Brunel University London

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Department of Electronic and Computer Engineering
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Title:

Self-Organising Network Management for Heterogeneous LTE-Advanced Networks

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy (PhD) in Electronic and Computer Engineering

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Abstract

Since 2004, when the Long Term Evolution (LTE) was first proposed to be publicly available in the year 2009, a plethora of new characteristics, techniques and applications have been constantly enhancing it since its first release, over the past decade. As a result, the research aims for LTE-Advanced (LTE-A) have been released to create a ubiquitous and supportive network for mobile users. The incorporation of heterogeneous networks (HetNets) has been proposed as one of the main enhancements of LTE-A systems over the existing LTE releases, by proposing the deployment of small-cell applications, such as femtocells, to provide more coverage and quality of service (QoS) within the network, whilst also reducing capital expenditure. These principal advantages can be obtained at the cost of new challenges such as inter-cell interference, which occurs when different network applications share the same frequency channel in the network.

In this thesis, the main challenges of HetNets in LTE-A platform have been addressed and novel solutions are proposed by using self-organising network (SON) management approaches, which allows the cooperative cellular systems to observe, decide and amend their ongoing operation based on network conditions. The novel SON algorithms are modelled and simulated in OPNET modeler simulation software for the three processes of resource allocation, mobility management and interference coordination in multi-tier macro-femto networks. Different channel allocation methods based on cooperative transmission, frequency reuse and dynamic spectrum access are investigated and a novel SON sub-channel allocation method is proposed based on hybrid fractional frequency reuse (HFFR) scheme to provide dynamic resource allocation between macrocells and femtocells, while avoiding co-tier and cross-tier interference. Mobility management is also addressed as another important issue in HetNets, especially in hand-ins from macrocell to femtocell base stations. The existing research considers a limited number of methods for handover optimisation, such as signal strength and call admission control (CAC) to avoid unnecessary handovers, while our novel SON handover management method implements a comprehensive algorithm that performs sensing process, as well as resource availability and user residence checks to initiate the handover process at the optimal time. In addition to this, the novel femto over macro priority (FoMP) check in this process also gives the femtocell target nodes priority over the congested macrocells in order to improve the QoS at both the network tiers. Inter-cell interference, as the key challenge of HetNets, is also investigated by research on the existing time-domain, frequency-domain and power control methods. A novel SON interference mitigation algorithm is proposed, which is based on enhanced inter-cell interference coordination (eICIC) with power control process. The 3-phase power control algorithm contains signal to interference plus noise ratio (SINR) measurements, channel quality indicator (CQI) mapping and transmission power amendments to avoid the occurrence of interference due to the effects of high transmission power.

The results of this research confirm that if heterogeneous systems are backed-up with SON management strategies, not only can improve the network capacity and QoS, but also the new network challenges such as inter-cell interference can also be mitigated in new releases of LTE-A network.

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Dedication

Dedicated to my Mother, Father and Fiancée.

Publications and Presentations

Publications

Journals

1. M. Behjati, J. P. Cosmas, R. Nilavalan, G. Araniti, and M. Condoluci, "Self-Organizing Comprehensive Handover Strategy for Multi-Tier Heterogeneous LTE-Advanced Networks," IET Journal of Science, Measurement and Technology, Special Issue on Green Wireless Internet Technology, vol. 8, no. 6, November 2014, pp. 441 – 451.

2. G. Araniti, M. Condoluci, A. Iera, A. Molinaro, J. Cosmas, and M. Behjati, "A Low-Complexity Resource Allocation Algorithm for Multicast Service Delivery in OFDMA Networks," IEEE Transactions on Broadcasting, vol. 60, no. 2, May 2014, pp. 358 – 369.

Conferences

1. M. Behjati, and J. Cosmas, "Self-Organizing Interference Coordination for Future LTE-Advanced Network QoS Improvements," IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Beijing, China, pp. 1 – 6, June 2014.

2. M. Behjati, and J. Cosmas, “Multi-Layer Cell Deployment Strategy for Self-Organizing LTE-Advanced Networks,” IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Cagliari, Italy, pp. 820 – 825, July 2013.

3. M. Behjati, J. Cosmas, and R. Nilavalan, “Hierarchical Self-Organizing Strategy in LTE-Advanced Networks,” 6th Annual Research Student Conference (ResCon’13), Brunel University, London, UK, pp. 16 – 17, June 2013.

4. M. Behjati, and J. Cosmas, "Self-Organizing Network Interference Coordination for Future LTE-Advanced Networks," IEEE International

Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), London, UK, pp. 1 – 5, June 2013.

5. M. Behjati, and J. Cosmas, “Cognitive Spectrum Allocation and Interference Mitigation in 4G LTE-Advanced Networks,” 5th Annual Research Student Conference (ResCon’12), Brunel University, London, UK, pp. E42 – E43, June 2012.

6. M. Behjati, S. R. Abdollahi, and H.S. Al-Raweshidy, “Photonic Sampled and Electronically Quantised Analogue to Digital Conversion in Access Networks,” IEEE International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT), Budapest, Hungary, pp. 1 – 6, October 2011.

N.B. More research papers have been submitted for publication, which are pending to be published.

Presentations

Poster Presentations

1. M. Behjati, and J. Cosmas, "Self-Organizing Interference Coordination for Future LTE-Advanced Network QoS Improvements," presented poster on IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), Beijing, China, June 2014.

2. M. Behjati, and J. Cosmas, "Self-Organizing Network Interference Coordination for Future LTE-Advanced Networks," presented poster on IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), London, UK, June 2013.

3. M. Behjati, and J. Cosmas, “Cognitive-based Spectrum Flexibility Enhancements in LTE-Advanced Networks (DAMAVAND),” presented poster on Graduate School Poster Competition, Brunel University, London, UK, March 2012.

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List of Abbreviations

Abbreviation	**Stands for**
ABS	Almost Blank Subframe
ACAE	Auto-Correlation based Advance Energy
ADSL	Asymmetric Digital Subscriber Line
AP	Access Point
ARP	Address Resolution Protocol
AS	Access Stratum
ASE	Area Spectral Efficiency
BLER	Block Error Rate
BS	Base Station
BTS	Base Transceiver Station
CA	Carrier Aggregation
CAC	Call Admission Control
CAPEX	Capital Expenditure
CC	Component Carrier
CDMA	Code division multiple Access
CI	Confidence Interval
CLT	Central Limit Theorem
CoMP	Cooperative Multi-Point
CPU	Central Processing Unit
CQI	Channel Quality Indicator
CQIA	Channel Quality Indicator Adjust
CRS	Cell-Specific Reference Signal
CSG	Closed Subscriber Group
CT	Cooperative Transmission
DFT	Discrete Fourier Transform
DL	Downlink
DLA	Downlink Allocation
DSA	Dynamic Spectrum Allocation

DSCP	Differentiated Services Code Point
DSL	Digital Subscriber Line
DVB	Digital Video Broadcasting
DwPTS	Downlink Pilot Time Slot
D2D	Device-to-Device
EDGE	Enhanced Data for Global Evolution
EESM	Effective Exponential SNR Mapping
EF	Expedited Forwarding
E-GPRS	Enhanced GPRS
eICIC	Enhanced Inter-Cell Interference Coordination
eNB	Evolved Node-B
eNodeB	Evolved Node-B
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EV-DO	Evolution-Data Optimised
FAP	Femtocell Access Point
FDCH	Femto Data Channel
FDD	Frequency Division Duplex
FFR	Fractional Frequency Reuse
FMC	Fixed Mobile Convergence
FoMP	Femto over Macro Priority
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GSM EFR	Global System for Mobile Coms. Enhanced Full Rate
GTP	GPRS Tunnelling Protocol
GW	Gateway
HA	Handover Acknowledgement
HARQ	Hybrid Automatic Repeat Request
HCM	Handover Command
HCN	Handover Confirm

HDCT	Hybrid Division Cooperative Transmission
HeNB	Home Evolved Node-B
HeNodeB	Home Evolved Node-B
HetNet	Heterogeneous Network
HFFR	Hybrid Fractional Frequency Reuse
HHT	Handover Hysteresis Threshold
HII	High Interference Indicator
HO	Handover
HOA	Handover Request Acknowledgement
HOR	Handover Request
HSCSD	High-Speed Circuit-Switched Data
HSPA	High Speed Packet Access
HSS	Home Subscriber Service
HTTP	Hypertext Transfer Protocol
ICIC	Inter-Cell Interference Coordination
iDEN	Integrated Digital Enhanced Network
IDFT	Inverse Discrete Fourier Transform
iMode	Idle Mode
IMT-Advanced	International Mobile Telecommunications-Advanced
IP	Internet Protocol
IS	Interim Standard
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MAC	Medium Access Control
MC	Measurement Control
MCS	Modulation and Coding Scheme
MDCH	Macro Data Channel
MeNodeB	Macro Evolved Node-B
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MNO	Mobile Network Operator

MPDU	MAC Protocol Data Unit
MR	Measurement Report
MS	Mobile Station
MU	Mobile User
MUE	Mobile User Equipment
M2M	Machine-to-Machine
NAS	Non-Access Stratum
NEM	Network Element Management
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OI	Overload Indicator
OLPC	Open Loop Power Control
OPEX	Operational Expenditure
OSFFR	Optimal Static Fractional Frequency Reuse
OSG	Open Subscriber Group
OSI	Open System Interconnection
PAPR	Peak to Average Power Ratio
PCC	Physical Channel Complete
PCID	Physical Cell Identity
PCR	Physical Channel Reconfiguration
PCRF	Policy and Charging Rules Function
PD	Packet Data
PDC	Personal Digital Cellular
PDCP	Packet Data Convergence Protocol
PDF	Packet Data Forwarding
PDN-GW	Packet Data Network Gateway
PDU	Protocol Data Unit
PPP	Point-to-Point Protocol
PRB	Physical Resource Block
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Resource Availability

RAN	Radio Access Network
RANAP	Radio Access Network Application Part
RANAP RC	RANAP Relocation Complete
RANAP RD	RANAP Relocation Detect
RB	Resource Block
RF	Radio Frequency
RN	Relay Node
RNC	Radio Network Controller
RNTP	Relative Narrowband Transmit Power
RoF	Radio over Fibre
RS	Relay Station
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
Rx	Receiver
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCTP	Stream Control Transmission Protocol
SDU	Service Data Unit
S-GW	Serving Gateway
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SON	Self-Organising Network
SONET	Synchronous Optical Networking
ST	Status Transfer
TCP	Transmission Control Protocol
TDA	Transmission Data Attribute
TDD	Time Domain Duplex
TP	Transmission Power
TPAL	Transport Protocol Adaptation Layer
Tx	Transmitter
UDP	User Datagram Protocol
UE	User Equipment
UE CR	UE Context Release

UL	Uplink
ULA	Uplink Allocation
ULPC	Uplink Power Control
UMTS	Universal Mobile Telecommunications System
U-Plane UA	User Plane Update Acknowledgement
U-Plane UR	User Plane Update Request
UpPTS	Uplink Pilot Time Slot
VoIP	Voice over Internet Protocol
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
1G	First Generation
3D	Three Dimensional
3GPP	Third Generation Partnership Project
4G	Fourth Generation

List of Symbols

Symbol	Description	Unit
c	Ratio of handover regions	
G	Antenna gain	Decibel-isotropic (dBi)
g_k	Total available resource blocks	
H	Normalised channel gain	Decibel (dB)
L	Pathloss	Decibel (dB)
N	Thermal noise power	Decibel-milliwatt(dBm)
P_b	Noise power	Watt (w)
P_i	Interference power	Watt (w)
P_r	Received transmission power	Watt (w)
r	Distance between base st. and mobile user	Meter (m)
RSRP_k	Ref. signal received power from the k^{th} cell	Watt (w)
s	Standard deviation	Same unit as the data
$SE_{\bar{x}}$	Standard error	Same unit as the data
$SINR$	Signal to interference plus noise ratio	Decibel (dB)
T	Traffic intensity	
$\bar{x}$	Mean value of x	Same unit as x
α	Handover rate	
β_i	Resource blocks consumed by the i^{th} user	
μ	Handover service rate	
λ	Handover session rate	
ϕ	Total number of resource blocks	

Chapter 1 Introduction

1.1. Cellular Network Evolution

A cellular network is defined as a wireless network which includes terrain areas called as cells, in which each individual cell is served by at least one fixed transceiver, called as base station (BS). To guarantee the bandwidth, as well as avoiding interference between the cells, each cell normally uses a different set of frequencies than the neighbouring cells. A cellular network provides a wide area coverage for different sorts of fixed and portable transceivers, e.g. mobile phones, tablets, etc. over a pre-defined geographic area supported by network providers. The concept of cellular network follows gradual trend, defined by its generation evolution from the first generation (1G) towards the current 4G and beyond, as shown in Figure 1-1. As the trend shows, the main spotlight of newly proposed 4G networks has been towards its additional network functionalities and capabilities over the existing 3G networks, by taking advantages of system compatibility.

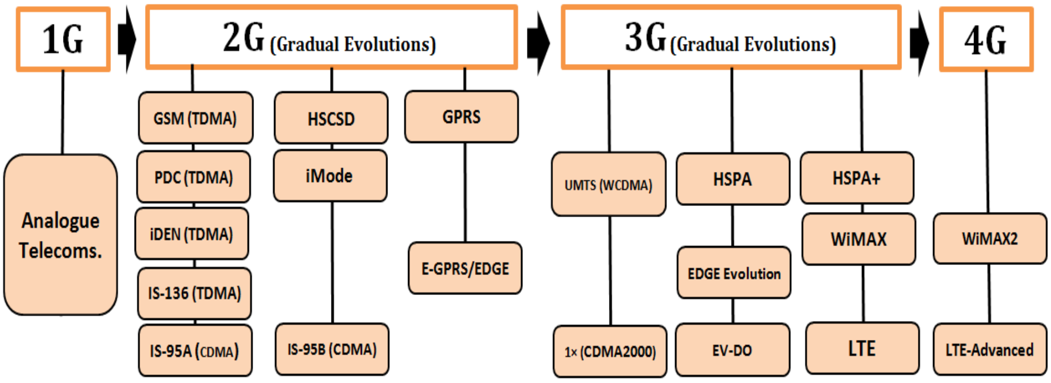


Figure 1-1: Cellular network evolutions

LTE-Advanced (LTE-A) is proposed as the continued improvement of Long Term Evolution (LTE) telecommunication standard, which is considered as the real 4G evolution step. LTE-A was recently standardised in 3GPP Release 10 and approved by International Telecommunication Union (ITU) and International

Mobile Telecommunications-Advanced (IMT-Advanced) to be implemented over the existing LTE systems [1-3].

The significant prospect of this evolution is to approach to higher data rates specifically in congested areas, whilst facing the least possible network interference. For such telecommunication standards and networks, the main expectations could be summarised by three constraints: data rate, delay and capacity. 3GPP defines the increased peak data rate for LTE-Advanced to be 3Gbps in downlink and 1.5Gbps in uplink, by adopting multiple input multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM) techniques. Delay could also be assumed as a principal target to reduce the latency for a packet sent from a server to clients. With growing demands, the resultant capacity shortage would degrade the quality of service (QoS) for the overall network, and therefore appropriate methods are essential to measure and manage spectral efficiency requirements. Interference is a critical factor which affects the entire key attributes by degrading network performances and expectations.

On the other hand, self-organisation network (SON) has been recently investigated as a reconfigurable networking technology to improve the spectrum efficiency for the wireless access technologies, such as LTE and Radio over Fibre (RoF). A self-organising strategy is basically known for its internal coordination and interactions among its elements within different stages, which could promote self-awareness, self-configuration and demand-base-architecture within an entire network. Therefore, the networks would be capable of adapting themselves to obtain more efficient communication, while taking into account the end-to-end goals. The currently available unlicensed spectrum is reaching its limits, while there are lots of demands for the wireless access and applications. Hence, the intelligent use of spectrum is urgently required to avoid the latency and difficulties in broadband communications, caused by the frequency interference through the networks. Critical enhancements are necessary to be applied on the existing LTE networks, which could improve the cellular interference during the spectrum usage. Therefore, novel approaches could fulfil network requirements by use of self-organising transceivers, and provide the anticipated capacity and quality of service for network subscribers [1].

1.2. HetNet Enhancements towards LTE-A

The existing LTE systems propose a number of techniques to raise network satisfaction compared to traditional 3G systems. Spectrum sensing and dynamic spectrum allocation (DSA) technologies are being proposed to exploit advantageous techniques, such as carrier aggregation, multi-antenna transmission, relaying and co-operative multi-point (CoMP) transmission (Figure 1-2). Furthermore, interference mitigation methods are considered to deliver the best available spectrum with the lowest inter-cell interference. The existing cognitive strategies also propose the use of small cell applications coupled with the conventional macrocells, as the secondary and primary systems respectively, within the existing LTE platforms [2,4,5].

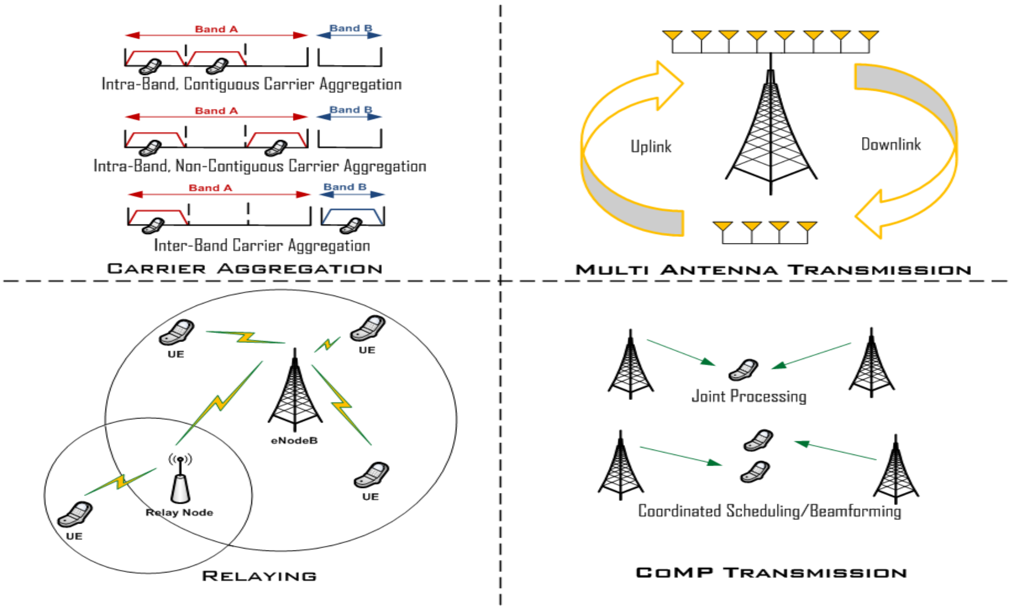


Figure 1-2: Existing LTE supportive techniques over the mobile networks

The conventional cellular network deployment is typically launched with homogeneous architecture, by using of macro-centric process, in which the base stations are operating in a planned layout to serve the user terminals. In this architecture, all the base stations have similar transmit power levels, receiver noise floors, antenna coverage patterns and also similar backhaul connectivity to the data network. Furthermore, all base stations in homogenous networks offer unrestricted access to the user terminals within the network, and serve roughly the equal number of users. Since the traffic requests on the network are growing and the radio frequency (RF) environment is being changed, additional sub-carriers are required to overcome the capacity and link resource limitations [1,6].

On the other hand, the term "Network Heterogeneity" is used in cellular networks to refer to an advanced level of the current network platform, by use of different transmission technologies, as well as spectrum allocation techniques. Hence, a heterogeneous network (HetNet) becomes an indisputable improvement in LTE-A, compared to the existing LTE with its proposed functionalities and methods [7,8]. Figure 1-3 shows a comprehensive HetNet architecture. The system includes macrocell as the main backbone of the network and low-power base stations, i.e. pico, femto and relay nodes, which are being deployed to eradicate the coverage holes in the macro-only systems and improve capacity in hot-spots.

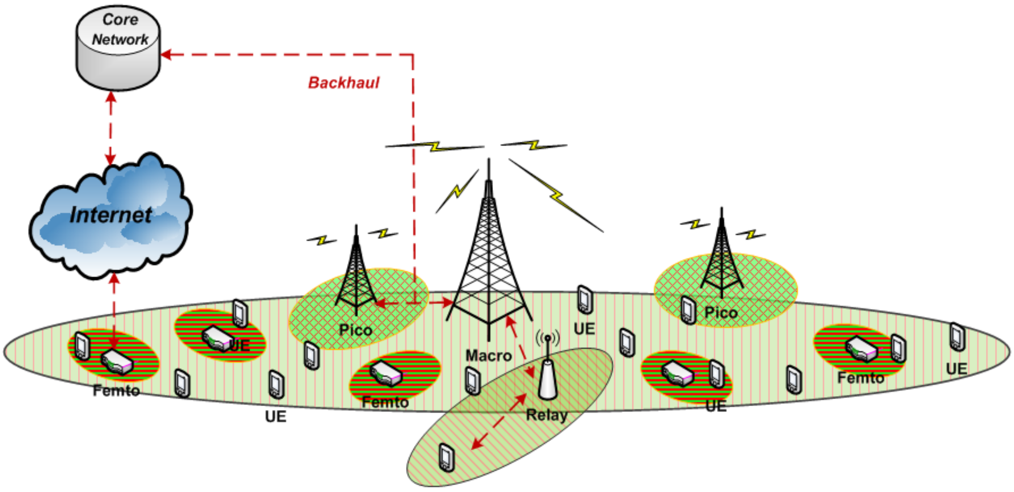


Figure 1-3: HetNet architecture in LTE-A networks

An important enhancement introduced in LTE-Advanced is the improvement of spectral efficiency per unit area, by deploying a combination of macro, pico, femto and relay base stations through a distinctive HetNet construction. HetNet architecture enables flexible and low-cost deployments and provides the broadband access for the users within the network platform. The important consideration in this architecture is the management and control of interference to deliver the benefits of such networks.

The enhanced channel estimation and allocation schemes will result in smaller number of packet drops within the designated network, which results in higher QoS on the network. Furthermore, reduction in packet drops could also result in obtaining higher data traffic throughput, as well as higher signal to noise ratio (SNR) in transmission, which aims to obtain a better quality of received signal within the designated network [1,2]. For indoor applications, the macro base stations need to boost their transmission power to cover their indoor users, which may result in a serious inter-cell interference and degradation in network performance. Implementing femtocells -as a good instance for indoor applications- to cover the indoor spaces provides quality cellular services by increasing the network capacity. This idea also allows the operators to offload significant amounts of traffic away from the existing macrocell network thereby satisfying more macrocell users. According to the recent research in network financial issues, it has been estimated that the traffic offload from the central macrocell to femtocells can decrease the costs for the network operators by up to 70% [9].

1.3. Self-Organising Attitudes

Self-Organising Network (SON) methodologies [10-12] are introduced to reduce the operational expenditure for the network operators. As a good example, the interference coordination is an important concept of SON. The inter-cell interference is one of the main challenges in orthogonal frequency division multiple access (OFDMA)-based networks, especially in downlink, where the broadband services exist. In this context, the coordinated usage of the network resources in related cells can be an effective SON approach to maximise the efficiency of the bandwidth. The intra-cell orthogonality between the users in both LTE uplink and downlink leads to only consider the inter-cell interference as the main interference source in this network, which could also affect the frequency reuse at the cell boundaries [13]. Figure 1-4 illustrates some SON functionalities over the HetNets, such as bandwidth allocation and handover optimisations, power saving, self-configuration, etc. The main aim of SON strategies through the HetNet deployment is the reduction of human-dependent functionalities of wireless networks and actualizing the machine-based network concepts, such as machine-to-machine (M2M) communications, device-to-device (D2D) communication, etc.

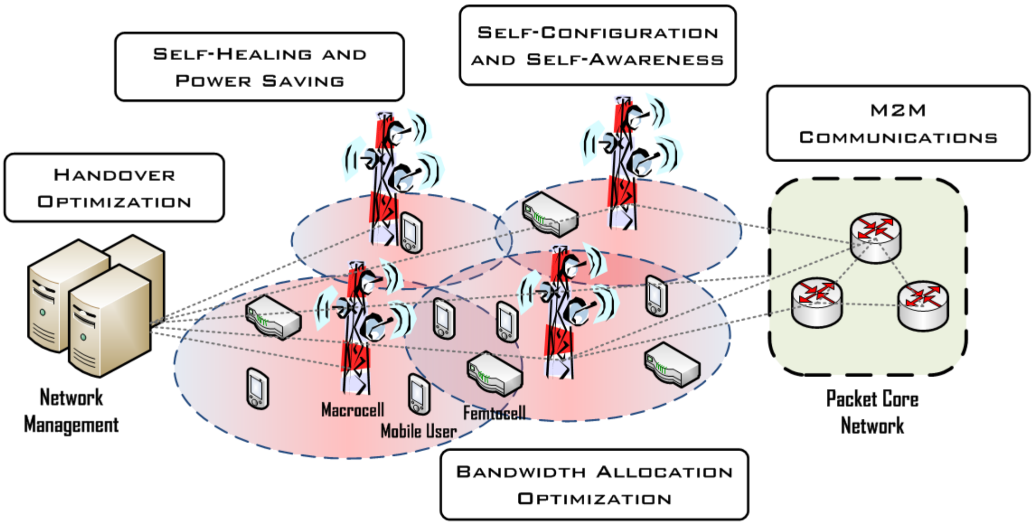


Figure 1-4: SON functionalities over HetNet deployment

In this regards, femtocells are being considered as low-power, user-deployed base stations, which provide high-quality cellular service for indoor environments by operating in licensed spectrum. The trade-off between the improvement of macrocell users' throughput and the degradation of femtocell user's throughput is the key design aspect of this scheme. As a consequence of the above mentioned SON functions, advanced interference management schemes are considered to be designed within the femtocells, to avoid either the interference among femtocells, or between a femto and a macro, known as co-channel interference. As a result, HetNet deployments are required to be supported by SON techniques to alleviate the network QoS degradations, e.g. interference [14-16].

1.4. Declaration of Challenges

When researchers and network planners consider about self-organisation solution for heterogeneous wireless networks, the foremost attention goes towards the sub-network cooperation. Furthermore, in case of collaboration between femtocell (as a recent indoor application) and the existing macrocell platform, interference could be a result if we do not carefully consider network plans for resource organisation and channel allocation, mobility management and handover, and power consumption issues.

From a general point of view, LTE-A is currently being proposed as a further step to LTE compatible system as a real 4G cellular standard on the cellular networks evolution trend. Alongside the increasing demand in mobile networks, the customers' satisfaction with a ubiquitous heterogeneous network is going to be the main challenge for the network operators. Hence, planning a multi-layer network with diverse range of base stations seems to be an appropriate solution for this deficiency in the first instance [1,14]. However, the cellular network evolution requires revised strategies to keep the network's quality of service, while trying to satisfy the increasing demands of subscribers. SON policy is therefore introduced and planned as a fitting approach to reduce the network hardware (e.g. supportive macro base stations, etc.), transmission complexity, implementation costs, etc., and to improve the quality of reception and transmission within LTE-A.

The interference mitigation plan is necessary to having an optimised bandwidth allocation for various classes of the network users, specifically when the bandwidth is shared between the network layers. Therefore, applying the SON strategy as a part of LTE-A new releases is a novel strategy to improve the network satisfaction by increasing network capacity, while mitigating the inter-cell interference. This could be completed by using internal communications among the macro and neighbouring base stations, inside the cellular LTE-A network. This thesis addresses new SON algorithms to be inserted into the existing HetNet LTE protocols and system algorithms, which could be considered for the expected network.

1.5. Research Aim and Objectives

The main aim of this thesis is expressed as developing a self-organising based methodology for new releases of heterogeneous LTE-Advanced networks to simultaneously improve both capacity and quality of service. The main keywords of this research could be expressed as (but not limited to): **SON**; **HetNet**; **LTE-A**; **Femtocell**; **Multi-Layer**; **Interference**; **Access Control**; **Handover**; **eICIC**; **Power Control**. The self-organising approach of this research is defined as the main target, to be obtained through the following objectives:

1. The first objective of the thesis focuses on coordinated resource allocation by applying self-organising methodologies. The efficient frequency reuse is proposed among macro and femto sub-networks, to apply bandwidth optimisation for the

multiple access cellular networks. The novel dynamic bandwidth allocation technique is planned over a unique algorithm to apply resource allocation for diverse base stations, by sharing the total accessible spectrum. The proposed resource optimisation technique boosts network throughput and reduces network complexity, while saving a significant fraction of the available resources within the entire network.

2. The second objective is to fulfil the mobility management requirements within the coordinated LTE-A network. This target is approached by proposing of a novel handover algorithm, which exploits the existing network mobility parameters. The novel handover strategy is introduced as a comprehensive algorithm, because it includes multiple controls -called as “checks”- to optimise the handover process, as well as avoid unnecessary handovers. The multi-check strategy contains a hierarchical algorithm to test the power and quality of the received signal, bandwidth availability, user residence duration and femtocell priorities over the macro stations. This algorithm is expected to meet the handover quality requirements, while avoiding unnecessary handovers.

3. The third objective of this research directly focuses on inter-cell interference mitigation based on power control techniques. The enhanced inter-cell interference coordination (eICIC) algorithm is designed based on downlink power reception among macro and femto sub-networks. To approach this target, self-organising power cooperation is introduced to be deployed between macro and femto stations. The novel eICIC algorithm reduces the overall interference, as well as improving the performance of victim mobile users, by adapting network transmission power.

1.6. Novel Research Contributions

This research introduces, evaluates and recommends new self-organising network management for HetNet LTE-A networks. The self-organisation methodology of this work is exploited by its various novel techniques to deal with bandwidth allocation, mobility management and interference mitigation. The main contribution chapters of this thesis are represented on Figure 1-5. The self-organising strategy is considered as the main methodology of the work to support all the contributions. The novel techniques and their relevant algorithms are described and explained as follows:

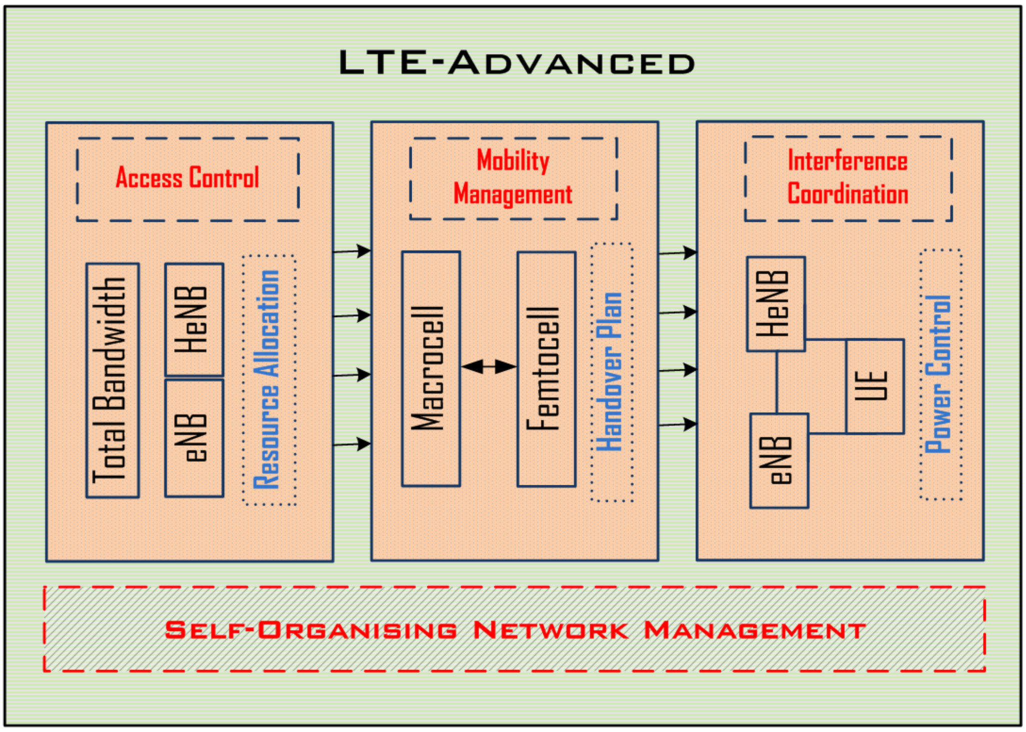


Figure 1-5: Thesis main contributions on LTE-A system

Access Control: Sharing of the available bandwidth using fixed frequency channels is applied for heterogeneous cooperation, to optimise the channel usage between macro and femto applications. A dominant challenge of this cooperation is discovered, when an appropriate method is required to distribute the available resources, either to a femtocell or macrocell at a particular time. Therefore, an appropriate resource allocation is needed to overcome this challenge.

- Resource Allocation: The novel frequency reuse algorithm is proposed for OFDMA-based LTE-A network by the use of self-organising functionalities. In this strategy, channel's physical resource blocks (PRBs) are considered as the units of this allocation, and each cell has the responsibility to inform the neighbouring cells about its occupied PRBs as part of self-organisation algorithm.

Mobility Management: The common mobile users between macro and femto applications are required to be satisfied in cases of mobility, especially from macro to femto, and vice versa. The foremost challenge in this scenario is either the omission of handovers, or facing unnecessary handovers during this process due to having inaccurate channel estimations to begin the handover process. Consequently, correct handover plan is required to plan an intelligent handover strategy.

- Handover Plan: An efficient handover plan is used by introducing a novel handover algorithm, based on self-organising communications. The proposed multi-check plan considers more accurate calculations in the handover initiation stage, while avoiding unnecessary handovers through the system.

Interference Coordination: Using of same frequency channel by both sub-networks is expected to produce higher levels of inter-cell interference. Hence, as a dominant challenge, network cooperation requires interference mitigation schemes to deliver smooth signals to the end users. Therefore, enhanced ICIC (eICIC) solution is introduced based on power control functionalities, for interference alleviation in macro-femto transmissions.

- Power Control: The novel power control algorithm is inserted into femto stations' functional blocks within the self-organising power balance algorithm. The power control technique focuses on downlink transmission, as the main link of interference between macro and femto sub-networks in LTE-A.

1.7. Methodology

The necessity of hardware implementation and expenditure is growing by cellular network evolutions. This matter has been the biggest motivation for this thesis to emphasise self-organising solutions for such sub-systems cooperation challenges in LTE-Advanced. The hierarchical SON trend in this work begins from the channel allocation issues as the first challenge, moves toward the mobility management concerns for the mobile nodes, and ends by the interference management resolution. In this PhD thesis, each of the proposed challenges are introduced and discussed in detail, followed by the problem formulation and solution inside the contribution chapters. This research is based on network simulations, as well as a literature review about the existing research work to identify the delivered novelty, compared to the identified relevant works. Since the analysis and modifications for the proposed new algorithms are for different layers in the open system interconnection (OSI) model, OPNET modeler network simulator has been used as the most appropriate software for our simulations.

The simulation-based experiments of this thesis include designing of appropriate algorithms for the aforementioned contributions at the first step. Afterwards, a number of different scenarios are designed and simulated based on multi-layer network architecture (Figure 1-6). The generated scenarios in OPNET modeler have been created according to physical structure of LTE and LTE-A networks, which are accompanied by additional configurations to check various network statistics.

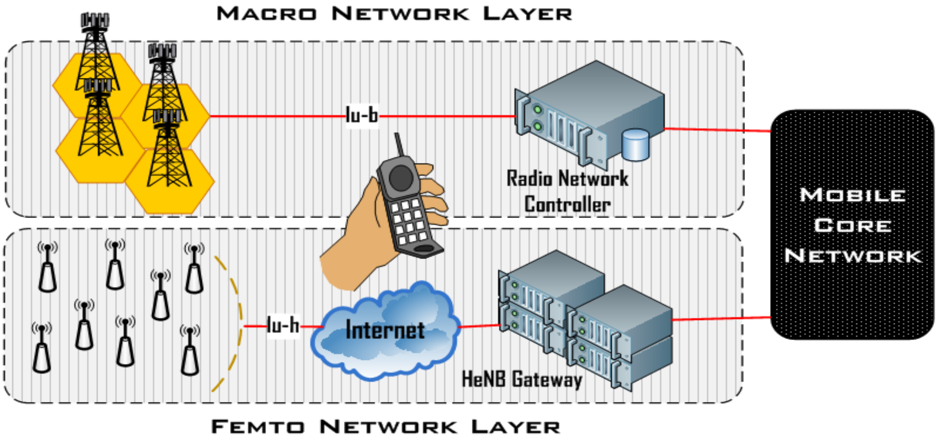


Figure 1-6: Multi-layer system architecture for LTE-A network

1.8. Thesis Outline

This thesis consists of a total of six chapters, which include three main contributions and one background chapter. The detailed thesis outline is introduced as follows:

Chapters 1 and 2 cover general introduction and background for whole the topic and express the motivation to exploit the major deliverables. The main contribution of this research has been defined as self-organising network management for heterogeneous LTE-Advance networks, which is divided into three contribution chapters. Each of the three contribution chapters (3, 4 and 5) of this thesis starts with a chapter introduction and related work, which illustrate more specifically about the background and previous works, their improvements and shortcomings, and also the required enhancements for each part. All the contribution chapters end with a chapter summary and references, to help the readers in finding the relevant outcomes and resources for each method. Chapter 6 makes an overall conclusion of the thesis, discussion about the area of research and future work for further improvements and assessment of the potential influence of this thesis for new releases of LTE-Advanced networks, based on SON functionalities.

Chapter 2 Technical Background in LTE-A and SON Management

The LTE and LTE-A cellular network systems are enhanced with a number of techniques to provide capacity and quality of service. The co-existence of both macro and femto nodes need to be carefully designed while considering the foreseen transmission challenges. It is also important before starting of any investigations in this field to become more familiar with the network backbone, as well as preliminary information about 3G transition towards LTE-A. This chapter aims to provide technical background and related information about the proposed contents, to permit a more confident study in LTE-Advanced networks. The required background in deployment strategies, modulation types, and internal interfaces are discussed, along with the channel and mobility specifications and interference avoidance techniques when deploying a femtocell beside the existing macrocell nodes.

2.1. Chapter Introduction

The evolution of third generation radio access networks (RANs) towards the existing fourth generation systems has been realised by innovative technologies and applications at each evolution step. This evolution towards new systems, such as LTE, LTE-A and worldwide interoperability for microwave access (WiMAX), is based on the increasing demands for ubiquitous service provisioning, bandwidth, high quality of service and low cost [17]. Furthermore, the proposed techniques for LTE developments mostly focus on transmission enhancements such as MIMO, CoMP, Range Extension, Resource Aggregation, etc., while the LTE-A innovations are mostly focused on heterogeneity and self-organisation attributes (see Figure 2-1), thanks to its compatibility with the existing LTE systems. In simple terms, The HetNet and SON could be expressed as two dominant added innovations for the existing LTE which are planned for specification in advanced releases.

HetNets are aiming to make a wide combination of outdoor/wide-range/high-power network systems with indoor/short-range/low-power applications, to fulfil the capacity and quality of service by offloading demands for resources from macrocells to femtocells. In this regard, new challenges of interference, implementation cost and network compatibility should be carefully considered by network operators. On the other hand, Self-organising networks are aiming to optimise usage of radio resources, to simplify the network management complexity, as well as reducing the operational costs [17].

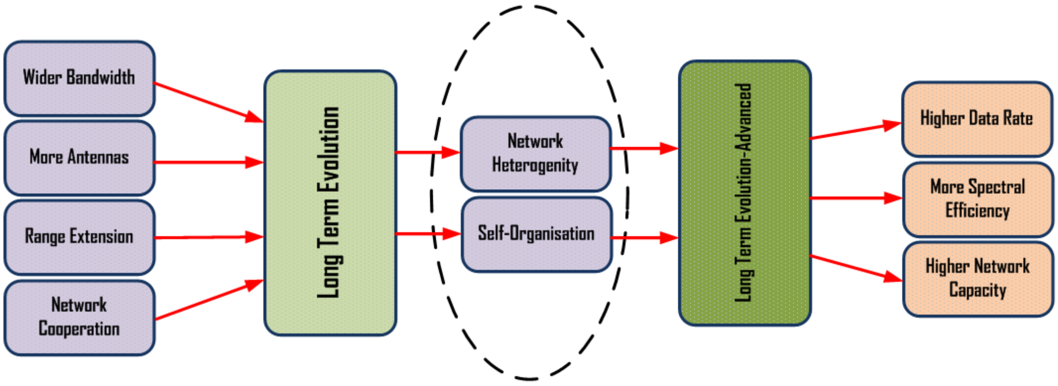


Figure 2-1: Network evaluation techniques towards LTE and LTE-A

The SON mechanism in heterogeneous access networks covers three main processes of self-optimisation, self-configuration and self-healing. In the self-optimisation process the User Equipment (UE) and cellular base station performance measurements are used to auto-tune the network. In the self-configuration process, the recently deployed nodes have automatic installations to obtain the appropriate configuration for the system operation. Whereas, in the self-healing process, the autonomous functions of fault detection, fault diagnosis, and fault recovery are performed [17].

In addition to network deployment strategy and arrangement methodologies, a number of fundamental frequency use techniques also make the technologies like LTE and LTE-A superior over 3G systems. As a good example, using of Multiple-Input Multiple-Output (MIMO) antennas for the efficient use of orthogonal Frequency Division Multiple Access (OFDMA) in both downlink and uplink transmissions is considered in 4G systems [18]. Nevertheless, since the concepts of multi-layer/tier deployment and self-organisation solutions are proposed during the advanced releases of LTE networks, these aspects need more investigations and comprehensive research to fully understand the implications of their deployment.

This chapter presents the technical background in heterogeneous and self-organising networks, as well as the challenges in multi-tier network deployments for LTE and LTE-Advanced systems. The modulation schemes, deployment methods and air interface descriptions are reviewed to identify network compatibility with existing LTE systems. Furthermore, existing access control and access modes are also described prior to the technical descriptions of resource allocation, mobility management and interference mitigation. This chapter aims to explain these background LTE technologies before presenting the novel contributions of this research. By presenting this background knowledge on LTE, at the same time as system level information on self-organising networks, an insight can be obtained for inventing novel solutions to the challenge of deploying femtocells in LTE networks. At the end, a brief chapter summary summarises the contents and issues presented in this chapter.

2.2. Fundamental Network Construction and LTE-Advanced Characteristics

As a true 4G cellular network, LTE-A and its proposed self-organisation should fulfil the network necessities to reach the target pick data rate and scalable system bandwidth. The additional functionalities are only applicable on the system, if there is a reliable network platform available from previous releases and network planning.

2.2.1. Existing LTE Characteristics and Compatibility

The conventional cellular network deployment is typically launched based on homogeneous architecture by applying a macro-centric planning process, in which the base stations are operating within a planned layout and serving the user terminals. The values of receiver noise floor, transmit power levels and antenna radiation patterns are similar for all the base stations in homogeneous networks.

Furthermore, all the base stations in homogenous networks prepare similar backhaul connectivity to the data network and unrestricted access to the user terminals in the network, while serving roughly the same number of users [6]. Therefore the additional carriers are required to overcome the capacity shortcomings when the traffic demands are growing. Nevertheless, as a main target of 3GPP LTE-A systems to improve the ITU requirements, the new releases of LTE-A systems are compatible to and share the frequency bands with the first LTE release.

2.2.2. Network Heterogeneity and Heterogeneous Architecture

Throughout this network heterogeneity investigation, two types of base stations are being considered within different HetNet architectures. One is the long-range macrocell base station, called as evolved Node-B (eNB), and the other is one or more short-range nodes, which in case of femtocell nodes are called Home evolved Node-B (HeNB). As a technical consideration, these two sub-networks could be assumed to contain two cooperating network layers, or tiers, which are linked through the core system [4]. By providing the indoor area coverage devices like femtocells, this will support a variety of services by using these low power access points, which can provide the higher data rate of several Mbps for the indoor areas [19,20].

The successful co-existence of both macro and femto nodes in an LTE network requires considered research for obtaining efficient and elegant solutions. Since the radio resource management protocols for coexisting macro and femto nodes are not specified by the standards (e.g. 3GPP’s UMTS LTE) [4], a solution could be found by applying network organisation and cognition schemes into the existing systems.

2.2.3. Base Station Application and Deployment

Small-cell concept is referred to networks with smaller size of implementation, shorter communication range, lower transmission power and lower deployment costs. To provide network users with the experience of a ubiquitous network with improved QoS at both the cell-centre and the cell-edge areas, a heterogeneous network solution should propose cooperative spectral efficiency algorithms by using a range of small-cell nodes. Figure 2-2 shows the various types of nodes in HetNet architectures, based on their coverage radius (rough distances).

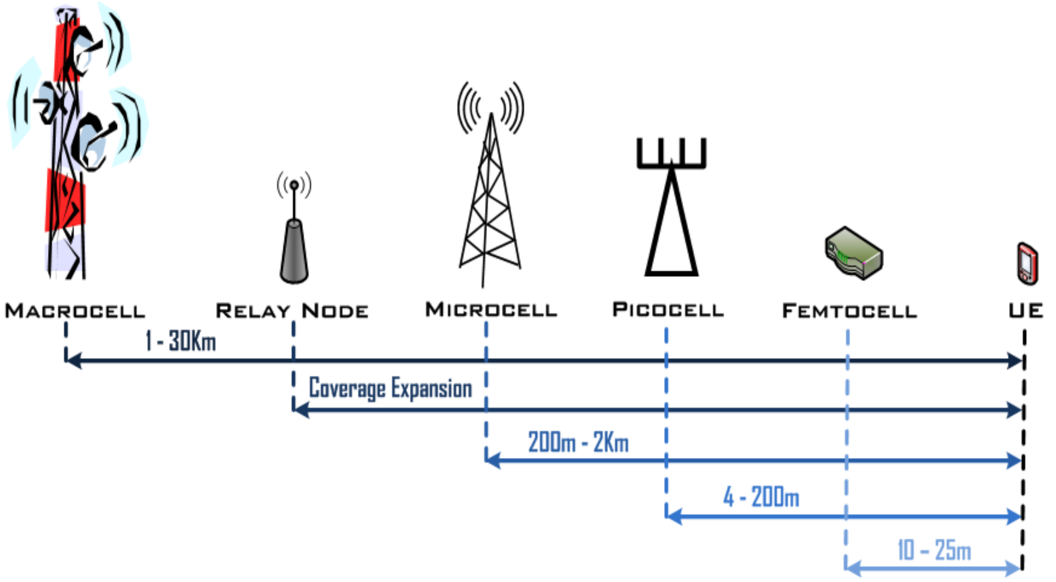


Figure 2-2: Variety of nodes in heterogeneous network architecture

2.2.3.1. Macrocell

Macrocell nodes provide wide coverage area up to about 40 Kilometres by a high transmission power of about 40 to 100 Watt. The number of users per base transceiver station (BTS) depends on deployment cell, but this is usually between 200 to more than 1000 users [21]. In LTE systems, the macro layer acts as the main support for small-cell nodes although facing several spectrum challenges e.g. interference and overloading.

2.2.3.2. Microcell

Microcell node has been used in outdoor areas to offload users from the macrocell nodes by its maximum cell radius of about 2 Kilometres and maximum transmission power of 2 to 10 Watts [21]. Microcells have also been used for 3G cellular systems as well as LTE releases, because of their capability to cooperate in outdoor areas.

2.2.3.3. Picocell

Picocells have substantially lower transmission power compared to macro nodes and are mostly deployed in an ad-hoc way in the network [22,23]. Furthermore, the networks using picocell nodes are expected to experience lower signal to interference ratio, because of their unplanned deployment on the network, which results in a challenging RF channel for control channel transmissions to the cell-edge users. An important point regarding macro-pico deployment is the large difference of the transmit power between macro and pico nodes in the network, which causes the smaller downlink coverage of a picocell compared to the macro. However, this is not the same case for uplink, which uses the same transmit power strength from user terminal to all the base stations, because this only depends on the user terminal's transmit power [6]. Picocell transceivers could be used either in indoor or outdoor areas, but their coverage radius is up to 200 meters only, which should be carefully considered while planning the network infrastructure. Figure 2-3 shows a macro-pico scenario in which the pico nodes are applied to enable range-extension to support additional number of UEs.

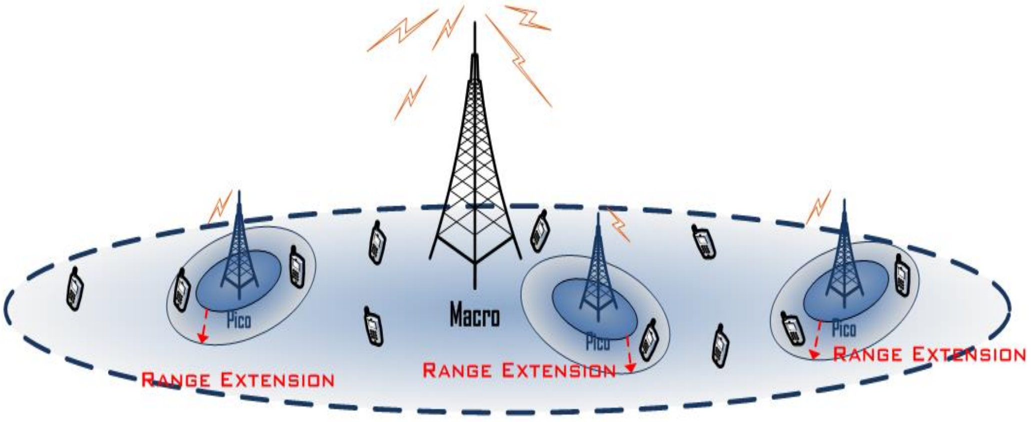


Figure 2-3: Range-extension for macro-pico network

2.2.3.4. Relay Node

Relay Stations (RSs) are planned to forward user information from the neighbouring user equipment (UE)/mobile station (MS) to a local eNode-B (eNB)/base station (BS) [24]. The RSs can enhance the total throughput of the system by extending the signal and service coverage of an eNB. The selection of the relay types and relay partners (collaborative strategy) play a great role on the performance of relay transmission. There are two types of rely nodes defined in 3GPP LTE-Advanced and 802.16j standards: type 1 (non-transparency), which could help a remote UE located far away from eNB to access to the eNB. This type of relay nodes need to transmit the common reference signal and the control information for the eNB, and its main aim is to extend the signal coverage and services. On the other hand, type 2 (transparency) could help a local UE, which is located within the coverage of eNB and has a direct communication link with eNB to improve the link capacity and service quality. So it does not transmit the common reference signal and the control information and its main aim is just to increase the overall system capacity, by achieving the transmission gain and multipath diversity for the local UEs [25]. Therefore, the general application of relay nodes in combination with macrocell is to pass transmission for out of range mobile nodes, as well as improving the existing connections.

2.2.3.5. Femtocell

Femtocell is introduced as an intelligent access point to support 3G and 4G mobile devices, which use cellular air interface, e.g. CDMA2000, UMTS, LTE and LTE-A. Femto nodes are tightly integrated with the existing macro networks, and so their use and switching between macro and femto are seamless for the users in particular. The femtocell network architecture and its specifications allow the ordinary users to install them with plug-and-play simplicity [26]. In case of using of femtocell within closed mode HetNet architecture, only the registered subscribers of femtocell are allowed to access. Hence, the nearby users, either from the neighbouring femto, or general macro node are likely to face severe interference caused by the femtocell [6]. Therefore, when deploying femto sub-network, which is an indoor application, there is a need to consider an appropriate control strategy to receive the maximum support from this cooperation.

There is an additional focus on femtocell in HetNet architecture, compared to the other small-cells, because of its low-power, low-complexity and compatibility with the existing core network mobile network operators (MNOs), while promoting different ranges of tariffs for home broadband.

2.3. Conventional LTE Network Multiplexing and Duplexes

LTE data transmission is mostly based on orthogonal frequency-division multiplexing (OFDM) to carry the data on multiple carrier frequencies. In this regards, the available bandwidth is divided into multiple overlapping sub-carriers. The OFDM sub-carriers are orthogonal to each other, so the inter-symbol interference is prevented by applying independent modulation for each subcarrier.

2.3.1. Supported Duplexes

In mobile systems duplex communication is the ability of the users to establish a dual-way communication for transmission and reception, rather than a simplex communication, which has only-transmit or only-listen modes of operation. Two types of duplexes are defined in LTE, namely: LTE time division duplex (LTE TDD) and LTE frequency division duplex (LTE FDD).

2.3.1.1. LTE TDD

The same frequency band is used for duplex in LTE TDD in both the directions, which is also called as “unpaired spectrum”. The same frequency channel hosts transmit and receive processes in different time-slots in asymmetric turns. Therefore, the number of time-slots in downlink is higher than the number of time-slots in uplink [27].

2.3.1.2. LTE FDD

In LTE FDD, the radio transmitter and receiver operate in different carrier frequencies at the same time. The uplink and downlink frequency bands are separated by the frequency offset, which prevents latency, although needing more complex circuits and deployment.

2.3.2. LTE Frame Structure

The system robustness is improved by splitting the transmission data between multiple carriers. The LTE frame structure based of OFDM slots and FDD duplex is shown on Figure 2-4. The typical LTE frame has the overall length of 10ms, which is divided into 10 subframes and 20 individual slots. The length of each slot in the radio frame is 0.5ms and two slots make one LTE subframe of 1ms. Each slot also contains 7 OFDM symbols including normal (short) cyclic prefix with a copy at the end of the symbol. The most important function of cyclic prefix is to perform as a guard interval to prevent the inter-symbol interference between the symbols. If to involve the frequency domain into our structure, each of the OFDM symbols includes 12 subcarriers, which altogether form one physical resource block (PRB) as the most important unit in LTE in different measurements. Therefore, we can say one two-dimensional unit in LTE is one PRB, which is made of one slot in time domain and 12 subcarriers in frequency domain. Another two-dimensional unit in LTE is one Resource Element, which is made of one symbol in time domain and one subcarrier in frequency domain.

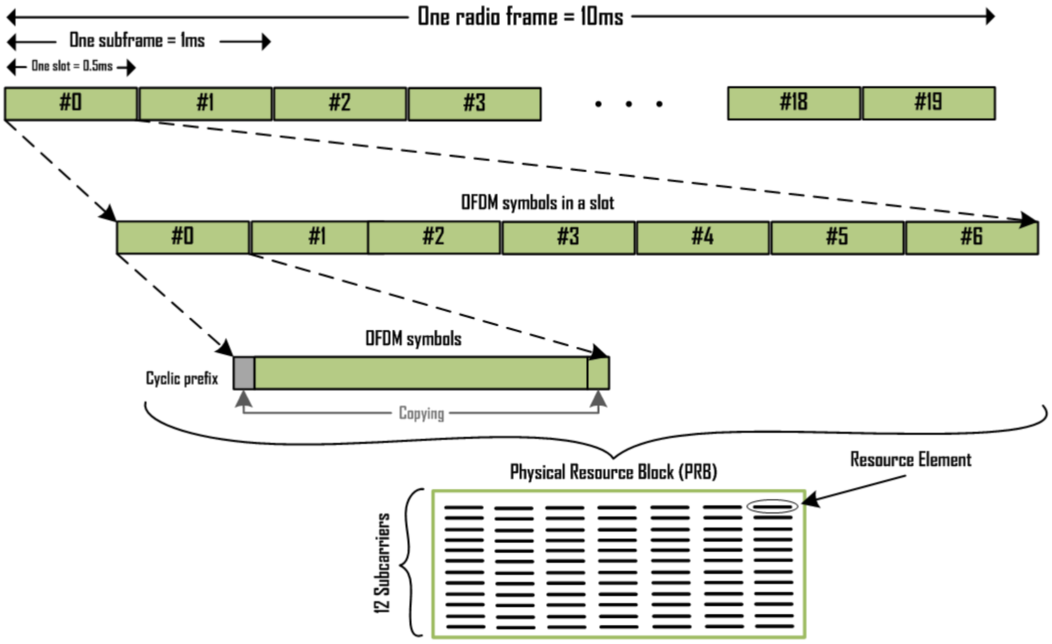


Figure 2-4: LTE frame format with OFDM

2.3.3. OFDMA in Downlink

LTE downlink uses orthogonal frequency division multiple access, which provides OFDM-based multiplexing for multiple access. OFDMA provides low-data rate transmission and lower maximum transmission power from multiple users. This also further improves the existing OFDM robustness, fading and interference avoidance. Figure 2-5 shows the subcarriers in OFDMA multiplex.

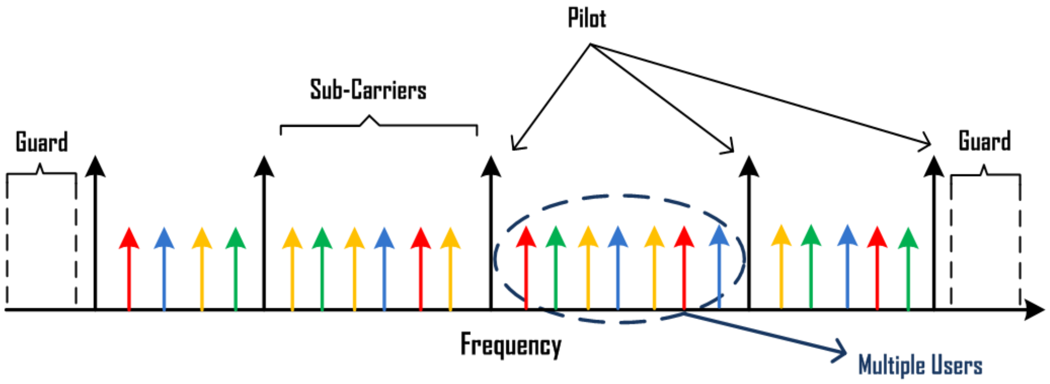


Figure 2-5: Multiple subcarriers configuration in OFDMA

The deployment flexibility across different frequencies needs minimum modification by using orthogonal frequencies in OFDMA. Scalability of OFDMA is one of the most important advantages, in which its subcarrier structure makes it able to support a wide range of bandwidth. The scalability of this multiplexing method also provides more flexibility of deployment with minimum modification to the existing air interface. This system is able to be deployed in different frequency band intervals to address the different spectrum allocation techniques. In the case of transmission methods, since the processing of OFDMA signal provides effectively frequency flat channels, full multi-input-multi-output (MIMO) technology could be deployed in combination with existing OFDMA system [28], which could be highly used in later versions of LTE-Advanced.

2.3.4. SC-FDMA in Uplink

In LTE-A uplink, single carrier frequency division multiple access (SC-FDMA) is preferred over OFDMA, because it reduces the peak to average power ratio (PAPR). The SC-FDMA process has similar structure to OFDM and OFDMA, except the addition of a discrete Fourier transform (DFT) block before mapping the subcarriers. Therefore, SC-FDMA could also be considered as an OFDMA modulation, but with an extra DFT block. SC-FDMA is more attractive compared to OFDMA, since it reduces the PAPR by a ratio of the dimensions of the inverse DFT (IDFT) and DFT in its modulator, which reduce cost of power amplifier for mobile users. Figure 2-6 [29] depicts the symbol transmissions for OFDMA and SC-FDMA [30].

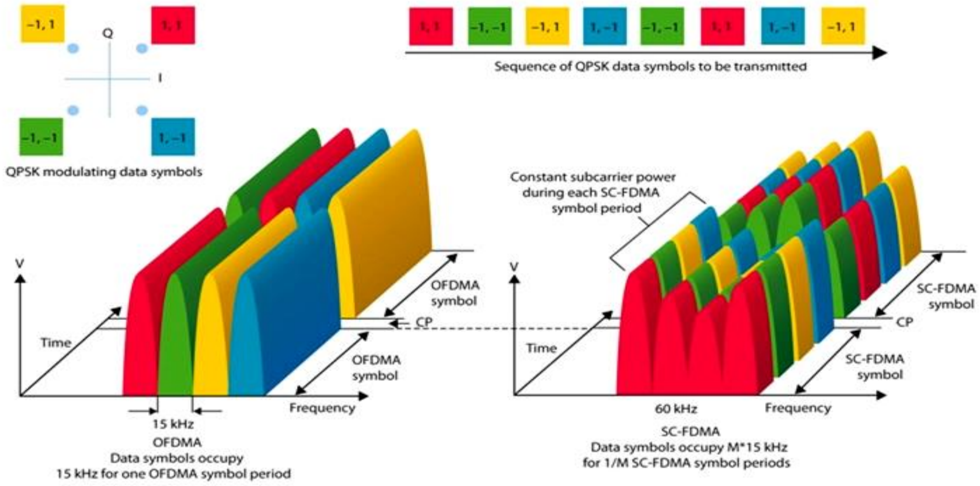


Figure 2-6: OFDMA vs SC-FDMA transmissions [29]

2.4. Necessity of Self-Organising Approaches for HetNet

Latest releases of LTE-A systems, which are more focused on heterogeneous networks, plans to fulfil coverage and capacity requirements. Relation of the advanced versions of LTE with heterogeneity from one side, and self-configuration plans in each step of LTE-Advanced form the other side, could form a heuristic process in this regard. Figure 2-7 shows the self-organisation process in cellular networks.

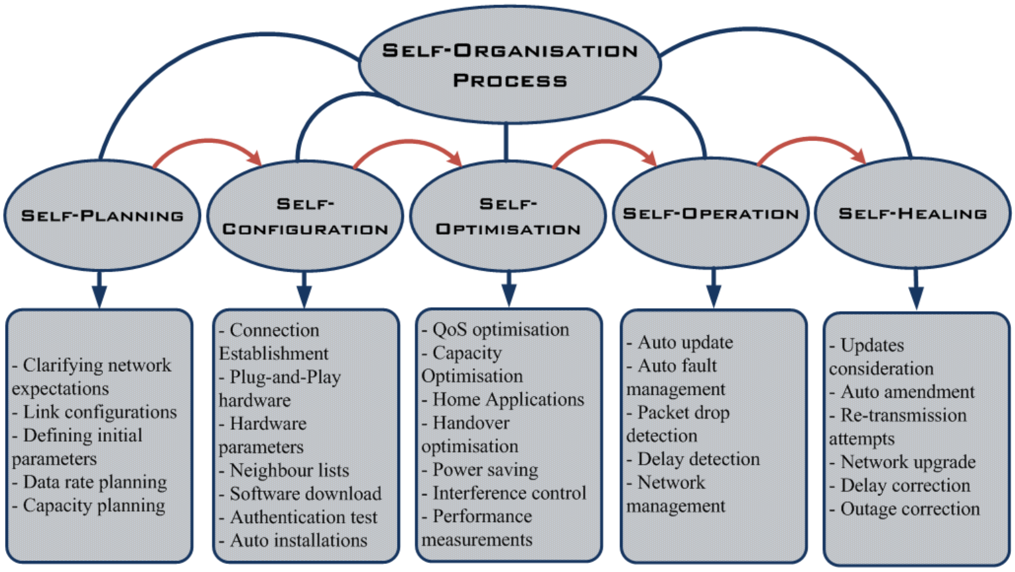


Figure 2-7: Self-organisation process in cellular networks

2.4.1. SON Solution for Resource Allocation

The LTE base stations are expected to be equipped with SON capabilities to reduce human involvement, as well as saving capital expenditures (CAPEX) and operational expenditures (OPEX) [31]. Considering the exponential growth of data traffic, channel optimisation is the main objective of resource allocation strategies in LTE-A systems. Therefore, strategies like fractional frequency reuse, partial reuse and channel sharing are planned along with SON algorithms for network cooperation, e.g. macro-femto cooperation, in case of frequency re-use schemes.

2.4.2. SON Solution for Mobility Management

Unnecessary handovers are known as the critical challenge in network mobility management, which are technically caused by inaccurate network measurements. Furthermore to plan a ubiquitous network support, it is necessary to avoid any needless handover, e.g. unnecessary macro to femto handovers. Self-Organising mobility management algorithms initiate a comprehensive handover process with more accurate network condition monitoring to maximise network reception and minimise the number of unnecessary handovers within the cells.

2.4.3. SON Solution for Interference Coordination

The network cooperation is introduced to reduce the total costs for the network operators. The inter-cell interference management has significance in concept of HetNets, because of the importance of interference as one of the major challenges in OFDMA-based networks [13]. In downlink side of network, where the network nodes transmit to a variety of users, more challenges are expected to be faced due to higher interference. Transmission power is also important to control in order to manage the interference in the neighbouring cell, as well as the target cell. Therefore, it seems very logical as a common practice for LTE, to use less transmit power near the cell border in order to apply interference mitigation measures and reduce the inter-cell interference [13].

2.5. Deployment Structure and Interfaces

As an OFDM-based technology, LTE technology is prioritised over the conventional 3G releases by its physical characteristics. The mentioned OFDMA and SC-FDMA transmissions are accompanied by channel optimisation techniques, like co-channel deployment, to obtain positive effects on QoS satisfaction for the end users. Furthermore, supported modulation schemes and interface architecture are also prominent characteristics of LTE network, which could bring network capacity enhancements.

2.5.1. Deployment Methodologies

In small-cell deployment, macro-femto cooperation requires specific network design to deploy a dual-way transmission by use of bandwidth resources. The deployment methodology of macro and femto sub-networks specifies channel allocation and resource blocks transmissions, either by sharing the frequency channels or by allocating separate channels.

2.5.1.1. Multi-Channel Deployment

In multi-channel deployment, macro and femto nodes use separate frequency channels for transmission. In this deployment, single or multiple frequency bands are allocated to each application, which could avoid co-channel interference because of using different frequency channels. Preventing interference by using separate channels could raise quality of service by decreasing number of dropped packets in the network layer and increasing the number of successful transmissions. However on the other hand, the multi-channel deployment strategy could not fulfil the channel optimisation and financial expectations.

2.5.1.2. Co-Channel Deployment

Use of same frequency channels for outdoor and indoor applications is preferred in LTE-Advanced. The co-channel deployment capabilities of heterogeneous networks provide the advantage of channel optimisation, which reduces the network implementation costs by saving more frequency channels. Nevertheless, a heuristic macro-femto cooperation strategy is required for this type of deployment, not only to avoid the co-channel interference, but also to manage other network layer responsibilities among the sub-networks, e.g. handover and resource managements.

2.5.2. Modulation Schemes

The quadrature amplitude modulation (QAM) is used to modulate the transmitted bits within the OFDM signal in LTE shared channels. Applying different modulation schemes in LTE makes the bit detection process more robust against distortion and noise within the transmission channel. Three types of modulation schemes are used as shown in Figure 2-8.

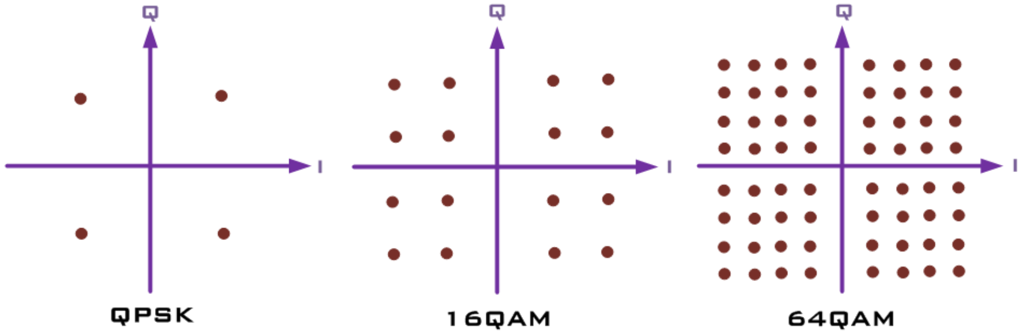


Figure 2-8: Modulation types in LTE

In case of having noisy channel conditions, the modulated data with quadrature phase shift keying (QPSK) provides more reliable decision at the receiver side, because of a large distance between the modulation points (2 bits per symbol). On the other hand, 16QAM and 64QAM map 4 and 6 bits onto one modulation symbol respectively, which results higher data throughput when the SNR on the transmission channel is higher.

2.5.3. Interface Architecture

The air interface of LTE network is called evolved universal terrestrial radio access network (EUTRAN), which is interfaced to the evolved packet core (EPC) configuration. The LTE interface architecture is depicted in Figure 2-9. The X2 interface provides inter-connections among macro nodes (eNodeBs). The entire X2 interface is applicable for the nodes within a unified network, and not individual networks like home or indoor applications.

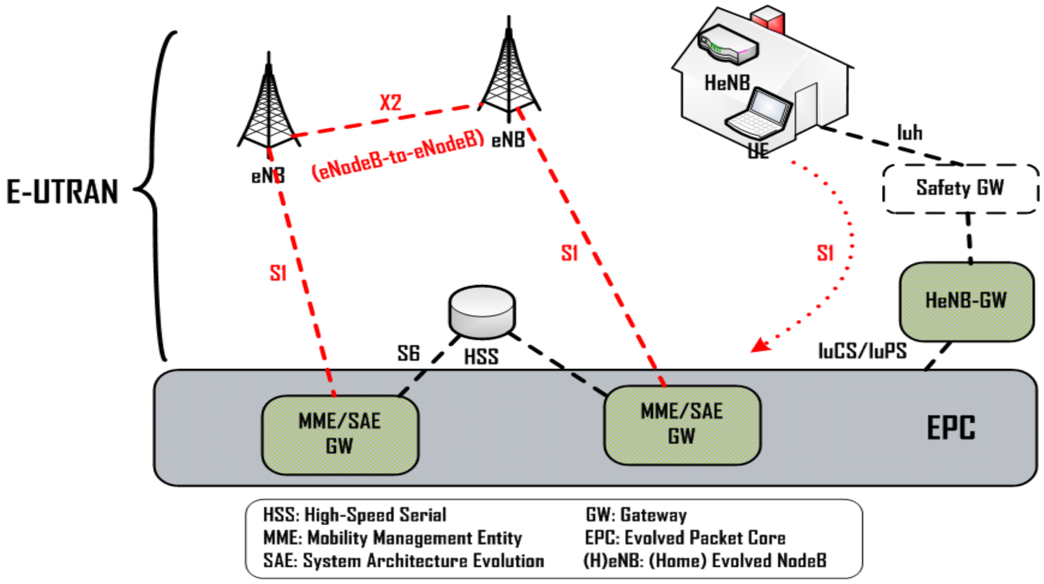


Figure 2-9: Entire LTE interfaces architecture

The S1 interface is used to connect eNodeBs to the EPC platform through the management and system architecture gateways. Therefore there is capability to deploy S1 interface between small-cell nodes, e.g. femtocells (HeNodeBs), and EPC through the appropriate gateways.

2.6. Channel Sharing and Access Control Necessity

The 3rd generation partnership project (3GPP) Release 10 LTE-A [32] has been revealed with further enhancements to the LTE systems to fulfil IMT-Advanced expectations. Heterogeneous networks, as a prominent improvement of LTE-A over LTE, requires channel use and access control to be considered to optimise the bandwidth allocation among variety of the sub-networks.

2.6.1. Resource Allocation Scheme

The node selection in LTE Rel-8 is based on downlink received signal strength. Considering the same strategy for LTE-A, the usefulness of low-power nodes will be highly decreased. The reason is, because of higher power and larger coverage of macrocell, they attract most of the user terminals, while not providing enough resources to efficiently serve those users [6]. Therefore, the foremost consideration of resource allocation is the fair distribution of channel resources, which is necessary to balance the traffic and avoid QoS drops within the network.

2.6.2. Frequency Reuse Pattern

Frequency reuse strategy is widely used on the existing generations of cellular networks, in which the transmission of different cells or sectors of a cell are orthogonalised in the frequency domain by splitting the total available spectrum into non-overlapping partitions [4]. The use of wide channels for LTE and LTE-A networks limits the available spectrum, which results in performance and quality reductions in each cell. Therefore, the application of enhanced techniques for frequency reuse is necessary to begin the channel optimisation. Figure 2-10 shows two different strategies for frequency reuse within neighbouring cells.

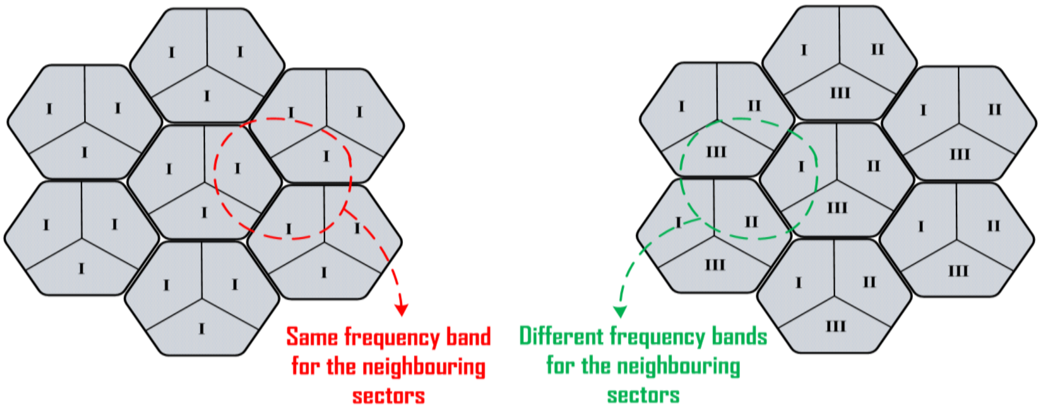


Figure 2-10: Different frequency reuse strategies

Although the frequency reuse pattern results in the saving of bandwidth resources, applying the same frequency for the neighbouring cell sectors results in interference and network quality degradations, especially for the users at cell boundaries.

2.6.3. Network Access Modes

It has been proven that the traffic offload to femtocells can decrease the costs for the network operators by up to 70% [33]. In this regard, network access is another important sub-network function, e.g. for indoor nodes, which is required for access by public users. Different network access modes are categorised based on network permission to the users to be managed by the transceivers within each geographic area.

2.6.3.1. Open Subcarrier Group

In open subcarrier group (OSG), also called as “Open Access” mode, the network user groups have instant access to any part of the network upon demand. In macro-femto network, both macro users and indoor users can use the femtocell, while there is no such list of allowed users in femto access points.

2.6.3.2. Closed Subcarrier Group

On the other hand, there are some problems due to deployment of a larger number of low-power nodes. Especially in co-channel deployment scenarios in heterogeneous networks, interference may become serious due to use of low-power nodes, which could lead to high outage of the macro users [9]. The femtocell is able to work in a closed subcarrier group (CSG), also known as “Closed Access” mode, in which a list of allowed users is provided for the femtocell. In this mode, only the users available on that list, i.e. CSG user, are allowed to access to the femtocell. Since the possibility of inter-cell interference in CSG is more than OSG, appropriate interference coordination schemes are necessary to be planned in network cooperation.

2.6.3.3. Hybrid Access Mode

Hybrid access mode is a new concept in addition to open and closed access modes, which is proposed in LTE release 9. In hybrid access mode, all the users have open access to the cell, but those users who are subscribed have priority to get access and get charged differently [34]. Therefore, the cell treats UEs as CSG if their ID is in the access list and gives them priorities, otherwise it treats them as OSG and serves them as normal.

2.7. LTE-Advanced Technical Challenges

Deploying the existing LTE platform in the transition to advanced LTE systems leads to challenges in various aspects such as network capacity, quality of service, resource scheduling, handover planning, inter-cell interference coordination, etc. A brief description and relevant suggestions are made in this section to become more familiar with the main technical challenges when dealing with new releases of heterogeneous LTE network. Figure 2-11 shows a typical HetNet scenario with its technical challenges.

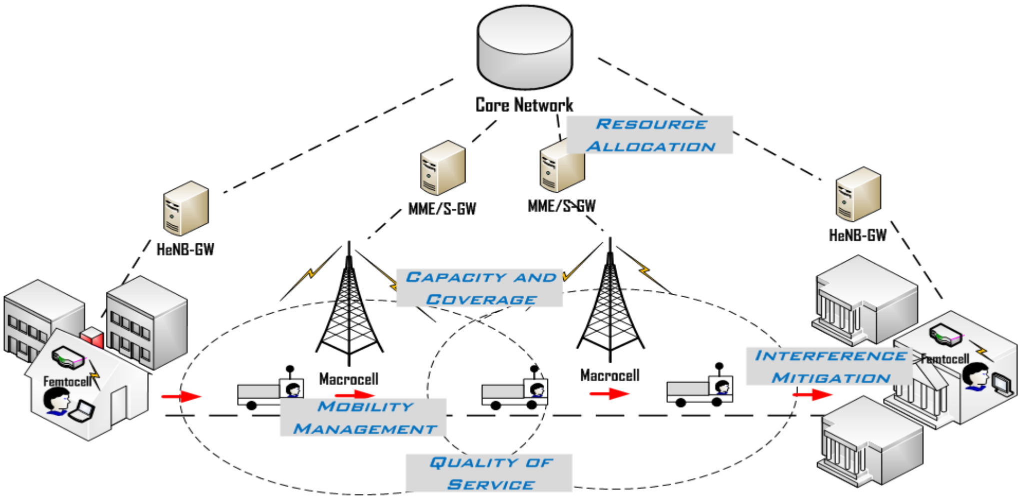


Figure 2-11: Technical challenges in a HetNet scenario

2.7.1. Capacity and Coverage Support

The average capacity of the network is defined as aggregated throughput from all users connected to a single cell. Furthermore, the average cell coverage is also defined as the lowest user throughput that can be guaranteed in 95% of cases [35]. The capacity and coverage optimisation algorithms could guarantee acceptable values for capacity and coverage by increasing the transmission power assigned to a physical resource block (PRB), but also causes more inter-cell interference. Therefore the proper ICIC technique is also needed to be considered along with these algorithms [13].

2.7.2. Overall Quality of Service in HetNets

Although the network MIMO is applied in LTE-Advanced systems, it does not suggest a guaranteed quality of service. There are some challenges related to timing issues of the packets belonging to different streams in a diverse QoS network. The first challenge is the use of MIMO to manage the packet transmissions with diverse QoS characteristics, and the second challenge is finding of appropriate radio resources for each stream to ensure QoS for different MIMO topologies [36]. Therefore, QoS satisfaction is required to be considered, while applying coverage and capacity planning.

2.7.3. Channel Optimisation and Resource Allocation

The necessity of having a heuristic resource allocation plan is more dominant when a variety of applications are deployed within HetNet architecture. The resource partitioning could be deployed with different techniques, such as time-domain, frequency-domain, or spatial-domain. The time-domain partitioning could better adapt to user distribution and traffic load changes, while the frequency-domain partitioning is less granular and flexible for resource allocation, but is more feasible in asynchronous networks [6]. Hence, applying a self-organising resource allocation could be more effective.

2.7.4. Mobility Management and Handover

Different issues need to be considered to obtain the maximum outcome in case of users' mobility. User speed, available bandwidth, macro and femto priorities, power of the transmitted signal, etc. are essential to be considered to maximise the network throughput. The unnecessary handovers also need to be minimised to get to the utmost efficiency in case of users' mobility.

2.7.5. Interference Challenge and Mitigation Plan

The interference mitigation scheme is generally categorised into three main techniques of: interference cancellation, interference averaging and interference avoidance techniques [14]. Applying of the interference avoidance plan results upgraded performance with less complexity within the network, comparing to the interference cancellation and averaging schemes. Therefore the interference avoidance technique is preferred to be applied within the entire network. The most significant challenge in this regard is making a trade-off between channel optimisation and an interference-free network, which is planned to be addressed by developing inter-cell interference coordination (ICIC) algorithms.

2.8. Summary

This chapter includes the background study in LTE-Advanced, heterogeneous and self-organising networks. The existing LTE characteristics and compatibility are discussed along with its new capabilities towards LTE-A. Using OFDMA in downlink, SC-FDMA in uplink, and a wide range of small-cell nodes would facilitate in the transition process towards LTE-Advanced generation. As further requirements, the application of self-organising methodology by using of self-configured algorithms among macrocell, femtocell and users, is proposed as the main contribution of this research.

In next chapters, a cooperative LTE-A network containing macro and femto tiers will be discussed, and a self-organising solution will be applied to deal with the proposed network challenges. The SON algorithms will be presented, simulated and analysed for resource allocation, mobility management and inter-cell interference coordination to obtain the maximum network capabilities.

Chapter 3 Multi-Layer Sub-Channel Allocation and Access Control

Implementation of a multi-layer network with coordination of outdoor and indoor applications requires a reliable channel allocation technique to fulfil the coverage fairness, as well as QoS expectations. Since all the network users share limited bandwidth and channel resources within the HetNet architecture, the channel allocation technique needs to consider a number of impediments, e.g. channel interference, to deliver the maximum efficiency to the end users. This chapter proposes a cooperative macro-femto LTE-A system followed by a novel channel allocation and access control technique to form a SON solution in case of channel sharing among the mobile users. The high-demand applications are planned and simulated through the intended network, in which the node and model statistics of the system are evaluated and analysed to compare the network performance with and without the suggested channel allocation technique.

3.1. Chapter Introduction

Femtocells are recently proposed as low-power, low-range and low-cost cellular base stations to be used as indoor applications for domestic and enterprise uses. The femtocell routers are directly connected to the backhaul network through the internet protocol (IP) by using of regular connection links, e.g. optical fibre and asymmetric digital subscriber line (ADSL) [37,38]. Femtocell networks could also cooperate with high-range base stations like macrocells to form a heterogeneous architecture, as part of the advanced networking method in new releases of cellular networks. In addition to the femtocell physical advantages, e.g. size, power, etc., its network planning could also facilitate the network optimisation by eliminating the existence of coverage holes, especially in cell boundaries. The plug-and-play capability of the femtocell routers make the users able to subscribe for this application and enhance their network coverage when they are located in their home, school or office. In new releases of LTE systems, there has been more focus to develop network heterogeneity in LTE-Advanced versions by using of short-range and medium-range base stations like microcell, picocell and femtocell. Following the first standardization in 2009, the 3rd generation partnership project (3GPP) has proposed its release 10 in March 2011. 3GPP Rel-10 mostly focuses on independent SON function as an important functionality of LTE new releases. The SON coordination in 3GPP strategy contains the two aspects of (1) coordination among configuration management and configuration changes by SON functions, and (2) coordination between different SON functions, analysed on a case by case basis [[39]].

The allowed bandwidths for component carriers in LTE are 1.4 MHz, 3.0 MHz, 5.0 MHz, 10.0 MHz, 15.0 MHz and 20.0 MHz. Table 3-1 shows the number of Physical Resource Blocks (PRBs) for each channel bandwidth.

Table 3-1: Number of physical resource blocks in each LTE bandwidth

Bandwidth (MHz)	Number of Physical Resource Blocks (PRBs)
1.4	6
3.0	15
5.0	25
10.0	50
15.0	75
20.0	100

Furthermore, the technical title of LTE-Advanced belongs to the LTE new release 11, which continues the work on SON attributes and network heterogeneity, aiming to develop improvements to the network capacity and data rate. The 3GPP new releases also propose carrier aggregation which let the users to use a wider bandwidth to increase their throughputs, by combining 5 LTE Rel-8 carriers of 20 MHz to form an aggregated bandwidth of up to 100 MHz (Figure 3-1).

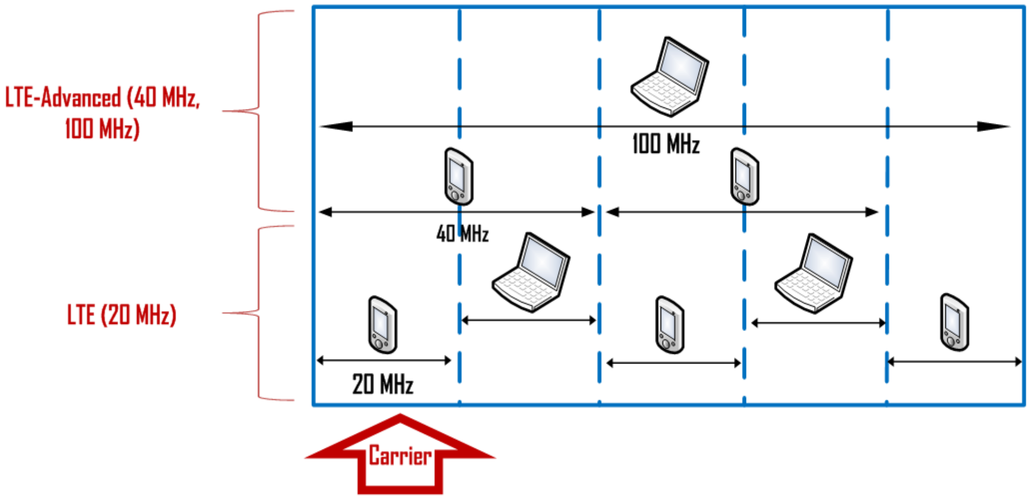


Figure 3-1: Carrier aggregation process in LTE-A systems

The necessity of network heterogeneity and use of indoor applications within a heterogeneous network are becoming more dominant, as network demands are increasing [40,41]. Moreover, the optimised use of available spectrum is also becoming a challenge for network operators to make their financial aims promising, while fulfilling network expectations. Since the self-organising characteristics of the heterogeneous network systems are proposed as a main feature of new releases in LTE-A, resource management planning should be carefully considered to prevent the foreseen challenges in cooperation between different types of base stations.

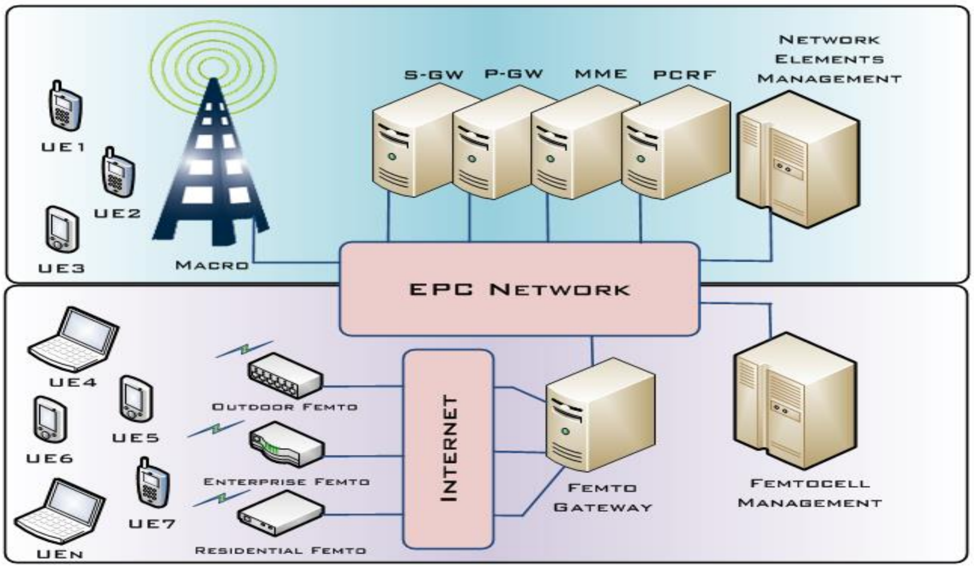


Figure 3-2: Hardware requirements for resource management in LTE-A

As is shown in Figure 3-2, the SON channel sharing management for macrocell and femtocell contains a number of self-configured processes and units, e.g. network elements management (NEM), policy and charging rules function (PCRF), mobility management entity (MME), and macro/femto gateway [42]. As is shown in this figure, the physical gateways for each of the macro and femto layers act as the main entrance to each network layer during the inter-connections. The processes also contain internal communications in order to provide the transmission decisions for different applications, based on their expected QoS.

This chapter proposes a macro-femto heterogeneous network on LTE-A platform, followed by a novel sub-channel allocation for spectrum management in presence of macrocell and femtocell base stations. The proposed technique is based on SON algorithms for hybrid fractional frequency reuse (HFFR) method between macrocell and femtocell users. The cell partitioning is designed as frequency reuse scheme to allocate appropriate sub-channels to the cell-centre and cell-boundary users of both macrocell and femtocell, while considering the network capacity and quality expectations.

In the simulation and analysis sections, different LTE-A network scenarios are conceived in OPNET modeler network simulator to simulate the application of the proposed resource allocation algorithm in macro-femto networks, and detailed analyses are made to compare different statistics of network, while presenting a range of applications. The main contribution of this chapter is development of a novel channel allocation technique with considering SON methodology as the main solution for the network cooperation among macrocell and femtocell sub-networks.

3.2. Related Work

Multiple features are needed to be considered as part of the LTE-A resource management and spectrum allocation process. Presentation of the femtocell capabilities, its arrangement as part of a multi-layer network in cooperation with macrocell, and macro-femto resource allocation by conventional frequency reuse schemes have been recently under research. An important development that appears in LTE-Advanced is the improvement of spectral efficiency per unit area, by using a mixture of macro, pico, femto and relay base stations through a heterogeneous network (HetNet), which enables flexible and low-cost deployments and provide broadband access for the users within the entire network. The important task is management and control of the interference to deliver the benefits of such networks [6]. In this regard the overlay and underlay strategies are being applied, in which the overlay method relates to the exploitation and use of the resource units, which are not utilised by the spectrum licence holders, called as spectrum white holes, and the underlay method represents the use of the spectrum grey holes, which means the sharing of same resources between primary and secondary users- in the transmission band [4].

The hybrid division cooperative transmission (HDCT) is introduced in research [43], which results in enhancement of throughput within femtocell systems. This scheme applies a cooperative transmission (CT) to the users at the edge of the femtocells base stations, whereas the conventional method is applied to the users elsewhere. Applying CT to a user makes it capable to receiving the desired signal from the serving femto base station, as well as from an adjacent femto base station. Therefore the signal to interference plus noise ratio (SINR) of the user would be improved by the two time synchronisation signals from adjacent femto base stations. This performance is evaluated in both the terms of call blocking probability and outage probability.

In research [44], heterogeneous networks are discussed based on random applying of femtocells on a macro network. The femtocells are planned to work as closed cells to evaluate the effects of dominant interference in proximity of the closed cells. The power control of HeNodeBs and using of advanced UEs with capability of operation at low geometries are suggested to mitigate the interference. However in research [45], the authors suggest an advanced solution for macro-femto challenges, by proposing of self-organisation for enterprise femtocells. The investigated SON method is to automatically tune multiple parameters, such as pilot power, resource blocks, radio spectrum and access control, at the cost of complexity in network calculations.

The coexistence of LTE femtocells with the conventional GSM cellular networks is also described in [46]. The performance of the system is evaluated mathematically based on the average SINR. The numerical results confirm that the availability of the spectrum in such systems depends on the number and the position of the femtocells in each GSM cell.

The authors in research [47] present a spectrum sharing scheme in advanced versions of the LTE system by using of cognitive methodologies. They believe that one of the solutions to the spectrum scarcity in LTE-Advanced system is to use the spectrum of digital video broadcasting (DVB) system by adopting spectrum sensing and sharing methods. However the biggest challenge in this solution is the trade-off problem between complexity and detection probability in spectrum sensing schemes. To overcome the challenges, the research proposes a cognitive-based spectrum sharing scheme, including auto-correlation based advanced energy (ACAE) spectrum sensing, as well as spectrum sharing procedure for sharing the spectrum between DVB and LTE-Advanced systems. The Suggested ACAE spectrum sensing method is based on DVB OFDM symbol calculation and decision making, which has lower complexity and higher accuracy. The spectrum sharing part of this strategy, which comes after the spectrum sensing scheme, is evolved and compared with the traditional spectrum sharing methods. Most of the traditional spectrum sharing schemes do not consider the neighbouring cells, which are not allowed to utilise the same frequency simultaneously in mobile communications system. Therefore, for those traditional systems, the spectrum efficiency of spectrum sharing schemes is not very successful. To resolve this problem on the proposed spectrum sharing scheme, the LTE-Advanced cells are separated into three groups based on frequency reuse method (assuming the frequency reuse factor is 3). The spectrum sharing procedure in this work includes spectrum decision, spectrum sharing, spectrum releasing and spectrum mobility. The proposed cognitive based spectrum sharing scheme for LTE-Advanced cells could reach higher performance –by using of ACAE spectrum sensing scheme– as well as better spectrum efficiency and fairness –by the spectrum sharing scheme– in its methodology.

To ease the channel availability variation in LTE-Advanced networks, it has been discussed in research [36] that the multiple-input-multiple-output (MIMO) technology could be applied, as well as proposing the statistical traffic control scheme, that comprise the packet transmission scheduling and the admission control for LTE-Advanced. The result of these applications will be promising a successful coexistence with wireless local area network (WLAN) in Industrial, Scientific and Medical (ISM) radio band. The network MIMO in this work includes a combination of both coordinated multi-point (CoMP) transmissions from multiple LTE-Advanced base stations (eNBs) to one user equipment (UE), and the cooperative relaying by applying multiple relay nodes (RNs) to forward the packet to the UE.

Spectrum aggregation method is also presented in [48], which could be used for dynamic spectrum access cases, by an admission control algorithm and a spectrum assignment strategy taking into consideration both the spectrum aggregation, as well as the channel switch based on the state statistics of each channel. Based on this research, the process of the spectrum aggregation generally contains the following aspects:

(1) Designing of the guard bandwidth between carriers. Reducing the guard bandwidth between the carriers improves the spectrum utilization efficiency.

(2) Selecting of the carrier bandwidths. The parameter called "Bandwidth Factor" indicates the multiple relationships between the bandwidth of the aggregated carriers of LTE. As an example, when the bandwidth factor is 2, one carrier bandwidth is twice as large as the other one. Defining the bandwidth factor could restrict the aggregation methods, but it reduces the complexity of transceivers.

(3) Aggregating of data stream. In this process, each carrier corresponds to an independent data stream. The data stream aggregation scheme could be applied either in MAC or physical layers, but the MAC layer is preferable for the development of spectrum aggregation technology.

(4) Designing of control channels. There are also two alternatives in this case. The first strategy will be based on the controlling process of one channel to the others, and the second strategy is the controlling process of each channel on its data. Comparing these two methods, the second method is preferred, in both cases of power dissipation and costs.

Furthermore, the frequency reuse scheme for OFDMA-based cellular networks resource allocation has been also proposed through the modulation and coding scheme (MCS), resource block (RB) and transmission power (TP), which are independently and dynamically allocated by each cell [31]. As the result, the total downlink transmit power is minimised, while satisfying the users' throughput demands. Furthermore in this method, each cell informs its neighbouring cell about its cell-edge users' allocated RBs, so preventing the other cells to target the same RBs for allocation. The proposed power control scheme is shown to improve 20% on throughput.

The relevant researches in literature review exploit a number of techniques for resource allocation in heterogeneous networks, aiming to plan an interference free network in early stages. The main aim of the existing resource allocation techniques is to use either the power control strategy or the random PRB selection for resource allocation, while fairness in bandwidth splitting among the users is less exploited. Furthermore, the existing techniques mostly focus on interference avoidance in the system, with fewer considerations about network complexity when applying their channel allocation process. This chapter aims to initially propose unique simulation scenarios for macro-femto network architecture including additional network-level hardware, and will be followed by proposing a novel self-organising resource allocation technique to obtain the improved channel optimisation.

3.3. Problem Statement

The proposing of femtocell base stations within a heterogeneous architecture is considered as a fundamental solution to the shortage of network capacity for mobile users [49,50]. The main application of femtocells could be expressed as offloading part of user congestion from the general macrocell base stations, by establishing short-range network spots within the entire network. However, obtaining such a ubiquitous network needs an effective plan for a consistent cooperation between the main macrocell application –defined as the first network tier– and the additional femtocell application –defined as the second network tier– by employing self-configuration techniques. It is very obvious for such a heterogeneous macro-femto network that the available spectrum should be fairly shared between the two network layers, to optimise the available spectrum channels, while simultaneously considering the network capacity issues. This fact shows the necessity of having an intelligent resource management which is able to allocate resources at the right time to the right users. Therefore, the expected challenge for LTE-A macro-femto network is to provide a cooperative resource management, channel allocation and access control for both the groups of macrocell and femtocell users, as is shown in Figure 3-3.

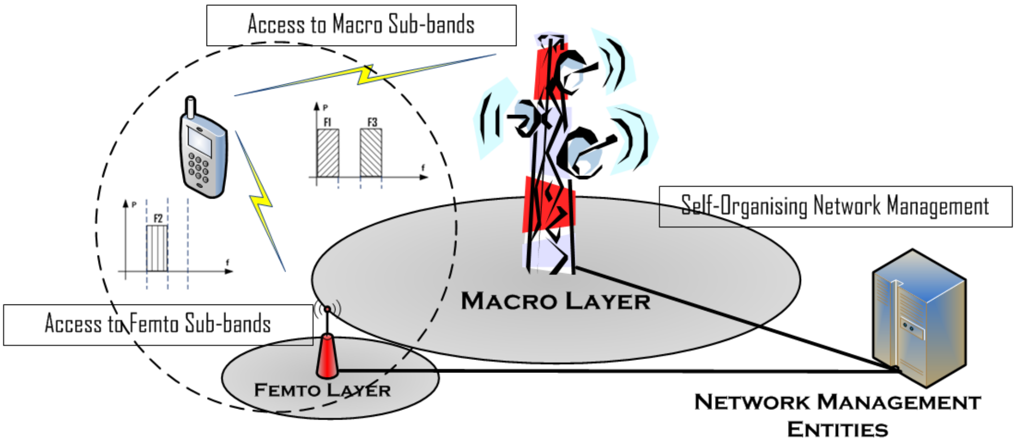


Figure 3-3: Cooperative resource management for a two-tier network

The proposed solution to the above mentioned problem is using of self-organising network (SON) technique to make a network-layer link among the two network tiers. In this solution, S1 and X2 interfaces are used as the links between macrocell stations, femtocell stations, serving gateways and management entities to establish the frequency reuse scheme in cell-edge and cell boundary areas. The co-tier and cross-tier interference avoidance are also considered in this technique while the sub-band allocations are planned in channel allocation. The proposed SON technique has also significant effects in network throughput and delay, as is confirmed by OPNET simulation results, compared to the macro-only network and the existing traditional spectrum management techniques.

3.4. System Model

In homogeneous networks, only a network of macrocells (MeNodeBs) serves the mobile users in each cell. In such networks, the MeNodeBs have similar characteristics, e.g. antenna pattern, transmission power, modulation, access method, etc. The cell splitting seems to be an applicable approach to solve the capacity problems in LTE networks, by allocation of more base stations in the cells. However this approach is not economically feasible in dense urban areas to deploy more number of MeNodeBs within the network. Therefore deploying a two-tier HetNet seems to be an appropriate solution in a cost-effective way for both the network operator and users. The two-tier network contains the macro nodes as the first tier, overlaid with the low-power/low-complexity nodes in the second tier [51].

In this part, the functions of the proposed SON resource management algorithm in macro-femto LTE-A networks are discussed. The application of the proposed resource management technique is to share the available spectrum band among both the macrocell and femtocell layers in a two-tier LTE-A network. In this regard, the additional femtocell sub-network (layer) is added into the existing LTE macro sub-network, followed by the proposed modification in node model of home evolved node-B (HeNodeB) in the network.

3.4.1. Channel Division

In this model, the initial resource channel of the system is divided into two main resource sections, called as “Macro Sub-Channel” and “Femto Sub-Channel” to support macrocell and femtocell users respectively. Each of the network sub-channels includes a number of component carriers (CCs) which are positioned into the spectrum band, as is shown in Figure 3-4.

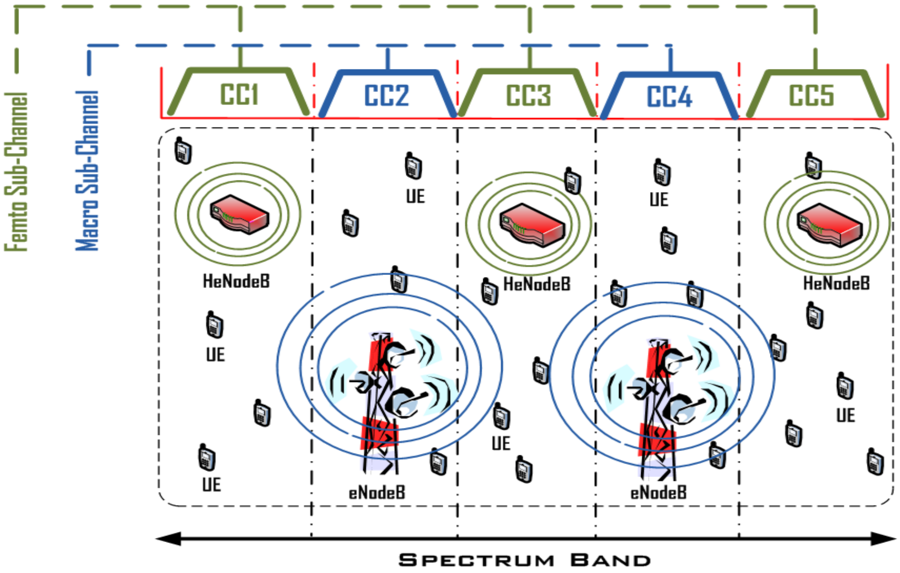


Figure 3-4: Sub-channel allocation for LTE-A macrocells and femtocells

To remove the coverage holes in homogeneous networks, picocells are generally used with a coverage area between 40-75 meters, and an omnidirectional antenna with about 5dBi antenna gain provides indoor coverage to users in public places e.g. schools, airports, etc. [52]. However on the other hand, femtocells with 10-25 meters coverage and 10-100 mW power are used as access points (APs) in home applications, which operate in licensed spectrum that is managed by mobile operators. Femtocells connect to the cellular network via broadband communication links, e.g. digital subscriber line (DSL) to enable fixed mobile convergence (FMC) [53].

3.4.2. Macrocell and Femtocell Air Interfaces

The macro-femto coordination architecture could be defined either within a centralised coordination, or a distributed coordination [54]. In centralised coordination architecture, the channel quality information from different BSs is gathered by a centralised controller. The controller could be part of the radio network controller (RNC) entity in previous technologies like HSPA and UMTS. However, in conventional LTE systems, due to the lack of RNC, this idea has not been applicable.

On the other hand, in distributed coordination architecture, there is direct coordination among the adjacent base stations to allocate appropriate resources to the users, especially the cell edge users, as well as to mitigate inter-cell interference. The coordination is established through the LTE interfaces X2 and S1 in evolved universal terrestrial radio access network (E-UTRAN) platform [55]. The LTE X2 interface is used to make a direct communication between different eNodeBs to exchange signalling information when needed, while a full mesh is not mandated within an E-UTRAN network. The X2 interface is mainly used to exchange two types of information: load/interference-related information and handover-related information. In addition to this, LTE S1 interface is widely used for eNodeBs in SON networks to communicate with the mobility management entity (MME) and serving gateway (S-GW) in the evolved packet core (EPC) unit. Each of the X2 and S1 interfaces are split into two interfaces of control plane, and user plane, which are based on stream control transmission protocol/IP (SCTP/IP), and general packet radio service (GPRS) tunnelling and user datagram protocols (GTP/UDP5/IP) stacks respectively [56]. At the proposed internal interfaces, as shown in Figure 3-5, the X2 interface is used to communicate with the macrocell stations (eNodeBs), but obviously this X2 implementation is not applicable to directly link the femtocell stations (HeNodeBs), because of their diversity and personal indoor implementation.

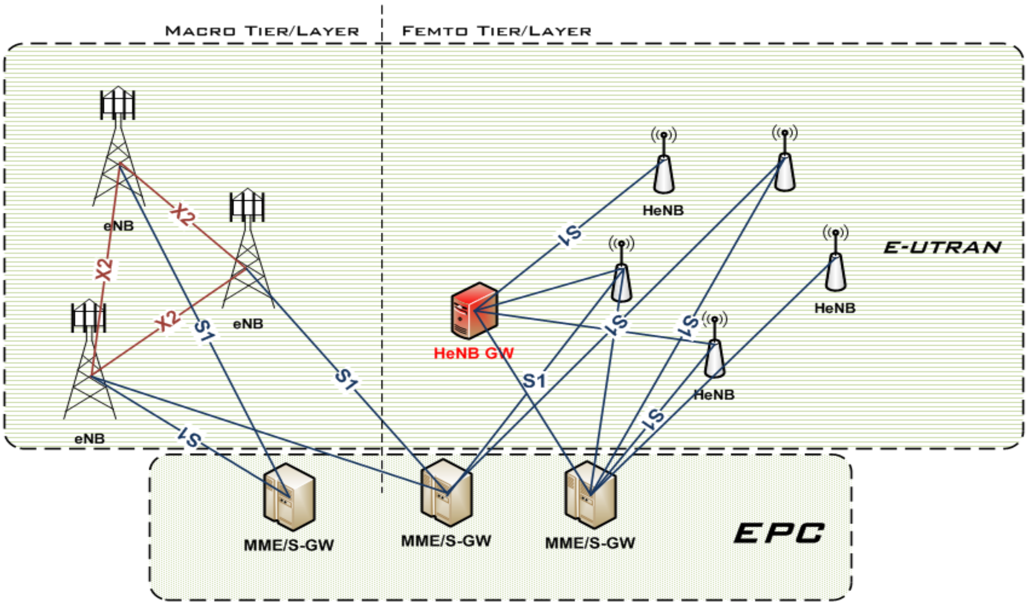


Figure 3-5: Interfaces map for macro and femto tiers in LTE-A network

As a solution to link the fomtocells to the systems, the HeNodeB gateway (HeNB GW) is proposed to be added into the system, as well as the existing MME/S-GW units for the femto tier within EPC. Therefore, the S1 interface is used to initiate communication between HeNBs and HeNB GW, as well as the MME/S-GW units [57]. LTE-A femtocells nodes use orthogonal frequency division multiple access (OFDMA) air interface technology in cooperation with the existing eNodeBs within the HetNets [51].

Figure 3-6 shows the S1 interface set in macro-femto interfaces, including the proposed gateways and units. The HeNB nodes communicate with EPC module via S1-U and S1-MME interfaces, while the HeNodeB gateway and management system entities and serving gateway are relaying the packets from and to the femtocell stations.

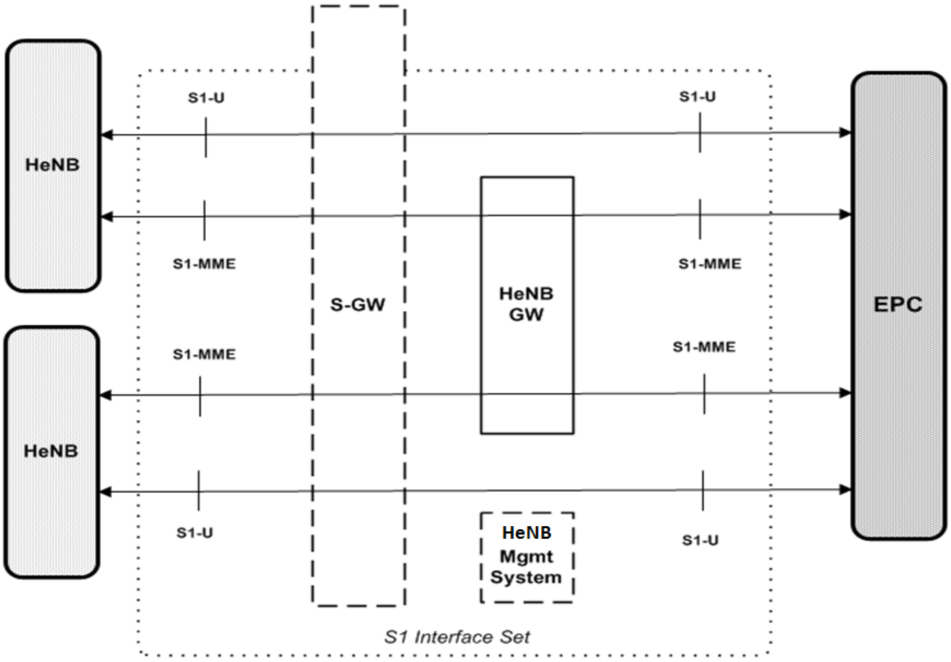


Figure 3-6: The S1 interface set in macro-femto interfaces

3.4.3. Fractional Frequency Reuse

A frequency reuse scheme is introduced as an applicable solution in channel optimisation, while also being the most effective solution in mitigating the effects of interference. All the interference types in this regard happen only when the aggressor node and victim node use the same frequency sub-channel [51]. Therefore, the fractional frequency reuse (FFR) scheme is required for a planned sub-channel allocation among macrocell and femtocell users.

In case of using the frequency reuse scheme for channel optimisation, the main types of interference are categorised into two main categories. The first category is when a femtocell station interferes with another femtocell user, because of using the same sub-band, which is called “Co-Tier Interference”. The second interference category is when a macrocell (or femtocell) station interferes with a femtocell (or macrocell) user because of using the same sub-band, which is called “Cross-Tier Interference”. Figure 3-7 shows the example scenarios of these interference possibilities in frequency reuse. In practical assumptions, because of considering macrocells as long-range base stations, the macro-to-macro co-tier interference is avoided in practice, due to the long distances between the macrocell base stations.

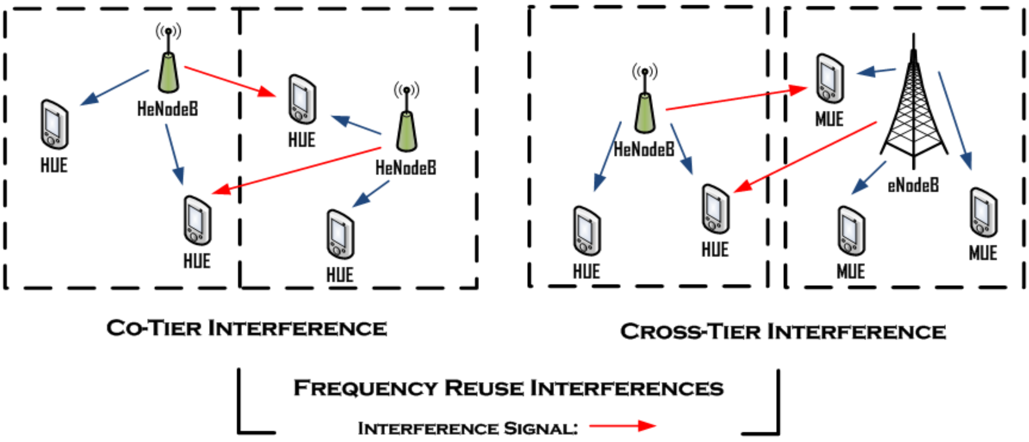


Figure 3-7: Co-tier vs. cross-tier interference in frequency reuse

3.4.3.1. Strict Fractional Frequency Reuse Scheme

To obtain better network optimisation, each cell is divided into two zones called as centre-zone and edge-zone. In strict FFR, for a cluster of N cells, the frequency reuse factor (FRF) of N is applied to edge-zone macro users (MUEs), while the centre zone MUEs are allocated with a common frequency sub-band, i.e. the FRF of 1. Therefore, the total of N+1 sub-bands are required to cover all the MUEs in the cells. Although, the inter-cell co-tier interference is mitigated for eNodeBs in strict FFR schemes, the cross-tier interference would be significant, especially near the transition areas of the centre-zone and edge-zone [51]. In addition to this, the co-tier interference may become severe for HeNodeBs in edge zones, as is shown in Figure 3-8.

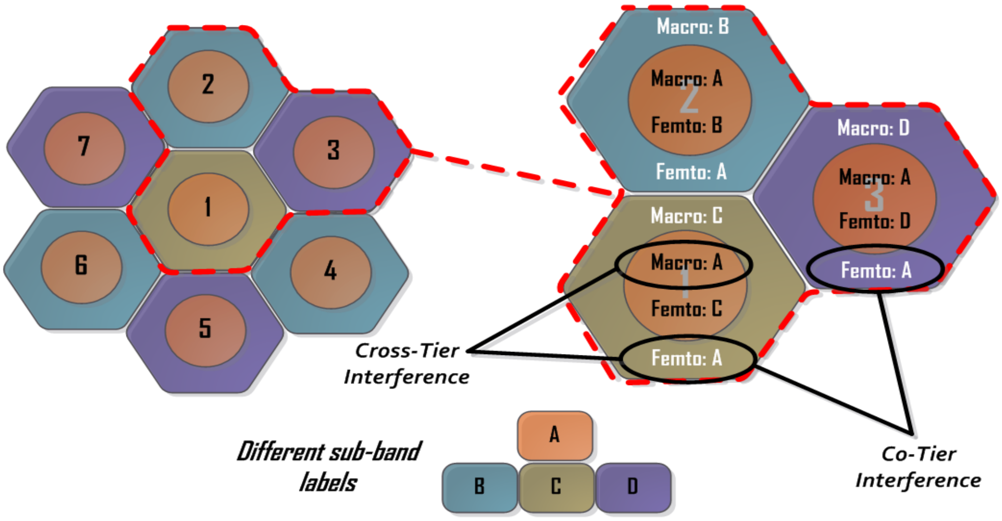


Figure 3-8: Strict fractional frequency reuse scheme

3.4.3.2. Soft Fractional Frequency Reuse Scheme

The cell partitioning in soft FFR is similar to the strict FFR scheme. However in soft FFR scheme the MUEs in the centre-zone are allowed to use the MUE sub-bands of the cell-edge zone of the neighbouring cells. Also for the femtocells, the FUEs in the centre zone are allowed to use the FUE sub-bands of cell-edge zone of the neighbouring cells, if is not used by macros in the same cell-centre. Therefore, the soft FFR scheme is more bandwidth efficient, i.e. has higher spectrum efficiency, in compared to the strict FFR. As a result of having more options in selecting the sub-bands by the nodes, the co-tier interference would be reduced for both macro and femto nodes.

However on the other hand, the cross-tier interference still needs to be mitigated for users near the boundary of the centre and edge zones, as is shown in Figure 3-9. As the different colours show the different combinations of sub-bands for the cell centres and also the cell edges (for macrocell), each of the cell-centre areas is also allocated with a sub-channel from a different sub-band compared to the neighbouring cells, which aims to reduce the drops in QoS by reducing the possibility of co-tier interference with the neighbouring cells.

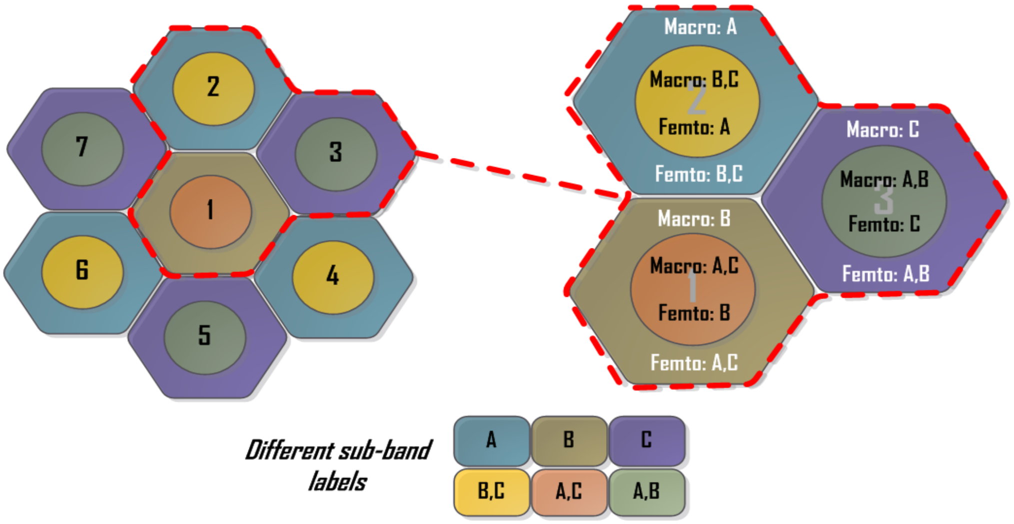


Figure 3-9: Soft fractional frequency reuse scheme

Figure 3-10 shows the sub-channel allocation for the cells 1, 2 and 3, using the power (p) versus frequency (f). It can be observed in this figure, for example in the hexagonal cell 1, both the macrocell in the cell centre and femtocell in the cell edge use F1 and F3 sub-bands, which could result in cross-tier interference, especially in the centre-border transition area. Therefore, it is also required for the sub-channel allocations, even in soft frequency reuse, to consider the cross-tier interference, as well as co-tier interference.

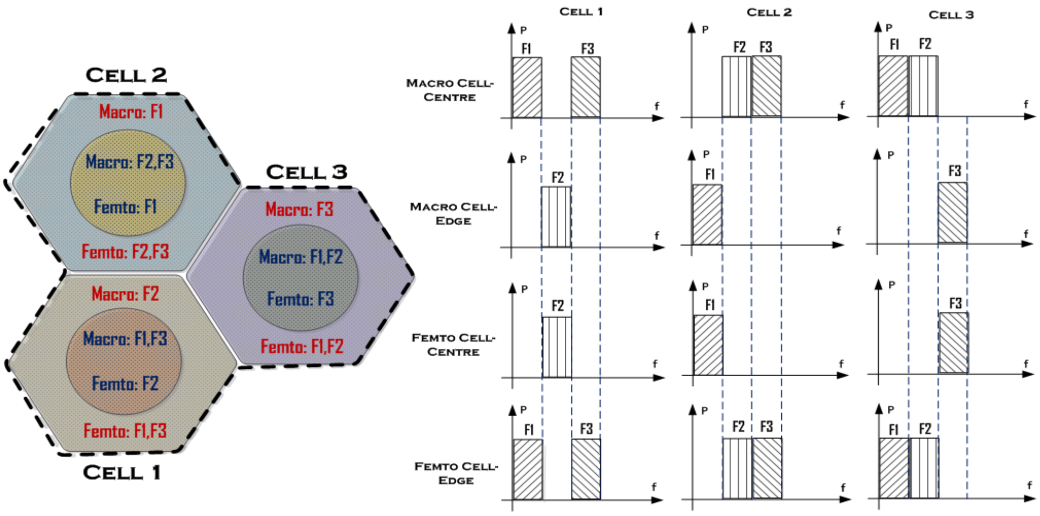


Figure 3-10: Sub-channel allocation function in soft frequency reuse

3.4.3.3. Hybrid Fractional Frequency Reuse (HFFR) Scheme

As is previously discussed in soft FFR scheme, the co-tier interference is reduced due to the dynamic sub-channel allocation, but on the other hand, the cross-tier interference still remains and requires mitigation. Therefore, the hybrid fractional frequency reuse (HFFR) scheme is proposed, which consists of both co-channel and orthogonal deployments for a two-tier network [58].

Figure 3-11shows the orthogonal resource allocation for macrocell and femtocell tiers in the proposed technique. At the first stage, the soft FFR is applied and the cell-centre nodes are allocated with sub-channels from different sub-bands, as well as the cell-edge nodes. In addition to this, the macrocell and femtocell tiers (including the cell-centre and cell-edge users) are allocated with sub-bands in an orthogonal way similar to OFDMA. Therefore, the cross-tier interference is also mitigated when the macrocells and femtocells with the same sub-bands follow the orthogonal allocations.

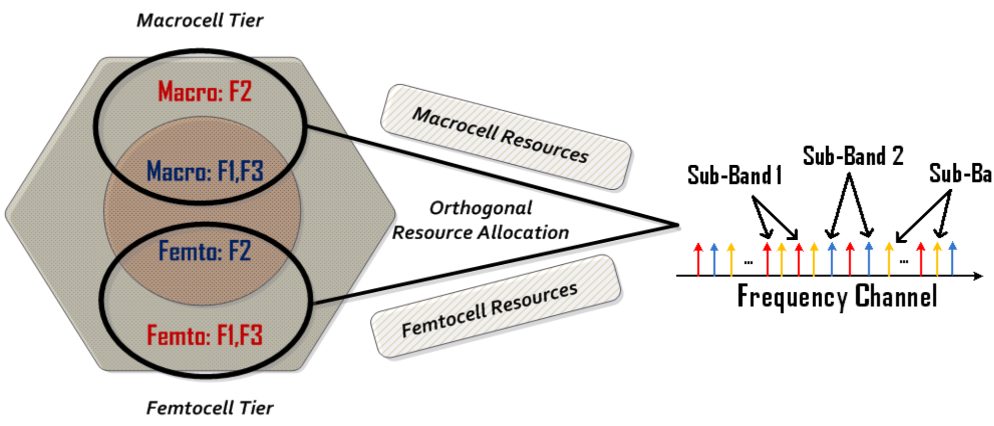


Figure 3-11: Resource allocation for macrocell and femtocell in HFFR

This approach comes from a similar idea in dealing with intra-frequency/intra-cell interference, which is normally avoided inside the cells due to the orthogonality between subcarriers in OFDMA. The quality of some reference signals received by UE also plays a great role in resource allocation of LTE networks. These reference signals in LTE are reference signal received power (RSRP) and reference signal received quality (RSRQ) and each user is assigned part of the spectrum based on these two signals. However RSRQ provides a more effective metric for the complex optimisation of the reference signal, since it is based on SINR [15,59].

The area spectral efficiency (ASE) is used as a tool to determine the FFR threshold distance under multiple parameters, e.g. cell loading, path loss, fading, shadowing, etc. The main aim of using an appropriate frequency reuse scheme is to attain an appropriate resource allocation, which totally results in obtaining improved overall spectrum efficiency in the system. In a static resource allocation for a fully loaded cell, the resource allocation is given as in Equation (3-1) [58]:

$$N = \Delta N_O + N_I \qquad \textbf{(3-1)}$$

In which Δ denotes the reuse factor for fractional frequency reuse for a set of N sub-channels (entire bandwidth), and N_I and N_O sub-bands allocated to the cell centre and cell edge areas respectively. The ASE parameter is defined as the achievable throughput per unit area per bandwidth in *bits/sec/Hz/cell* in the network. Therefore, calculation of the total ASE in two-tier networks is important to analyse the overall network throughput and network capacity. Considering the high power cell edge areas with smaller resource allocation of $\frac{2}{3}N_O$ for our calculations, the ASE for the home user femtocells is calculated as in Equation (3-2) [58].

$$ASE_{femto} = \frac{2N_O}{3N}(\lambda_f^{(CC)} C_{femto}^{(CC)} + \lambda_f^{(CE)} C_{femto}^{(CE)}) \tag{3-2}$$

The intensity of the femtocell base stations in inner cell and outer cell are defined as in the two Equations below respectively:

$$\lambda_f^{(CC)} = \frac{N_{fCC}}{|H_1|} \tag{3-3}$$

$$\lambda_f^{(CE)} = \frac{N_{fCE}}{|H_2|} \tag{3-4}$$

Where the inner circle region of $|H_1| = \pi \mathrm{R}_{th}^2$ and the outer circle region of $|H_2| = \pi(\mathrm{R}^2 - \mathrm{R}_{th}^2)$ are defined for the inner radius or threshold distance R_{th} and cell radius R. Furthermore, $C_{femto}^{(CC)}$ and $C_{femto}^{(CE)}$ are the average capacity of the femtocell users located in the macrocell cell centre and cell edge areas respectively.

On the other hand, the normalized area spectral efficiency for fractional frequency reuse is defined as the average capacity per cluster cell over the cluster size times the total channel times bandwidth. Assuming the three cluster cells with three cell centres and three cell edges, the average ASE for macrocells FFR is given as in Equation (3-5) [58]:

$$ASE_{FFR} = \frac{3.N_I.C_{CC} + 3.\left(\frac{N - N_I}{3}\right).C_{CE}}{3.N} \tag{3-5}$$

Where the ergodic capacity for the fractional frequency reuse cell centre and cell edge are calculated as in the two Equations below respectively:

$$C_{CC} = \log_2(1 + SINR_{CC}) \tag{3-6}$$

$$C_{CE} = \log_2(1 + SINR_{CE}) \tag{3-7}$$

In a multi-tier network with macrocells and femtocells, the total ASE for femtocells inside a fractional frequency reuse macrocell is calculated as in Equation (3-8):

$$ASE = ASE_{FFR} + ASE_{femto} \tag{3-8}$$

In which the average ASE for femtocell in our formulations is calculated based on our assumption to consider the home user femtocells, as the second tier of the network.

3.4.4. Sub-Channel Allocation Mechanism

The proposed SON resource allocation module is implemented in femtocell node model in OPNET, as is shown in Figure 3-12. The node model includes media access control (MAC), address resolution protocol (ARP), internet protocol (IP) entities, e.g. TCP, UDP, RSVP, etc. and antenna modules.

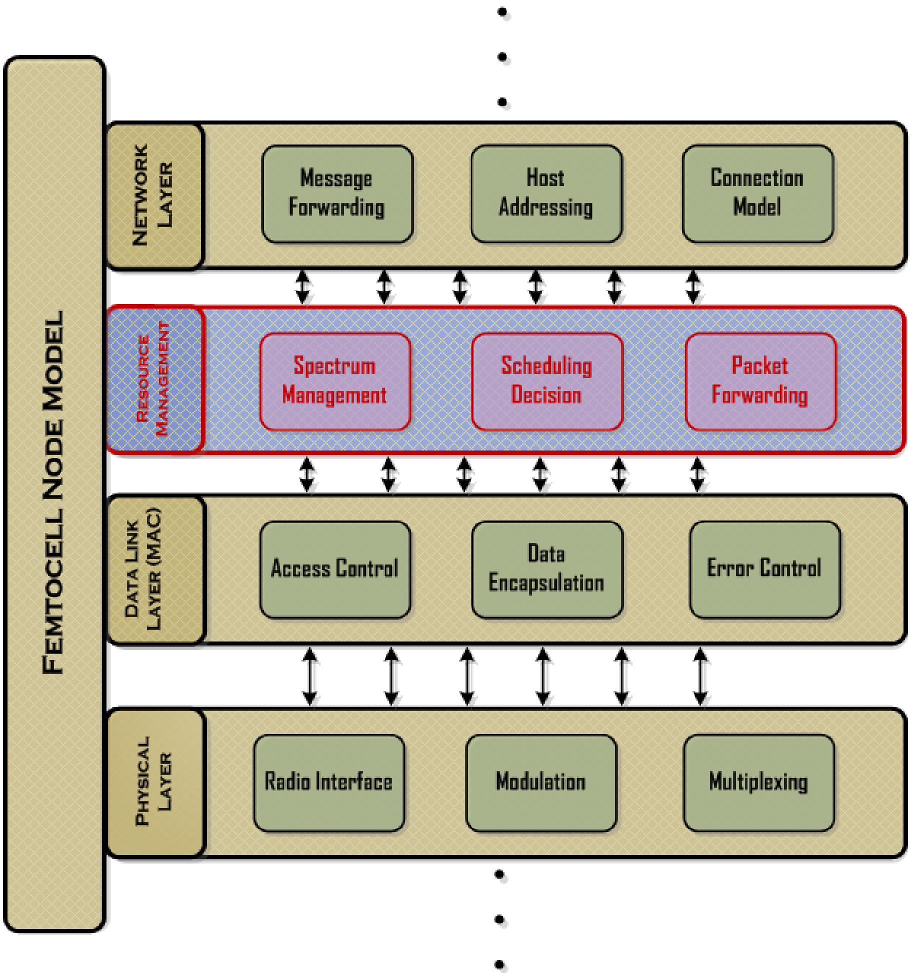


Figure 3-12: Proposed resource management module in femtocell node model

The proposed resource management module is located between the MAC and ARP modules in the HeNodeB node model, to transmit and receive packets through its process model and apply management, scheduling and channel allocation tasks as follows:

Spectrum Management: Obtain the channel information from MAC layer and find out about the available resources;

Scheduling Decision: Make decision for the best available packet transmission considering the frequency sharing issues;

Packet Forwarding: Forward the packets to the appropriate destinations in the network layer;

The process flowchart of the self-organising scheduling decision system for resource allocation is shown in Figure 3-13.

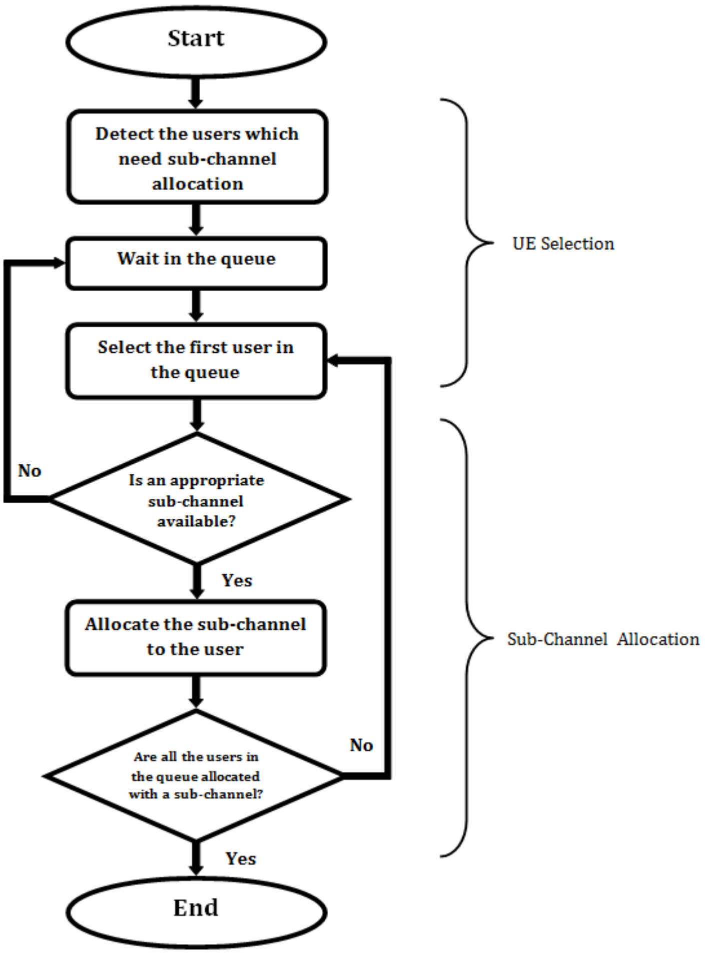


Figure 3-13: The self-organising resource allocation flowchart

The process is dependent on the sub-channel availability and network user satisfactions to allocate the available sub-channels of the shared spectrum band. The proposed model for resource allocation is implemented in OPNET network simulator and described in later sections, based on application definition, user identification and sub-channel allocation. Figure 3-14 shows the pseudo code for the presented resource allocation algorithm. The process details and specifications is defined later on and are based on different application configurations for the macro-femto network. The SON resource allocation algorithm is inherently based on fractional frequency reuse scheme, while considering the other required transmission issues, such as the different types of applications, as well as the users' demand for each of the configured applications.

```
1.  start
2.  // Data arrival
3.  receive data from HeNB GW unit
4.  //Application classifications for different users
5.  define the apps. on Application Config and Profile Config
6.  // UE request for coverage
7.  New/existing UE is added and waits on the queue
8.  // Hybrid fractional frequency reuse
9.  if free sub-channel available then
10. select the first UE in the queue
11. transmit the configured data to the selected UE
12. else
13. return to cmd. 7
14. end if
15. return
```

Figure 3-14: The proposed resource allocation process

The main aim of the proposed algorithm is to share the spectrum in an interference-free network among macrocell and femtocell users, which is approached by applying of this technique into the femtocell node model.

3.5. System Implementation

In this section the proposed resource allocation technique is implemented into the system by creating a number of different simulation scenarios in OPNET modeler.

Firstly a brief introduction to OPNET modeler network simulator is made, followed by the applied configurations and adjustments for each of the presented scenarios.

3.5.1. Network Simulator Software

The proposed sub-channel allocation and access control technique is applied into a two-tier LTE-Advanced platform with macrocell and femtocell applications. A number of different scenarios in this regard are implemented in OPNET modeler software version 17.5 (64-bit) to evaluate the network performance with and without the proposed SON technique. OPNET modeler consists four functional layers of: Network Layout, Node Model, Process Model and C++ Codes at the inner layer for network function blocks and executives, as is shown in Figure 3-15. The new versions of modeler also support LTE network functionalities by providing LTE node models and applications, such as file transfer protocol (FTP), voice over internet protocol (VoIP), video conferencing, etc., as well as LTE terrain configurations, e.g. propagation models, pathloss, fading, etc.

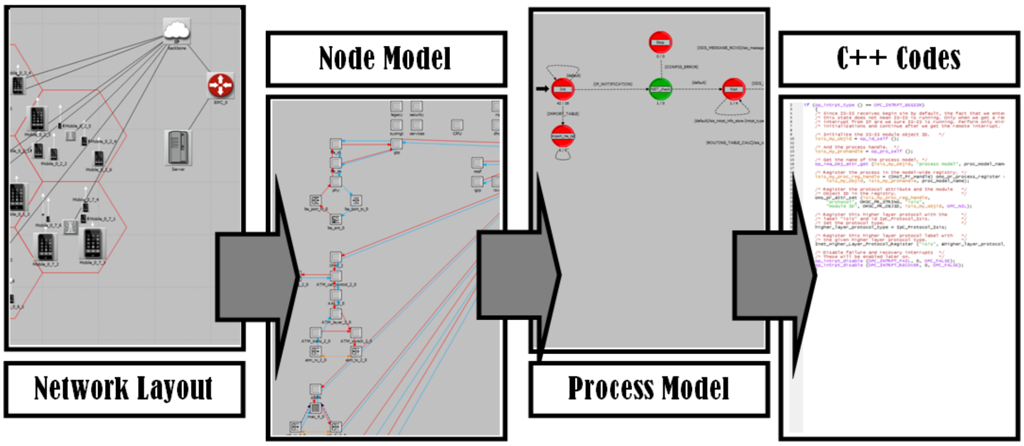


Figure 3-15: Simulation layers in OPNET modeler network simulator

Our network implementation is made by performing our algorithm development in all the four simulation layers. Firstly the initial network layout is planned based on the network specifications, such as the base station types, users' trajectories, communication links and terrain customization. As the second step, the required node models are modified based on each project's expectations and the proposed algorithm. The modifications may include additional module insertion, while carefully considering the open system interconnection (OSI) model for each node model.

The process model also needs modifications by creating the required Enter and Exit Executives and conditions according to the higher layers input and output variables. The inner layer, which contains C++ codes are located in process model executives, as well as model blocks, i.e. termination, diagnostic, function and header blocks and also temporary and state variables.

3.5.2. Simulation Scenarios

The general simulation parameters are defined as in Table 3-2, which remains constant in all the scenarios. All the users are defined with random movement trajectories within their allocated cell areas, without exceeding their boundaries.

Table 3-2: General parameters in the simulation scenarios

Macrocell Parameter	**Simulation Value**
Number of Cells	*7*
Macro Cell Radius	*100 meters*
eNodeB Max. Transmission Power	*41 dBm*
HeNodeB Max. Transmission Power	*21 dBm*
Carrier Bandwidth	*20 MHz*
Duplex	*FDD*
LTE Frequency Band	*1*
Uplink Access	*SC-FDMA*
Uplink Frequency	*1920 MHz*
Downlink Access	*OFDMA*
Downlink Frequency	*2110 MHz*
Propagation Model	*HATA-small city*
Pathloss Model	*Pedestrian-Urban Macrocell (3GPP)*
Shadow Fading	*Urban Macrocell (3GPP)*
MUE Mobility	*Random*
MUE Speed	*1 m/sec (3.6 Km/h)*
Number of Tx and Rx Antennas	*2×2*
eNodeB Antenna Gain	*15 dBi*

In our simulation, a two-tier LTE-Advanced network is simulated in OPNET modeler through three different scenarios. The preliminary LTE-A network scenario contains seven hexagonal cells, six of which with one macrocell base station, called as evolved NodeB (eNodeB), and six macro users, called as mobile user equipment (MUE). The central hexagonal cell in this scenario exceptionally covers eight MUEs to perform different applications. The femto tier will be later added into the existing macro tier in next scenarios.

In the next scenarios the femto tier will be inserted into the system to cooperate with the existing macro-only network. This network tier includes four femtocell stations which are located in an indoor area, each of which supporting three indoor users. The last scenario then applies the proposed sub-channel allocation technique into the two-tier network to evaluate the network performance in capacity and QoS.

3.5.2.1. Applications' Specification

The following sections present the configured parameters and attributes for each network application. Each application is defined with a common value called: "Type of Service" or ToS. As an upgraded redefinition of ToS in wireless communications, "Differentiated Services Code Point" or DSCP parameter is being used as a simple mechanism to classify and manage the applications' traffic, as well as providing QoS expectations in the network. It provides low-latency in the critical network applications, e.g. VoIP and video conferencing, as well as providing best-effort service to the other applications, e.g. FTP and Email. Among the different types of DSCP in OPNET, the applications in our simulation are configured with expedited forwarding (EF) type of service, which presents low loss and low transmission delay as the valuable advantages for real time applications.

The value of "Traffic Mix" is also configured in the simulation to adjust the user behaviour activities within the network, which form the traffic model. The following descriptions illustrate the adjusted attributes for the expected QoS in each of the simulated network applications:

VoIP Traffic Configuration: The voice over IP (VoIP) traffic is configured with the GSM enhanced full rate (GSM EFR) encoder scheme, which is a speech codec working with 12.2 kbit/sec data rate and provides a wire-like condition in different background noise conditions. The DSCP type for the voice application is configured to EF, as was explained earlier.

Application Parameter	**Configured Value**
Voice Frames per Packet	1
Encoder Scheme	GSM EFR
Differentiated Services Code Point (DSCP)	Expedited Forwarding (EF)
Traffic Mix (%)	All Discrete
Conversation Environment	Land phone – Quiet room

FTP Traffic Configuration: The file transfer protocol (FTP) traffic in the simulation scenarios is configured with the file size of 1.5 Mb per each transmitted file. The percentage of download to upload in FTP is denoted by a value called “Command Mix”. In this simulation, this value is adjusted to 100%, which means that the application is configured to only perform the FTP download. The “Inter-Request Time” value is only 1 second, means that the application sends the next file download request only one second after finishing the current file downloading.

Application Parameter	**Configured Value**
Inter-Request Time (seconds)	Constant (1)
Command Mix (Get/Total)	100%
File Size (bytes)	Constant (1500000)
Differentiated Services Code Point (DSCP)	Expedited Forwarding (EF)

Video Conferencing Traffic Configuration: The video pixel size of 128×240 pixels is defined for the simulated video application for frame inter-arrival time of 15 frames per second. The type of service in video conferencing application is also defined by DSCP parameter, which is set to expedited forwarding.

Application Parameter	**Configured Value**
Frame Size Info. (bytes)	128×240 pixels
Frame Inter-arrival Time Info.	15 frames/sec
Differentiated Services Code Point (DSCP)	Expedited Forwarding (EF)
Traffic Mix (%)	All Discrete

HTTP Traffic Configuration: The hypertext transfer protocol (HTTP) is the communication protocol for World Wide Web. Hypertext is structured text that uses logical links between nodes containing text. The HTTP page values are configured as constant values, shown on the table, for the simulation scenarios.

Application Parameter	**Configured Value**
HTTP Specification	HTTP 1.1
Page Inter-arrival Time (seconds)	constant (120)
Page Object Size	constant (500)
Number of Objects (per page)	constant (1)
Differentiated Services Code Point (DSCP)	Expedited Forwarding (EF)

Email Traffic Configuration: There is a separate application type for email traffic in OPNET modeler simulator. As shown in the table below, the application inter-arrival times are configured as constant values and the email size is 1Mbytes per email to be defined for the configured users.

Application Parameter	**Configured Value**
Send Inter-arrival Time (seconds)	constant (120)
Receive Inter-arrival Time (seconds)	constant (120)
E-Mail Size (bytes)	constant (1000)
Differentiated Services Code Point (DSCP)	Expedited Forwarding (EF)

3.5.2.2. Macro-Only Scenario

The general and common parameters between all the scenarios are already configured in Table 1 to be set for all our simulation scenarios. The first scenario is to evaluate the overall network performance within a LTE-A network with macrocell implementation. The network layout of the first scenario in OPNET modeler is shown in Figure 3-16. The eNodeB in the centre hexagonal cell is configured with a number of different applications for each macro user, as is already described. There are a total of eight macro users (MUEs) in the centre cell, of which three are configured with VoIP application, two users are configured with a FTP application and each of the three remaining users are configured with video conferencing, HTTP and email applications. It has been decided to implement only one cell with application profiles, to reduce the simulation run-time latency, due to the additional functions of application and profile configuration units.

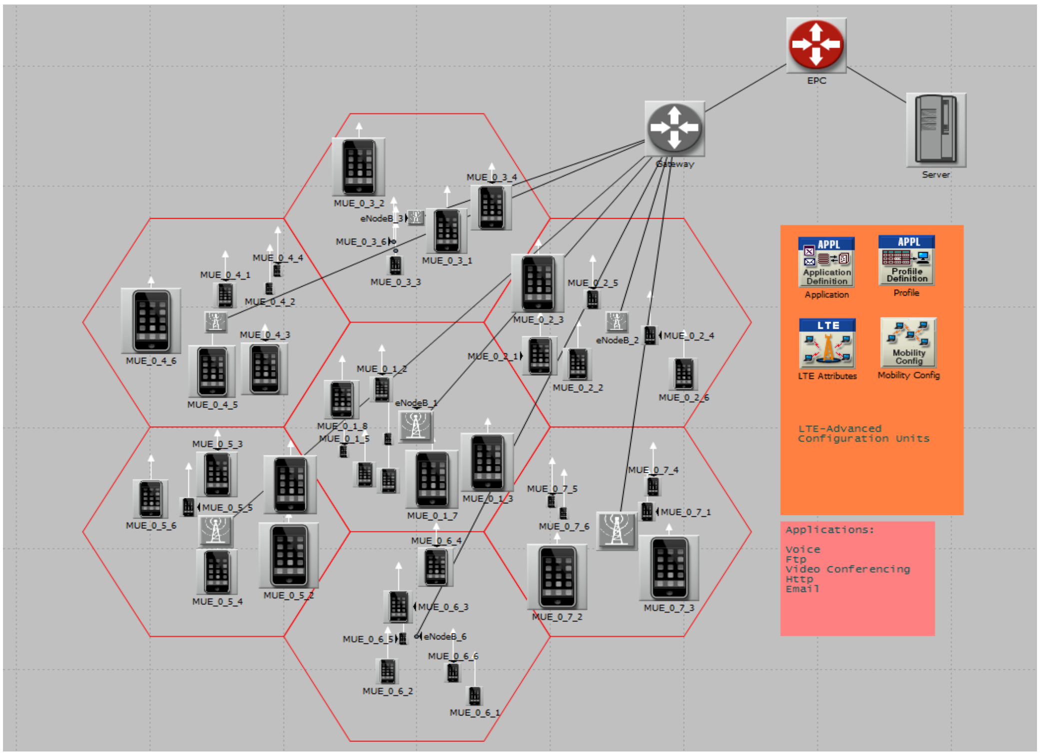


Figure 3-16: LTE-Advanced macro-only scenario in OPNET modeler

In absence of the femtocell tier, the eNodeBs are connected to the router via point-to-point protocol (PPP) link, which is configured as synchronous optical networking (SONET) with an optical carrier of OC-192. The transmission speed of this transmission line is up to 9.953 Gbit/sec, so it is a good option to be implemented in high data rate applications and networks. The Gateway unit is linked to the evolved packet core (EPC) unit, which is the core network in LTE systems and contains the network elements, i.e. mobility management entity (MME), serving gateway (S-GW), packet data network gateway (PDN-GW), and home subscriber server (HSS). The Server, Application and Profile configuration units are used to define the application specifications on the selected cells and users, and LTE Attributes and Mobility configuration units are responsible for general LTE and mobility configurations in the network respectively.

Figure 3-17 shows the adjusted node model for eNodeB base stations. The designated eNodeB structure includes Ethernet and PPP ports in the physical layer to provide capability of communication to the servers by Ethernet and optical fibre links. The LTE-Advanced coverage is also provided by LTE antenna (with 15 dBi antenna gain) and Rx/Tx ports.

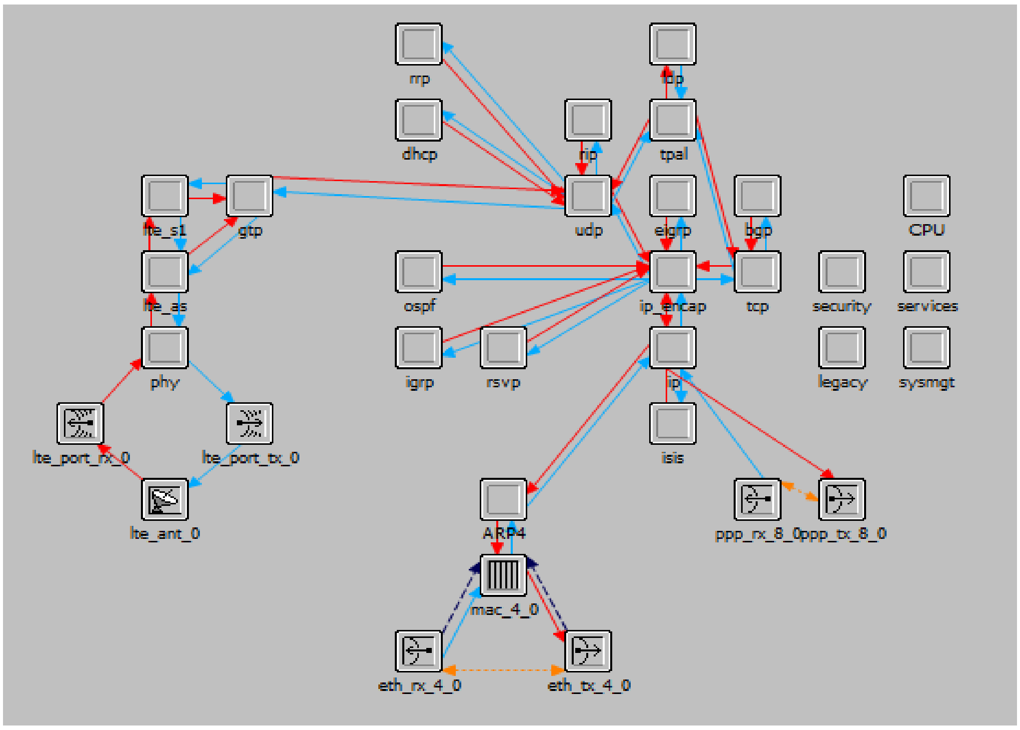


Figure 3-17: The eNodeB node model and internal communications

3.5.2.3. Macro-Femto Scenario without Resource Allocation

The second scenario in our simulations is to add the second network tier into the existing macro network to see its effects on packet transmission while still not using the proposed channel allocation algorithm. Four HeNodeB base stations are placed inside the centre of the network coverage area near to the cell borders. The femtocells are configured to work in closed subscriber group (CSG) mode while each of them covers three femto users (FUEs) in their indoor areas. The users located in the cell-edge areas are the main victims for inter-cell interference because of their proximity to the other cells, as well as their greater distance to the covering macrocells, compared to cell-centric users.

Therefore, it is more logical for the location of the implemented femtocell to be in the cell-edge areas, firstly to mitigate the coverage holes, and secondly to examine the interference possibilities. Figure 3-18 shows the LTE-A macro-femto network in the second simulation scenario.

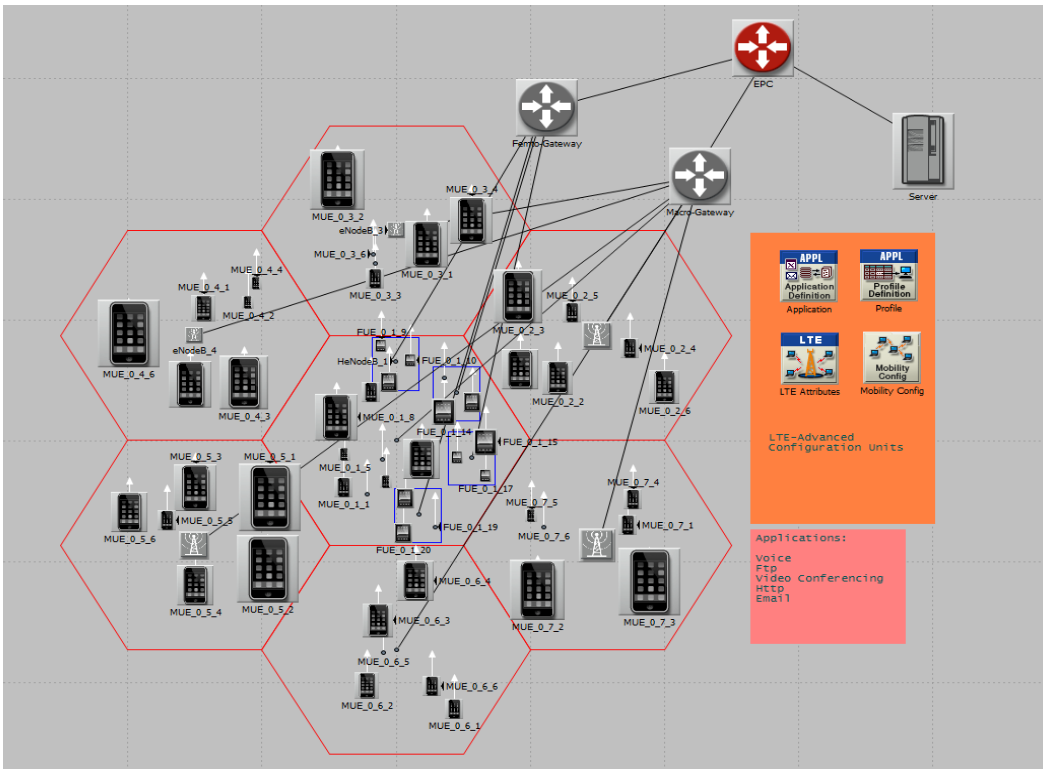


Figure 3-18: The heterogeneous macro-femto network scenario

The designated HeNodeB node model is shown in Figure 3-19. This node model contains Ethernet and PPP ports to link to the serving gateways, as well as femtocell wireless port named as *femto_port_rx* and *femto_port_tx* for indoor coverage. The node model is planned with no resource management module and the scenario is designed to provide femto access to the additional femto users via femto_gateway and core network in higher simulation layer. In this case, the *ARP* module in the network layer obtains the process information from the higher *IP* module and conveys the information to the lower layer modules (*MAC*). The *MAC* module is then responsible to access the femtocell configuration attributes, reading the value of physical characteristics, and also creating the appropriate *MAC* process model [60].

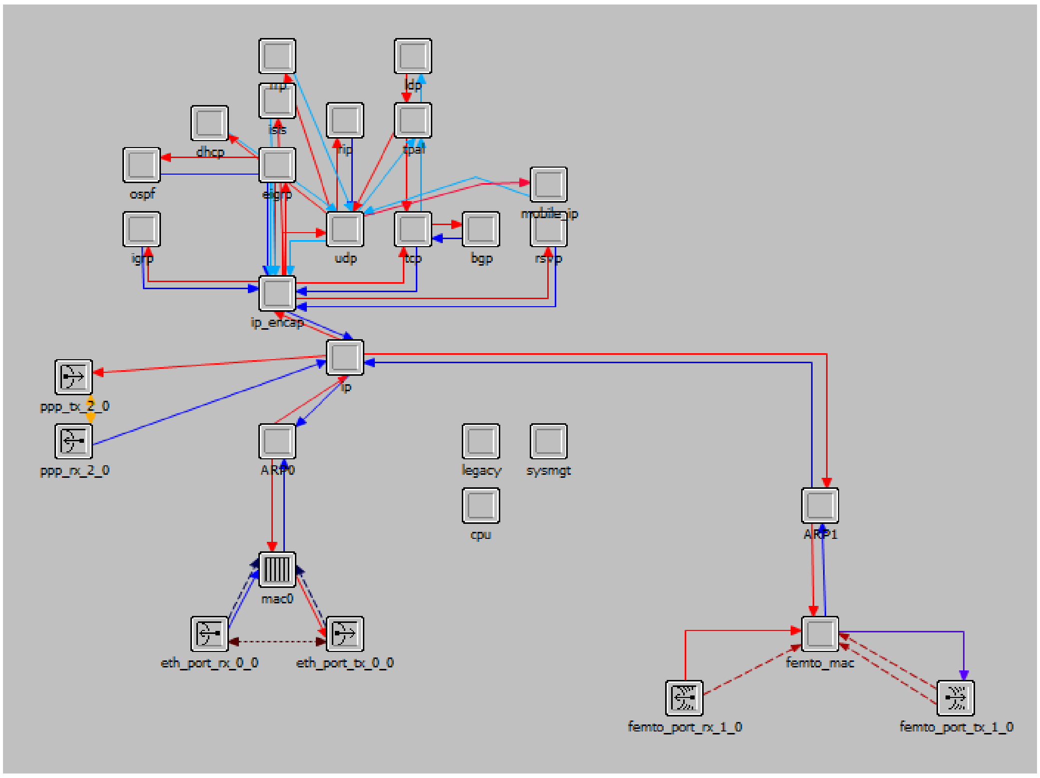


Figure 3-19: The HeNodeB node model and internal communications

The defined processes for each node model are set by their built-in process models in an inner simulation layer. The raw bits are transmitted through the communication links to arrive into the physical layer, which provides the electrical and mechanical interfaces, as well as the required procedures to the transmission medium. Furthermore, the physical functions such as interfacing with MAC sub-layer, character encoding and decoding, modulation and multiplexing are performed at the physical layer. Nevertheless, the internal packet transmission and decisions are made inside the MAC and Network layers by performing the access control and message forwarding processes respectively (Figure 3-12). To implement the SON sub-channel allocation mechanism into the system, the femtocell node model is required to be enhanced with an additional resource management module in connection with MAC and Network layers. For this reason, the next section presents the third simulation scenario with our configured eNodeB and HeNodeB models, while proposing a novel resource management module, implemented in HeNodeB node model.

3.5.2.4. Macro-Femto Scenario with SON Resource Allocation

Figure 3-20 shows the macro-femto scenario, in the presence of the proposed resource management technique.

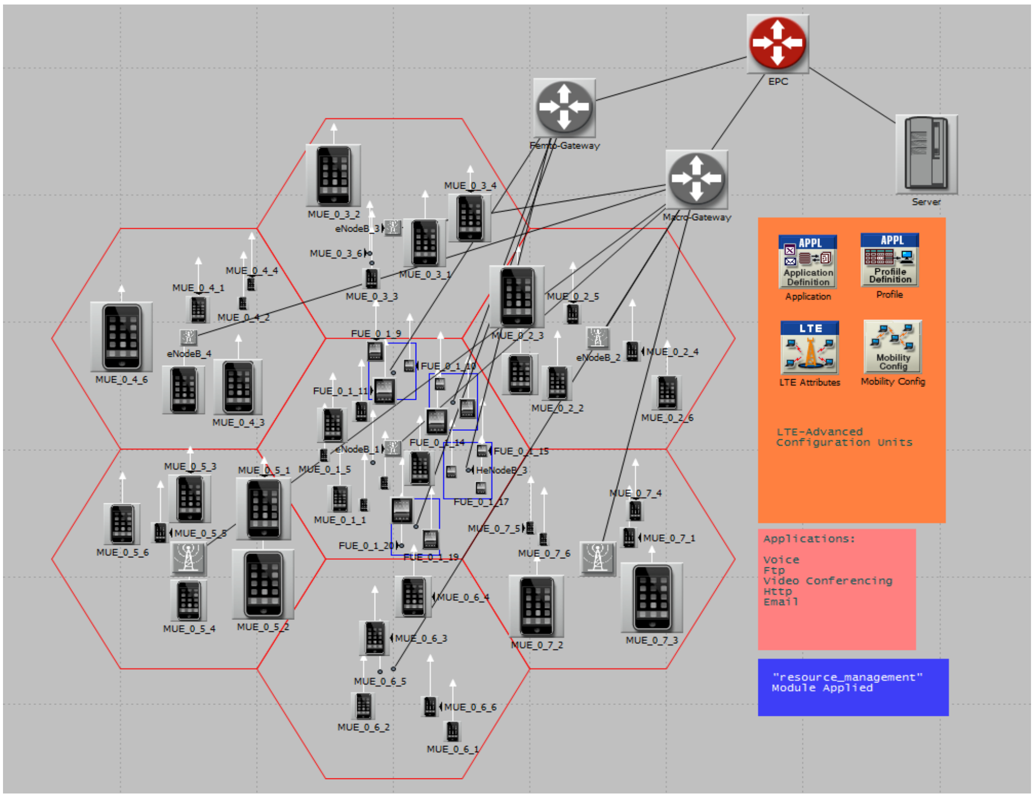


Figure 3-20: The macro-femto network scenario with sub-channel allocation

The additional HeNodeB base stations are located and configured with femtocell functionalities similar to the previous scenario, to cover their indoor users, but the resource management module is inserted into the system by modifying the HeNodeB node model.

The network QoS parameters of this scenario are examined and compared to the other scenarios to evaluate the effects of the proposed sub-channel allocation in conjunction with node configurations. The HeNodeB with the SON sub-channel allocation contains additional *resource_management* module, which is linked to *femto_mac* and *ARP1* modules in its node model, as shown in Figure 3-21. The *resource_management* receives the MAC and packet information from the *femto_mac*, and applies the channel scheduling and management. Next, the user group ID and channel details are forwarded to the *ARP1* to be prepared for message forwarding to the higher layers.

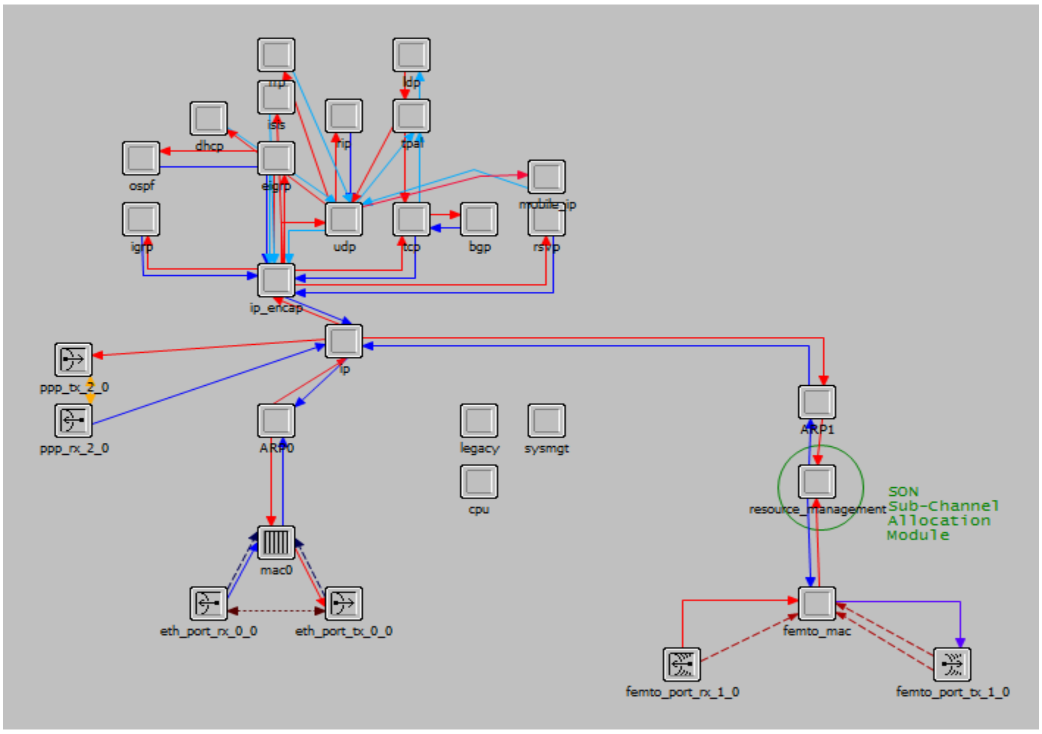


Figure 3-21: The HeNodeB node model with the SON sub-channel allocation

The resource management process model includes forced and unforced states for initialization, management, allocation and packet arrival, which is shown in Figure 3-22.

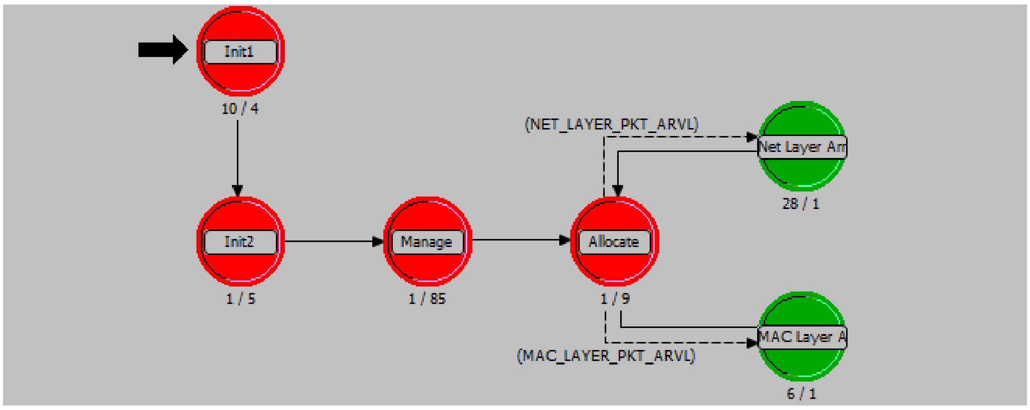


Figure 3-22: SON sub-channel allocation process model

In this model the "*Manage*" process obtains channel information and initiates the sub-channel allocation process, and the "*Allocate*" process is responsible to initiate packet forwarding for the mac and network layers. The "*Net Layer Arrv*" and "*MAC Layer Arrv*" act as the gates for packet arrival from the network layer and MAC layer modules in the node model respectively.

3.6. System Analysis

This section presents the system analysis for the configured scenarios to evaluate the network statistics, while applying different approaches in dealing with macrocell and femtocell coordination. Prior to the result comparisons, the standard deviation for statistical evaluation of the results is described as the utilised process for result estimations and presentation.

3.6.1. Standard Deviation Method for Simulation Results

The OPNET simulation results for each individual scenario have been performed with several runs using different seeds to obtain the most accurate estimation of values. The different seeds in the simulation runs produce different sequences of random numbers, thus resulting in different network configurations [60]. Therefore, using different seeds in network simulations means that the carefully defined parameters by the system (e.g. the random user movements) are randomly configured with a different value in each simulation run. In our simulations, each scenario is defined with 5 seed values, so each simulation is repeated 5 times with different seeds. The results preparation is then performed by using of "Standard Deviation" method and confidence interval for the obtained results.

The standard deviation method calculates the amount of dispersion or variation from the average, which make more clear observation about the results variety for a specific parameter. If $x_1, x_2, x_3, \ldots, x_N$ would be a set of the observed results (population), the average (mean) value of the samples is calculated by Equation (3-9).

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3-9}$$

And the variance of the samples is also calculated as:

$$s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 \tag{3-10}$$

In this regards, the standard deviation value of the chosen samples is calculated by taking square roots from the variance, which is called as corrected sample standard deviation:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{3-11}$$

To demonstrate the accuracy range of the presented samples in its wider population, the "Standard Error" is calculated from the obtained standard deviation, and then the error bars are plotted for each result along with the mean value of the extracted results. The standard error ($SE_{\bar{x}}$) calculation is derived as in Equation (3-12).

$$SE_{\bar{x}} = \frac{s}{\sqrt{N}} \tag{3-12}$$

In case of normal distribution of the results, different values of "Confidence Interval" could be considered to calculate the upper and lower levels of the mean. For more accuracy of the results, the confidence interval (CI) is considered, as measure of reliability in our estimation. In our simulations, the confidence interval of 95% is considered. According to the central limit theorem (CLT) [61], 95% of the area under a normal curve lies within about roughly 1.96 standard deviation of the mean, as is shown in Figure 3-23.

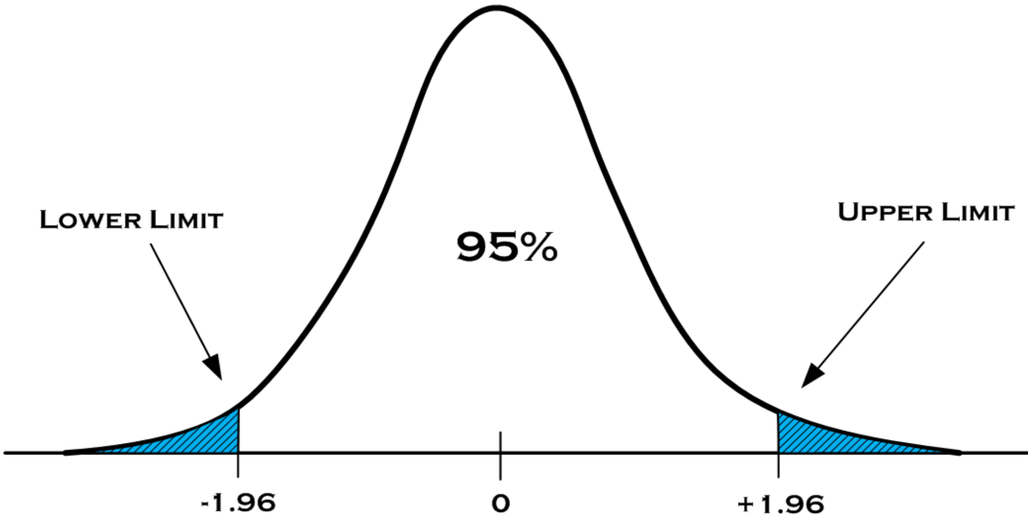


Figure 3-23: Normal distribution for confidence level of 95%

To apply the confidence interval on standard error values, the upper and lower 95% limit values can be calculated by considering of ±1.96 as the coefficient of the standard error:

$$\text{Upper 95\% limit} = \bar{x} + (SE_{\bar{x}} \times 1.96) \tag{3-13}$$

$$\text{Lower 95\% limit} = \bar{x} - (SE_{\bar{x}} \times 1.96) \tag{3-14}$$

Considering the above explained calculations for the standard deviation method, the exported results for each statistic in the simulation scenarios are then plotted in the format of mean value, standard error and confidence interval as is shown in Figure 3-24. The error bars in our figures represent the upper and lower 95% limit, as the maximum and minimum values of results distribution.

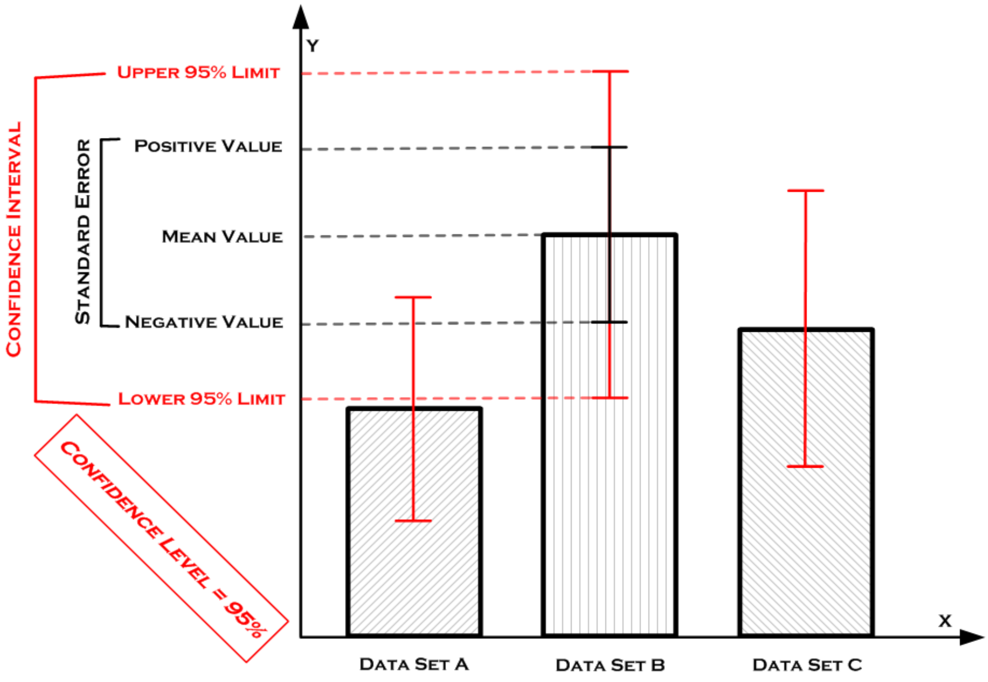


Figure 3-24: Mean value, error and confidence interval in results analysis

3.6.2. Simulation Results

The exploited simulation results for the presented macro-femto heterogeneous network are analysed for the five applications of Voice, FTP, Video, HTTP and Email, all in 5 seeds with confidence interval of 95% in the error bars. The proposed sub-channel allocation technique is applied in the last scenario, the desired statistics are extracted, and the results are compared to the two previous scenarios, with no femtocell and with no resource management respectively. To evaluate the effects of resource management objectives, e.g. spectrum management, scheduling decision and packet forwarding, the following global and node statistics are chosen to be circulated by the network simulator:

Block Error Rate (BLER): The ratio of the number of erroneous blocks to the total number of blocks in transmission, in percent (%).

Signal to Interference plus Noise Ratio (SINR): The ratio to show the level of the useful signal to the level of background noise, including the received interference, in decibels (dB).

Total Throughput: The rate of successful messages delivery in time within the network, in megabits per second (Mbits/sec).

End-to-End Delay: The actual time needed by a packet to be transmitted to the destination across the network, in seconds (sec).

Figure 3-25 shows the block error rate values for the configured applications with 95% confidence interval. The comparison is made between the three scenarios of macro-only network and macro-femto network with and without the proposed resource management technique. The mean values of BLER are collected from the steady state average graph for each simulation seed to reflect the overall number of erroneous blocks in the network, independent to the simulation time and users' random trajectories.

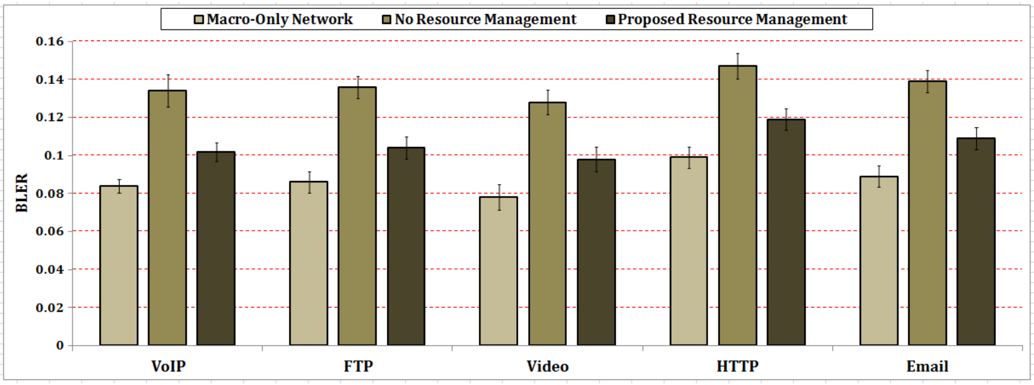


Figure 3-25: BLER values for different applications in simulation scenarios

As is clear in this figure, the lowest BLER value belongs to the macro-only scenario as the ideal case, because of its interference-free network and so there are the least number of blocks in error. When the femtocells are added into the system the number of erroneous blocks rapidly increases due to the lack of channel sharing plan in the second scenario. Nevertheless, the values of BLER become improved when the same macro-femto cooperation is supported by the proposed resource management technique, due to its channel sharing and lower dropped packets between macrocells and femtocells.

The improvement of BLER in the scenario with the proposed resource management compared to the scenario without resource management are as 23.88%, 23.52%, 23.43%, 19.04% and 21.58% for VoIP, FTP, Video, HTTP and Email applications respectively. The values of standard error in some cases are higher, which means the biggest range of results for different simulation runs for each application. In LTE systems, the value of signal to noise ratio (SNR) play a great role to evaluate the quality of signal in presence of its accompanying obstructions e.g. background noise, interference, signal jammers, etc. To include the drawbacks of interference in this evaluation, the value of signal to interference plus noise ratio (SINR) is calculated in LTE systems, which is the fraction of the power of transmission signal over the power of interference and background noise. However in OPNET statistics, the value of interference is included inside the noise value, and therefore the total value of SINR is same as the value of SNR in our calculations. Figure 3-26 shows the SINR comparison for the configured applications and three presented scenarios with the same 95% confidence interval.

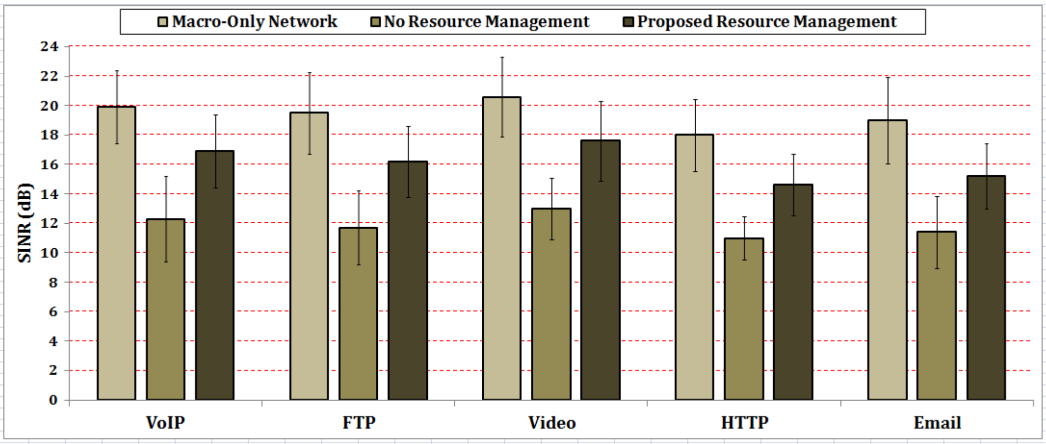


Figure 3-26: SINR values for different applications in simulation scenarios

The values of SINR is expected to be the reverse of the BLER values, as the bigger erroneous blocks results a clear drop in SINR fraction. The improvement of SINR in the scenario with the proposed resource management compared to the scenario without resource management are as 37.39%, 38.46%, 35.38%, 32.72% and 33.33% for VoIP, FTP, Video, HTTP and Email applications respectively. The throughput results are collected to reflect the rate of successful message deliveries over the entire network as a focused evaluation on the network capacity with femtocell users. Figure 3-27 shows the trend of the total throughput when more number of users are attracted to the femtocells in an open access mode. The users and their serving HeNodeBs are randomly selected and the eNodeB stations continue to transmit to the users. In some points the throughput degradation could be noticed as drops in the graph, which is due to the temporary bandwidth shortage for the femtocell users, while sharing the channel with macrocells. As an overall view, the throughput value and capacity for the proposed resource management is improved compared to the traditional macro-femto cooperation. On the other hand, the throughput for Video Conferencing and VoIP applications have higher values compared to the other applications, as the packet transmission for these applications is bigger during a constant period of time.

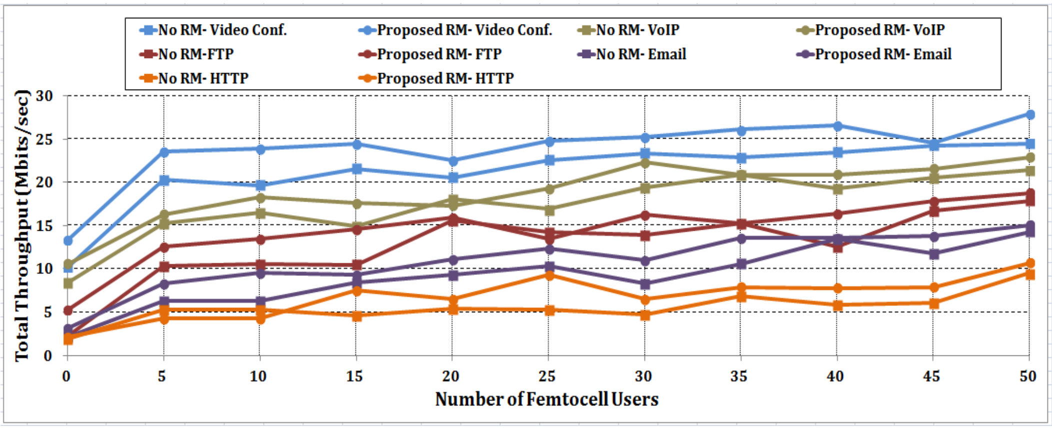
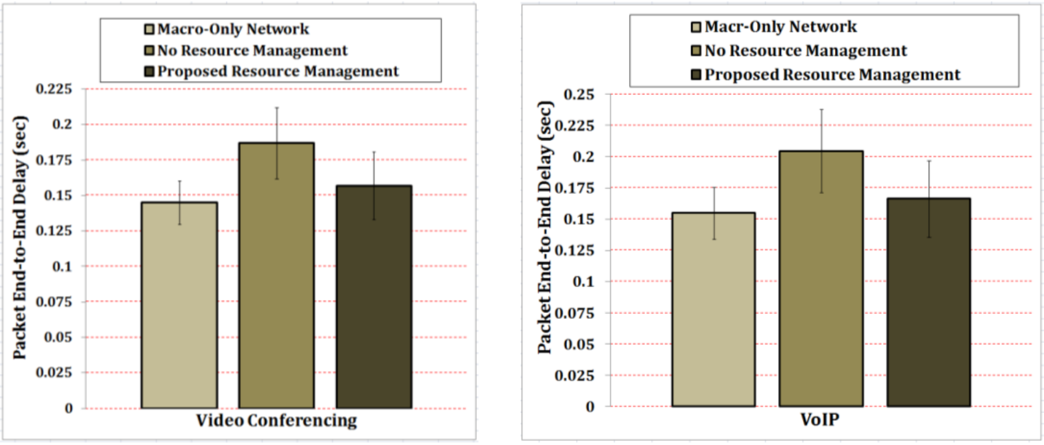


Figure 3-27: The values of throughput vs. the total number of femtocell users

The fluctuations in the results are expected due to using random movement trajectories for the mobile users and signal attenuations in some areas. But as an example, when configuring 50 femtocell users, the throughput value is improved in the range of about 7.0% to 15% for different applications.

Figure 3-28 depicts the packet end-to-end delay with 95% confidence interval for Video Conferencing and VoIP applications respectively. The mean value of end-to-end delay reflects the actual time needed for the packets to be transmitted to their destination through the network. Due to the fewer channel calculations for resource allocation in the absence of femtocells, the ideal case of macro-only network has the lowest packet end-to-end delay with about 145 ms and 155 ms for Video Conferencing and VoIP applications respectively.

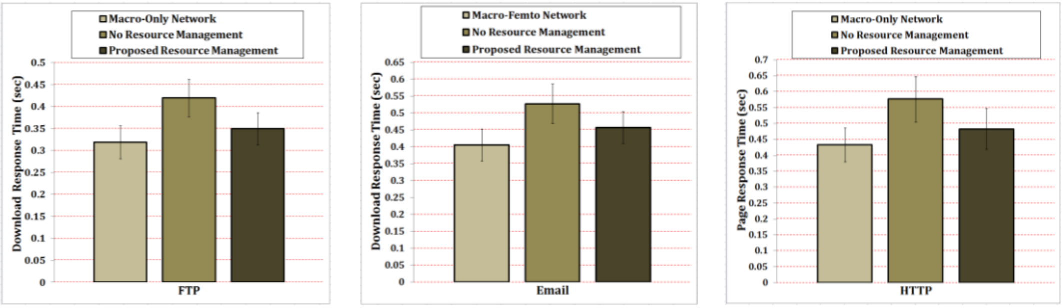


(a) **(b)**

Figure 3-28: Packet end-to-end delay for (a) Video Conferencing, (b) VoIP

The macro-femto scenario with the proposed resource management has the closest value to the ideal case, because of the sub-channel management with the shared channel. If to compare the two scenarios with femtocells, the improvements for this value are 16.04% and 18.68% for Video Conferencing and VoIP applications respectively.

In case of FTP, Email and HTTP applications, the network delay is evaluated via download/page response time in the simulated scenarios.



(a) **(b)** **(c)**

Figure 3-29: Download/page response time for (a) FTP, (b) Email, (c) HTTP

Figure 3-29 shows the download/page response time with 95% confidence interval for these applications, in which the same trend as end-to-end delay for Video Conferencing and VoIP is also observed for the response time in FTP, Email and HTTP applications. Comparing the two scenarios with femtocells, the improvements for download and page response time values are 16.59%, 13.23% and 16.20% for FTP, Email and HTTP applications respectively, when applying the resource management technique.

The analysed results for the proposed sub-channel resource management implementation in OPNET modeler confirm that the QoS based statistics in the network are clearly improved for the two-tier network scenario when we apply the SON resource management. As was expected, before applying the femtocell tier in the network, the ideal case with macro-only architecture has the higher signal values, as well as lower delays compared to the other scenarios, due to having no interference from HeNodeB base stations. Nevertheless, the macro-only scenario is not preferred in LTE-A because of its shortage in network capacity, as the throughput evaluation showed. The results confirmed that the total network throughput is improved when more mobile users in the network are supported by implemented femtocell base stations, as well as their serving macrocells. Also, in case of network coverage, the traditional LTE network with macrocell base stations can not satisfy the general load of users, especially in congested spots like indoor applications, which affects the overall network capacity. Hence, the heterogeneous network with a self-organising cooperation between macrocells and femtocells is a logical solution to fulfil the network capacity requirements, while keeping up with the QoS user satisfaction.

3.7. Summary

This chapter designed and developed the cooperative macro-femto LTE-A system and a novel channel allocation and access control technique for the channel sharing between macrocell and femtocell network layers, based on self-organising techniques. To present the macro-femto heterogeneous architecture, the air interfaces between eNodeBs, HeNodeBs and additional gateways are described as the internal coordination between E-UTRAN and EPC units of the system, followed by detailed functionalities of X2 and S1 interfaces. Furthermore, as the novel resource management technique, the novel hybrid fractional frequency reuse (HFFR) scheme is presented with a self-organising algorithm into the system. The proposed system and resource management are then implemented into the OPNET modeler network simulator in 5 random simulation seeds with consideration of 95% confidence interval, which is applied in the error bars to demonstrate the dispersion of each statistic. The simulation results for BLER, SINR and delay values clearly confirmed that the proposed resource allocation technique improves the network QoS by arranging the available frequency channel among macrocell and femtocell users. On the other hand, the total network capacity is highly improved for the end users due to the throughput enhancements that occur when more femtocells are inserted into the system, especially when the resource management solution is also applied.

As the conclusion to this chapter, if the heterogeneous LTE-Advanced network architecture is accompanied with self-organising network management, then the improved bandwidth utilization obtains higher network capacity and QoS for the growing number of mobile users within the network. In addition to this, planning such a cooperative system with higher number of low-cost/low-power base stations has undeniable consequences in overall savings for mobile network operators in their implementation and operation costs.

Chapter 4 Comprehensive Handover Strategy

The use of femtocell, indoor/short-range/low-power cellular base stations in cooperation with existing long-range macrocells require a variety of network planning considerations in a multi-tier configuration. As an important instance, the shortage of network coverage during the users' movements is a major concern for network operators, which forces them to spend additional attention to overcome the degradation in performance by an appropriate handover plan. This chapter investigates the handover between the different layers of a heterogeneous LTE-Advanced system, which is a critical strategy to plan the best way of interactive coordination within the network for the proposed HetNet. The proposed comprehensive handover algorithm takes into account multiple factors in both the handover sensing and decision stages, based on signal power reception, resource availability and handover optimisation, as well as prioritization among macro and femto stations, to obtain maximum signal quality while avoiding unnecessary handovers.

4.1. Chapter Introduction

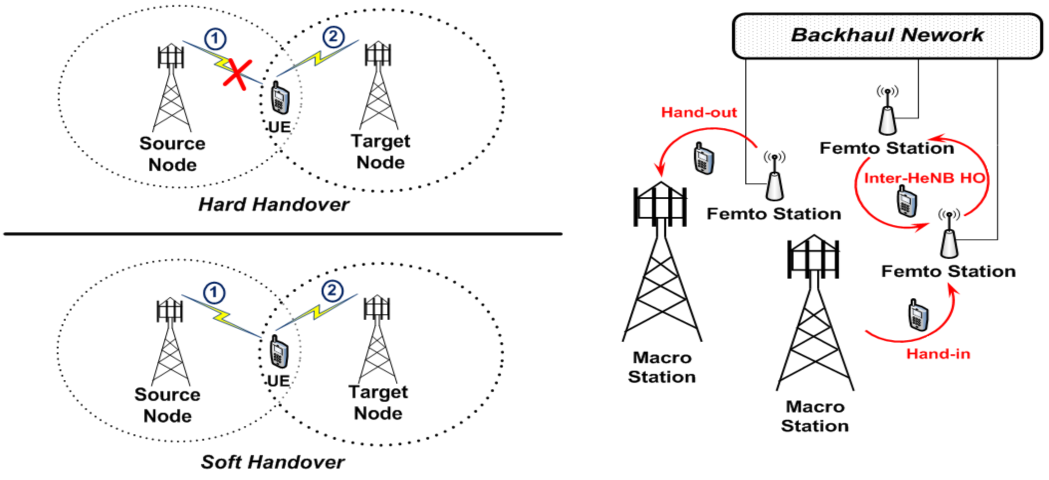
The mobility issue in cellular networks has been regarded as a critical challenge for the network operators, especially in presence of different types of serving base stations in heterogeneous networks (HetNets) [62,63]. The location and speed of mobile users, the call duration, and the serving signal quality are defined as significant parameters when the handover is planned in HetNets. The self-organising network (SON) concept in this regard contains a number of management methods, which are planned and executed by network entities through a pre-defined algorithm. As the preliminary stages of SON, the link configuration, capacity planning and authentication test will be followed by its operational processes such as QoS optimisation, packet drop detection and re-transmission attempts. However network heterogeneity could alleviate the discussed difficulties in capacity and quality of service by the integration of various sub-networks, e.g. marcocell, picocell, femtocell, relay nodes, etc. [64-66].

The handover concept in HetNets is classified into two separate categories, as inter-cell and intra-cell handovers. In inter-cell handover the source and target nodes are located on different cells, even if they are allocated to the same cell site, whereas in intra-cell handover both the source and target nodes belong to the same cell, and therefore the cell is not changed during the handover process.

The purpose of intercell handover is to keep the signal quality and coverage when the user moves to a new cell area. However in case of intra-cell handover, the purpose is to change one channel inside the existing cell, due to fading or interference, to a new channel with better conditions.

In other classifications, handover is classified as hard handover and soft handover, as shown in Figure 4-1 (a). In hard handover (break-before-make) the channel in the source node is completely released first, and then the channel in the target node is engaged. Therefore the connection of the User Equipment (UE) and the source node is broken before or exactly when the new connection to the target node is made. Hard handover is considered as an “Event” during the ongoing communication and requires the least processing by the network. On the other hand, in soft handover (make-before-break) the channel in the source node continues to be used in parallel with the new connection to the target node. Therefore, the connection to the target node is established for a while before the connection to the source channel is fully broken. The soft handover is considered as a “State” of the call during the ongoing communication rather than an event. There can also be more than two parallel connections and the used signals could also be combined to produce a stronger signal for transmission, both in downlink and uplink, which is called as softer handover. Softer handovers are feasible only when the handover cells have a single cell site.

Handovers could be also classified based on the type of target and source nodes, as shown in Figure 4-1(b) [67].



(a) **(b)**

Figure 4-1: (a) Different handover types, (b) Different handover directions

Unnecessary handover in heterogeneous networks is considered as a significant cause for network degradation in the systems with different application layers. As was already discussed, using of multi-tier structure in networks also brings some additional challenges, despite its advantageous ability to improve the capacity and quality of service. The time and conditions for handover [68,69], the transmission power configuration for various transmitter types, inter-cell interference, etc. are examples of those challenges [14,70,71].

This chapter presents a novel comprehensive handover strategy for the proposed multi-tier network construction in LTE-A, to facilitate mobile users' mobility between general and sub-general network transmitters. The main contribution of this chapter is to address the problem of unnecessary handover in two-tier HetNets by proposing a novel algorithm for the new releases of LTE-A networks.

The proposed two-way handover algorithm contains received power calculation as its sensing process, as well as resource availability, handover optimisation and femtocell priority checks as parts of the handover decision process.

4.2. Related Work

A number of different methods have been proposed so far to deal with mobility management in LTE systems. Handover latency is considered to be the significant metric for an efficient multi-objective handover solution for LTE cellular systems as is investigated in research [72]. The proposed solution considers different parameters e.g. available bandwidth and signal strength in the selection of the optimal target cell. This proposed multi-objective handover scheme results in a considerable improvement in the session blocking rates, handover latency, session queuing delay, and throughput during handover. Femtocells offload large amount of traffic from the macrocell network in cases of dense deployment of femto applications, but the handover optimisation among macro and femto parts of the network presents a key challenge, which needs to be considered to reduce the unnecessary handovers in the network.

Research [73] evaluates the effects of bandwidth and channel environment on signal measurements for handover, i.e. reference signal received power (RSRP), reference signal received quality (RSRQ) and receive signal strength indicator (RSSI). The proposed technique obtains the real strength of signal using the RSRP calculation, and the signal and noise relation using the RSRQ, which are used to reduce the effects of noise. The presented algorithm and measurements are applied in downlink simulation platform, however the complexity of calculations in signal measurements remains as a challenge in the system.

To plan handover management in high-dense networks, research [74] considers intelligent femto/macro network architecture as the main contribution. The neighbour cell list with a minimum number of femtocells and effective call admission control (CAC) are considered by proposing a novel algorithm for the handover. The algorithm aims to create a neighbour cell list with a minimum, but appropriate number of cells for handover, as well as a novel handover procedure and traffic model for macro/femto networks. Results show that the proposed CAC could be effective in handling various calls. However, the algorithm needs to consider more options as potential target nodes for handover in congested areas.

In a more general level, the different categories of handover process for macro-femto LTE networks are discussed in research [75], where the hand-in, hand-out and inter-femto access point (FAP) handovers are analysed. In addition to this, the proactive and reactive handover strategies are discussed to reduce the unnecessary handovers in the network. The proactive handover is applicable to the situation where the handover may occur any time before the receive signal strength indicator (RSSI) of current eNodeB reaches the handover hysteresis threshold (HHT). The reactive handover is applied to the conditions which the femtocell UE initiates unnecessary handovers when moving from one FAP to another FAP. Hence, the presented handover signalling is used to mitigate the frequent and unnecessary handover problems that occur in the system in a limited number of conditions.

The signal measurement by UEs, whether located in or out of range, and also the large number of idle femtocells as a result of having a dense deployment of macrocells, are addressed in research [76] as the two major challenges of handover. The research proposes an efficient measurement procedure and appropriate solutions for the two above mentioned challenges. Seamless handover issue is also planned and simulated by reactively multicasting the data to both the source and target cells after the handover is actually initiated, which results in a reduction in the downlink service interruption time, as well as the avoidance of packet loss compared to the standard 3GPP, with only limited extra requirements [77].

Newly proposed 3-D Markov Chain model for indoor applications and LTE femtocell are also discussed in research works [78] and [79] respectively, which are required to define priority in the handover algorithm. On the other hand, different mobility patterns and dynamic network conditions might cause a challenging situation for mobile users, despite the femtocell’s capability of providing services in shadowed areas by cell coverage enhancements.

The reduction of unnecessary handovers is specifically investigated based on the call admission control (CAC) mechanism between WiMAX and femtocells [80]. The femtocell capability of providing services in shadowed areas of WiMAX cell coverage is used to relieve the main traffic from the macro network, as well as reducing the costs for the network operators, improving service quality in indoor environments and increasing capacity.

Most of the existing research in handover strategies for HetNets only consider up to two conditions amongst signal strength, resource availability and handover optimisation conditions in their proposed algorithms, while paying less attention to the femtocell priority over macrocell. Furthermore, the complexity of signal calculations in some of the existing algorithms result in drops in handover efficiency in the network. Nevertheless, the proposed comprehensive handover algorithm considers all the three mentioned conditions. The additional process of assigning femtocell priority over the macrocell nodes also improves the network capacity and QoS in the network, by offloading the congestion (due to users' traffic) from the macro nodes to the femtocell nodes.

4.3. Problem Statement

Mobility management is one of the main challenges to be addressed in heterogeneous networks, in which different types of base stations serve the mobile users with random trajectories. Hence, a network management entity, or self-organising algorithm is required to initiate and manage the seamless user handovers to the users, while providing constant connectivity and constant quality of signal. The main difficulties to initiate such a handover are how to obtain the reliable information about network availability in surrounding cells, while avoiding the unnecessary handovers within the network [81,82].

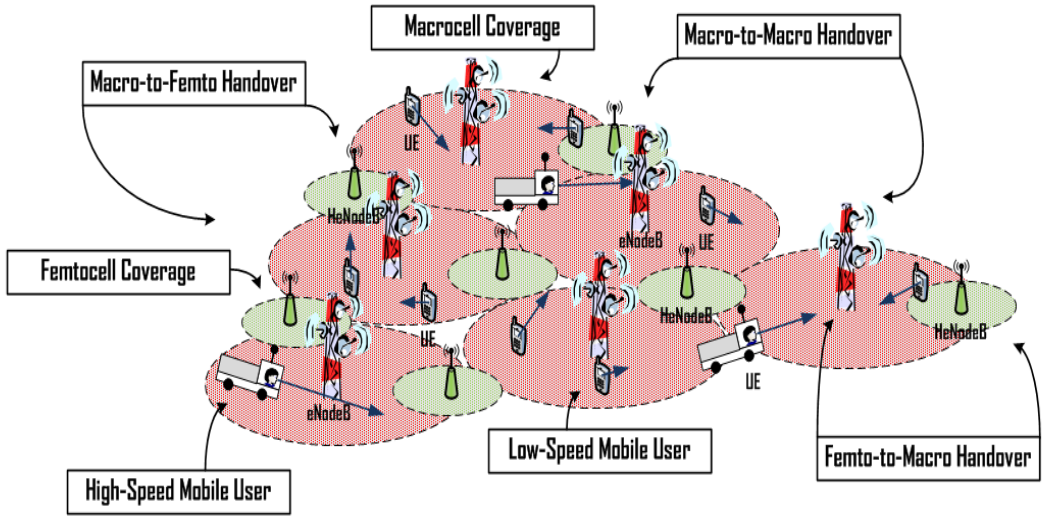


Figure 4-2: Handover possibilities in heterogeneous LTE-A network

As an example for the first issue, there will be a huge drop in overall network QoS, if the system initiates several handovers without bandwidth availability, or with inaccurate signal strength estimation at the destination nodes. Also as an example for the second issue, initiating unnecessary handovers for the mobile users in the network could result in an increase in internal calculations, as well as raising the number of handover failures for the further handovers to the same destination nodes. Hence, a comprehensive handover algorithm needs to be developed to obtain the right user handovers to the right destination nodes. Figure 4-2 shows all the possible types of handover in a heterogeneous LTE-A network.

The proposed comprehensive handover technique addresses all these types of handover issues by presenting a self-organising algorithm, which includes the handover sensing and decision processes. The process model of this technique uses the reference signal received power (RSRP) and reference signal received quality (RSRQ) system measurements for the handover sensing process, whilst also taking into account resource availability, handover optimisation and femtocell priority for the handover decision process in the system. The novel handover technique is implemented in OPNET modeler, which is used to verify the overall network improvements in handover initiation decisions, as well as avoiding unnecessary handovers.

4.4. System Model

The proposed comprehensive handover strategy is based on a two-way handover for both macro-femto and femto-macro sides and the general processes of the handover sensing and decision are made in the source node, either eNB or HeNB. Since having no direct interface between macro and femto stations, the communications between eNB and HeNB are implemented through the mobility management entity (MME) and gateways [[67]]. In this part, the system model for the novel handover technique is described by presenting the process model and algorithm flowchart and codes. The sensing and decision processes and their corresponding checks on the system are described in detail, which will be later used to implement the proposed algorithm into our simulation model.

4.4.1. Technical Considerations

Most of the related researches in handover (HO) formulation for LTE systems consider only one or two statistics to be controlled on the handover decision step. However this work follows a more comprehensive strategy to consider more parameters than beforehand. For this reason, some additional considerations have to be taken into account for more accurate system analysis. An important first consideration is that blocking a handover call in the system does not result in dropping that call. Also the handover from femto to macro station (outbound handovers) are not taken into account, because they are not as complex as the handovers from macro to femto (inbound handovers). This is because there is no option other than a handover to the near macro station each time an outbound handover is being made. In a system with complete spectrum sharing, the total spectrum band is shared by macro and femto stations, and in a system with open access, the femto stations are free to be arbitrarily used by any users. The latter approach also expands the network capabilities and coverage with an inexpensive solution for network operators. Hence, the complete spectrum sharing and open access mode are assumed for this work to obtain the maximum accuracy of desired parameters for analysis. The considered total channel bandwidth is 20MHz up to 100 MHz, which contain 100 and 500 resource blocks (RBs) respectively. RB is the smallest time-frequency resource consisting of 12 subcarriers, which can be allocated to a UE. Therefore, significant reduction in blocking probability and queuing delay are anticipated when using this handover operation, compared to the existing handover mechanisms.

4.4.2. SON Measurements and Signalling

The reference signal received power (RSRP) and reference signal received quality (RSRQ) values are measured by the UE and reported via measurement report (MR) to the source eNB/HeNB, and the available capacity of resource blocks (RBs) is reported by target eNB/HeNB via handover request acknowledgement (HOA) to the source eNB/HeNB. The proposed comprehensive handover algorithm is enhanced by using multiple checks to first avoid unnecessary handovers, and second prioritise low-power femto stations over high-power macro base stations. The algorithm mainly focuses on the handover sensing and decision processes. The proposed multi-objective handover algorithm initially considers the signal received power and quality in the handover sensing process, which is followed by bandwidth availability check, user residence check, and femto over macro priority check. The novelties of this algorithm consist of both its sensing and decision processes, as well as its unique extra checks.

4.4.3. Process Model

The handover process in this model is considered as a repeating procedure, in which the network serving and management entities follow an organised order to serve the mobile users during their handover. The operational entities of the handover process model are as following:

UE: The mobile user equipment moves through the cells, from/to a macrocell/femtocell base station, either by a configured or random trajectory.

Source eNB/HeNB: The serving macrocell/femtocell base stations are working in open mode, which make the sensing and decision processes based on the received information from the other cooperative units.

Target eNB/HeNB: The destination macrocell/femtocell base stations are working in open mode, which receive the handover request and issue the acknowledgement signal.

Target GW: The gateway linked to the destination macrocell/femtocell node, which routes and forwards the user data packets in handover process.

MME: The mobility management entity, which is the control node for access in LTE networks and is responsible for idle UE and retransmission in handovers.

Serving GW: The gateway linked to the serving base station, which routes and forwards the user data packets and also performs as an anchor for mobility between different network layers, i.e. macrocell and femtocell.

The focus of this work is to propose novel algorithms for both the sensing and decision processes within the handover model. The proposed algorithms are based on different steps, called “checks”, which confirm that the algorithm can continue with the handover process, or return back to the beginning of the algorithm.

Table 4-1: Table of abbreviations for the handover algorithm

Abbreviation	Description	Abbreviation	Description
MC	Measurement Control	***DLA***	Downlink Allocation
MR	Measurement Report	***Sensing***	Handover sensing process
HOR	Handover Request	***Admission Ctrl.***	Allocate the required sources
HOA	Handover Request Acknowledgement	***Decision***	Handover decision process
HCM	Handover Command	***Detachment***	Detach from source node
PCR	Physical Channel Reconfiguration	***Delivery***	Deliver packets to target node
PCC	Physical Channel Complete	***Buffer***	Buffer packets from source node
HCN	Handover Confirm	***Switch***	Switch downlink path
ST	Status Transfer	***UL Sync.***	Uplink synchronisation
PDF	Packet Data Forwarding	***Release***	Release the sources
PD	Packet Data	***U-Plane UR***	User Plane Update Request
RANAP	Radio Access Network Application Part	***U-Plane UA***	User Plane Update Acknowledgement
RANAP RD	RANAP Relocation Detect	***RSRP***	Reference Signal Received Power
RANAP RC	RANAP Relocation Complete	***RSRQ***	Reference Signal Received Quality
UE CR	UE Context Release	***RSSI***	Received Strength Signal Indicator
ULA	Uplink Allocation	-	-

The proposed novel handover checks are included inside the handover process mode. If one of the checks in the algorithm is passed, it means that the corresponding handover condition is satisfied and the process moves forward to check the next check in the algorithm. However, if a check in the algorithm is not passed, it means that the handover condition is not satisfied and the algorithm returns back to the beginning.

Consequently, by applying of this multi-check algorithm in the system, the user handover is only initiated when all the checks are passed, which means all the handover conditions are satisfied.

The table of abbreviations for the proposed handover algorithm is depicted on Table 4-1. The main part of exchanged commands in the handover process is based on request and acknowledgement messages, which are exchanged between the cooperated network entities. The control and report functions are also generated when specific signalling and measurement information are required for further operations.

This chapter only focuses on the “Sensing” and “Decision” processes by proposing novel algorithms, as the main operations to optimise the handovers. However, further handover functions are also mentioned as part of the proposed algorithm to demonstrate the functions of different network entities during the handover process.

To illustrate the involved sections and the order of processes in the proposed handover mechanism, the proposed comprehensive handover process model is shown in Figure 4-3. The process model shows the message exchanges between the introduced network entities, as well as the main handover processes, which contain the novel algorithms.

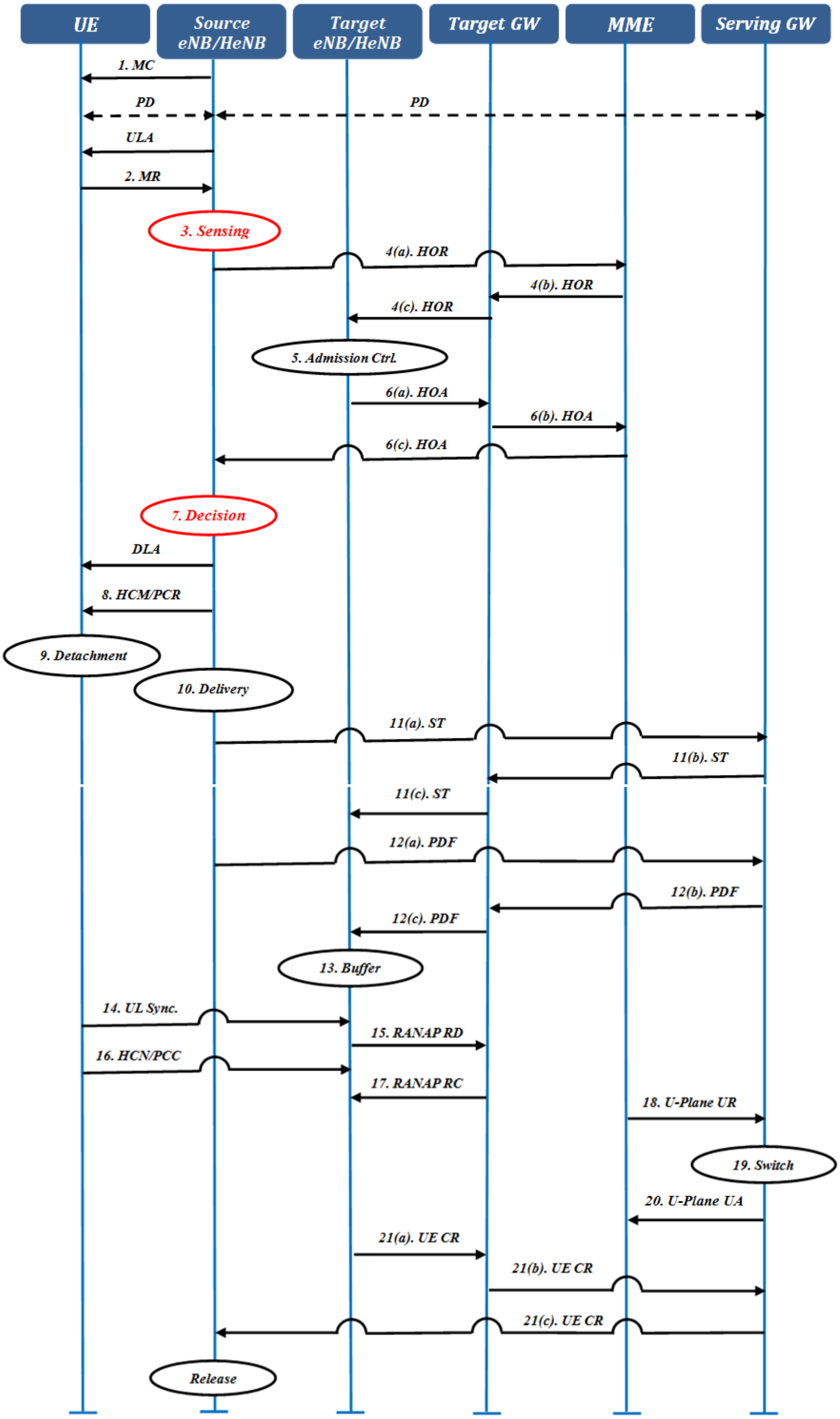


Figure 4-3: The process model in comprehensive handover algorithm

Figure 4-4 shows the flowchart of the sensing and decision processes in the proposed handover method.

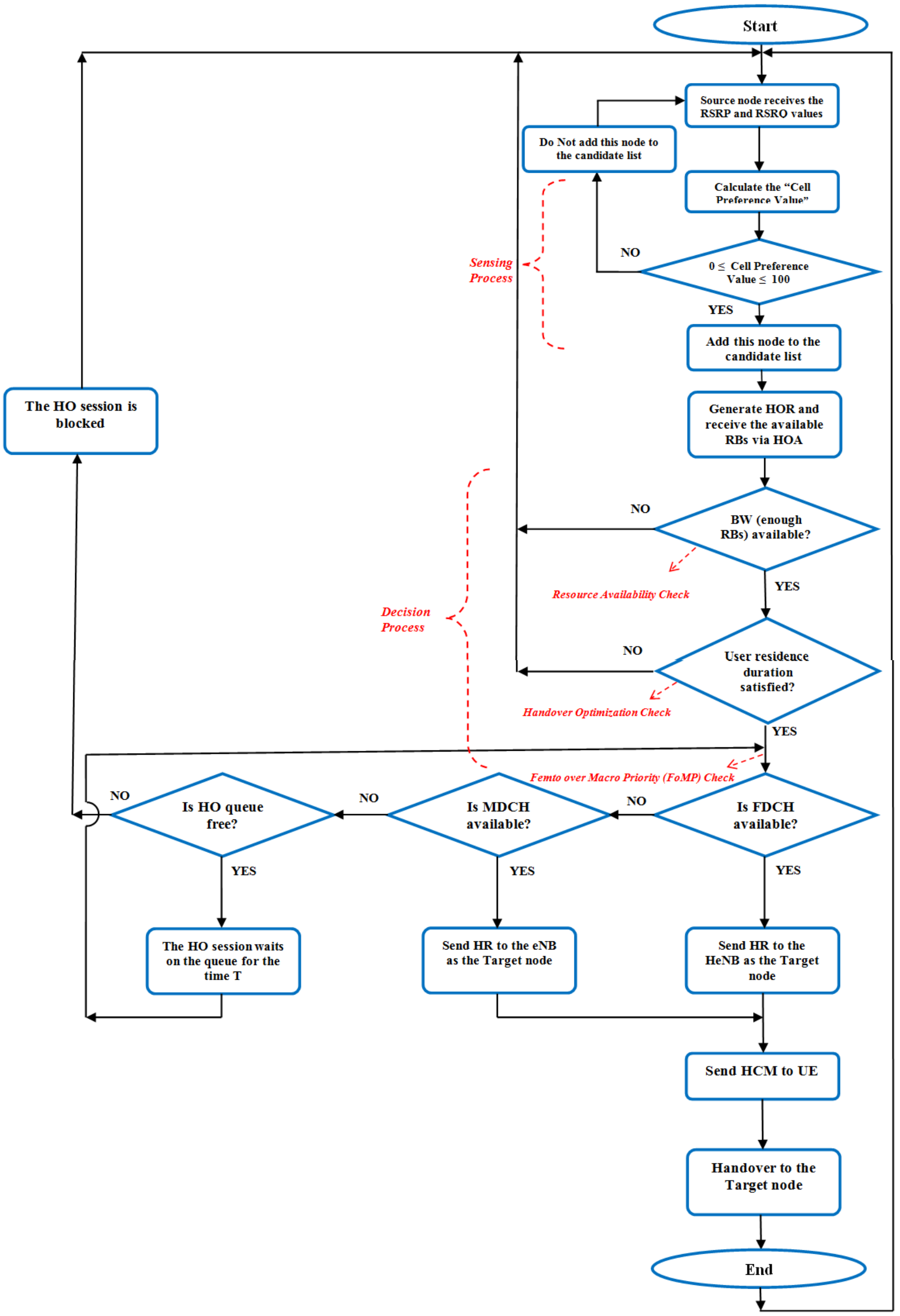


Figure 4-4 Flowchart of handover sensing and decision processes

4.4.4. Handover Sensing Process

The user handover process becomes initiated when the necessity of handover is confirmed by the source node. At the first step, the reference signal received power (RSRP) is measured and reported by UE and includes antenna gain, pathloss, log-normal shadowing, and fast fading information, which are averaged over all the reference symbols within the measurement bandwidth. Considering P as downlink received power and $G_{k,j}$ as estimated channel gain for the j^{th} symbol of the k^{th} eNodeB, the downlink-received RSRP from the k^{th} cell is estimated as in Equation (4-1) [72].

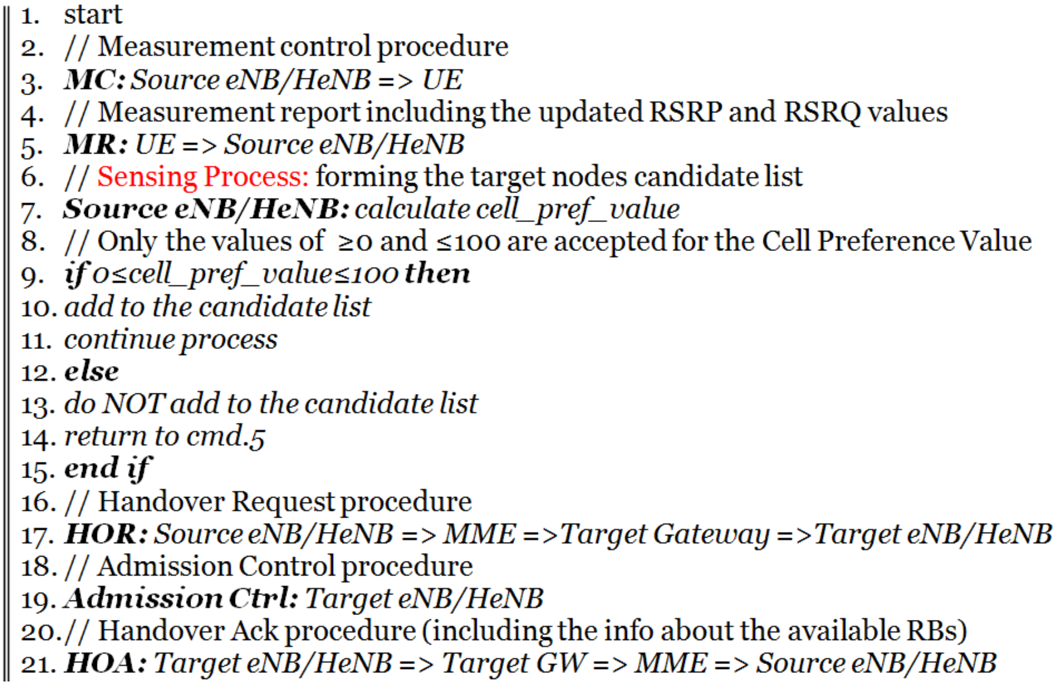
$$\mathrm{RSRP_k} = P \sum_{j} G_{\mathrm{k,j}} \qquad (in\ which\ j \epsilon all\ symbols) \tag{4-1}$$

The received signal strength indicator (RSSI) and RSRQ are also calculated based on the proposed algorithm definitions in the simulation platform. RSSI comprises the linear average of the total received power (in watts), which is only observed in OFDM symbols containing reference symbols, and is calculated by the simulation source codes. The RSRQ value is also calculated for N number of RBs of the E-UTRAN carrier RSSI as in Equation (4-2).

$$\mathrm{RSRQ} = N \times \frac{\mathrm{RSRP}}{\mathrm{RSSI}} \tag{4-2}$$

Since the RSSI includes the noise generated in the receiver and also thermal noise within the bandwidth defined by the receiver pulse shaping filter in a specified timeslot, then RSRQ expresses the relation between signal and noise [73].

OPNET uses both the RSRP and RSRQ values to calculate a parameter called as "Cell Preference Value" in the source node. The calculation process of the cell preference value is then followed by a condition test, which if it is between 0 and 100 (inclusive), allows the candidate to be added to the list of handovers. The process codes for handover sensing and its following message forwards are depicted on Figure 4-5, which are used to modify the relevant node models.



```
1.  start
2.  // Measurement control procedure
3.  MC: Source eNB/HeNB => UE
4.  // Measurement report including the updated RSRP and RSRQ values
5.  MR: UE => Source eNB/HeNB
6.  // Sensing Process: forming the target nodes candidate list
7.  Source eNB/HeNB: calculate cell_pref_value
8.  // Only the values of ≥0 and ≤100 are accepted for the Cell Preference Value
9.  if 0≤cell_pref_value≤100 then
10. add to the candidate list
11. continue process
12. else
13. do NOT add to the candidate list
14. return to cmd.5
15. end if
16. // Handover Request procedure
17. HOR: Source eNB/HeNB => MME =>Target Gateway =>Target eNB/HeNB
18. // Admission Control procedure
19. Admission Ctrl: Target eNB/HeNB
20.// Handover Ack procedure (including the info about the available RBs)
21. HOA: Target eNB/HeNB => Target GW => MME => Source eNB/HeNB
```

Figure 4-5: The sub-algorithm for handover sensing process

4.4.5. Handover Decision Process

The handover decision process is performed as the second stage of handover optimisation in the system to make sure about the handover initiation conditions. The proposed handover decision includes a number of checks, based on the explained network conditions for user handover, which are detailed in the following section.

4.4.5.1. Resource Availability Check

The first assessment of the handover decision process is to check the available radio resources or wireless bandwidth in the target node, and if the resource availability is satisfied, the process qualifies to start the handover optimisation check (Figure 4-6). This test is computed by the RBs available in the target node, which results in the target node offering the maximum available resources for selection.

```
22. // Decision Process: checking the best target node
23. // "Resource Availability" check: availability of enough RBs on the target node
24. if BW available then
25.     continue process
26. else
27.     return to cmd.3
28. end if
29. // "Handover Optimization" check
30. Calculate the MU speed
31. // Making decision based on the MU speed (v)
32. if v ≤ 15Km/h then
33.     continue process
34. else if 30Km/h ≥ v >15Km/h then
35.     if real-time then
36.         continue process
37.     else
38.         return to cmd.3
39.     end if
40. else if v >30Km/h then
41.     return to cmd.3
42. end if
```

Figure 4-6 Resource availability and handover optimisation processes

The fraction of the total available RBs is mathematically calculated by Equation (4-3).

$$g_k(\eta,\beta) = \frac{\phi - \sum_{i=1}^{\eta} \beta_i}{\phi} \tag{4-3}$$

Where $\boldsymbol{\phi}$ is the total number of RBs of the target node, β_i is the RBs consumed by the i^{th} UE, and η represents the number of active UEs in the k^{th} Target node. The distribution of the RBs, given by $\beta = \sum_{i=1}^{\eta} \beta_i$, could vary for each different application through the network, e.g. voice calls, data transmission, etc. Furthermore, the total number of RBs ($\boldsymbol{\phi}$) is fixed for any node across the entire frequency for a particular channel bandwidth, and every eNodeB or HeNodeB allocates a portion of these RBs between different users depending on its current channel conditions and cell-load [72].

4.4.5.2. Handover Optimisation Check

Since having low power capabilities, the femtocell indoor application provides low range and limited coverage for the mobile user, which could result in a notable number of unnecessary handovers in some circumstances. As a very possible scenario, a high speed UE might possibly enter the cell and be covered by multiple femto stations, each for a short period of time, which causes multiple successive unnecessary handovers and therefore a noticeable reduction in quality of service. Therefore, minimizing the number of unnecessary handovers is considered as a dominant objective for the novel handover strategy. For this reason, a new call admission control (CAC) mechanism is proposed as part of the handover decision process. The critical parameters that are considered in this check include the expected UE dwell time in the femto coverage area, by considering the UE speed (in Km/h), in cooperation with the signal quality checks, to minimise any unnecessary handovers. Hence, the pre-defined UE dwell state is initially defined in Table 4-2 [80,83].

Table 4-2: Pre-defined UE residence states for different speed ranges

UE Dwell State	UE Speed (Km/h)
Low Speed	*0 to 15*
Medium Speed	*More than 15 to 30*
High Speed	*More than 30*

The calculations for the optimised handover check need more complexity to calculate the UE speed and consider the appropriate UE dwell state, which the process is designated to consider after the resource availability check. The flowchart for the handover optimisation check, which is based on the defined speed ranges for a mobile user (MU), is shown in Figure 4-7.

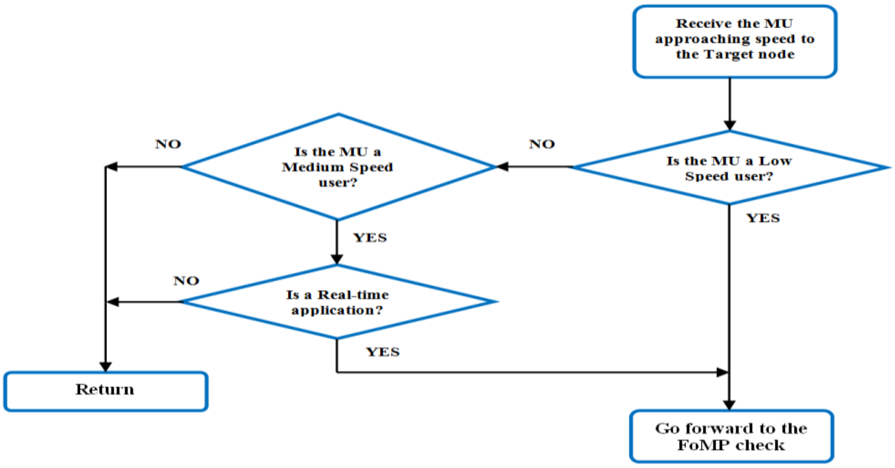
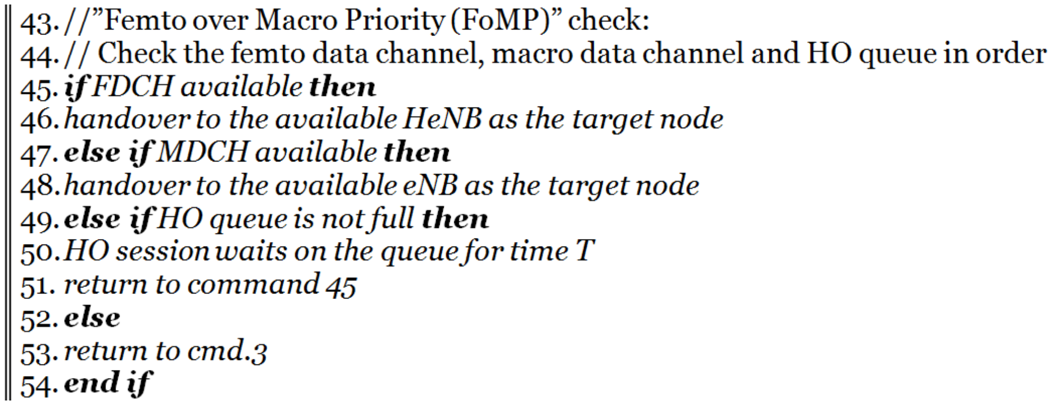


Figure 4-7: Handover optimisation check flowchart

4.4.5.3. Femto over Macro Priority (FoMP) Check

As a technical comparison between the general macro and supportive femto applications, femto services deliver lower power requirements, higher quality of signal, and also encouragingly low cost of services, which altogether make the use of femtocell base stations a priority over the macrocells. Therefore, as the final stage of handover decision process, macro-femto handover (hand-in) is considered to have priority over the handing over to a macro station in the algorithm (Figure 4-8).



```
43. //"Femto over Macro Priority (FoMP)" check:
44. // Check the femto data channel, macro data channel and HO queue in order
45. if FDCH available then
46.     handover to the available HeNB as the target node
47. else if MDCH available then
48.     handover to the available eNB as the target node
49. else if HO queue is not full then
50.     HO session waits on the queue for time T
51.     return to command 45
52. else
53.     return to cmd.3
54. end if
```

Figure 4-8: Femto over macro priority (FoMP) process

In this figure, FDCH and MDCH stand for femto data channel and macro data channel respectively. To obtain the best available network quality and coverage with lower service charges, the femtocell nodes are preferred over the macrocell nodes to be selected as the target node in handovers. This means the UE is more likely to be assigned a femto sub-channel, if available, and then in case of no available femto sub-channel, the macro sub-channel will be assigned to the UE. If also no macro sub-channel is available, the session queuing and session block statuses have the next priorities respectively. To describe the function of FoMP process, we assume the serving eNodeB as the source node and its neighbouring eNodeBs/HeNodeBs as the potential target nodes. Therefore, the incoming and outgoing handovers are considered as ongoing handover sessions, which entring and leaving the source eNodeB, from the viewpoint of the source eNodeB. Also, to reduce the calculations, the blocked handover sessions (in cases when the queue is full) are not counted in the analysis and the self-organising algorithm returns to repeat the process in those cases. Furthermore, a UE in the queue does not move to another eNodeB to leave the process. Figure 4-9 shows the handover sessions model from the viewpoint of the source eNodeB [72].

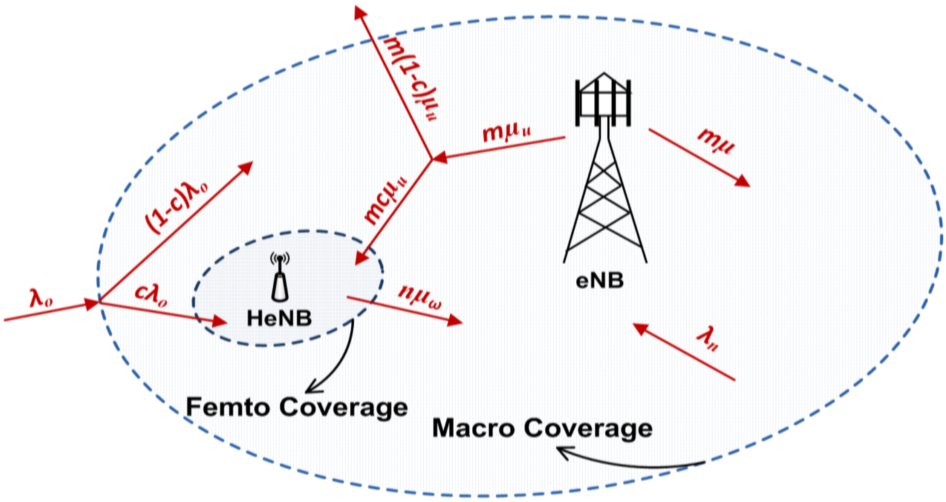


Figure 4-9 Handover sessions model

All the sessions are assumed to be generated based on Poisson distribution [84], with average rates of λ_n and λ_o for new sessions and handover sessions respectively, which are independent of the time since the last event. It is assumed in this model that the location of the handover is uniformly distributed over the whole handover region. Therefore, it can be said that a handover session is initiated within the HeNodeB's handover region with the probability of c. The symbols m and n represent the number of macro and femto data channels being used respectively. Table 4-3 shows the parameters and normalised values for the handover sessions [72].

Table 4-3 The handover sessions parameters and values

Handover probability	c
New Session arrival rate	λ_n
Handover Session rate	λ_o
Handover service rate from eNB	μ_u
Handover service rate from HeNB	μ_ω
Session service rate	μ
Normalised traffic intensities of new sessions	$T_n = \frac{\lambda_n}{\mu}$

Normalised traffic intensities of handover sessions	$T_o = \frac{\lambda_o}{\mu}$
Normalised handover rates in eNodeB	$\alpha_u = \frac{\mu_u}{\mu}$
Normalised handover rates in HeNodeB	$\alpha_\omega = \frac{\mu_\omega}{\mu}$

When the system traffic is statistically stable, the traffic intensity of the incoming handover is equal to that for the outgoing handover, as is shown in Equation (4-4).

$$T_o = \alpha_u\, T_n \tag{4-4}$$

To characterise the behaviour of the macro and femto channel allocation within the handover process, the handover transitions and probabilities estimations are introduced using the three dimensional (3D) Discrete Markov Chain [74]. In this regard, the potential target node is selected from the nearby femto nodes, if available [85]. If not, the target node is selected from the available macro stations to enhance the signal reception. A state in the 3D discrete Markov chain is defined as $(m, n, b), 0 \le m \le M, 0 \le n \le N, 0 \le b \le B$ with the major parameters and symbols which are described as in Table 4-4 [72].

Table 4-4: Major parameters and definitions for 3D Markov Chain

Symbol	Description
m	*Number of macro data channels being used*
n	*Number of femto data channels being used*
b	*Number of new session requests waiting in the queue*
M	*Total number of macro data channels*
N	*Total number of femto data channels*
B	*Total number of session requests*
H	*Number of macro data channels reserved for HO*

The state transition probabilities for the mentioned handover scenario are depicted as in Figure 4-10. The updated network situations for macrocell, femtocell and queue conditions are considered through a process and the probability of each transition is calculated as a function of traffic intensities.

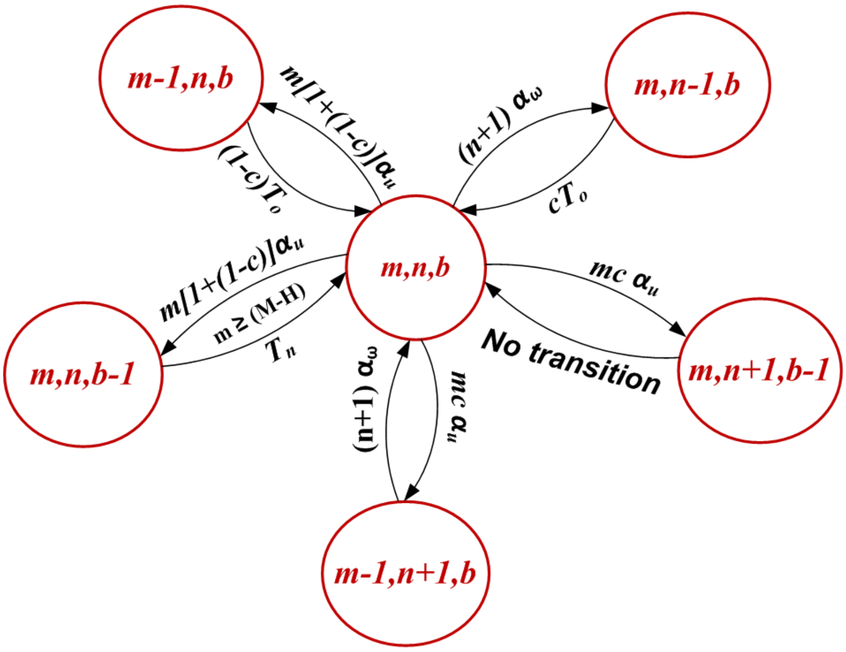


Figure 4-10 The state transition probabilities in handover

Considering the different possibilities of the available channels at the time of the handover process, the state transition from (m_i, n_i, b_i) to (m_j, n_j, b_j) are as the following states; In this case, the allocation priority is with the femto, macro and handover queue (if available) respectively, as defined in the following [72]:

a. ***Session completion at HeNodeB:*** The femto sub-channel is released ($n_j = n_i - 1$).

b. ***Session completion at eNodeB:*** The macro sub-channel is released ($m_j = m_i - 1$). Now if the macro sub-channel available ($m_i - 1 < H$) then it is assigned to a new session waiting in the queue ($b_j = b_i - 1$ and $m_j = m_i$), otherwise $b_j = b_i$ and $m_j = m_i - 1$.

c. ***Incoming session to HeNodeB coverage area:*** If femto sub-channel available ($n_i < N$), then it is assigned ($m_j = m_i$ and $n_j = n_i + 1$). Otherwise if macro sub-channel available then it is assigned ($m_j = m_i + 1$ and $n_j = n_i$). Otherwise if the queue is not full then wait on the queue ($m_j = m_i$, $n_j = n_i$ and $b_j = b_i + 1$).

d. ***Incoming session out of the HeNodeB coverage area:*** If macro sub-channel available then it is assigned ($m_j = m_i + 1$ and $n_j = n_i$). Otherwise if the queue is not full then wait on the queue ($m_j = m_i$, $n_j = n_i$ and $b_j = b_i + 1$).

e. ***Outgoing session from HeNodeB:*** The femto sub-channel is released ($n_j = n_i – 1$). If another femto channel available then is assigned ($n_j = n_i$). Otherwise if macro sub-channel available then ($m_j = m_i + 1$).

f. ***Outgoing session from eNodeB:*** The macro sub-channel is released ($m_j = m_i – 1$) and then the femto sub-channel (if available) is assigned $n_j = n_i + 1$. If any macro sub-channel now available ($m_i – 1 < H$) then it is assigned to a new session waiting in the queue ($b_j = b_i – 1$ and $m_j = m_i$), otherwise $b_j = b_i$ and $m_j = m_i – 1$.

g. ***New session:*** Waits on the queue if the queue is not full ($b_j = b_i + 1$).

The mentioned hierarchical states consider the session completion, incoming session and outgoing session statuses with respect to the available macro and femto sub-channels. The priorities, as already explained, are to assign an incoming session to the femtocell and macrocell respectively, if available, or to wait on the queue subject to the queue availability. By using all the available femtocell coverage within the LTE-A, as the initial priority, the maximum capability of network heterogeneity will be consumed to obtain the channel availability and optimisation goals, by assigning the available resources as part of the channel allocation procedure.

When all the handover checks are completed followed by downlink allocation (DLA) to the UE, the algorithm continues exchanging of the internal messages, as the remaining functions towards the end of handover algorithm (Appendix A).

4.5. System Implementation

In this part, the novel comprehensive handover technique is implemented into OPNET modeler network simulator, to express the LTE-A network improvements by the proposed algorithm. General information about the network simulator software, different user applications and standard deviation method for the results presentation has already been discussed in previous chapter.

4.5.1. Packet Transmission from IP Payload

The LTE packet transmission process in OPNET is shown in Figure 4-11. The radio packet transmission in this part is configured initially to be generated as the internet protocol (IP) traffic, followed by the LTE packet data convergence protocol (PDCP) functions. PDCP sub layer is responsible for header compression of IP data flows and transfer of data in user plane or control plane [86]. At the next stage, the IP packets become classified into the evolved packet system (EPS) bearers, and the radio link control (RLC) is then operated to perform the required functions for the link control, e.g. retransmissions and status reports. The scheduler decisions determine the dynamic protocol data unit (PDU), which contain address information and user data, and MAC service data unit (SDU). The MAC PDU (MPDU) units are then formed and are transmitted in different LTE sub frames by hybrid automatic repeat request (HARQ) process.

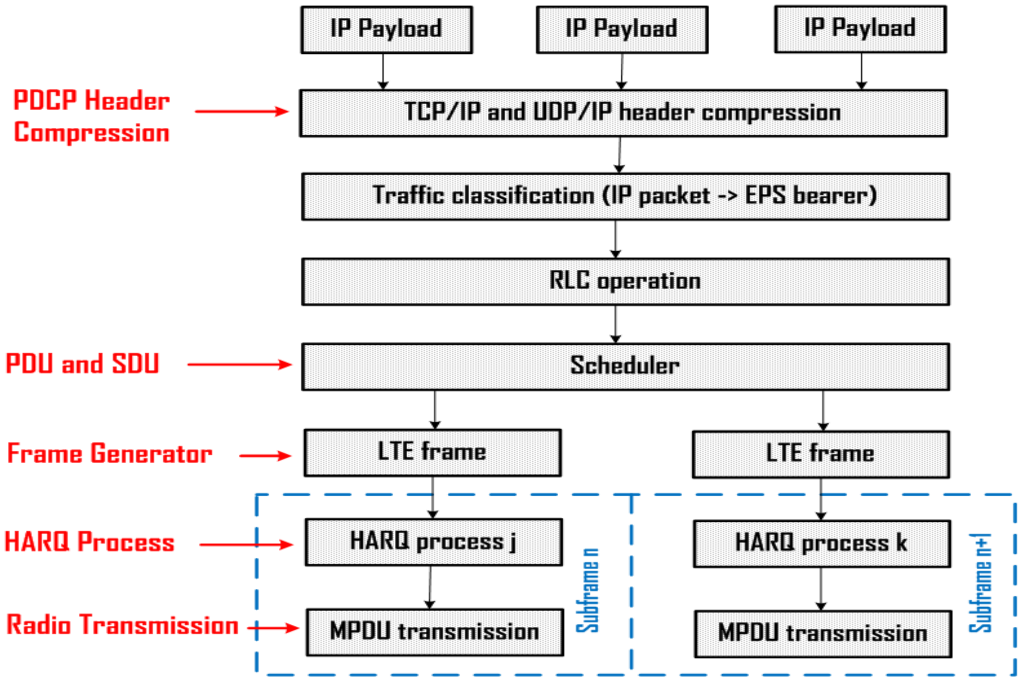


Figure 4-11: LTE packet transmission process in OPNET

4.5.2. Simulation Parameters

To fully illustrate the impacts of the novel comprehensive handover strategy within a multi-tier LTE-A network, a LTE-Advanced platform with the closest characteristics to a real-life network is simulated in OPNET. The simulation parameters and values for all the scenarios are revealed in Table 4-5 [87]. In the simulated network, the maximum capabilities of a LTE-A system is applied, e.g. maximum physical profile and LTE bandwidth, for more visual demonstration of the results.

Table 4-5: Configured simulation parameters and characteristics

Entire Parameter	**Simulation Value**
Number of Cells	*4*
eNodeB Max.Transmission Power	*41 dBm*
HeNodeB Max.Transmission Power	*21 dBm*
Carrier Bandwidth	*20 MHz*
Terrain Model and Type	*Urban, Terrain Type A*
Propagation Model	*HATA*
Building Percentage	*31.6%*
IP Routing ID	*Auto Assigned*
Duplex	*FDD*
Bandwidth	*20MHz*
Uplink Frequency	*1920 MHz*
Downlink Frequency	*2110 MHz*

For the packet transmission values of interference power (Pi), noise power (Pb) and the received power (Pr), the value of signal to noise ratio (SINR) is calculated by Equation (4-5).

$$SINR\ (dB) = 10\log_{10}[\frac{P_r}{P_b + P_i}] \tag{4-5}$$

Further to the signalling values, the blocking rate of the network is also computed within the value of block error rate (BLER). This depends on the value of the received error over the total number of the blocks, and can be calculated as in Equation (4-6).

$$BLER = \frac{Number\ of\ Erroneous\ \text{Blocks}}{\text{Total Number of Received Blocks}} \tag{4-6}$$

The insufficient capacity of macrocell when considering the growing demands, leads to experiencing drops in quality of service if to consider both the cases of SNR and BLER values. This has been taken into account while designing the femto network layer to alleviate the network capacity shortage problem in new releases of LTE-A architectures.

4.5.3. Simulation Scenarios

In the simulation section, four different scenarios have been simulated, analysed and compared by using of OPNET modeler network simulator. Figure 4-12 shows the presented LTE-A platform for all the simulation scenarios in OPNET modeler version 17.1 (64-bit). The first scenario contains a heterogeneous macro-femto LTE-Advanced network with the traditional handover sensing and decision making processes in the system. In traditional handover management, the moving mobile users with a defined or random trajectory are handed over to the nearest available base station depending upon their movement activities.

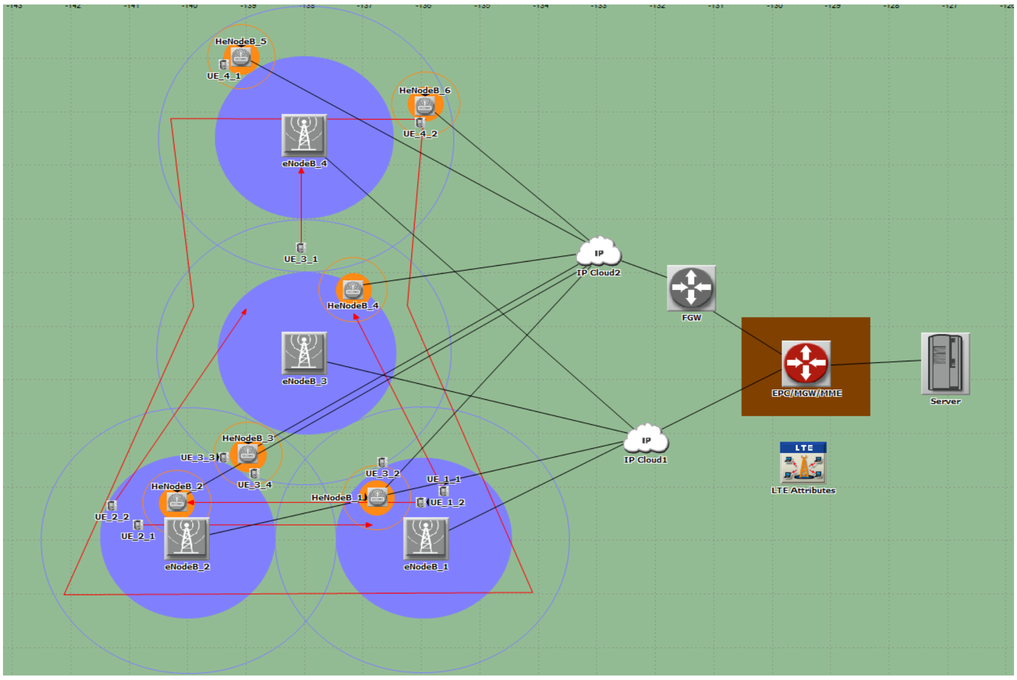


Figure 4-12: The LTE-A platform in OPNET network simulator

The handover process in this scenario is not initiated based on the new QoS conditions, e.g. new signal strength and resource availability, but only based on the location of source and target nodes. In this mode, the cell selection attribute of the network simulator is set to “First Available Node” in the settings.

In the second scenario, the similar LTE-Advanced network platform is presented, but with the handover management only based on resource availability. In this handover plan, the radio resources or wireless bandwidth availability is checked in the target node, and the handover is initiated only in case of satisfactory resource availability.

In the third scenario, there is a more complete algorithm, where the handover management plan is proposed based on both resource availability and handover optimisation checks, to also avoid the unnecessary handovers beside its existing function. In this case, the unnecessary handovers are minimised by applying the call admission control (CAC) mechanism, which considers the mobile users’ speed to initiate the handovers or not.

The fourth scenario, which is our presented comprehensive handover scenario, contains the required checks for existing resource availability and handover optimisation, as well as the novel femto over macro priority (FoMP) check to assign more users to the femtocells, if available and possible. To obtain an improved performance, the low-power plug and play devices like femtocells are preferred to the existing macrocell stations, subject to their availability. The wider application of the small cells unload the network traffic from the macrocell base stations, which also helps the macro users to receive better QoS from their serving network. Hence, this comprehensive handover technique considers the femtocell advantages and priorities over the macrocell, alongside the resource availability and handover optimisation requirements.

This needs to be mentioned that all the last three simulation scenarios are planned with the proposed handover sensing process based on RSRP, RSRQ and cell preference value. Furthermore, all the same scenarios also use the proposed SON sub-algorithms for resource availability, handover optimisation and FoMP process, as part of the analysis.

Figure 4-13 shows the relevant considerations in the simulation scenarios. Each scenario uses one or more of the network layout and system checks for comparison in the analysis section.

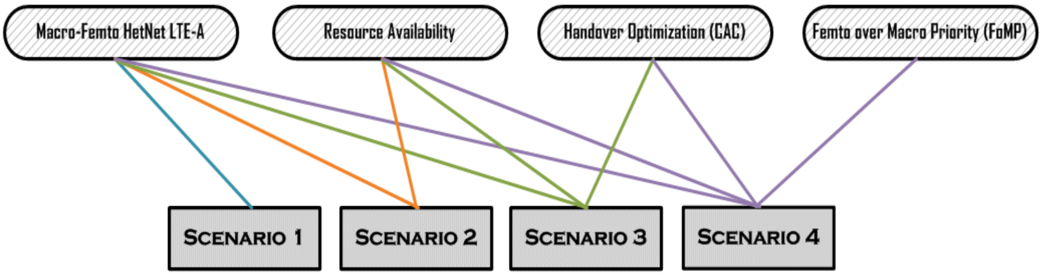


Figure 4-13: The simulation scenarios and their relevant considerations

4.5.4. Handover Algorithm Insertion into the System

Considering macrocell and femtocell sub-networks as the two main components in our presented HetNet system, different handover scenarios are possible to be initiated in the network, but we need to focus on a unique scenario with the highest possibility of occurrence. Based on this consideration, the femto-to-femto handover is initially excluded in our simulations, because our comprehensive algorithm is designed to be implemented in macrocell node model, with its internal stratum units, i.e. access stratum (AS) and non-access stratum (NAS), as well as its interfaces, i.e. S1 and X2, which are not fully available in the femtocell base station node model.

As our next assumption, despite the novel handover management in this chapter can be used for both macro-to-femto (inbound) handover and femto-to-macro (outbound) handover as part of the proposed algorithm, but, as was mentioned in the considerations section, the outbound algorithm does not need to be planned as complex as the inbound handover, because of the limited options of macro base stations in each cell. Therefore, to provide a more clear vision to follow the handover process from the source node to the destination node, the simulation scenarios are designed and demonstrated for the inbound handovers, in which a mobile node is handed over from a macrocell to a nearby femtocell base station.

Considering the mentioned assumptions in the simulation scenarios, the following parts explain the corresponding modules to configure and apply the novel handover checks in our simulation models.

4.5.4.1. Sensing Process with RSRP and RSRQ

In the handover sensing process, the cell preference value is calculated from the reference signal received power (RSRP) and reference signal received quality (RSRQ) values. In our simulations this function is generated in the function block of the eNodeB access stratum (AS) module called as *lte_enb_as* inside the eNodeB node model. The access stratum is a functional layer positioned between radio network and user equipment in the LTE wireless telecom protocol stacks [85], and is responsible for data transport over the wireless connection, as well as managing the radio resources. Figure 4-14 shows the UE and eNodeB node models with its internal modules.

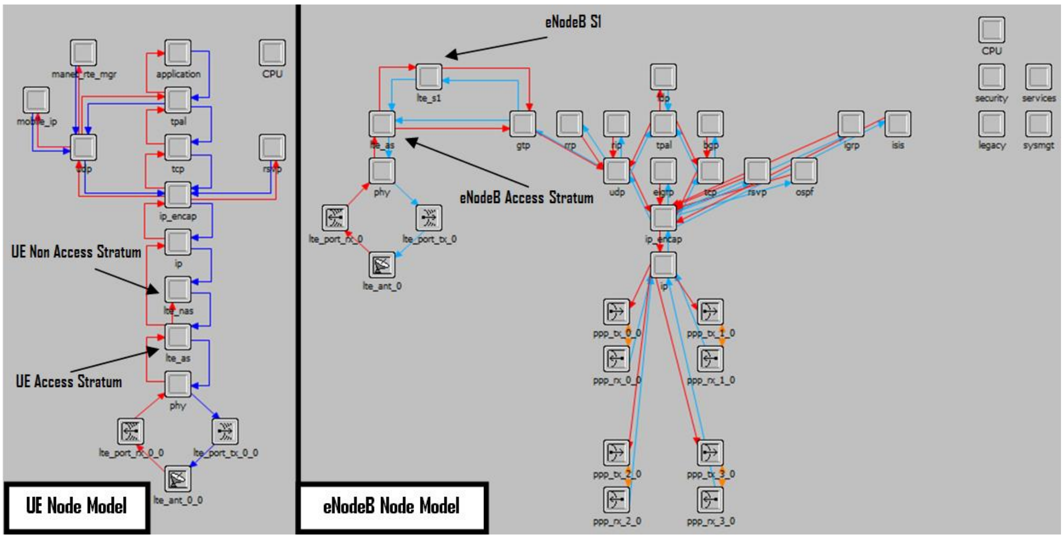


Figure 4-14: UE and eNodeB node models

4.5.4.2. Resource Availability Check with Resource Blocks (RBs)

To operate the resource availability check in handover decision process, the total number of resource blocks (RBs) is also calculated in eNodeB AS module named as *lte_enb_as* in the eNodeB node model.

4.5.4.3. Handover Opt. Check with Call Admission Control (CAC)

The call admission control (CAC) process is applied to the system as part of user Non-Access Stratum (NAS) module named as *lte_ue_nas* in the LTE user node model. The non-access stratum is also a functional layer, but positioned between the core network and user equipment in the LTE wireless telecom protocol stacks, which is responsible for maintaining continuous communications with the UE during its movement, as well as managing the establishment of communication sessions. The information is then passed over the internal link to the user AS module (*lte_ue_as*), followed by the forwarding of them to the same module in eNodeB (*lte_enb_as*) to be processed.

4.5.4.4. Femto over Macro Priority (FoMP) Check with Data Channels

The choosing process of the target femtocell station and the considered priority for the available femtocell nodes over the potential macrocells are applied in the eNodeB S1 module, named as *lte_s1* in the eNodeB node model. We already assumed femtocells as the target nodes for handover, however to evaluate the function of the novel FoMP process in the system, we also consider nearby macrocells as potential target nodes in the algorithm to apply the priority before selecting the destination (target) node. Decision in choosing one of X2 or S1 interfaces result in selecting a macrocell or femtocell as the target node respectively.

4.6. Simulation Results and Analysis

As was explained in chapter 3 for the results demonstration and analysis in simulation scenarios, the simulation results for the desired scenarios are exploited by 5-time simulation run (5 random seeds) in confidence interval (CI) of 95%, and the standard deviation, standard error and upper and lower distribution limits are calculated accordingly to show the error bars for each entire value. The following OPNET statistics are analysed through the simulations to compare the effects of the proposed comprehensive handover strategy in LTE-A networks:

Traffic End-to-End Delay: Average end-to-end delay experienced by the transmitted information, while travelling between the nodes, in seconds (sec).

Throughput: Total traffic delivered from LTE to the higher layers, collected by all base stations, in bits per second (bits/sec).

Total Number of Admitted GBR Bearers: Total number of admitted guaranteed bit rate (GBR) bearers available in access stratum (lte_as) unit of macrocell base stations.

Figure 4-15 shows the packet transmission process from the eNodeB and HeNodeB base stations to the users with and without predefined trajectories.

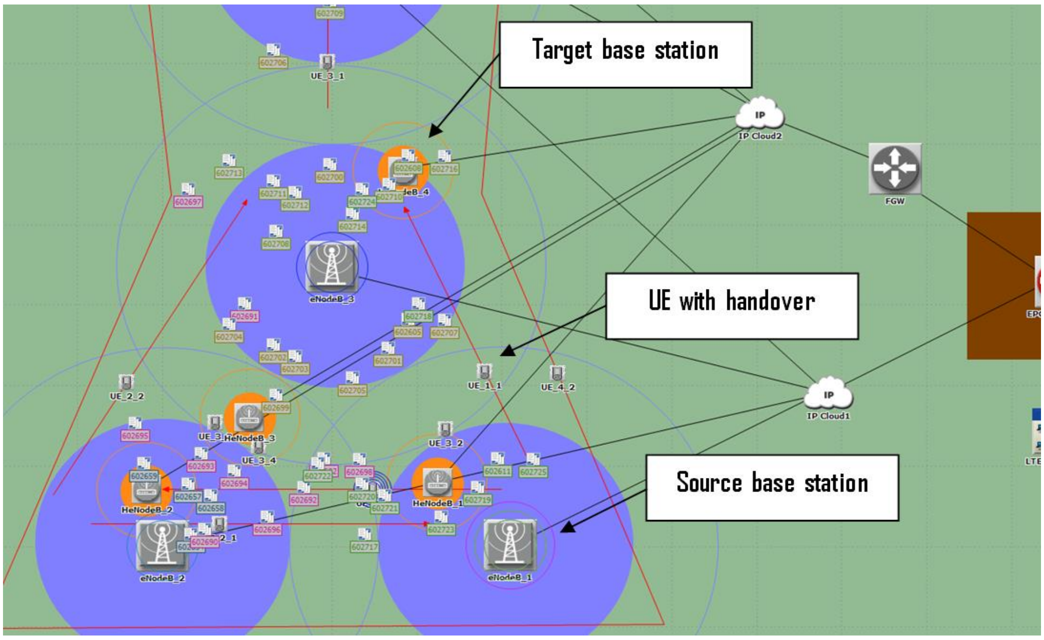


Figure 4-15: Handover process in OPNET simulation

The annotations in this figure show a specific mobile user (UE 1_1) with a predefined handover trajectory towards northwest, as well as its serving and destination nodes in the handover process. The target node will be selected according to the updated positioning information of the moving user, while the macro connection is consistent from the supporting eNodeBs during the UE traverse. The four configured scenarios are simulated in OPNET and different statistics are evaluated to present the improvements in admission control, transmission delay and packet delivery when we apply the novel handover algorithm. For each of the estimated statistics, the total of 100 simulation runs have been made to cover 5 simulation seeds for 4 handover scenarios in 5 different conditions of connection time or number of femtocell users (5×4×5=100).

The comparison in traffic end-to-end delay is shown in Figure 4-16 with the error bars for 95% confidence interval. The average handover latency for the users involved in the handover process is directly dependant to the value of end-to-end delay in the transmitted information. The proposed mobility management applies the comprehensive handover algorithm in LTE-A macro-femto combination, which speeds up the handover latency in the user roaming process, and finally results in notable decrease in traffic delay. The figure shows that although there are improvements in traffic delay when resource availability (RA) and call admission control (CAC) is applied in the system, but the best value relates to the proposed comprehensive handover technique to manage the users' mobility. Since the additional FoMP process in this scenario makes priority for the HeNodeBs over the available eNodeBs, part of the user congestion becomes offloaded from the main macrocell eNodeBs towards the nearest HeNodeB, which will also result in improved overall capacity of the network.

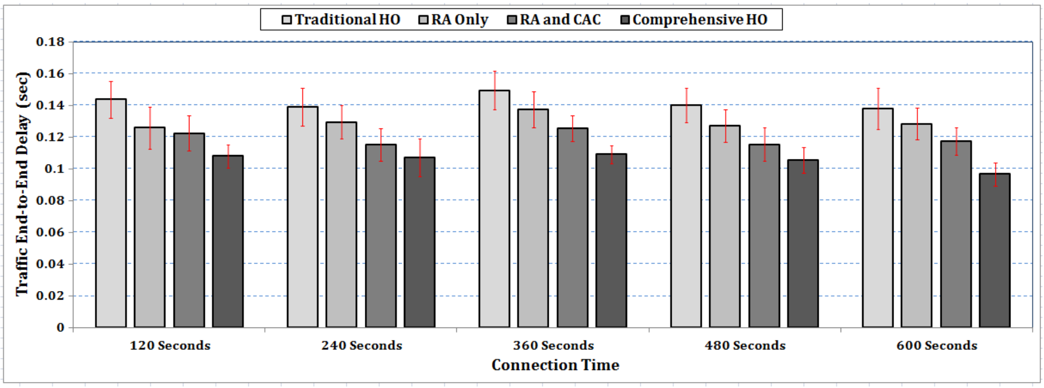


Figure 4-16: Traffic end-to-end delay with 95% confidence interval

In our simulation, considering the steady state values of the end-to-end delays in seconds for 600 seconds connection time, the values of traffic delay in the second and third scenarios are improved as about 6.9% and 14.8% respectively, while the improvement for the comprehensive handover (HO) technique is about 29.9%, as compared with the traditional handover scenario.

For network throughput analysis, additional UEs are inserted into the network to evaluate the network performance when a bigger part of existing users are supported by the nearby HeNodeBs rather than the existing eNodeBs. Figure 4-17 shows the comparison of average throughput between our handover scenarios in

95% confidence interval. The comparison has been made for different numbers of users allocated to the HeNodeB base stations. Compared to the traditional scenario for 50 femtocell users as an example, the improvements for the second and third scenarios are about 50% and 58%, while the improvement for the scenario with the proposed HO technique is about 67% compared to the traditional HO scenario. We also observe that the total throughput in the network is generally increased after allocating more users to use the femtocells. This result means providing higher data rates for the entire network and reaching to a higher network satisfaction for the subscribers.

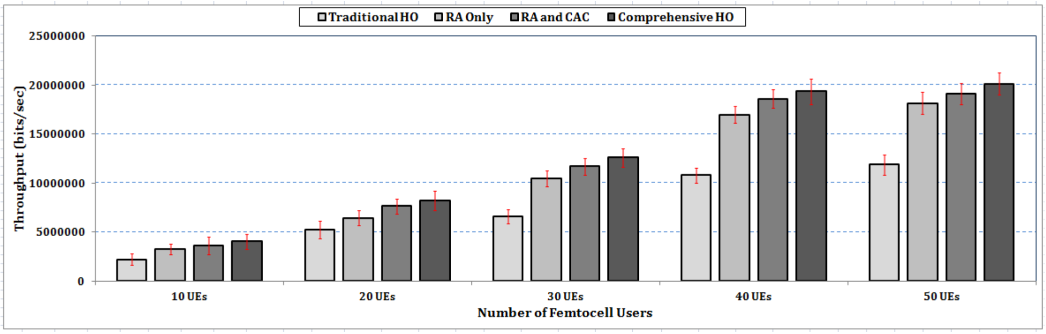


Figure 4-17: Network throughput with 95% confidence interval

For more detailed comparison, Figure 4-18 shows the improvement of throughput for all the scenarios, compared to the traditional HO scenario as the reference. In this figure, the percentage of improvements in this figure is not necessarily a function of femtocell users. It can just confirm that the value of improvement in throughput for the scenario with comprehensive handover algorithm remains higher than the other scenarios, either in a network with lower or higher number of the users allocated to femtocells. In either of the scenarios with more macrocell users or more femtocell users, applying a reliable handover mechanism with bandwidth optimisation, admission control and femtocell functionalities lead to obtain higher throughput in the network, which results in improved network capacity, as well as QoS, independent to the number of users in each network layer. This comparison proves that the proposed handover technique is the closest mechanism to the state of the art in HetNet mobility management, regardless to the users’ conditions in the network.

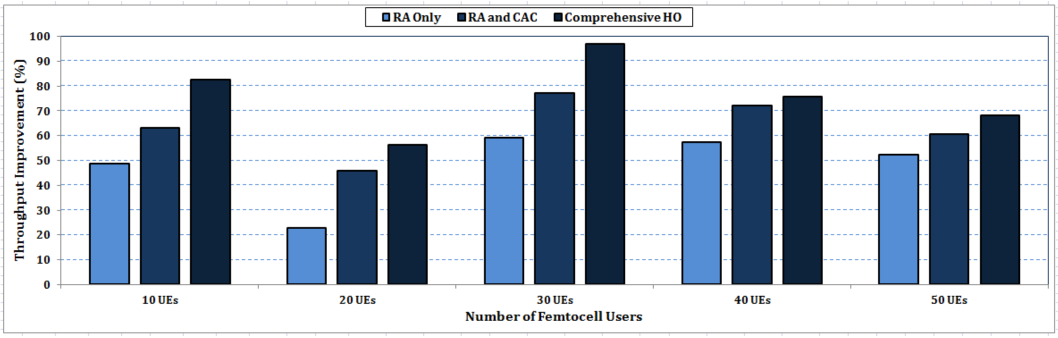


Figure 4-18: The throughput improvements from the Traditional HO scenario

The minimum bit rate expected to be available in networks with packet transmissions is defined with guaranteed bit rate (GBR) value in macrocells. In this context, a certain amount of the total bandwidth is always reserved for the data packet transmission, even if there is no traffic in an instant. The total number of admitted macrocell GBR bearers can therefore reflect the users' dependency to the macrocell as an important consideration in LTE admission control, which immunise the macrocell users from packet loss, while reducing the bandwidth optimisation in heterogeneous networks. In LTE-A heterogeneous networks, the lower value of admitted macrocell GBR bearers in macrocells can occur if the users are managed to be connected to the small cells, e.g. HeNodeBs, which is a sign of network dynamism. Figure 4-19 shows the admitted macrocell GBR bearers in different scenarios for different connection times from 2 minutes to 10 minutes. Since the number of bearers is an integer value with high accuracy in different simulation seeds, the error bars are expected to be set on zero for each of the bars in the graph.

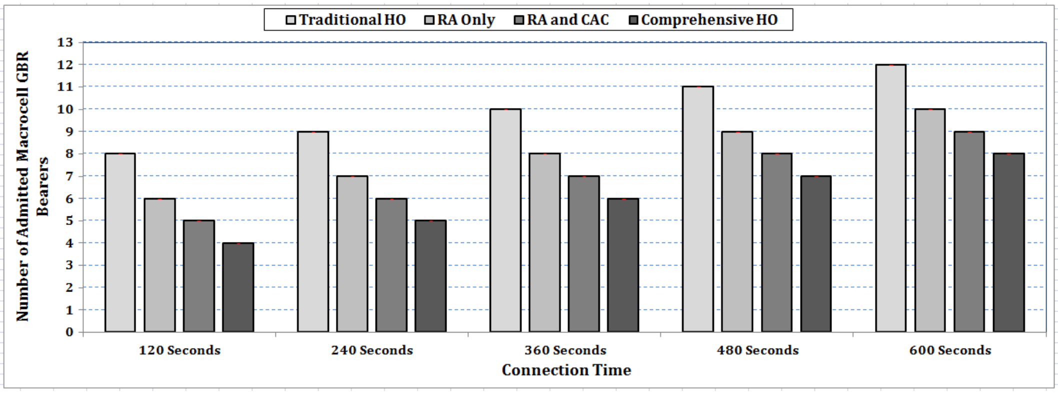


Figure 4-19: Number of admitted macrocell GBR bearers during handover

It is observed in the figure that the lowest number of admitted GBR bearers in each time period of the connection belongs to the proposed comprehensive handover scenario, because of its preference to forward more users to the available HeNodeBs. If to also compare the other three scenarios, the first scenario has the biggest numbers of admitted macrocell GBR bearers, compared to the other two scenarios, due to the more dependency of the users to the serving macrocells.

Compared to the traditional scenario where the connection time is 600 seconds, the number of admitted GBR bearers in macrocells decreased in the second and third scenarios by about 17% and 25% respectively, while this improvement is about 33% for the comprehensive handover scenario. Therefore, applying the handover management methods in heterogeneous networks leads to obtain more successful and optimised handovers, beside additional macrocell resource optimisation.

The analysed simulation results confirm that the proposed comprehensive handover technique, which simultaneous considers resource availability (RA), call admission control (CAC) and femto over macro priority (FoMP) checks, results in more improvements from the traditional handover management, compared to the RA-only and RA-and-CAC scenarios. This is due to the improvement of the comprehensive algorithm to include more checks before initiating the handovers. Furthermore, the additional FoMP process in the proposed method directs the mobile users towards the femtocell base stations, subject to availability, which results in improved network performance.

4.7. Summary

This chapter proposed a comprehensive handover strategy for LTE-Advanced heterogeneous networks which include macrocells and femtocells, to improve the mobility management in cellular platforms, while avoiding unnecessary handovers among the base stations. As was mentioned in the literature review, the existing research in this subject only considers one or two conditions from signal strength, resource availability and handover optimisation, as the decision making factors to initiate the mobile user handovers. While in this chapter, all the three mentioned conditions are designed to be checked by the proposed algorithm, plus an additional femto over macro priority check to unload a large part of user congestions from the macrocells. As the simulation results confirmed, the multi-check feature of the proposed comprehensive handover algorithm results in system improvement in both the desired aspects of quality of signal and mitigation of unnecessary handovers. The values of traffic end-to-end delay, throughput and total number of admitted macrocell GBR bearers were measured and analysed as the simulation performance statistics for different mobility management scenarios and the proposed comprehensive algorithm improvements compared favourably with the traditional mobility management algorithms for all simulation scenarios.

In conclusion to this chapter, applying a more inclusive algorithm for mobility management in HetNets, to consider resource availability and handover optimisation, as well as macro-femto selection, obtains the more optimum results, especially in congested networks, where using more femtocells improves the network coverage. Offloading a part of user traffic from the existing LTE macrocell base stations exploits both the macrocell and femtocell functionalities and helps to fulfil the user expectations.

Chapter 5 Inter-Cell Interference Coordination

Heterogeneous networks (HetNets) are constructed based on sub-network layers' cooperation between the main macrocell and shorter-range cellular base stations like micro, femto and relay nodes. This network cooperation allows innovative research solutions towards network satisfaction in the latest networks like LTE-Advanced (LTE-A). Nevertheless, since any network cooperation is expected to include a number of challenges, this cooperation is susceptible to the degrading effects, such as interference, among the sub-network elements and is required to find solutions to deal with it.

This chapter presents a self-organising interference coordination technique based on power control in the network, and relies on self-organising network (SON) management algorithms. The presented power control algorithm in this work is based on channel quality indicator (CQI) adjustments, mainly focused on the planned cooperation among macro and femto sub-networks within the central platform of LTE-A network. The consideration of SON attributes and statistics for the interference management is clarified as the main novelty of this chapter.

5.1. Chapter Introduction

The demands for ubiquitous coverage and higher data rates have been increasing in wireless networks industry, especially with more than one billion wireless subscribers today, which are predicted to be tripled over the next five years. In order to support the high demand for data traffic, the third generation partnership project (3GPP) LTE release has been offering significant advantages with respect to its predecessor, high speed packet access (HSPA), such as lower latency due to its flat all-IP network layer, higher spectral efficiency and larger throughputs at the physical layer. However, the international mobile telecommunications (IMT)-Advanced expectations for the new generations of the cellular networks are not completely satisfied by this release. Therefore, to fulfil the necessities, the new releases 10, 11 and beyond, introduced as LTE-Advanced (LTE-A), are currently under investigation [57,88,89]. On the other hand, self-organising networks (SONs) are expected to enhance the usage of radio resources, as well as simplifying network management and reducing the cost of operation [17]. Apart from the mentioned novel technologies and advanced features of this new release, the title of LTE-A is always accompanied with the dominant concept of heterogeneity within a unique characterization of a heterogeneous network (HetNet). As already mentioned, HetNets aim to obtain the utmost possible quality and capacity of the network, by making a configured cooperation between existing macro, and the shorter-range applications, e.g. micro, femto and relay nodes. However, this cooperation, beside its valuable benefits, would also bring some new challenges for network designers, such as interference due to sharing the channel between the higher and lower sub-networks (tiers), as is shown in Figure 5-1. The basic simulation results in previous research confirm that the inter-cell interference between macro and femto applications results in a huge packet drop at the network layer, which in turn results in the overall degradation in the network.

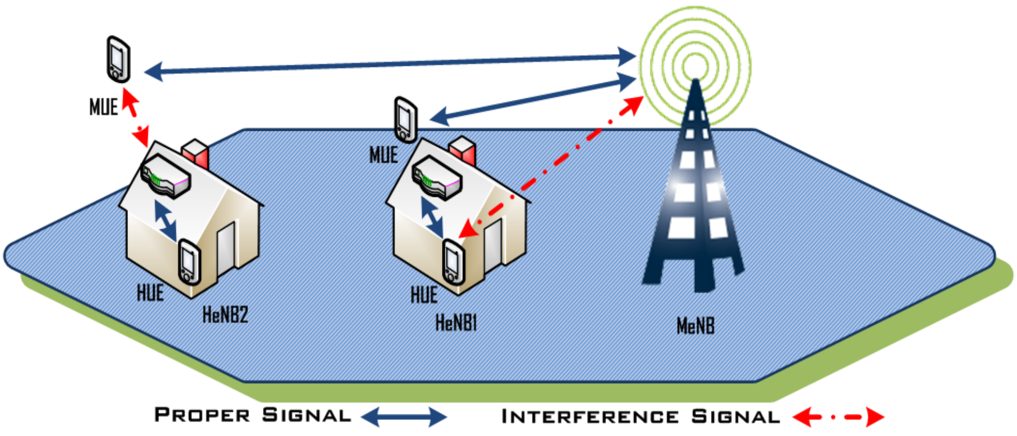


Figure 5-1: Inter-cell interference in HetNet sub-networks

Therefore, a smooth transmission platform should be planned by interference mitigation plan in the new releases of LTE-A systems [14]. Having an interference-free network platform operating at its optimum conditions, results in obtaining high bandwidth optimisation in the network, whist also providing the desired network capacity and QoS for the subscribers.

In LTE releases 8 and 9 the inter-cell interference coordination (ICIC) messages can be exchanged via the X2 interface between macro stations and short-range stations. The ICIC messages, which are transferred through the X2 interface, are listed as: relative narrowband transmit power (RNTP), overload indicator (OI) and high interference indicator (HII). However, despite such messages over the X2 interface having the capability to alleviate the inter-cell interference on microcells, picocells and relay nodes, this trend does not consider the full HetNet settings and principal scenarios, and so does not exist for femtocells. Therefore new interference coordination approaches need to be considered to deal with femtocell within the cells [88]. As a result of having no X2 interface between the first network layer (the main macrocells) and the second network layer (the femtocell stations), an alternative path is required to be selected through the network to initiate this communication. One possible solution is exchanging the information between macrocell and femtocell via the backhaul. Furthermore, because the same network operators may not be responsible for femtocell wire line backhauls, the delay also needs to be carefully considered.

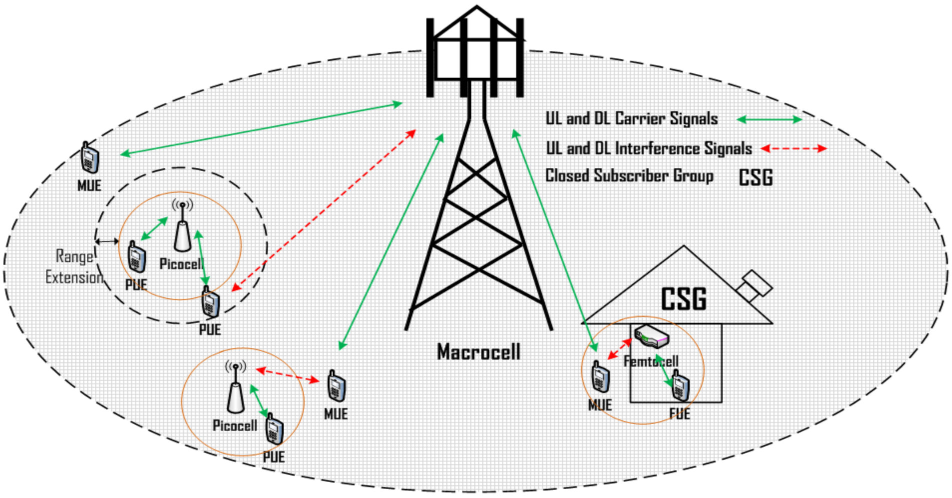


Figure 5-2: Cross-tier interference in presence of closed subscriber group

To overcome this difficulty, the applicable solution is introduced as using of UE to relay data between the neighbouring cells, or the exchange of messages between macro and femto nodes through the wireless channels, as is shown in

Figure 5-2. In case of inter-cell interference in this approach, for example, the victim macro user (MUE) could be detected either by macrocell or femtocell stations to take the best action through the backhaul connections.

To address the interference difficulties within the new LTE-Advanced systems, which are almost always based on HetNet characteristics, enhanced ICIC (eICIC) techniques have been investigated on recent releases, which are categorised into time-domain, frequency-domain and power control methods [88,90]. This chapter develops a novel power control algorithm for eICIC in which is relevant to the new releases of LTE-A, and which is based on SON strategy and simulated by OPNET modeler software. The proposed power control technique is based on the received SINR and the corresponding CQI to adjust the transmission power for interference coordination in a two-tier network.

5.2. Related Work

Various ideas have been investigated to apply interference mitigation in macro-femto heterogeneous networks. In case of downlink power control, in research [9], a downlink power control scheme is presented in LTE HetNet network, which is based on the reference signal received power (RSRP) report with the corresponding cell’s physical cell identity (PCID) and channel quality indicator (CQI). Femtocells are considered as low-power user-deployed base stations, which provide a high-quality cellular service in indoor environments via operating in licensed spectrum. In this work, the co-channel deployment of femtocells with a macrocell in a hierarchical cell structure is presented to keep the interference caused by femtocell low enough to have the least impact on the macrocell users in their proximity. However, the complexity of power control reports need to be considered when high number of various information types are included to forward the required messages.

Further to the downlink strategies, in the case of uplink power control, research [35] is concerned with the LTE/LTE-A uplink power control (ULPC) procedures in co-channel operation of macro and femto base stations in heterogeneous networks. The Uplink power control for LTE is defined by 3GPP as a combination of open and closed loop components. The open loop power control (OLPC) is responsible for a rough setting of UE transmit power and compensates slow changes of path-loss (including shadowing) in order to achieve a certain mean received signal power for all users. According to this work, there are two different cases of interference that might happen with uplink transmission in heterogeneous networks. First is the very high interference level that exists at the edge of a macrocell. This is because the macro-UEs transmit with high powers to overcome high path-loss towards their serving macro-eNBs located at a farther distance. The femto-UEs are the main victims in this case. The second case is the interference caused by a femto-UE on a nearby macro-eNB. Comparing these two different cases of interference in the uplink, the level of the interference at the edge of a macrocell that is generated by macro-UE is more intensive, and therefore the femto-UEs at such locations should use a higher power to overcome this interference. On the other hand, the femto-UEs close to the macro-eNB should transmit at a lower power to avoid causing interference to the macrocell.

Paper [1] focuses on multi-layer cell deployment when deploying femtocell nodes, and applying the self-organising concept in the network as the main contribution of the work. This work could open new doors by its novelties in multi-layer deployment for the networks, when the femtocell network layer shares the same frequency channels with the existing macrocells. The idea of multi-layer cell deployment is used in this research along with message forwarding process for power control. Furthermore in paper [91], authors propose a distributed method of ICIC based on dual decomposition for cellular networks. The proposed formulation decomposes the problem into a number of small sub-problems, each of which with an independent solution through an iterative sub-gradient method. The problems are also addressed with binary-valued variables within the proposed method. The simulation results with the proposed algorithm show the effectiveness of the algorithm with small number of iterations especially for femtocells, although it proposes a complex formulation with a large number of calculations.

In research [51] a different approach has been considered for interference coordination. The fractional frequency reuse scheme is used to manage the interference among different nodes in heterogeneous networks to ensure better QoS. This research focuses on evaluating three fractional frequency reuse (FFR) deployment schemes: strict FFR, soft FFR and FFR-3. Furthermore, a variation of the FFR-3, referred to optima static FFR (OSFFR) scheme is presented. In its results analysis, some performance values such as spectral efficiency, average network sum rate and outage probability are evaluated using Monte Carlo simulations. The simulation results of this work show the improvements of spectral efficiency (b/s/Hz) of the network for the suggested technique compared to the strict FFR, soft FFR and FFR-3 techniques. However, the presented method mostly focuses on interference avoidance and needs to be accompanied with dynamic power control techniques within a hybrid scheme to obtain the optimum results in LTE-A systems.

As a more usual implementation mode, femtocell users work in a closed subscriber group (CSG), in which only the users available on the subscriber list are allowed to join the network, while the remaining users can only use the macrocell as the public network. Paper [92] focuses on control channel interference mitigation in femto-overlaid LTE-A networks when the closed subscriber group is only allowed to access. In this case, only a limited number of subscribed users are served with femtocells, which interfere with both the control and data channels of the non-subscribed users. The paper mostly focuses on control channel interference in LTE-A networks overlaid by CSG femtocells, which is the main reason of link or access failures. The final results of this work shows the effect of the femtocell deployment density and control region load on the frequency domain, time domain, power control and resource allocation approaches inside the cell. The coordination seems to be a principal feature for carrier aggregation (CA) and almost blank subframes (ABS) schemes, while both the schemes can guarantee interference avoidance caused by coordinated interference nodes. Furthermore, power control and resource allocation techniques can be adapted to the interference level, while alleviating interference from the uncoordinated nodes.

The interference issue has been discussed as a main challenge in mobile networks, which is tied with bandwidth optimisation. The existing research in interference coordination of LTE systems are generally divided into two main categories. The first category relates to the techniques of resource allocation, which try to avoid the interference by allocating different sub-channels to macrocell and femtocell users. However in the second category, the investigations mostly relate to applying a power control strategy for uplink and downlink transmissions to reduce the number of interferences during the transmission. Nevertheless, both of the categories of interference coordination techniques have not fully considered self-organisation network management with low complexity in their proposed algorithms, which is the main novelty of this chapter to improve the network complexity and the cost of implementation.

5.3. Problem Statement

It is true to say that interference is the most dominant challenge in heterogeneous networks, when two or more network layers/tiers share the same frequency channels to cover their users. The intra-cell interference inside each cell is already avoided due to using OFDMA and orthogonality between the subcarriers [15]. Nevertheless, inter-cell interference among different base stations still needed to be highly considered, especially for the situations with higher transmission power. The high level of inter-cell interference results in huge packet drops, increases in BLER, which affect the SNR, and also deteriorates the throughput in whole the network. Figure 5-3 shows the possibilities of inter-cell interference in the network in the areas with high transmission power.

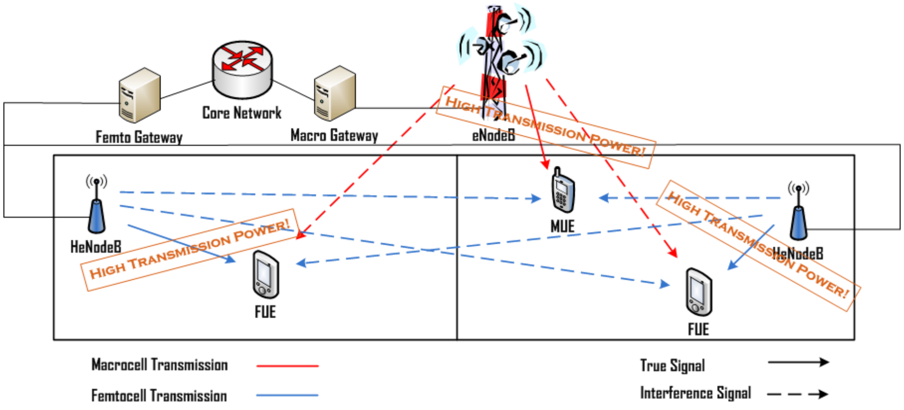


Figure 5-3: Interference in LTE-A caused by high transmission power

Different approaches are presented to deal with inter-cell interference in LTE-A, and a variety of techniques are being used, but with not enough attention to the network complexity. The proposed enhanced inter-cell interference coordination (eICIC) method in this chapter uses power control and self-organising techniques at the same time, to reduce the number of dropped packets for the end users caused by interference, while avoiding the increase in number of calculations and network complexity. This chapter mostly focuses on how to learn from the uplink channel, and then adjust the transmission power accordingly, which results in improvements in the level of interference, QoS and network throughput.

5.4. Inter-Cell Interference Coordination Categories

Based on the network characteristics and compatibilities, a range of coordination techniques have been investigated to alleviate the effects of interference in LTE and LTE-A networks. The additional network layers and interfaces in new releases have made additional capabilities in time and frequency domains possible, as well as power control techniques.

5.4.1. Inter-Cell Interference Coordination in LTE Releases 8 and 9

In LTE Releases 8 and 9 the ICIC messages are exchanged via the X2 interface between the existing base stations, i.e. macrocells, picocells and relay nodes. The ICIC messages, which are transferred through the X2 interface, could be listed as follows [88,93,94]:

Relative Narrowband Transmit Power (RNTP) Indicator: For DL transmissions, a certain cell uses an RNTP indicator transmission to inform the neighbouring cells on whether the transmit power for the specified resource blocks (RBs) will be set below a specific threshold value.

Overload Indicator (OI): The OI signal is used by a base station to notify the adjacent cells' base stations about the results of interference power (interference-plus-thermal-noise power) measurements for each RB and classifying of those results into multiple levels. The adjacent cells who receive the notification can adjust their transmission power to reduce the level of interference.

High Interference Indicator (HII): A certain base station uses HII to inform the neighbouring cells' base stations about uplink transmission (RB allocation) of one of its cell-edge users in near future. Therefore the neighbouring cells may withdraw from scheduling their own cell-edge users, or any users, in those specified RBs and allocate the users to different bands, just as in downlink approach.

However, despite having good influences to alleviate the inter-cell interference on different cellular base stations by such messages over the X2 interface, this approach does not exist for femtocells. Therefore, the network capabilities and interfaces need to be used to deal with femtocells in LTE-A networks.

5.4.2. Enhanced Inter-Cell Interference Coordination

To address the interference challenges and difficulties in new LTE-Advanced systems based on HetNet functionalities, such as macro-femto cooperation, the enhanced inter-cell interference coordination (eICIC) techniques have been recently investigated in LTE-A releases 10 and 11. The new eICIC techniques are generally categorised into three different approaches as shown in Figure 5-4.

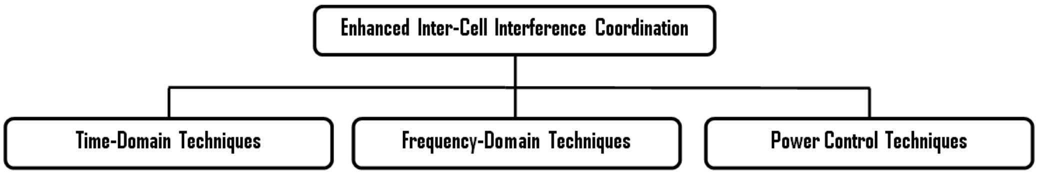


Figure 5-4: Different categories of eICIC technique

5.4.2.1. Time-Domain Techniques

In this approach, the serving cell (e.g. macrocell) stops transmission at a certain subframe, so the other cells (e.g. femtocell) gets the chance to transmit signal during the period when the macrocell has no transmissions. In other words, the transmission of the victim users is scheduled in time-domain resources, where the interference from other nodes is mitigated. Considering this definition, the time-domain approach is classified into the following two categories [88,95]:

1. Subframe Arrangement by ABSs: We expect some new challenges and difficulties if the transmission completely stops for a period of time. So the solution is transmission at a very low power instead of fully stopping the transmission. Those subframes with very low transmission power are called almost blank subframes (ABS). ABSs can be scheduled in femtocells, in which no data or control signals, but only the reference signals will be transmitted. Therefore, when there are some MUEs in the vicinity of a femtocell base station, they can be scheduled within the corresponding subframes, which overlap with ABSs in femtocells. This scheduling in the serving femtocell prevents the overlapping of data channels and control channels of macrocell and femtocell, as the main plan for inter-cell interference mitigation.

2. OFDM Symbol Shift: In this time-domain category, to avoid the overlap between the control channels of femto and macro signals, the subframe boundary of a femtocell station is shifted by a number of orthogonal frequency division multiplexing (OFDM) symbols with respect to the subframe boundary of a macrocell station. However the interference from the femto data channels to the macro control channels still remains. To address this problem, two solutions are presented. First is the shared-channel symbol muting, in which the overlapping OFDM symbols (with the control channels of the victim MUEs) are muted. The other solution is the consecutive subframe blanking at femtocells, in which the overlapping subframes of the femtocell (with the control channels of the victim MUEs) are arranged as ABSs.

As an important point, which was mentioned in the use of ABSs for interference mitigations between femtocells and macrocells, the reference signals still need to be transmitted by the femtocell and cannot be ignored or muted. The reference signal may lead to severe interference problems in some interference settings in the network [88], which is required to be considered in time-domain interference mitigations.

5.4.2.2. Frequency-Domain Techniques

In frequency-domain eICIC solutions, a general way to mitigate the inter-cell interference is the allocation of resource blocks (RBs) from multiple neighbouring cells in such a way that they do not overlap with each other. As more detail of frequency-domain solution, the synchronisation and reference signals of different cells are scheduled in reduced bandwidths to have entirely orthogonal transmission of the signals at different cells. This frequency-domain orthogonalization may be implemented dynamically through victim UE detection, either with macrocell or femtocell base stations [88]. As an example, the macrocell base station can detect the victim MUEs by utilizing the measurement reports of the MUEs and signal their identities to the femto station through the backhaul.

Alternatively as another example, the MUEs may also be detected by the femto station itself.

5.4.2.3. Power Control Techniques

One of the most recent and effective approaches to alleviate the inter-cell interference in HetNet is applying power control techniques at femtocells [96,97]. While the power reduction at femtocells may reduce the total throughput of femtocell users, it highly improves the performance of victim MUEs. The power control techniques mostly focus on downlink (DL) transmission, which is the main cause of interference between macro and femto. Different DL power control approaches can be generated in femtocells, each of which focuses on one different parameter through power control calculations, e.g. strongest eNodeB received power, pathloss between HeNodeB and macro user, objective SINR of femto user and objective SINR of macro user [88].

Our proposed eICIC technique in this chapter is a self-organising downlink power control technique, based on channel quality indicator (CQI) adjustments and transmission power amendments. However, the main focus in this approach is to present a simplified configuration including both SINR and CQI calculations, as well as power amendment algorithm within a single method, to apply a dynamic measure-report-amend process. Compared to the time-domain and frequency-domain approaches, the proposed eICIC approach is similar to stopping transmissions in some subframes by the aggressor node to protect the edge UEs in the protected cell, which is discussed in following sections.

5.5. System Model

In the proposed self-organising power control eICIC model, the CQI can be adjusted by estimating the interference caused by the aggressor Nodes. The three main phases of this power control technique is shown in Figure 5-5. As the first and second phases of the process, the signal to interference plus noise ratio (SINR) value is measured and the channel quality indicator (CQI) is calculated at the UE respectively. At the third phase, the CQI value is used to amend the transmission power of the base stations according to the received signal and channel quality requirements, to mitigate the high interference generated from the base stations to their neighbouring nodes.

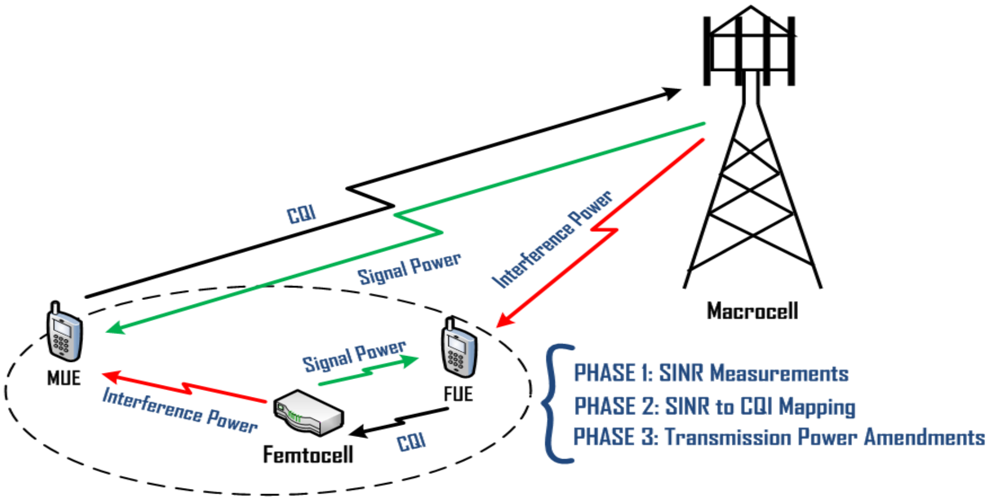


Figure 5-5: Main phases of the eICIC with power control

In downlink, the base stations which cause interference to the neighbouring mobile users are called as *Aggressor Nodes*, and the victim users are considered to belong to the *Protected Nodes*. We know this fact that femtocells are mainly considered as the secondary sub-network, which are added into the existing LTE system with macrocells. Since we are focused on femtocell configuration and applications in heterogeneous networks, the aggressor nodes in our model are considered as femtocell base stations, which need to amend their transmission power in case of interference, and the protected nodes are considered as macrocell base stations.

5.5.1. PHASE 1: SINR Measurements

The aggressor nodes stop transmission in some of the subframes in order to protect the edge UEs in protected cells, and might only transmit downlink reference signalling, such as the cell-specific reference signal (CRS), etc. The considered assumptions for SINR measurement are as follows:

- All the aggressor nodes deploy the same almost blank subframes (ABSs) configuration pattern.

- The special subframes are considered as downlink subframes. The reason is because each special subframe contains downlink pilot time slot (DwPTS), guard period (GP) and uplink pilot time slot (UpPTS), in which DwPTS occupies most part of the special subframe. DwPTS is used for downlink transmission like any other downlink subframe, but has a shorter duration.

- The protected node is aware of the positions of its users, as well as the position of all the other nodes (position information is provided by GPS and network configurations). Therefore it can estimate the distance between its associated UEs and the aggressor Nodes [98].

Figure 5-6 shows the basic subframes structure in aggressor and protected cells and the difference in their received SINR. Due to the time delay of CQI report, the measured subframe by the small cells may or may NOT be the same type (i.e. an almost blank, normal or protected subframe) as the true corresponding subframe of the CQI. So, if the CQI using and measuring subframes are different, the channel estimation will not be reliable, and therefore the selected modulation and coding scheme (MCS) index may result in transmission inefficiency or transmission failure. Therefore, using different CQIs for normal and protected subframes is necessary [98].

On the other hand, reporting multiple CQIs, i.e. the separate CQIs in normal and protected subframes, is not an appropriate solution due to the additional signalling, potential conflict and longer report period required. Hence, it is necessary to estimate the interference (SINR value) from the aggressor nodes and then adjust the reported CQIs of the UEs in the protected nodes, in order to reduce the signalling overhead of the CQI reports.

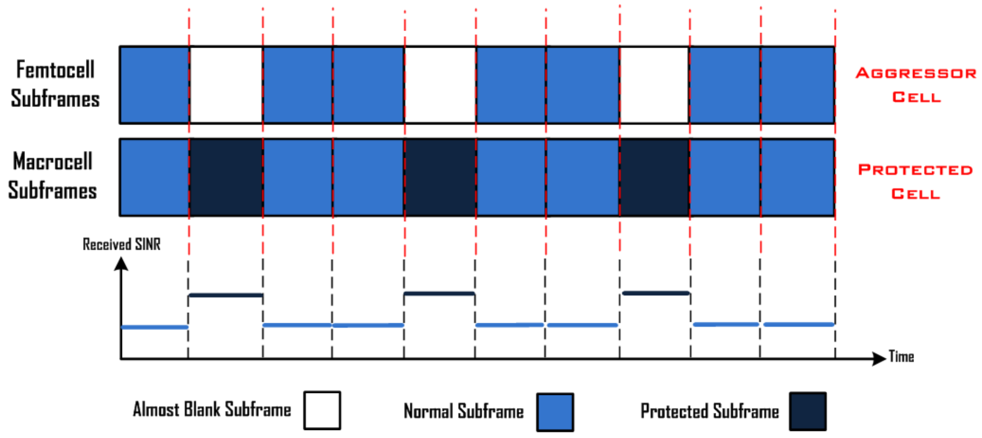


Figure 5-6: Subframe structure and SINR in different cell types

As a general process in SINR measurement and CQI report (phases 1 and 2), the ABS configuration of the aggressor node is reported to the protected node via its UE. The protected node can therefore arrange its worst UEs in the protected subframes. In this ABS configuration report, if no ABS is deployed, the UE (in the protected cell) can measure SINR at any time and report the corresponding CQI to the protected cell.

However, if ABS is deployed, the SINR measurement by the UE in a normal subframe and its use in a protected subframe to report to the protected cell results in selecting a lower MCS (due to the lower measured SINR) and so the improved channel quality (due to the blanked subframe in the aggressor node) will be wasted. Also SINR measurement in a protected subframe and its use in a normal subframe results to selecting higher MCS (due to the higher measured SINR) and so possibly results in transmission failure (because it does not match the poor channel quality). Therefore as a solution, the SINR measurement is restricted from the beginning by assigning a predefined bitmap to specify the subframes of SINR measurement. This predefined bitmap can be signalled to UEs via broadcasting or other signals by the protected node [98].

The protected node will later compare the SINR measurement subframe type with the current subframe type to determine if in this case the further CQI adjustment is required.

Figure 5-7 shows the SINR measurement using the SINR measure bitmap, when the SINR is measured in normal (blue) and protected (navy blue) subframes respectively. The downlink and uplink transmission subframes are denoted by letters D and U respectively, and letter S represents the explained special subframe. The CQI Adjust (CQIA) indicator is 1 in the bitmap when CQI needs further adjustment in the protected node, and is 0 when NO CQI adjustment is required.

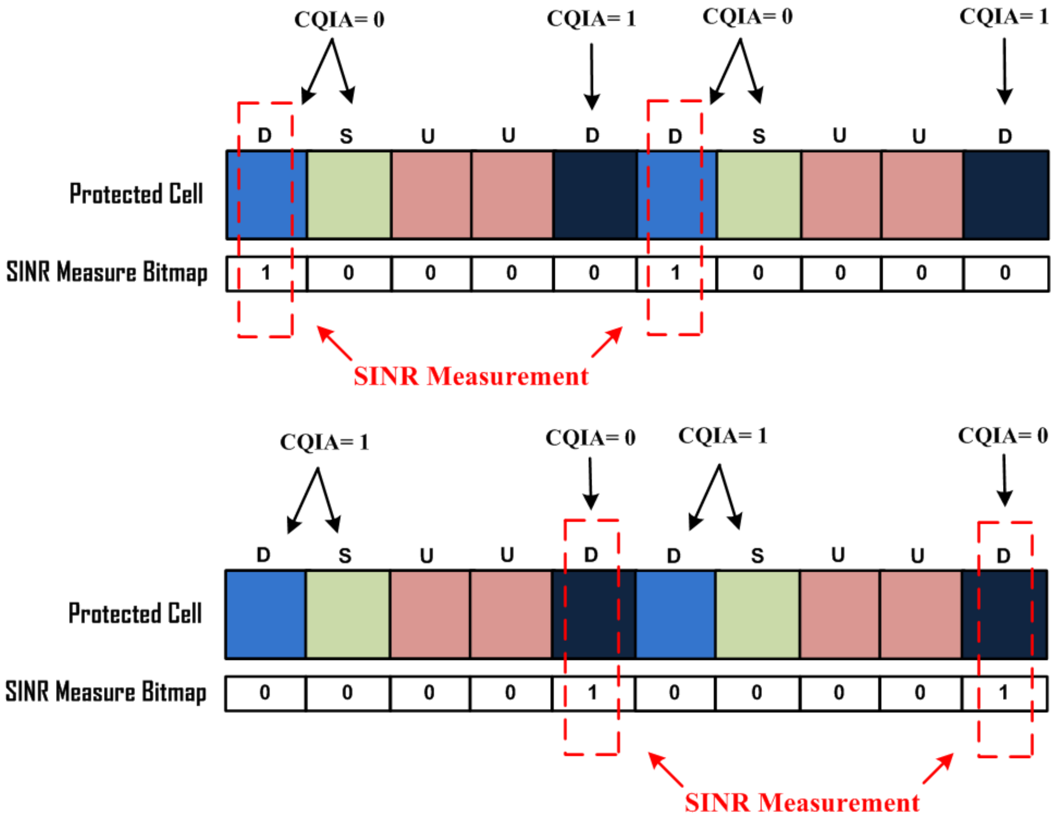


Figure 5-7: SINR measurement process using the SINR Measure Bitmap

The CQI adjustment at protected cell (in cases if required) will be initiated in different ways, such as using the historical CQI information [98]. However, further CQI adjustment in protected nodes will be performed at the cost of extra delays to assign protected subframes to the UEs. Hence, in our method, the CQI adjustment process is replaced with power amendment process inside aggressor base stations, as the final phase of our eICIC method.

A general scenario in SINR measurement is when the SINR is measured in normal subframes, which includes both interference from a protected node and a aggressor node [98]. Therefore, in a cellular system with M macrocells and F interfering femtocells, MUE v served by eNB m is interfered by other M-1 eNBs, as well as from the neighbouring HeNBs [99].

To calculate the received SINR in this scenario, the required parameters and their corresponding descriptions are shown in Table 5-1.

Table 5-1: Table of symbols for the SINR calculations

Symbol	Description
$P_{m,v}^{macro}$	*Received power from the serving macrocell*
$P_{i,v}^{macro}$	*Received power from the interfering macrocells (to the MUE)*
$P_{j,v}^{femto}$	*Received power from the interfering femtocells*
N	*Thermal noise power*
$P_{f,u}^{femto}$	*Received power from the serving femtocell*
$P_{i,u}^{macro}$	*Received power from the interfering macrocells (to the FUE)*
$P_{j,u}^{femto}$	*Inter-femtocell interference*
$P_{Tx,i}^{macro}$	*Transmitted power of the i*th *eNB*
$G_{Tx,i}^{macro}$	*Antenna gain of the i*th *eNB*
$H_{i,u}^{macro}$	*Normalised channel gain between the i*th *eNB and u*th *UE*
$L_{i,u}^{macro}$	*Pathloss between the i*th *eNB and u*th *UE*
$r_{i,u}$	*Distance between i*th *eNB and u*th *UE*
A, B	*Empirically calibrated parameters*

Considering different levels of signal powers received by a mobile UE, the SINR of the macro user (MUE) *v* is calculated by Equation (5-1).

$$SINR_v = \frac{P_{m,v}^{macro}}{\sum_{i=1,i\neq m}^{M} P_{i,v}^{macro} + \sum_{j=1}^{F} P_{j,v}^{femto} + N_v} \tag{5-1}$$

Furthermore, for the SINR of the femto user (FUE) *u* is also calculated by Equation (5-2) .

$$SINR_u = \frac{P_{f,u}^{femto}}{\sum_{i=1}^{M} P_{i,u}^{macro} + \sum_{j=1,j\neq f}^{F} P_{j,u}^{femto} + N_u} \tag{5-2}$$

The inter-femtocell interference is likely to exist only when the femtocells are densely located in indoor places. Further to this, although both the power and noise values typically change over time, but for simplicity, the time indices are omitted in our calculations and the formulas are valid for a snapshot in time [99]. The received power on UE for both macrocell and femtocell users is a function of several parameters, including the transmission power, antenna and channel gains and pathloss of the wireless link between the base station and the user. As an example, the received power of a FUE from the interfering macrocells is calculated by Equation (5-3).

$$P_{i,u}^{macro} = \frac{P_{Tx,i}^{macro} G_{Tx,i}^{macro} H_{i,u}^{macro}}{L_{i,u}^{macro}} \tag{5-3}$$

Regardless to the type of the received signal, the signal power is a function of the above mentioned transmitter and link parameters. Therefore, the same calculation is used to calculate the received power from the serving node in femto users, as well as the received power from the interfering macrocells and femtocells. The pathloss of the wireless link usually has an empirical value with the following typical form:

$$L_{i,u}^{macro} = A + B \ log \ r_{i,u} \tag{5-4}$$

The pathloss value is dependent on the distance between base station and mobile user, and other empirical parameters, which are defined according to the terrestrial fading parameters, such as wall penetration loss [99].

5.5.2. PHASE 2: SINR to CQI Mapping

As the second phase of the proposed eICIC method, the mobile users need to map the calculated SINR to the relevant channel quality indicator (CQI) value to be used later for power adjustments. One way to do this mapping is to use additional calculations to obtain an accurate model of this mapping, as explained in reference [100]. In this way, the effective exponential SNR mapping (EESM) calculation is used to obtain the CQI values by converting different gains of multiple sub-channels, through which a codeword is transmitted, into a single effective flat-fading gain with the same codeword error rate. In this technique, each user computes the accurate CQI value and feeds it back to the base station, which results in facilitating link adaptation. Although the accurate values of CQI are calculated in this way, the non-linearity of EESM makes the analysis of adaptation and scheduling difficult and complicated.

In our proposed model with OPNET network simulator, the operating CQI index is calculated as a function of target link quality in downlink, which is defined by the maximum acceptable block error rate (BLER), as well as the current SNR statistic. In this way, based on the target quality, an SNR metric defines the best operating modulation and coding scheme (MCS) index, which is later mapped into the CQI index [101]. Each CQI corresponds to a unique modulation and coding scheme (MCS) which contains information of modulation type, code rate and spectral efficiency according to the MCS-CQI mapping table, as is shown in Table 5-2. The function of SNR (or SINR) mapping into the MCS values, and then conversion to the corresponding CQI index is a predefined function in OPNET modules.

Table 5-2: MCS-CQI mapping table for transmission power adjustments

CQI Index	Modulation Type	Code Rate ×1024	Efficiency [bits/s/Hz]
0	Out of Range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

In case of quality improvements in the link, higher MCS index is supported for the target link quality, and therefore the CQI index is increased [60]. Later the quantised CQI index is sent from UEs to macrocell or femtocell base station and result is a finite solution set, which makes the power control easier.

The SINR is measured at the UE, compressed into 4-bit CQI by using of its MCS details, and sent back to the base station. Therefore, for high measured SINR, the eNodeB or HeNodeB can use high-order modulation and high coding rate for high spectral efficiency, and the node can use low-order modulation and low coding rate for error protection in channels with low SINR.

The CQI report is generally preferred to be used as an indicator of SINR to report the channel quality because of the downlink SINR level is typically unavailable at the base station in LTE systems. The reason of this preference is because CQI is the most accurate information available about the downlink SINR. Furthermore, in contrast with the continuous variable of SINR, the CQI is a discrete value and has a relatively small cardinality which can simplify the optimisation process [99].

5.5.3. PHASE 3: Transmission Power Amendments

In the last phase of the proposed eICIC technique, the aggressor base station amends its transmission power according to the user's reported CQI by the use of a self-organising algorithm. The dynamic downlink power control scheme in this work is based on user type identification. Since the femtocells are generally deployed by the end users, transmission in a closed subscriber group (CSG) is considered in this work [102].

The proposed power control technique gradually raises the transmission power from a minimum value until it reaches a value which satisfies the FUEs [99]. By using this algorithm, the QoS is guaranteed without causing huge interference to the other UEs. Figure 5-8 shows the process algorithm for power amendment (PHASE 3) in the eICIC method [99,103]. This algorithm is considering the femtocell base station as the aggressor cell, as was assumed in our previous phases.

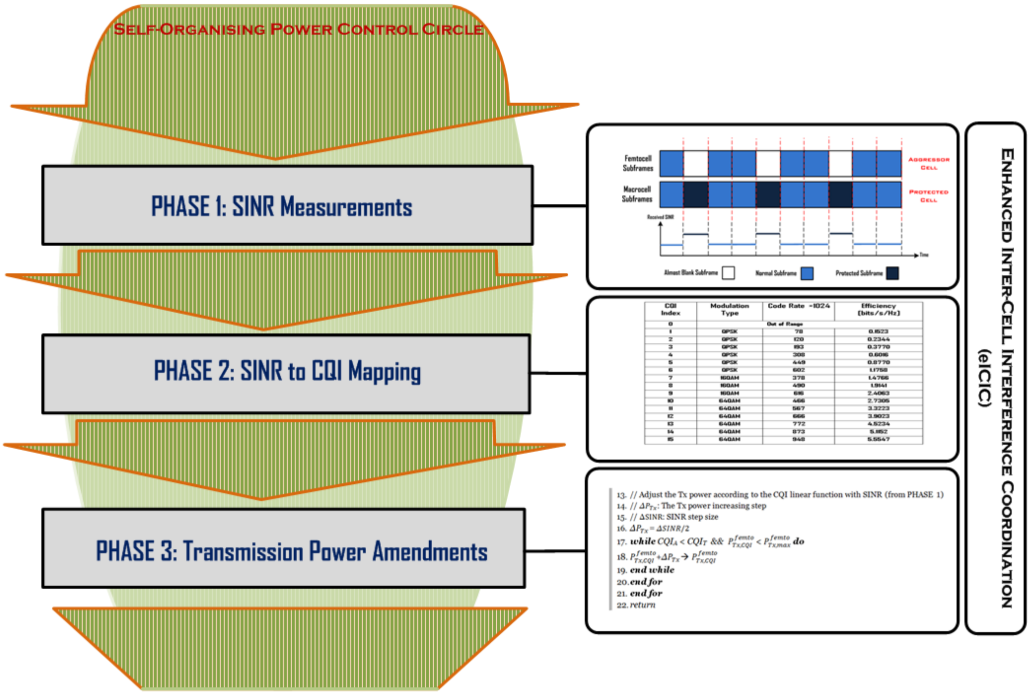
```
start
// Set the HeNodeB Tx Power to minimum
for the aggressor HeNodeB do
    $P_{Tx,min}^{femto} \rightarrow P_{Tx,CQI}^{femto}$
    // Calculate target throughput (=Sum of data rate demands of all the FUEs served by this HeNodeB)
    $\sum_{u=1}^{N_{UE}^{femto}} T_{target,u}^{femto} \rightarrow T_{target}^{femto}$
    // Calculate the required number of PRBs ($N_{PRB,u}^{femto}$) for each of its FUEs
    for all FUEs do
        $[\frac{T_{target,u}^{femto}}{T_{target}^{femto}} . ( N_{PRB}^{femto} - N_{UE}^{femto} + 1)] \rightarrow N_{PRB,u}^{femto}$
        // Calculate the spectral efficiency and use MCS-CQI mapping table again for $CQI_T$ (from PHASE 2)
        // $CQI_A$: Actual CQI, $CQI_T$: Target CQI
        $[map\left(\frac{T_{target,u}^{femto}}{N_{PRB,u}^{femto}}\right)] \rightarrow CQI_T$
        // Adjust the Tx power according to the CQI linear function with SINR (from PHASE 1)
        // $\Delta P_{Tx}$: The Tx power increasing step
        // $\Delta$SINR: SINR step size
        $\Delta P_{Tx} = \Delta SINR/2$
        while $CQI_A < CQI_T$ && $P_{Tx,CQI}^{femto} < P_{Tx,max}^{femto}$ do
            $P_{Tx,CQI}^{femto} + \Delta P_{Tx} \rightarrow P_{Tx,CQI}^{femto}$
        end while
    end for
end for
return
```

Figure 5-8: Self-organising power control algorithm based on CQI report

As illustrated in this algorithm, the HeNodeB first sets its Tx power to the minimum, followed by the target throughput calculation. The target throughput in the network is the sum of the data rate demands of all the FUEs served by the aggressor HeNodeB. This value is then used to calculate the required number of PRBs for each of the FUEs, which belongs to the aggressor HeNodeB. The algorithm uses both the target throughput and required number of PRBs to calculate the spectral efficiency. The efficiency values (in bit/s/Hz) exist in MCS-CQI table as the data rate of transmission over the given bandwidth. The calculated value of spectral efficiency is therefore mapped onto its corresponding CQI value, which is an integer index from 0 to 15. The power amendment algorithm puts this index as the target CQI value (CQI_T), which is the target point that the base station stops its Tx power increase. The base station keeps increasing its Tx power as long as the existence of the following two conditions persist: The first condition is if the actual CQI is still smaller than the target CQI, and the second condition is if the Tx power of the base station is still smaller than the maximum Tx power. To avoid the effects of nearby femtocells to each other, the power increasing step (ΔP_{Tx}) is defined as the half of SINR step size, which is obtained from PHASE 1. The power increase will stop at the point where any of these two conditions are changed, and the algorithm repeats this process by returning to the start point to form a self-organising power control algorithm.

5.6. System Implementation

In this section, the proposed 3-phase power control algorithm for eICIC is implemented into OPNET modeler network simulator to analyse the network performance in the presence of the suggested interference coordination. The SINR measurement, its mapping to the appropriate CQI index and the transmission power amendments are being repeated through a self-configuring algorithm, as is shown in Figure 5-9. An important point to mention is that the proposed power control method in this chapter aims to mitigate the inevitable interference in the system, when we use the same frequency in different network layers. In other words, there is no actual threshold of interference to activate or deactivate the transmission power adjustment in the system, but the implemented eICIC algorithm continues to check repeatedly and amend the base stations transmission power if needed.



CQI Index	Modulation Type	Code Rate ×1024	Efficiency [bits/s/Hz]
0	Out of Range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

```
// Adjust the Tx power according to the CQI linear function with SINR (from PHASE 1)
// $\Delta P_{Tx}$: The Tx power increasing step
// ΔSINR: SINR step size
$\Delta P_{Tx} = \Delta SINR/2$
while $CQI_A < CQI_T$ && $P_{Tx,CQI}^{femto} < P_{Tx,max}^{femto}$ do
$P_{Tx,CQI}^{femto} + \Delta P_{Tx} \rightarrow P_{Tx,CQI}^{femto}$
end while
end for
end for
return
```

Figure 5-9: Self-organising power control implementation

5.6.1. Simulation Parameters

To design, simulate and analyse the proposed power control algorithm for interference coordination in LTE-A system, a macro-femto network has been designed in OPNET modeler with the simulation parameters illustrated in Table 5-3.

Table 5-3: Simulation parameters for power control algorithm

Parameter	**Simulation Value**
Simulation Time	*600 sec*
Subframe Length	*1ms*
Subcarriers per PRB	*12*
Duplex	*FDD*
Bandwidth	*20MHz*
LTE Frequency Band	*1*
Uplink Access	*SC-FDMA*
Downlink Access	*OFDMA*
Terrain Model and Type	*Urban, Terrain Type A*
Propagation Model	*HATA*
Pathloss Model	*Outdoor to Indoor & Pedestrian*
SINR Measurement Period	*1ms*
eNodeB Min.Transmission Power	*38 dBm (6.31 Watt)*
eNodeB Max.Transmission Power	*41 dBm (12.59 Watt)*
HeNodeB Min. Transmission Power	*18 dBm (0.06 Watt)*
HeNodeB Max. Transmission Power	*21 dBm (0.12 Watt)*
Traffic Models	*VoIP, Video Conferencing*

The minimum and maximum values of transmission power for macrocell and femtocell base stations are configured as in the table to define a realistic range of transmission power, when the power control is applied to the system.

5.6.2. Simulation Scenarios

To evaluate the effects of self-organising power control method in interference coordination, four scenarios are made for simulation in OPNET modeler version 17.1 (64-bit). The simulated network platform is a LTE-A network with one eNodeB, one HeNodeB, and two mobile nodes as is shown in Figure 5-10. The number of cells and mobile users in this simulation has been minimised to focus only on channel interference with no effects from network load and congestion.

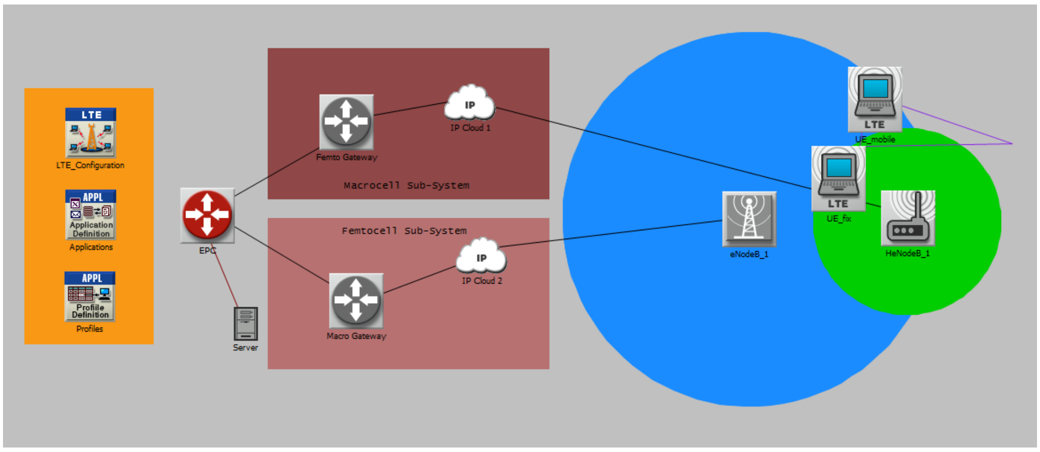


Figure 5-10: LTE-A simulation platform in OPNET for power control

The two cells in the simulations are configured with 20MHz FDD physical profile, which are based on OFDMA in downlink access and SC-FDMA in uplink access. The channel profile of eNodeB in all the scenarios is configured with the fixed values of 1.92GHz in uplink and 2.11GHz in downlink. However for HeNodeB, the physical profile attribute is promoted to OPNET higher level, which means that the frequency channel configurations and settings in each simulation run is adjusted by *LTE-Configuration* unit in the network. This configuration helps to make a parametric study on a single parameter in OPNET, e.g. channel setting, by allowing the simulation kernel to simultaneously run the simulation for different predefined values of a single parameter. In the first scenario, the HeNodeB physical profile is configured with 1.94GHz in uplink and 2.13GHz in downlink. In the second scenario the channel setting of the eNodeB remains same as its general setting, but for HeNodeB these values are set to 1.93GHz in uplink and 2.12GHz in downlink. However, in the third scenario, the physical profile values for HeNodeB are set to same as eNodeB, which is 1.92GHz in uplink and 2.11GHz in downlink. Since both the cells are configured with 20MHz FDD physical profile, it can be declared that in the first scenario there is no channel overlap between macrocell and femtocell sub-networks, called "*No Interference*" scenario. Furthermore, the channel overlap in the second scenario is 50% which is called "*Low Interference*" scenario, while the channel overlap between macrocell and femtocell in the third scenario is 100%, called as "*High Interference*" scenario. We also implement the forth scenario with the same channel settings as the High Interference scenario, but with the effects of our proposed power control algorithm inside the HeNodeB as the aggressor node in our simulation, which is named as "*Power Control*" scenario.

In our simulation, the femtocell user (UE_fix) is a fixed user with mobile user capabilities, but without any movement trajectories. This user has been designed as part of the indoor application closed subscriber group (CSG), so the serving base station ID for this user is fixed to its serving HeNodeB ID. However the macrocell user (UE_mobile) has been defined with a movement trajectory, which first moves away from its serving eNodeB and then changes its direction towards the neighbouring HeNodeB and moves back to its cell. This user is a free macrocell user, so its serving base station ID is set to perform cell search. To evaluate the packet transmission with Tx power adjustments and deferent levels of interference, two applications of voice over internet protocol (VoIP) and video conferencing are defined to be generated for both the fixed and mobile users during the packet transmissions.

5.6.3. Power Control Implementation in OPNET

To implement the explained power control algorithm into OPNET modeler, the radio transmitter pipeline is modified in our suggested network model. The functionality of a wireless link between LTE transmitter and receiver depends on different physical characteristics of the existing components, as well as time varying parameters which are modelled in the transceiver pipeline stages [60].

5.6.3.1. Transceiver Pipeline Model

The transceiver pipeline models the transmission of packets across a link, determines if a packet can be received at the link's destination, and implements the physical layer characteristics. As is shown in Figure 5-11, there is total of 14 stages with C/C++ codes in the pipeline model, each of which models a specific element of the channel, e.g. node location, antenna power, interference noise, propagation delay, etc.

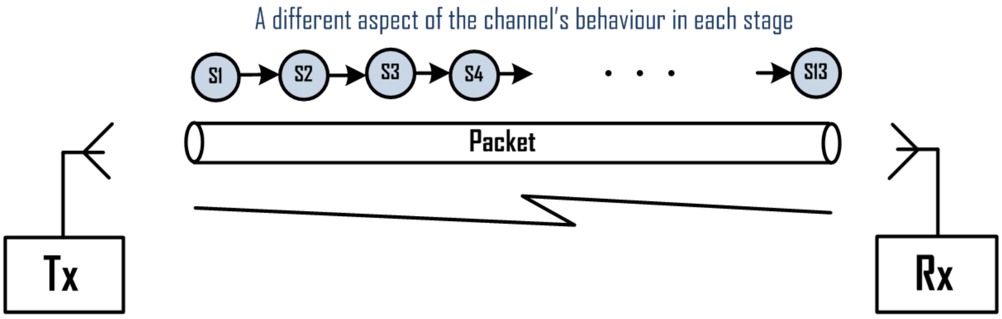
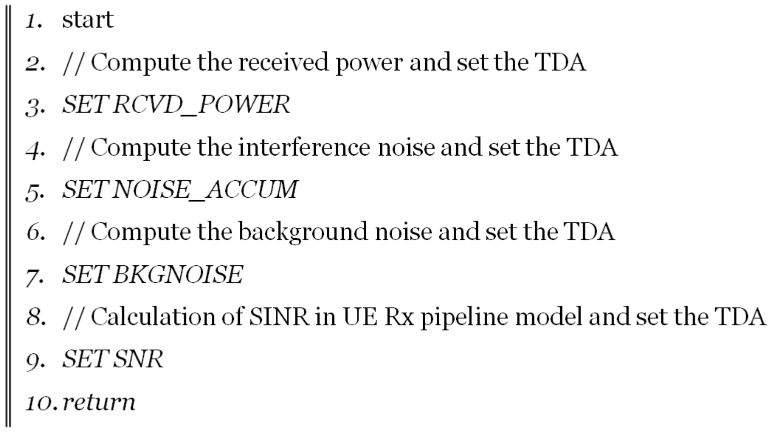


Figure 5-11: Transceiver pipeline model in OPNET

From the 14 stages in the transceiver pipeline model, 6 stages (0-5) are associated with radio transmitter (Tx) and 8 stages (6-13) are associated with radio receiver (Rx) and each stage performs a different function, such as SINR calculation. The simulation kernel calls each function at each stage of packet transmission only when it is needed [60]. Therefore, to speed up the simulation when a particular calculation is needed, e.g. transmission power, the other unnecessary stages in pipeline model are skipped and the fixed pre-defined values are used as the result of computation for the skipped stages.

5.6.3.2. Pipeline Model Modifications for Power Control

For SINR measurement in mobile users, stage 10 of the pipeline model is to compute the current average SNR, as the interference noise is included as part of the total received noise in calculations. The SINR value is based on received power, interference noise and background noise, which are obtained from stages 7, 8 and 9 of the pipeline model respectively. In these stages, special packet storage areas are called transmission data attributes (TDAs), which are designed as part of every packet to carry numerical values. TDAs are initialised by the simulation kernel at the start of transmission and are writable only in the pipeline to convey the link information from kernel to pipeline stage, pipeline stage to kernel and between pipeline stages. The Rx side of the mobile user typically calculates the received power in stage 7 based on the transmitter power and frequency, distance and antenna gains, and sets the value of *RCVD_POWER* TDA for the next stages. In stage 8 of the pipeline model, the interference noise is also calculated in Rx side without any interference mitigation at this level and computes the effect of noise on valid packets. The value of *NOISE_ACCUM* TDA is then set to accumulate the noise level of interfering packets to be used in next stages. As another requirement for the complete noise calculations in pipeline model, the background noise is also computed in stage 9, which typically includes thermal or galactic noise, emission effects from nearby network elements and other unwanted radio transmission effects. The value of *BKGNOISE* TDA is then set to save the computed background noise to be used for SINR calculation. Finally in stage 10 of the pipeline model, the current average SINR is calculated based on the computed values in stages 7, 8 and 9 and the value of SNR TDA is set. The received power for SINR calculation is obtained from *RCVD_POWER* TDA, the interference noise is obtained from *NOISE_ACCUM* TDA and the background noise is obtained from *BKGNOISE* TDA. As shown in Figure 5-12, the calculated SINR value is then used inside the UE node model to map into the appropriate CQI index for future power control amendments.



```
start
// Compute the received power and set the TDA
SET RCVD_POWER
// Compute the interference noise and set the TDA
SET NOISE_ACCUM
// Compute the background noise and set the TDA
SET BKGNOISE
// Calculation of SINR in UE Rx pipeline model and set the TDA
SET SNR
return
```

Figure 5-12: SINR calculation process in UE Rx pipeline stages

As shown in Figure 5.12, the calculated SINR value is then applied inside the UE node model to map into the appropriated CQI index for future power control adjustments. The CQI mapping calculations are available in the function block of *lte_ue_as* module which is located inside the UE node model.

5.7. Simulation Results and Analysis

In this section the simulation results in OPNET are presented and the effects of the self-organising power control algorithm in a simulated LTE-A macro-femto network are analysed. As mentioned in the prior sections, comparisons are made between four simulation scenarios, each of which uses different interference conditions between eNodeB and HeNodeB. The physical profile (channel settings) of the macrocell is set to a defined value, but this attribute is promoted to the higher level for HeNodeB. Since the focus of the analysis of this chapter is to compare the trend of statistics, and not necessarily the real-time values, therefore the exact OPNET figures are demonstrated with point to point or average values, to show the improvements in each instance of transmission duration.

Figure 5-13 shows different time sequences of packet transmissions in the two presented cells, while the femto UE is fixed and the macro UE follows its defined trajectory out and back to its serving cell.

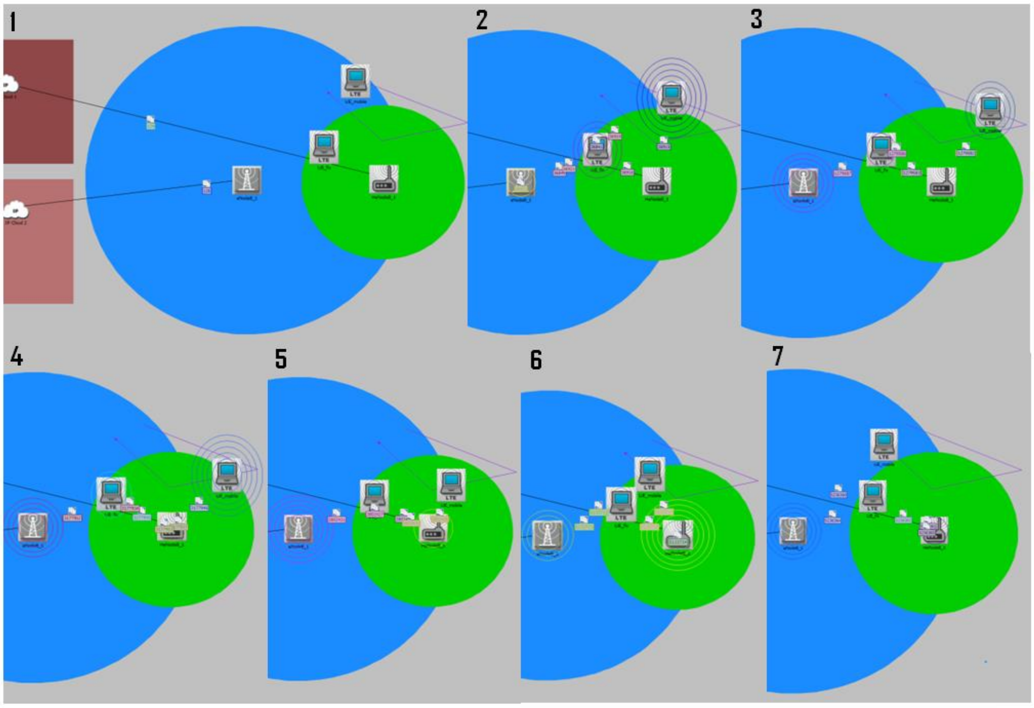


Figure 5-13: Simulation time sequences of packet transmission in OPNET

For the transmission duration of 420 second the following statistics are analysed in the presented scenarios [60]:

Average Uplink SNR: Value of signal to noise ratio in decibels (dB), measured at each base station for all packets arriving from a particular UE. The SNR equals to the value of signal to interference plus noise ratio (SINR) in OPNET, because the effects of interference noise is already included in the noise power value.

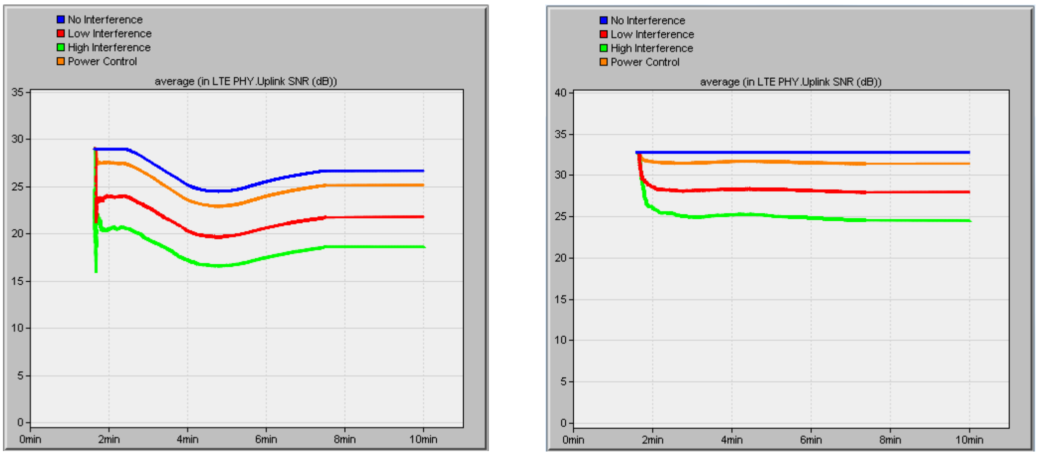
Average Uplink BLER: Value of block error rate in percent (%), obtained from the SNR-BLER curves in OPNET. The BLER is measured at each base station for all packets arriving from a particular UE.

Uplink Dropped Packet Rate: Rate of dropped packets in packets per second (packets/sec), in uplink hybrid automatic repeat request (HARQ). The dropped packet rate is only recorded when the maximum number of retransmissions are exceeded and the packet is dropped as a result at the HARQ layer.

Uplink Retransmission Rate: Rate of retransmissions in packets per second (packets/sec), on uplink HARQ. The retransmission rate does not include the first time transmissions of the base stations.

Uplink Delay: Uplink LTE layer delay in seconds (sec), which is measured from the time that traffic arrives to the LTE layer of the UEs, until it is delivered to the higher layer of the corresponding base stations.

Packet transmissions at LTE base stations in heterogeneous scenarios are generally started after the initialization period of about 100 seconds of simulation time `in OPNET simulations, in which the EPC and gateway units exchange primary information before sending packets into their serving base stations. Figure 5-14 shows the average uplink SNR for both the presented users in four simulation scenarios. In part (a) of this figure, it is observed that the average values of SNR initially drop when the mobile user moves away from its serving eNodeB towards out of the cell coverage area, but this drop gets compensated when the mobile user returns back to the cells. The changes in SNR value is because of pathloss, which is due to the node mobility across different cells. In the return trajectory, the mobile user first inters the HeNodeB boundary and switches its serving base station to a new node, and the serving base station is switched back to the eNodeB when the UE changes its direction again towards its own cell. For the fix user in part (b) of this figure, no dominant fluctuations are observed, which is because the node does not move during the transmission period. In both the figures it is seen that the closest SNR to the No Interference scenario belongs to the Power Control scenario. It is worth mentioning that the instantaneous drop in SNR still remains in No Interference and Power Control scenarios in case of the mobile user, duo to the continual effects of propagation delay, when the transmission distance is increased [60]. The propagation delay is part of end-to-end delay and depends on the values of wave propagation speed and distance, which affects the level of signal in SNR value.

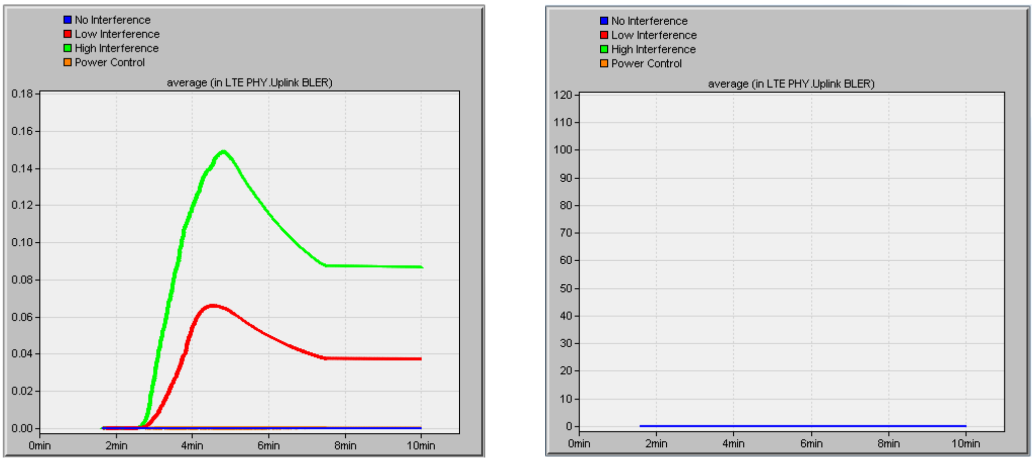


(a) **(b)**

Figure 5-14: Average uplink SNR for (a) mobile user, (b) fix user

The proposed power control technique results in obtaining the closest SNR values to the interference-free network, as the ideal case scenario. As a comparison, the average SNR for mobile user is improved by 15% and 35% when using the proposed power control for interference coordination, compared to Low Interference and High Interference scenarios respectively. The average SNR for the fixed user is also improved by 13% and 29% respectively.

The average uplink BLER for the users in each scenario is shown in Figure 5-15, which illustrates the rate of erroneous blocks through the packet transmission.

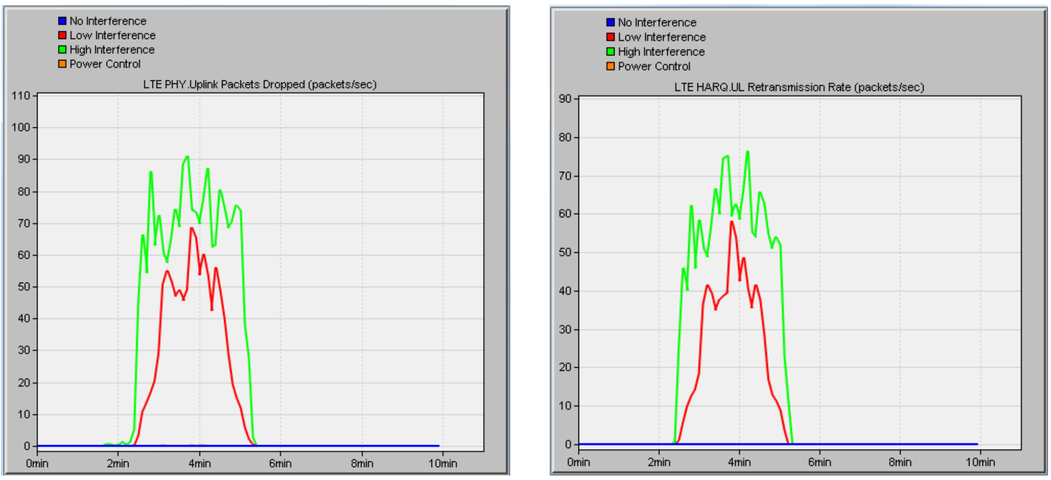


(a) **(b)**

Figure 5-15: Average uplink BLER for (a) mobile user, (b) fix user

For the mobile user, the highest BLER value belongs to the High Interference scenario, due to its higher number of unsuccessful packet deliveries from this particular user when it follows a movement trajectory. The average BLER for the Low Interference scenario with partial channel overlap is improved compared to the High Interference scenario with full channel overlap, while the average of BLER of the two scenarios with no interference and the proposed power control is very close to zero. On the other hand for the fix user in part (b) of this figure, it is observed that the average BLER for all the scenarios remain at zero, because of having no block errors during the packet transmission to the fix user.

In Figure 5-16 the uplink dropped packet rate and uplink retransmission rate are compared for the mobile user. In part (a), the mobile user packets drop around 4 minutes, when exactly the mobile user is at a maximum distance away from both the eNodeB and HeNodeB. This drop is much higher for the High Interference scenario than the Low Interference scenario. However the dropped packet rate for the other two scenarios remains zero. Furthermore in part (b), the retransmission rate is increased for that period to retransmit the dropped packets. The reason of having a lower retransmission rate compared to the packets dropped is because of incremental redundancy implementation in HARQ. This means when the MAC protocol data units (MPDUs including control information in MAC) are sufficiently small, redundant bits may also be included in the first packet transmission.

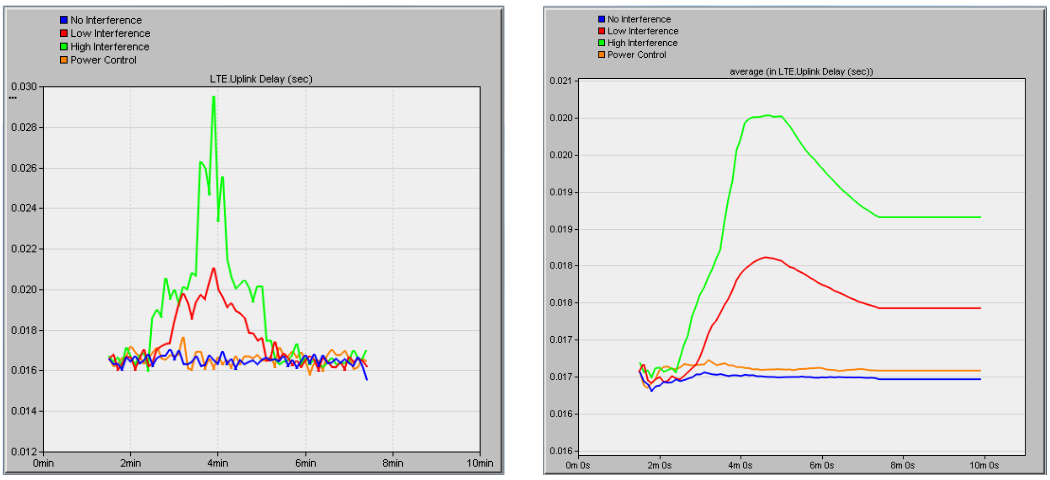


(a) **(b)**

Figure 5-16: Mobile UE's uplink (a) Packets dropped, (b) Retransmission rate

Therefore, even in case of the packet drops in the physical layer, the HARQ process may be able to decode them, and therefore there will be no HARQ retransmission. This case is also valid for the fix user, which there is no retransmission despite having small fluctuations in dropped packet graphs.

In Figure 5-17, the four scenarios are compared with their overall network (a) point to point uplink delay, and (b) average uplink delay during packet transmissions. As is expected, the highest transmission delay belongs to the High Interference scenario because of its more dropped packets and higher retransmission attempts.



(a) **(b)**

Figure 5-17: Overall network (a) Uplink delay, (b) Average uplink delay

The Low Interference scenario has lower transmission delay, but the transmission delay for the Power Control scenario is very close to the No Interference scenario with the ideal packet transmissions. The existing delays for these two scenarios relate to the transmission end-to-end delays, e.g. propagation delay, as was mentioned earlier about the mobile user. The self-organising power control algorithm at the aggressor node (HeNodeB) in our scenarios results in lower transmission delays in whole the network, and obtains higher QoS to support mobile users. These results show that at the simulation time of 4 minutes (when the mobile user is at the maximum distance away from the base stations), the exact value of uplink delay is improved by about 42%, when the proposed power control is applied, compared to the High Interference scenario.

The simulation results in this section confirm that applying of the novel inter-cell interference coordination based on power control, into the system with a shared channel, will mitigate the problems caused by interference. The increase in signal power, decrease in block error rate and packet drops, as well as improving QoS by reducing the overall transmission delay are important advantages reached by the suggested interference mitigation solution in this chapter.

5.8. Summary

Inter-cell Interference in heterogeneous networks is known as a key challenge, especially in new releases of LTE networks, where the small cells are densely applied in the same frequency as the macrocells for the reason of channel optimisation. So far a variety of methods have been investigated for interference mitigation, either as time-domain, frequency-domain and power control methods. In this chapter, a self-organising power control algorithm is presented as enhanced inter-cell interference coordination in LTE-A networks. The proposed model is based on CQI report, but with a self-organising trend, which is useful for heterogeneous macro-femto coordination. The algorithm includes three main phases in its process, which measures SINR on a regular basis, maps the value to its appropriate CQI index, and amends the transmission power of the aggressor node according to the received CQI index. The signal power measurements are mostly simulated in the transceiver pipeline model in OPNET, which includes a number of stages to compute a specific element of the channel. After the required measurements have been made, the power control amendments are performed with a self-organising algorithm to mitigate the inter-cell interference when sharing the same channel. The simulation results with OPNET confirmed that the LTE-A systems with suggested transmission power control algorithm have improved signal power and lowest packet drops and delays in the network.

Chapter 6 Conclusions, Discussion and Future Work

As the ending part of this research, this chapter produces the conclusions from the proposed network management techniques and the delivered contributions of the thesis. Furthermore, discussion on the effects of this research in relation to the state of the art, and suggestion of future work for further investigations in this subject are made at the end of this chapter.

6.1. Conclusions

The cellular network evolution has been extended in the last years to support the increasing demands for a ubiquitous wireless network, in which the quality of service is guaranteed with satisfactory network capacity. As an evolution to the existing LTE systems, LTE-Advanced offers higher data rate for a wide range of wireless applications and users, while its systems and functionalities are compatible with the earlier releases of LTE. The available techniques in LTE, e.g. carrier aggregation, multi-antenna transmission, relaying and cooperative multi-point transmission are widely used in LTE-Advanced, while the additional functionalities are proposed for additional bandwidth utilisation, e.g. heterogeneous network (HetNet) deployments. The implementation of long-range/high-power cells, such as macrocell base stations, in cooperation with short-range/low-power cells, such as femtocell base stations, within a larger cooperative network is a novel idea in this regard. This means, both the network tiers (now called as sub-networks) share the same frequency bands, which totally results in supporting a bigger number of mobile users, at the same time whilst keeping the bandwidth fully utilised. This thesis addresses the most critical challenges in heterogeneous LTE-Advanced network, by proposing the implementation of self-organising network (SON) solutions.

In this research, three main contributions to the LTE-Advanced systems are delivered in the thesis chapters 3, 4 and 5, which follow the general introduction and technical background about LTE and LTE-A network functionalities and self-organising network management, which are delivered in chapters 1 and 2 respectively. This thesis initially presents the multi-tier heterogeneous deployment of macrocell and femtocell and their restrictions and solutions when they are in cooperation, followed by the sub-channel allocation and resource management techniques in the network. The general information about the OPNET modeler network simulator, standard deviation and confidence interval, and also network statistical configurations are presented, which are widely used in all the delivered contributions. The novel channel allocation method is proposed based on hybrid fractional frequency reuse (HFFR) scheme, which aims to optimise the channel usage, overcome the potential co-tier and cross-tier interferences, and apply self-configuration inside the system layers. The simulation results in this part are collected for different network scenarios, with and without the proposed resource management algorithm in OPNET simulator. The results confirm that the proposed SON resource management technique improves the QoS by arranging the available frequency channels among macrocell and femtocell users. The network throughput is also improved in the system, which results in capacity enhancements, while reducing the network implementation and operational costs by applying femtocells in cooperation with macrocells. The next chapter of the thesis addresses the mobility management in heterogeneous network cooperation, by proposing a comprehensive handover strategy for HetNet LTE-Advanced systems. This section proposes a novel handover algorithm for macrocell and femtocell users with multiple checks, including the received signal strength and resource availability checks, as well as user residence calculations to avoid unnecessary handovers. Furthermore, the novel femto over macro priority (FoMP) check is also included in the algorithm, which results in directing more users towards femtocell base stations subject to availability and offloads traffic from the nearby macrocell base stations and results in service improvement in both macrocells and femtocells. The OPNET simulation results confirm that the comprehensive handover algorithm with multiple checks obtains more optimum results in quality of the received signal especially in congested networks, by reducing the number of unnecessary handovers in the system. Furthermore, offloading a large part of traffic form the macrocell base stations helps to fulfil the user expectations in all the parts of heterogeneous network. This research also proposes a direct solution to the inter-cell interference problem in heterogeneous networks. In the final contribution chapter of the thesis, the interference mitigation is presented based on transmission power control between macrocell and femtocell, as an effective method for enhanced inter-cell interference coordination (eICIC). First the different ICIC and eICIC techniques, such as time-domain and frequency-domain approaches, are discussed prior to our suggested model. Then, a novel 3-phase power control approach is proposed, including SINR measurement, CQI mapping and transmission power amendments all inside a single self-organising algorithm for the whole of the transmission period. At the final stage, the simulation results in OPNET confirm that by applying the self-organising power control algorithm as the suggested, the inter-cell interference coordination was enhanced thereby obtaining higher signal quality, as well as lower packet drops and network delays.

6.2. Summary of Thesis Contributions

This research reveals a number of contributions by proposing novel techniques in three contribution chapters, in addition to its overview of the subject. Below are the summary of main contributions and novelties of the thesis, which are suggested can be used in upcoming LTE-A releases to improve the overall network performance:

In chapter 3, a hybrid fractional frequency reuse model with a self-organising algorithm is proposed to firstly optimise the usage of the available channel by sharing the same frequency between macrocell and femtocell, secondly mitigate both the possible co-tier and cross-tier interferences by its hybrid method, and thirdly perform a self-configuring algorithm with less calculations between MAC layer and Network layer, to exchange the data inside the femtocell node model.

Chapter 4 presents a comprehensive handover algorithm to include both the received signal strength (as the handover sensing process) and resource availability, as well as additional handover initiation checks. So, this self-organising algorithm first makes sure about the necessity of handover in a particular time instance, and then instigates the handover if it is required. Furthermore, the novel femto over macro priority (FoMP) check chooses to direct more users towards femtocell base stations (if available) as the preference, rather than directing them into the near macrocells. This part of the algorithm improves the network performance in both the macrocell and femtocell sides by offloading the traffic from the macro base station and supporting them with low power femto base stations.

In chapter 5 of the thesis, an enhanced inter-cell interference coordination (eICIC) method is proposed based on a novel 3-phase power control algorithm, which includes SINR measurement, CQI mapping and transmission power amendments, all inside a unique self-organising algorithm. The power control algorithm is repeated for the full duration of network transmission to configure itself and make sure the transmission power does not exceed the allowed limit. Therefore, the possibility of inter-cell interference is lowered in LTE-A system by the application of repeating transmission power control from the start to the end of packet transmission.

6.3. Discussion

SON management in HetNets is an innovative approach to be used for a wide range of applications in many research white papers. The state of the art in this subject is an entirely smart system invention, which includes self-organising functionalities, machine to machine (M2M) connections, low network complexity, high resource efficiency and reduced expenditure, to facilitate reaching the foremost objectives in post-4G and future 5G cellular systems. This thesis basically focuses on the self-organizing functionalities and network solutions, as its main evaluated aspect, while the further aspects and requirements to obtain an entirely smart system in cellular networks still remain as open topics for further researches. A number of potential limitations also affect the research works in this subject, which of an important example is the need of system implementation into a real test bed with advanced hardware equipment. This requirement needs to be considered in the research works to obtain optimum results with a confident proof of financial expectations, when applying the novel network applications.

6.4. Future Work

After having completed the research into this investigated subject, a number of relevant further researches could be started as the future work. The following research titles propose a number of potential research issues, but obviously these further investigations are not limited to these topics:

6.4.1. Further Investigations on Spectrum Sharing

In chapter 3, the channel allocation for macrocell and femtoccel users are discussed based on fractional frequency reuse scheme, while taking into account additional issues about network applications. To initiate more optimised spectrum reuse, further research can be focused on the other methods of spectrum sharing process, such as using of a central controller unit in parallel with SON management algorithms, as well as deploying the other types of cellular base stations, such as picocells, in cooperation with the existing network.

6.4.2. Further Investigations on Handover Initiation

A comprehensive multi-check mobility management algorithm is proposed in chapter 4 to be implemented in handovers between macrocell and femtocell. The future work in this area is additional research to explore and implement further system control checks to obtain further improvements in handover optimisation process. As an example, the repeating handovers can be minimised by identifying the high-speed users and allocating them to a long-range base station, by using of appropriate relay nodes, which could reduce unnecessary inbound and outbound handovers.

6.4.3. Further Investigations on Interference Sensing

Chapter 5 of this research discusses the inter-cell interference coordination based on power control amendments. The self-organising algorithm runs on a regular basis and checks the network to keep the transmission power below a limit which is defined by CQI report. A potential work for the future in this section is to design an algorithm to predict and alert the interference, with high accuracy, before getting to the stage for power control amendments. This interference avoidance method will highly reduce the system complexity in new releases of the network, by eliminating part of internal interference calculations in the system.

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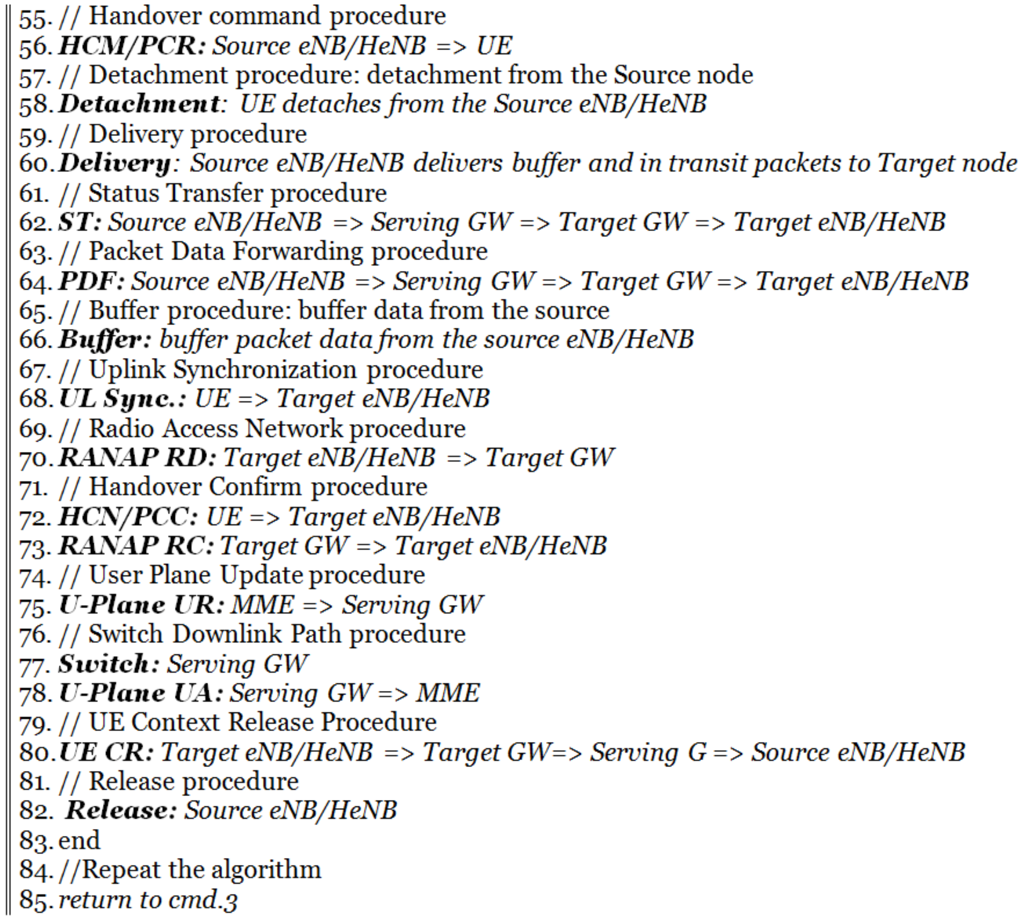
Appendix A

The remaining exchanged messages after the handover checks:



```
55. // Handover command procedure
56. HCM/PCR: Source eNB/HeNB => UE
57. // Detachment procedure: detachment from the Source node
58. Detachment: UE detaches from the Source eNB/HeNB
59. // Delivery procedure
60. Delivery: Source eNB/HeNB delivers buffer and in transit packets to Target node
61. // Status Transfer procedure
62. ST: Source eNB/HeNB => Serving GW => Target GW => Target eNB/HeNB
63. // Packet Data Forwarding procedure
64. PDF: Source eNB/HeNB => Serving GW => Target GW => Target eNB/HeNB
65. // Buffer procedure: buffer data from the source
66. Buffer: buffer packet data from the source eNB/HeNB
67. // Uplink Synchronization procedure
68. UL Sync.: UE => Target eNB/HeNB
69. // Radio Access Network procedure
70. RANAP RD: Target eNB/HeNB => Target GW
71. // Handover Confirm procedure
72. HCN/PCC: UE => Target eNB/HeNB
73. RANAP RC: Target GW => Target eNB/HeNB
74. // User Plane Update procedure
75. U-Plane UR: MME => Serving GW
76. // Switch Downlink Path procedure
77. Switch: Serving GW
78. U-Plane UA: Serving GW => MME
79. // UE Context Release Procedure
80. UE CR: Target eNB/HeNB => Target GW=> Serving G => Source eNB/HeNB
81. // Release procedure
82. Release: Source eNB/HeNB
83. end
84. //Repeat the algorithm
85. return to cmd.3
```