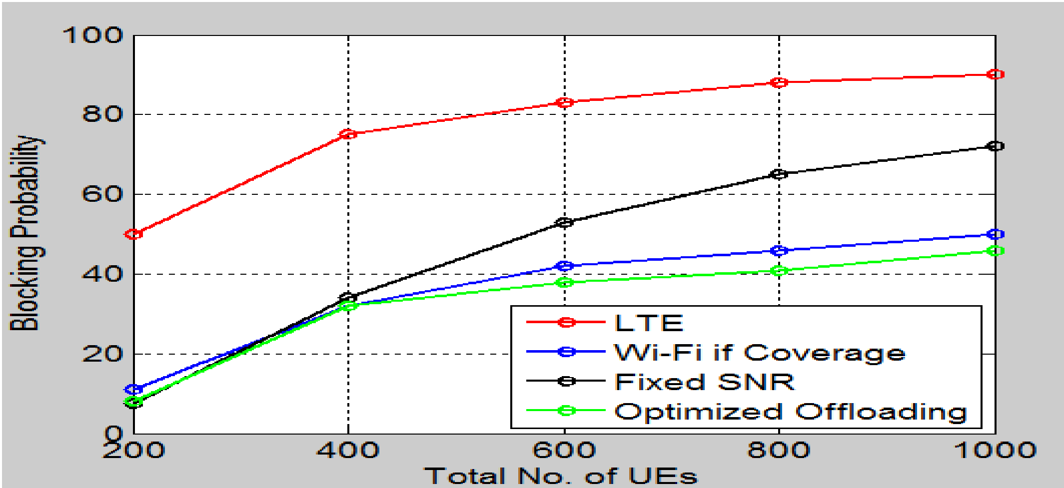

Figure 51: Blocking Probability vs. Total No. of UE for VoIP Service

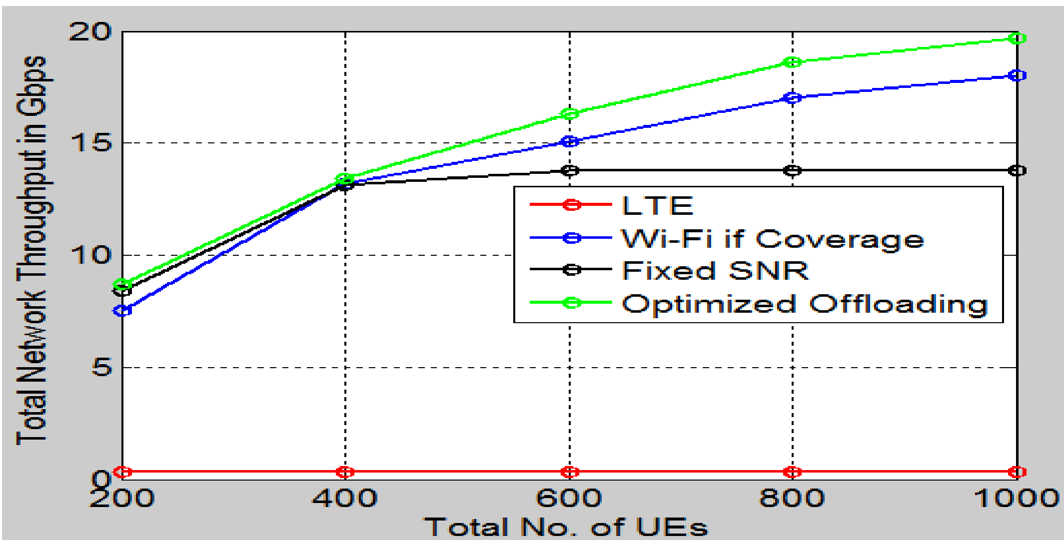

Figure 52: Total Network Throughput vs. Total No. of UE for VoIP Service

Chapter 6

Conclusion and Future Works

6.1 Thesis Summary

This Thesis investigates at the possible offloading schemes for a Macro-cell user to switch to a Wi-Fi access point in a cellular network with the objective of increasing the capacity for the overall system. The author overviews at the beginning the state of art in LTE field and Wi-Fi characteristics along with the newest trends in small cell formation. The first significant contribution of this research work, the author has introduced a novel classification of energy efficient Het-Nets categories along with the possible offloading approaches in each category.

It is worth pointing out that, the existing surveys usually cover one type of Het-Nets. The main purpose of the author in surveying the literature review is to present a detailed view and exhaustive information for all new possible enhancement schemes for capacity and energy consumption problems, as the data growth increased. Most of the research paper covers the Single Rat category either with Pico-cells or Femto-cell. Unlike these works, this survey aims at giving an overview for both categories with a detailed description of the possible challenges and solutions in each, and that is the novelty aspect about this literature review "survey", which allows it to be a good reference for any reader interested in the basics of different types of Het-Net.

The Focus of this thesis is to find a suitable cell association method to assign users to the best tier. This will happen by choosing the most suitable base station/access point to the UE based on specific service requirements in order to balance the load among the different Het Net tiers. This can be done by taking into account suitable approaches to managing the network selection method, in order to gain the expected capacity enhancements. The second significant contribution of this research is developing a new offloading algorithm based on optimization cost function. This Optimized Wi-Fi offloading algorithm, not only optimize three important criteria in balancing the load, it can guarantee a QoS to the successfully connected user to any tire based on the type of service wanted. The two services have been assumed and tested with all offloading algorithms along with standard LTE case, web browsing and VoIP.

Capacity enhancement can be interpreted either with enhancing the total throughput of the network or by enhancing the number of successfully connected users. These two criteria have been set as the main performance metrics for evaluating the tow offloading algorithms from literature compared to the novel offloading algorithm proposed by the author, Optimized Wi-Fi offloading algorithm. The LTE standard case has been tested and compared to all of the three offloading algorithms as well. It is worth mentioned that the author modified the throughput calculations for the Wi-Fi by incorporating the load of the users connected to the APs contending with each other with CSMA/CA contention domain for the bandwidth used as mentioned in section 4.8.3.

6.2 Conclusion

This research adapted two offloading algorithms from the literature to compare their performance with the proposed offloading algorithm by the author, along with the standard LTE case. The three offloading algorithms tested in research work are: Wi-Fi if Coverage, Fixed SNR Threshold, and Optimized Wi-Fi Offloading. The first two algorithms do not guarantee a QoS to connected users for any type of service requested by a user. This is enhanced with the Optimized Offloading algorithm, as all connected users are served with the required QoS based on service type, which is assumed to be a web browsing and VoIP services. Results shows, that under a given assumption, deploying Wi-Fi offloading can successfully enhance the performance in terms of connected users, blocking ratio and total network throughput compared with the LTE standard case with any offloading algorithm.

Optimized Wi-Fi offloading algorithm outperform Fixed SNR threshold in all three performance metrics, while it has a close performance to Wi-Fi if Coverage. Optimized Offloading is better than Wi-Fi if coverage as it guarantees QoS to all connected users, and it enhances the overall system capacity by optimizing three criteria at the same time. Optimized Wi-Fi Offloading improves the network capacity by 431 % with VoIP and 440 % with web browsing services, in terms of connected users with QoS.

As a summary of all results for performance compassion reasons, Table 14, 15 will demonstrate all the enhancements based on the three performance metrics: 1) number of connected users, 2) blocking ratio, 3) network throughput. The comparison for each algorithm is with the LTE standard case at the maximum user density 1000 UEs, tested in the simulation performed in this study. This is presented for both type services being assumed for UEs, web browsing and VoIP services.

Table 14: Summery results compared to LTE with 1000 UEs for web browsing service

	Performance Metric	Wi-Fi if Coverage	Fixed SNR Threshold	Optimized Wi-Fi Offloading
Single LTE Cell DL **Web Browsing**	Connected UEs	415%	18 %	440 %
	Blocking Ratio	45.5 %	22.2 %	48.8 %
	Network Throughput	15.9 %	13.4 %	19.4 %

Table 15: Summery results compared to LTE with 1000 UEs for VoIP service

	Performance Metric	Wi-Fi if Coverage	Fixed SNR Threshold	Optimized Wi-Fi Offloading
Single LTE Cell DL **VoIP**	Connected UEs	315 %	180 %	431 %
	Blocking Ratio	44.4 %	20 %	48.8 %
	Network Throughput	17.7 %	13.5 %	19.4 %

Capacity enhancement achieved by increasing the number of connected users in the whole network. Network throughput could be the second indicator for capacity enhancement when it’s improved. Optimized Wi-Fi offloading algorithm proves to be a valuable chance for high user density areas in improving network capacity Table 15 and 14 shows that Optimized Offloading outperforms the other two algorithms enhancements based on the basic LTE standard case.

Table 16: Optimized offloading Capacity Enhancement comparisons

	Optimized Offloading Enhancmnet Web Browsing Service		**Optimized Offloading Enhancement VoIP Service**	
	Wi-Fi if Coverage	Fixed SNR Threshold	Wi-Fi if Coverage	Fixed SNR Threshold
Connected UEs	5 %	92 %	27.95 %	89.64 %
Network Throughput	21 %	43 %	9.44 %	42.75 %

Table 16 shows the significant capacity enhancement done by the Optimized offloading algorithm compared with the capacity enhancement achieved by offloading algorithms from the literature. Table 16 presents the enhancement percentage achieved by Optimized offloading over Wi-Fi if Coverage and Fixed SNR threshold, with web browsing and VoIP services. It is clearly shown from the results that Optimized algorithm enhance network capacity with a significant percentage for VoIP service more than Wi-Fi if Coverage and Fixed SNR threshold. Number of connected users are enhanced with a considerable amount of 89.64 % and 42.75 % in terms of network throughput. The Capacity enhancement in terms of connected UEs and throughput in web services for Optimized Wi-Fi Offloading algorithm is less than the percentage it can achieve with VoIP services compared to Wi-Fi if Coverage. This might indicate that Optimized Offloading could be a great solution to deal with congested areas requiring voice services.

6.3 Future Work

As an extension to this work, the performance of the given algorithms is to be tested using different Wi-Fi AP deployment Scenario. Moving on from testing single LTE cell overlaid with multi Wi-Fi APs, to Multi LTE cell scenario in the DL. This will need to apply a power control system to avoid interference between adjacent LTE Cells. RBs operating on the same frequency might cause interference to each other. This concept has been applied as in Figure 53, showing a Multi LTE Cell in the DL case. Connected users are shown in green color nodes, while red nodes are for blocking users from LTE connection. This scenario will be tested first with a none-overlapping scenario by taking LTE interference into account. Second, this scenario will be tested with partially overlapping channels.

The Multi LTE cell area, then will be considered, to apply a specific case study of Mina (City of Tent) during the Hajj. Tent locations and coverage will be modeled to have something near to Figure 54. Each tent will be assumed to be covered with one Wi-Fi AP, and different channel assignment would be tested. A comparison between the performances of the standard LTE case along with three offloading algorithms will be tested. Deploying different numbers of Wi-Fi APs in LTE cells will be investigated to find the optimum number of APs that enhance the capacity and overall network performance. This would be beneficial, especially in the case of considering co-channel interference between APs deployed. Different Wi-Fi offloading algorithms will be implemented to evaluate their performance compared to Optimized Wi-Fi Offloading scheme. Future work may investigate Software-defined networking (SDN), which is used to encompass several kinds of network technology together. This might be a good control panel for deciding when the offloading might occur.

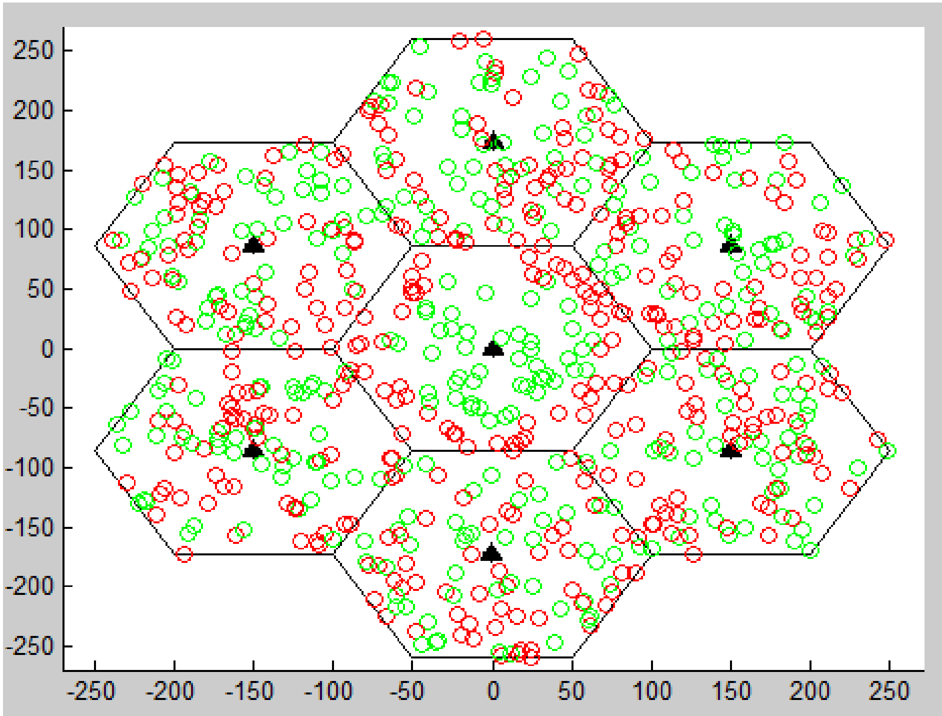

Figure 53: Multi LTE Cell in the DL case

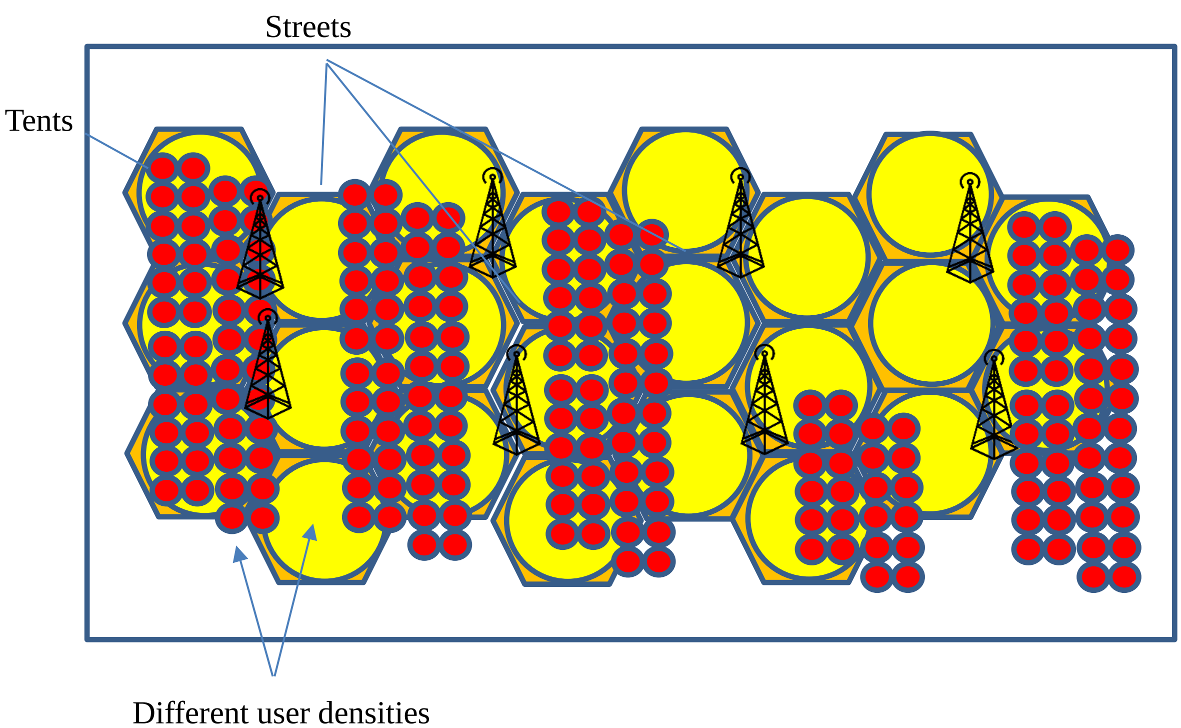

Figure 54: Case Study of Mina (City of Tent)

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